VOLUME 2 □ NUMBER 8 AUGUST 1965

IEEE spectrum

features

Departments: *please turn to the next page*

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

departments

the cover

The front cover is a reproduction of a scratch-board drawing of artist S. Sillman's interpretation of water. The world's need for potable water has been increasing at a rapid rate in proportion to the increasing population and decreasing water supplies. One answer to the shortage problem is to convert the salt water of the seas into pure water. Dual-purpose power generating and desalination plants are being planned. For a comprehensive discussion of the desalination problem, please turn to the article that begins on page 53.

Spectral lines

The IEEE's Manpower Requirements. Professional societies have a unique characteristic in being dependent on voluntary contributions of time and effort by members in order to operate. Yet as these societies have grown in size and complexity it becomes increasingly clear that systematic methods must be developed for locating among the members those capable of accepting significant responsibility for the development of the societies. Not only must able and willing individuals be located, but they must also understand the societies' problems in sufficient detail to be able to find appropriate solutions.

Consider some of the characteristics of the IEEE. It is a society of more than 130 000 members located in 104 countries. In addition it has more than 25 000 Student members attending a great number of educational institutions of widely ranging character. It has 183 Sections located in 23 countries. It has an annual budget in excess of $5 million. It employs a full-time staff of 275 people. It publishes 35 technical periodicals and many special publications, including standards, conference records, and various brochures. Its Sections publish 54 periodicals devoted to Section news. It sponsors or cosponsors an average of more than 80 nonlocal technical meetings a year in addition to the more than 2500 meetings per year sponsored at the Section level. It has a large number of committees and maintains relations with a large number of professional organizations and governmental agencies.

It is clear that an organization of this size and scope cannot be managed on an amateur basis nor can its operating policies and future planning be left to inexperienced or untested members no matter how well intentioned.

At the time of the merger of the AIEE and IRE, it was decided that a highly capable staff would have to be developed to handle the complex problems of the enlarged organization. Much progress has already been made by General Manager Fink in the development of this staff. Although there is room for improvement, it is clear that an adequate managerial structure is available, and means for coping with the problems of a staff nature are at hand.

However, the procedure of identifying and locating the talent needed in the voluntary service category is not as well-developed. Too frequently those members who have held responsible positions in the recent past are asked to undertake new duties simply because they are well-known to the present members of the Board of Directors and the Executive Committee. The net effect of this procedure is that the Institute tends to develop an ingrown character, and its major policy decisions are made by men who may not be closely enough in touch with newly developing areas of importance to the IEEE. It is clear that a more systematic "executive development program" is needed for the Institute. A means of identifying members who have demonstrated their capability in solving problems of both technical and administrative nature and are willing to devote time to Institute affairs is essential if the Institute is to develop far-sighted policies and to keep abreast of the rapid developments that are characteristic of today's technology and science.

Some steps were taken recently by the Executive Committee to develop such a procedure. The various organizational units of the IEEE, such as the Sections, Groups, and various Boards and committees, are being requested to recommend members who have done outstanding jobs, for nomination to those Boards and committees responsible for making the important decisions which will determine the future of the Institute. These recommendations should include sufficient documentation so that the individual's capabilities are clearly recognizable. It should also be recognized that seniority should not be the determining factor in making recommendations for such positions of increased responsibility. The need is for far-sighted and bold thinking as well as for sound judgment. The Institute should be run by those of its membership who are capable of directing its affairs with skill and foresight. *F. Karl Willenbrock*

1964 Nobel Lecture

Production of coherent radiation by atoms and molecules

The techniques of quantum electronics allow interesting new ways to generate and explore most of the acoustic spectrum and much of the electromagnetic domain. We can look forward to another decade of rapid development in this field

Charles H. Townes *Massachusetts Institute of Technology*

General and historical comments

From the time when man first saw the sunlight until very recently, the light which he has used has come predominantly from spontaneous emission, like the random emission of incandescent sources. So have most other types of electromagnetic radiation—infrared, ultraviolet, or gamma rays. The maximum radiation intensities, or specifically the power radiated per unit area per unit solid angle per unit frequency bandwidth, have been controlled by Planck's black-body law for radiation from hot objects. This sets an upper limit on radiation intensity—a limit which increases with increasing temperature, but we have had available temperatures of only a few tens of thousands or possibly a few millions of degrees.

Radio waves have been different. And perhaps without our realizing it, even much of our thinking about radio waves has been different, in spite of Maxwell's demonstration before their discovery that the equations governing radio waves were identical with those for light. The black-body law made radio waves so weak that emission from hot objects could not, for a long time, have been even detected. Hence their discovery by Hertz and the great use of radio waves depended on the availability of quite different types of sources—oscillators and amplifiers for which the idea of temperature and black-body radiation even seems rather out of place. For example, if we express the radiation intensity of a modern electronic oscillator in terms of temperature, it would typically be in the range 10^{10} to 10^{30}°K.

These two regimes, radio electronics and optics, have now come much closer together in the field known as quantum electronics, and have lent each other interesting insights and powerful techniques.

The development of radar stimulated many important applications of electronics to scientific problems, and what occupied me in particular during the late 1940s was microwave spectro copy, the study of interactions between microwaves and molecules. From this research, considerable information could be obtained about molecular, atomic, and nuclear structure. For its success, coherent microwave oscillators were crucial in allowing a powerful high-resolution technique. Consequently, it was important for spectroscopy, as well as for some other purposes, to extend their range of operation to wavelengths shorter than the known limit of electronic oscillators, which was near one millimeter. Harmonic generation and some special techniques allowed interesting, though rather slow, progress. The basic problem with electronic amplifiers or oscillators seemed to be that inevitably some part of the device which required careful and controlled construction had to be about as small as the wavelength generated. This set a limit to construction of operable devices.[1] It was this experimental difficulty which seemed inevitably to separate the techniques that were applicable in the radio region from those applicable to the shorter waves of infrared or optical radiation.

Why not use the atomic and molecular oscillators already built for us by nature? This had been one recurring theme which was repeatedly rejected. Thermodynamic arguments tell us, in addition to the black-body law of radiation, that the interaction between electromagnetic waves and matter at any temperature* cannot produce amplification since radiation at the temperature of matter cannot be made more intense by interaction of the two without violating the second law. But already by 1917, Einstein had followed thermodynamic arguments further to examine in some detail the nature of interactions between electromagnetic waves and a quantum-mechanical system. A review of his conclusions almost immediately suggests a way in which atoms or molecules can in fact amplify.

The rate of change of electromagnetic energy confined in a region where it interacts with a group of molecules must, on the basis of Einstein's work, have the following form:

$$\frac{dI}{dt} = AN_b - BIN_a + B'IN_b \qquad (1)$$

where N_a and N_b are the numbers of molecules in the upper and lower of two quantum states, which we assume for simplicity to be nondegenerate (i.e., single). A and B are constants, and thus the first and second terms represent spontaneous emission and absorption, respectively. The third term represents emission from the upper state produced by the presence of a radiation intensity I, and is hence called stimulated emission.

At equilibrium, when $dI/dt = 0$,

$$I = \frac{AN_b}{BN_a - B'N_b}$$

Rather simple further thermodynamic reasoning shows that $B' = B$ and gives the ratio A/B. Although Boltzmann's law $N_b = N_a e^{-W/kT}$ requires $N_b < N_a$ at any temperature T, it is immediately clear from (1) that if $N_b > N_a$, dI/dt will always be positive and thus there is amplification. This condition is, of course, one of nonequilibrium for the group of molecules, and hence it successfully obviates the limits set by black-body radiation. The condition $N_b > N_a$ is also sometimes described as population inversion, or as a negative temperature,[2] since in Boltzmann's law it may be obtained by assuming a negative absolute temperature.

Thermodynamic equilibrium between two states of a group of atoms requires not only a Boltzmann relation $N_b = N_a e^{-W/kT}$, but also a randomness of phases of the wave functions for the atoms. In classical terms this means that if the atomic electrons are oscillating in each atom, there must not be a correlation in their phases if the entire group can be described as in temperature equilibrium. Einstein's relation (1) in fact assumed that the phases are random. And if they are not, we have another condition which will allow the atoms to amplify electromagnetic waves, even when $N_b < N_a$. This represents a second type of loophole in the limits set by the black-body law and thermodynamic equilibrium, and one which can also be used alone or in conjunction with the first in order to produce amplification.

Thermodynamic arguments can be pushed further to show that stimulated emission (or absorption) is coherent with the stimulating radiation. That is, the energy delivered by the molecular systems has the same field distribution and frequency as the stimulating radiation and hence a constant (possibly zero) phase difference. This can also be shown somewhat more explicitly by means of a quantum-mechanical calculation of the transition process.

Stimulated emission received little attention from experimentalists during the 1920s and 1930s when atomic and molecular spectroscopy were of central interest to many physicists.

Later, in the 1940s, experiments to demonstrate stimulated emission were at least discussed informally and were on the minds of several radio spectroscopists, including myself. But they seemed only rather difficult demonstra-

* Strictly speaking, at any *positive* temperature. Negative absolute temperatures can be defined as will be noted subsequently.

tions and not quite worthwhile. In the beautiful 1950 paper of Lamb and Retherford on the fine structure of hydrogen,[3] there is a specific brief note about "negative absorption" with reversal of population. And a year later, Purcell and Pound[4] published their striking demonstration of population inversion and stimulated emission. As a matter of fact, population inversion and its effects on radiation had already shown up in a somewhat less accented form in the resonance experiments of Bloch[5] and others. But all these effects were so small that any amplification was swamped by losses due to other competing processes, and their use for amplification seems not to have been seriously considered until the work of Basov and Prokhorov,[6] of Weber,[7] and of Gordon, Zeiger, and Townes[8,9] in the early 1950s.

My own particular interest came about from the realization that probably only through the use of molecular or atomic resonances could coherent oscillators for very short waves be made, and the sudden discovery in 1951 of a particular scheme[8] which seemed to really offer the possibility of substantial generation of short waves by molecular amplification.

Basic maser principles

The crucial requirement for generation, which was also recognized by Basov and Prokhorov, was to produce positive feedback by some resonant circuit and to ensure that the gain in energy afforded the wave by stimulated molecular transitions was greater than the circuit losses. Consider a resonant microwave cavity with conducting walls, a volume V, and a quality factor Q. The quality factor is defined by the fact that power lost because of resistance in the walls is $\overline{E^2}V\nu/4Q$, where $\overline{E^2}$ is the electric field strength in the mode averaged over the volume and ν is the frequency. If a molecule in an excited state is placed in a particular field of strength E, the rate of transfer of energy to the field is

$$\left(\frac{E\mu}{\hbar}\right)^2 \frac{h\nu}{3\,\Delta\nu}$$

when the field's frequency coincides with the resonance frequency ν between the two molecular states. Here μ is a dipole matrix element for the molecular transition and $\Delta\nu$ is the width of the molecular resonance at half maximum (if a Lorentz shape is assumed). Hence for N_b molecules in the upper state and N_a in the lower state, the power given the field in the cavity is

$$(N_b - N_a)\left(\frac{E\mu}{\hbar}\right)^2 \frac{h\nu}{3\,\Delta\nu}$$

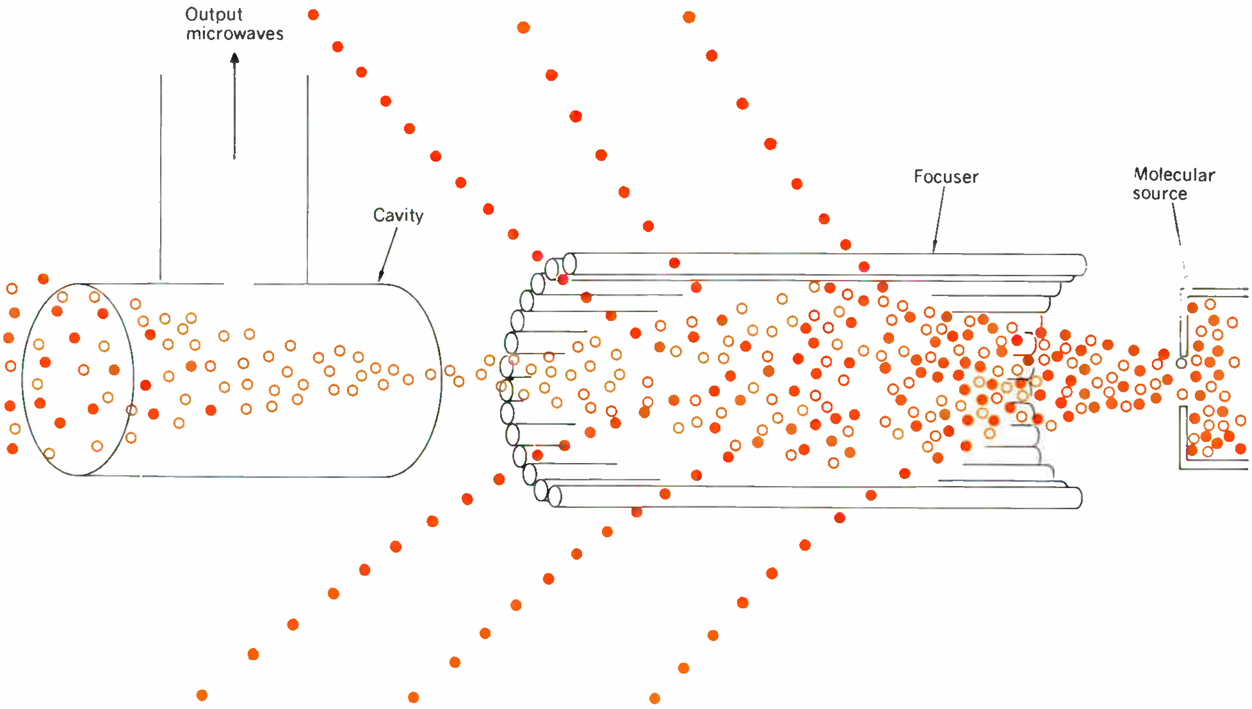
If the molecules are distributed uniformly throughout the cavity, E^2 must be averaged over the volume. For the net power gain to be positive, then,

$$(N_b - N_a)\left(\frac{\overline{E}\mu}{\hbar}\right)^2 \frac{h\nu}{3\,\Delta\nu} \geq \frac{\overline{E^2}V\nu}{4Q}$$

This gives the threshold condition for build-up of oscillations in the cavity

$$(N_b - N_a) \geq \frac{3hV\Delta\nu}{16\pi^2 Q\mu^2} \qquad (2)$$

There is by now an enormous variety of ways in which the threshold condition can be met, and some of them are strikingly simple. But the system which first seemed to give an immediate hope of such an oscillator involved a beam of ammonia molecules entering a resonant cavity, as shown in Fig. 1. The transition used was the well-known inversion transition of ammonia at 23 870 Mc/s. A "focuser," involving inhomogeneous electric fields, tends to remove molecules in the ground state from the



beam and to focus molecules in the excited state along the axis of the beam and into the cavity, thus ensuring that $N_b \gg N_a$. J. P. Gordon played a crucial role in making operable the first such system in 1954, after 2½ years of experimental work,[9,10] and H. J. Zeiger was a valuable colleague in the first year of work and early designs. We called this general type of system the maser, an acronym for microwave amplification by stimulated emission of radiation. The idea has been successfully extended to such a variety of devices and frequencies that it is probably well to generalize the name—perhaps to mean molecular amplification by stimulated emission of radiation. But in the radio-frequency range it is sometimes called the raser, and for light the term laser is convenient and commonly used. Maser amplification is the key process in the new field known as quantum electronics—that is, electronics in which phenomena of a specifically quantum-mechanical nature play a prominent role.

It is well known that an amplifier can usually be made into an oscillator, or vice versa, with relatively minor modifications. But it was only after experimental work on the maser was started that we realized this type of amplifier is exceedingly noise-free. The general reason for low noise can be stated simply. The molecules themselves are uncharged, so their motions, in contrast to motions of electrons through vacuum tube amplifiers, produce no unwanted electromagnetic signals. Hence a signal introduced into the resonant cavity competes only with whatever thermal noise is in the cavity as the result of thermal radiation from the cavity walls, and with spontaneous emission from the excited molecules. Spontaneous emission can be regarded for this purpose as that stimulated by a fluctuating field of energy $h\nu$. Since $kT \approx 200\, h\nu$ for microwaves in a cavity at room temperature, the thermal radiation kT in the cavity is much more important than spontaneous emission. It is, then, only the thermal radiation present that sets the limit to background noise, since it is amplified precisely as is the signal.

The above discussion also shows that, if the cavity is at 0°K and no extraneous noise enters the cavity with the input signal, the limiting noise fluctuation is determined by the spontaneous emission, which is equivalent to only one quantum of energy in the cavity. It can be shown, in fact, that masers can yield the most perfect amplification allowed by the uncertainty principle.

The motion of an electromagnetic wave is analogous to that of a mechanical harmonic oscillator, the electric and magnetic fields corresponding to position and momentum of the oscillator. Hence the quantum-mechanical uncertainty principle produces an uncertainty in the simultaneous determination of the electric and magnetic fields in a wave, or equivalently in determination of the total energy and phase of the wave. Thus one can show that, to the extent that phase of an electromagnetic wave can be defined by a quantum-mechanical operator, there is an uncertainty relation[11]

$$\Delta n\, \Delta\phi \geqslant \tfrac{1}{2} \qquad (3)$$

Here Δn is the uncertainty in the number of photons in the wave, and $\Delta\phi$ is the uncertainty in phase measured in radians.

Any amplifier that gives some representation of the phase and energy of an input wave in its output must, then, necessarily involve uncertainties or fluctuations in intensity. Consider, for example, an ideal maser amplifier composed of a large number of molecules in the upper state interacting with an initial electromagnetic wave, which is considered the signal. After some period of time, the electromagnetic wave will have grown to such magnitude that it contains a very large number of quanta and hence its phase and energy can be measured by classical means. By using the expected or average gain and phase relation between the final electromagnetic wave and the initial signal, the maser amplifier thus allows a measurement of the initial wave.

A calculation by well-established quantum-mechanical techniques of the relation between input and output waves shows that this measurement of the input wave leaves an uncertainty just equal to the minimum required by the uncertainty principle.[11] Furthermore, the product $\Delta E\, \Delta H$ of uncertainties in the electric and magnetic fields has the minimum value allowed while at the same time $(\Delta E)^2 + (\Delta H)^2$ is minimized. The uncertainty in number n of quanta in the initial wave is

$$\Delta n = \sqrt{n+1}$$

and in phase it is

$$\Delta\phi = \frac{1}{2\sqrt{n}}$$

so that

$$\Delta n\, \Delta\phi = \frac{1}{2}\sqrt{\frac{n+1}{n}}$$

The phase has real meaning, however, only when there are as many as several quanta, in which case $\Delta n\, \Delta\phi \to \tfrac{1}{2}$, the minimum allowed by (3). The background noise that is present when there is no input signal ($n = 0$) is seen to be equivalent to a single quantum ($\Delta n = 1$) of input signal.

Fig. 1. The ammonia (beam-type) maser. Molecules diffuse from the source into a focuser, where the excited molecules (open circles) are focused into a cavity and molecules in the ground state (solid circles) are rejected. A sufficient number of excited molecules will initiate an oscillating electric field in the cavity, which is emitted as the output microwaves. Because of energy given to the field, some molecules return to the ground state toward the end of their transit through the cavity.

A somewhat less ideal maser might be made of N_b and N_a molecules in the upper and lower states, respectively, all interacting with the input signal. In this case fluctuations are increased by the ratio $N_b/(N_b - N_a)$. If the amplifier has a continuous input signal, a continuous amplified output, and a bandwidth for amplification $\Delta\nu$, the noise power output can be shown to be equivalent to that produced by an input signal[12]

$$N = \frac{h\nu\,\Delta\nu}{1 - (N_a/N_b)}$$

The noise power N is customarily described in terms of the noise temperature T_n of the amplifier, defined by $N = kT_n\,\Delta\nu$. Thus the minimum noise temperature allowed by quantum mechanics is that for a maser with $N_a/N_b \ll 1$, which is

$$T_n = \frac{h\nu}{k} \tag{4}$$

This is equivalent to the minimum energy uncertainty indicated above of one quantum ($\Delta n = 1$). In the microwave region, T_n given by (4) is approximately 1°, whereas the best other microwave amplifiers when maser amplifiers were first being developed had noise fluctuations about 1000 times greater.

It is interesting to compare an ideal maser as a detector with a perfect photodetector, such as a gamma-ray counter. The gamma-ray counter can detect a single photon with almost no false signals, whereas a maser must always have a possible false signal of about one photon. But the photodetector gives no information about the phase of the signal; it only counts quanta, which is why the uncertainty principle allows $\Delta n \to 0$. Unfortunately, there are no perfect photodetectors in the microwave or radio regions, so the maser is our best available detector for these waves.

The same freedom from noise that makes the maser a good amplifier helps make it a strikingly good source of monochromatic radiation since, when the threshold condition is fulfilled and the maser oscillates, the low noise implies that there is a minimum of random frequency fluctuations.

Consider now a maser oscillator consisting of a group of excited molecules in a resonant cavity. Let the molecular transition frequency be ν_m, its half width at half-maximum intensity $\Delta\nu_m$, and the resonant cavity frequency be ν_c with a half width $\Delta\nu_c$. If ν_m and ν_c differ by much less than $\Delta\nu_m + \Delta\nu_c$, the radiation produced by the oscillation can be shown to occur at a frequency[13]

$$\nu = \frac{\nu_m Q_m + \nu_c Q_c}{Q_m + Q_c} \tag{5}$$

where the quality factors Q_m and Q_c are $\nu_m/\Delta\nu_m$ and $\nu_c/\Delta\nu_c$, respectively. Thus if the molecular resonance is much sharper than that of the cavity, as in the ammonia beam maser ($Q_m \gg Q_c$), the frequency of oscillation is given by[10]

$$\nu = \nu_m + (\nu_c - \nu_m)\frac{Q_c}{Q_m} \tag{6}$$

If the cavity is tuned so that $(\nu_c - \nu_m)$ is small, then the frequency of oscillation coincides very closely with the natural molecular frequency ν_m, and one has an almost constant-frequency oscillator based on a molecular motion—a so-called atomic clock.

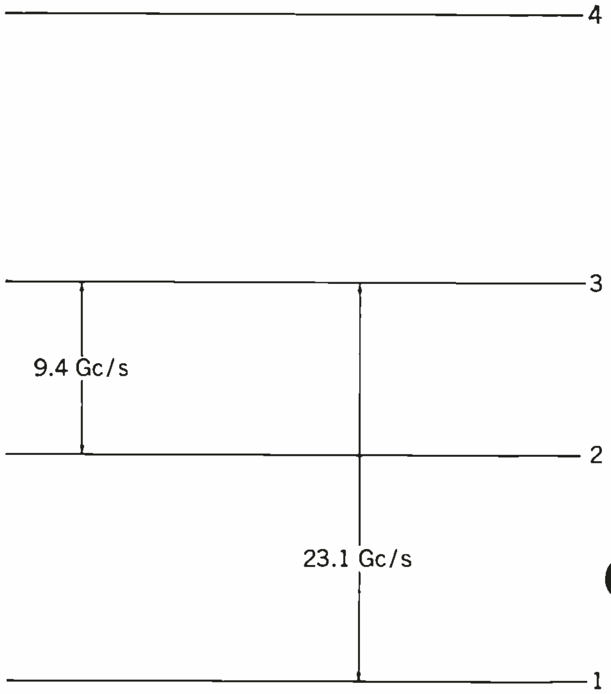
The frequency ν is not precisely defined or measurable because of noise fluctuations, which produce random phase fluctuations of the wave. In fact, the maser is essentially like a positive feedback amplifier which amplifies whatever noise source happens to be present and thereby produces a more-or-less steady oscillation. If Q_m or Q_c is high, and the amplifier gain is very large, then the bandwidth of the system becomes exceedingly small; but it is never zero, nor is the frequency ever precisely defined. The average deviation in frequency from (5) which these phase fluctuations produce when averaged over a time t is[14]

$$\epsilon = \Delta\nu \left(\frac{W_n}{Pt}\right)^{1/2} \tag{7}$$

where $\Delta\nu = \Delta\nu_c\,\Delta\nu_m/(\Delta\nu_c + \Delta\nu_m)$, P is the power generated by the oscillator, and W_n is the effective energy in the source of fluctuations. Where $kT \gg h\nu$ in a cavity at temperature T and resonant frequency ν, the effective energy comes from thermal noise and $W_n = kT$. If the noise fluctuations come from spontaneous emission, as they do when $kT \ll h\nu$, then $W_n = h\nu$.

It is also useful to state the spectral width of the radiation emitted from a maser oscillator, as well as the precision to which the frequency can be determined. The half width of the spectral distribution is again determined by the same noise fluctuation and can be expressed by the relation[10,15,16]

Fig. 2. Energy levels of Cr^{+++} in ruby with a particular crystalline orientation in a magnetic field of 3900 oersteds. For a three-level maser, 23.1 Gc/s is the frequency of the pumping field and 9.4 Gc/s is the frequency of amplification or oscillation.



$$\delta = \frac{2\pi W_n}{P} (\Delta\nu)^2 \tag{8}$$

where $\Delta\nu$, W_n, and P are the same as in (7). This width δ is typically so small in maser oscillators that they provide by far the most monochromatic sources of radiation available at their frequencies.

Maser clocks and amplifiers

Although the ammonia beam-type maser was able to demonstrate the low-noise amplification which was predicted,[17] its extremely narrow bandwidth makes it and other beam-type masers more useful as a very monochromatic source of electromagnetic waves than as an amplifier. For the original maser, the power output P was about 10^{-9} watt, and the resonance width $\Delta\nu$ about 2 kc/s, as determined by the length of time required for the beam of molecules to pass through the cavity. Since the frequency of oscillation ν_m is 23 874 Mc/s, the fractional spectral width according to (8) is $\delta/\nu \approx 10^{-14}$. In a time $t = 100$ seconds, Eq. (7) shows that the frequency can be specified to a fractional precision $\epsilon/\nu = 2 \times 10^{-14}$, and of course the precision increases for longer times proportionally to $1/t^{1/2}$.

As a constant-frequency oscillator or precise atomic clock, however, the ammonia maser has an additional problem, which is not so fundamental but which sets a limit on long-term stability. This comes from long-term drifts, particularly of the cavity temperature, which vary ν_c. These variations can be seen, from (6), to "pull" ν. Variations of this type have limited the long-term stability[18] of ammonia masers to fractional variations of about 10^{-11}; however, this still represents a remarkably good clock.

A beam-type maser using the hyperfine structure transition in the ground state of hydrogen, which is at 1420 Mc/s, has recently been developed by Goldenberg, Kleppner, and Ramsey.[19] In this case, the excited atoms bounce many times from glass walls in the cavity and thereby a resonance width as small as 1 c/s is achieved. Present designs of the hydrogen maser yield an oscillator with long-term fractional variations no larger than about 10^{-13}. This system seems likely to produce our best available clock or time standard.

Masers of reasonably wide utility as amplifiers came into view with the realization that certain solids containing paramagnetic impurities allowed attainment of the maser threshold condition.[20] Microwave resonances of paramagnetic atoms in solids, or in liquids, had been studied for some time, and many of their properties were already well known. The widths of these resonances vary with materials and with impurity concentration from a small fraction of a megacycle to many hundreds of megacycles, and their frequencies depend on applied magnetic field strengths, so that they are easily tunable. Thus they offer for maser amplifiers a choice of a considerable range of bandwidth and a continuous range of frequencies.

A paramagnetic atom with spin of $\frac{1}{2}$ has two energy levels which, when placed in a magnetic field, are separated by an amount usually of about $\nu = 2.8H$ Mc/s. Here H is the field in gauss, and from this it is clear that most of the microwave frequency range can be covered by magnetic fields of normal magnitudes. The first paramagnetic masers suggested involved impurity atoms of this type in crystals of Si or Ge. Relaxation between the two states was slow enough in these cases that a sufficient population inversion could be achieved.[20] However, before very long a very much more convenient scheme for using paramagnetic resonances was proposed by Bloembergen,[21] the so-called three-level solid-state maser. This system allowed continuous inversion of population, and hence continuous amplification, which was very awkward to obtain in the previous two-level system.

Paramagnetic atoms with an angular momentum due to electron spin S greater than $\frac{1}{2}$ have $2S + 1$ levels, which are degenerate when the atom is in free space. But these levels may be split by "crystalline fields," or interaction with neighboring atoms if the atoms are imbedded in a solid, and frequently the splittings lie in the microwave range. The energy levels of such a system, involving a spin of 3/2 and four levels, can be as indicated in Fig. 2 when the system is in a magnetic field. If a sufficiently large electromagnetic wave of frequency ν_{13} (the transition frequency between levels 1 and 3) is applied, the population of these two levels can be equalized or "saturated." In this case, the ratio of the population of level 2 to that of level 1 or 3 under steady conditions is

$$\frac{n_2}{n_1} = \frac{\dfrac{1}{T_{12}} \exp\left(\dfrac{-h\nu_{12}}{kT}\right) + \dfrac{1}{T_{23}}}{\dfrac{1}{T_{12}} + \dfrac{1}{T_{23}} \exp\left(\dfrac{-h\nu_{23}}{kT}\right)}$$

Here T is the temperature of the crystal containing the impurities, and T_{12} and T_{23} are the times for relaxation between states 1 and 2 or 2 and 3, respectively. For $h\nu_{12} \gg kT$ and $h\nu_{23} \gg kT$, as occurs at very low temperatures or at ordinary temperatures if the levels are separated by optical frequencies,

$$\frac{n_2}{n_1} = \frac{T_{12}}{T_{23}}$$

When $h\nu_{12} \ll kT$ and $h\nu_{23} \ll kT$, which is more commonly the case for microwaves,

$$\frac{n_2}{n_1} = 1 + \frac{h}{kT} \frac{\left(\dfrac{\nu_{12}}{T_{12}} - \dfrac{\nu_{23}}{T_{23}}\right)}{\left(\dfrac{1}{T_{12}} + \dfrac{1}{T_{23}}\right)} \tag{9}$$

Thus if $(\nu_{12}/T_{12}) > (\nu_{23}/T_{23})$, there is an inversion of population between levels 2 and 1, or if $(\nu_{12}/T_{12} < \nu_{23}/T_{23})$, there is an inversion of population between levels 3 and 2, since the populations n_3 and n_1 have been equalized by the "pumping" radiation. Equation (9) is essentially the result obtained by Bloembergen,[21] who also suggested several promising paramagnetic materials that might be used. Basov and Prokhorov had already proposed a rather similar three-level "pumping" scheme for application to a molecular beam system.[22]

The first successful paramagnetic maser of this general type was obtained by Scovil *et al.*,[23] using a rare-earth ion in a water-soluble crystal. But before long, other more suitable crystals such as ruby[24] (chromium ions in Al_2O_3) became more or less standard and have provided amplifiers of remarkable sensitivity for radio astronomy, for satellite communication, and for communication to space probes.[25] They have considerably improved the potentialities of radio astronomy, and have already led to some new discoveries.[26,27] These systems generally require cooling with liquid helium, which is a technological difficulty that some day may be obviated. But otherwise they represent rather serviceable and convenient amplifiers.

A maser amplifier of microwaves can rather easily be built which has a theoretical noise temperature as low as 1° or 2°K, and experimental measurements have confirmed this figure.[28] However, such a low noise level is not easy to measure because almost any measurement involves attachment of input and output circuits which are at temperatures much higher than 1°K, and which radiate some additional noise into the amplifier. The lowest overall noise temperature so far reported for an entire receiving system[29] using a maser amplifier is about 10°K. This represents about 100 times the sensitivity of microwave amplifiers built before invention of the maser. But masers have stimulated other amplifier work; and some parametric amplifiers, using the more or less classical properties of materials rather than quantum electronics, now have sensitivities that are within a factor of about 5 of this figure.

Optical and infrared masers, or lasers

Until about 1957, the coherent generation of frequencies higher than those that could be obtained from electronic oscillators still had not been directly attacked, although several schemes using molecular-beam masers for the far-infrared were examined from time to time. This lack of attention to what had been an original goal of the maser came about partly because the preliminary stages, including microwave oscillators, low-noise amplifiers, and their use in various scientific experiments, had proved so interesting that they distracted attention from the high-frequency possibilities.

But joint work with A. L. Schawlow,[15] beginning at about this time, helped open the way for fairly rapid and interesting development of maser oscillators in the far-infrared, optical, and ultraviolet regions—as much as 1000 times higher in frequency than any coherent sources of radiation previously available. It is masers in these regions of the spectrum, frequently called lasers (light amplification by stimulated emission of radiation), that have perhaps provided the most striking new scientific tools and results. Important aspects of this work were clear demonstrations that there are practical systems which can meet the threshold condition of oscillation, and that particular resonator designs allow the oscillations to be confined to certain specific and desirable modes. The resonator analyzed was composed simply of two parallel mirrors—the well-known Fabry–Perot interferometer, but of special dimensions.

For light waves, the wavelength is so short that any macroscopic resonator constructed must have dimensions that are large compared with the wavelength. In this case, the electromagnetic field may to some reasonable approximation be considered to travel in straight lines and be reflected from the walls of the resonator. The threshold condition may be written

$$\left(\frac{\mu E}{\hbar}\right)^2 \frac{h\nu\,(N_b - N_a)}{12\pi\,\Delta\nu} \geq \frac{E^2}{8\pi}\frac{V}{t} \tag{10}$$

where t is the decay time for the light in a cavity having reflecting walls and a volume V. If the light has a random path in the cavity, the decay time can be expressed generally in terms of the reflection coefficient r of the walls, the volume V, the wall area A, and the velocity of light c, as

$$t = \frac{6V}{(1 - r)Ac}$$

Hence (10) becomes[15]

$$N_b - N_a \geqslant \frac{\Delta\nu}{\nu}\,\frac{h(1 - r)Ac}{16\pi^2\mu^2 V} \tag{11}$$

It can be seen that this critical condition is almost independent of frequency if the fractional line width $\Delta\nu/\nu$ does not change with frequency (as, for example, in the Doppler effect). The reflection coefficient and dipole moment matrix element μ are not particularly dependent on frequency over the range in question. Hence if the critical condition can be met for one frequency, it can probably be met over the entire range from the far-infrared to the ultraviolet.

There is a problem with a resonator which is large compared to a wavelength in that there are many modes. Hence, unless the modes in which oscillations occur are successfully controlled, the electromagnetic field may build up simultaneously in many modes and at many frequencies. The total number of modes in a cavity with frequencies which lie within the line width $\Delta\nu$ of the atomic molecular resonance is

$$p = 8\pi^2\,\frac{V\nu^2\Delta\nu}{c^3}$$

or about 10^9 for a cavity volume of 1 cm^3, a frequency in the optical region, and ordinary atomic line widths. But fortunately the possibility of oscillation can be eliminated for most of these modes.

Two small, parallel mirrors separated by a distance much larger than their diameter will allow a beam of light traveling along the axis joining them to travel back and forth many times. For such a beam, the decay time t is $(L/c)\,(1 - r)$, where L is the mirror separation and r the reflectivity. Hence the threshold condition is

$$N_b - N_a \geq \frac{3\Delta\nu}{8\pi^2\nu}\,\frac{hc(1 - r)}{\mu^2 L}$$

This assumes that diffraction losses are negligible. A beam of light that is not traveling in a direction parallel to the axis will disappear from the volume between the mirrors much more rapidly. Hence the threshold condition for off-axis beams will require appreciably more excited atoms than that for axial beams, and the condition for oscillation can be met for the latter without a build-up of energy in off-axis light waves.

Many features of the modes for the electromagnetic wave between two square, plane, parallel mirrors of dimension D and separation L can be approximately described as those in a rectangular box of these dimensions, although the boundary conditions on the enclosed sides of the "box" are of course somewhat different. The resonant wavelengths of such a region for waves traveling back and forth in a nearly axial direction are[15]

$$\lambda = \frac{2L}{q}\left[1 - \frac{1}{2}\left(\frac{L}{D}\frac{r}{q}\right)^2 - \frac{1}{2}\left(\frac{L}{D}\frac{s}{q}\right)^2\right] \tag{12}$$

where q, r, and s are integers, and $r \ll q$, $s \ll q$. More precise examination of the modes requires detailed numerical calculation.[30] For a precisely axial direction, $r = s = 0$, and the modes are separated by a frequency $c/2L$. If this frequency is somewhat greater than the atomic line width $\Delta\nu$, then only one axial mode can oscillate at a time. The axial wave has an angular width due to diffraction of about λ/D, and if this is comparable with the angle D/L, then all off-axis modes (r or $s \neq 0$) are appreciably more lossy than are the axial ones, and their oscillations are suppressed.

If one of the mirrors is partially transparent, some of the light escapes from the axial mode in an approximately plane wave and with an angular divergence, approximately λ/D, determined by diffraction.

A number of modified resonator designs have been popular and useful in optical masers, in particular designs that are based on the confocal Fabry–Perot interferometer. However, the plane–parallel case appears to offer the simplest means for the selection of an individual mode.

Although a number of types of atomic systems and excitation seemed promising in 1958 as bases for optical masers, optical excitation of the alkali vapors lent itself to the most complete analysis and planning for an operable oscillator. One such system has been shown to oscillate as expected,[31] but the alkali vapors are no longer of great interest because other systems, which were at the time much less predictable, have turned out to be considerably more useful.

The first operating laser, a system involving optical excitation of the Cr ions in ruby and yielding red light, was demonstrated by Maiman in 1960.[32,33] He took what seemed at first a rather difficult route of inverting the population between the ground state and excited states of the Cr ion. This technique requires that at least half of the very large number of atoms in the ground state must be excited in order to have the possibility of a population inversion. In the case of two normally unpopulated atomic states, the total amount of excitation required is much less. However, Maiman succeeded handsomely in exciting more than half the Cr ions in a ruby with chromium concentration of about 1/2000 by applying a very intense pulse of light from a flash tube. This type of system is illustrated schematically in Fig. 3. Success immediately yielded a very-high-energy maser oscillation, because if population inversion is to be achieved at all, a large amount of energy must be stored in the excited atomic states. Surfaces of the ruby served as the reflecting mirrors. Collins *et al.*[34] quickly demonstrated that the ruby laser showed many of the characteristics predicted for such an oscillator.

The ruby laser is operated normally only in pulses, because of the high power required to reach threshold, and emits intense bursts of red light at power levels between about 1 kW and 100 MW. It has given rise to a whole family of lasers involving impurities in various crystals of glasses, and covering frequencies from the near-infrared into the optical region.

Not very long after the ruby laser was developed, Javan, Bennett, and Herriott[35] obtained maser oscillations from Ne atoms excited by collisions of the second kind with metastable He, in accordance with an idea previously put forward by Javan.[36] This system, illustrated in Fig. 4, requires only a gaseous discharge through a tube containing

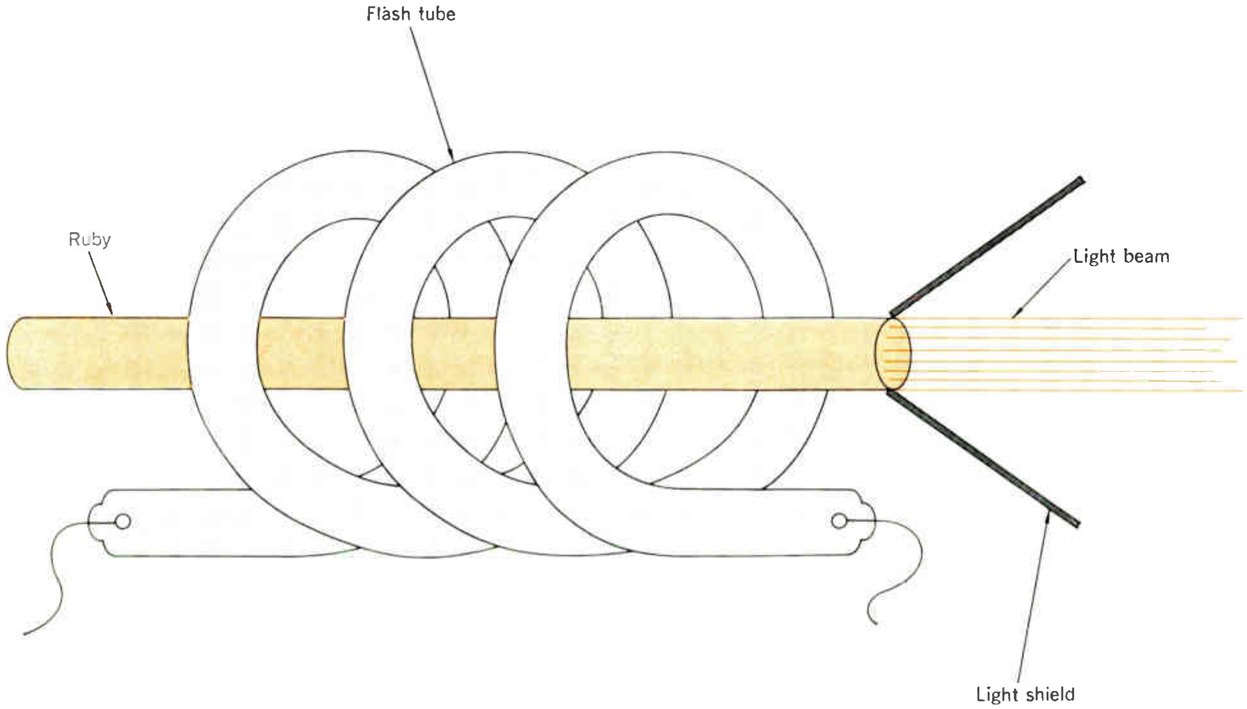


Fig. 3. Schematic diagram of a ruby (optically excited solid-state) laser. When the gas flash tube is activated, electromagnetic oscillations occur within the ruby rod, and some of these light waves are emitted in a beam through one partially reflecting end of the rod.

a mixture of He and Ne at low pressure, and two reflectors at the ends of the tube. It oscillates at the relatively low power of about one milliwatt, but approaches ideal conditions much more closely than the ruby system, and affords a continuous source of infrared radiation of great purity and directivity.

The technique of gaseous excitation by electrical discharge has also led to a large family of lasers, producing hundreds of different frequencies from many different gases which range from wavelengths as long as a few tenths of one millimeter down into the ultraviolet. For some systems, a heavy discharge pulse in the gas is needed. Others, particularly some of the infrared frequencies in rare gases, oscillate so readily that it seems probable that we have had lasers accidentally all along. Very likely some neon or other rare gas electric signs have been producing maser oscillations at infrared wavelengths, which have gone unnoticed because the infrared could not escape from the glass neon tubes. Some of these oscillation frequencies represent atomic transitions which were previously undetected; for others, the transition has not yet even been identified.

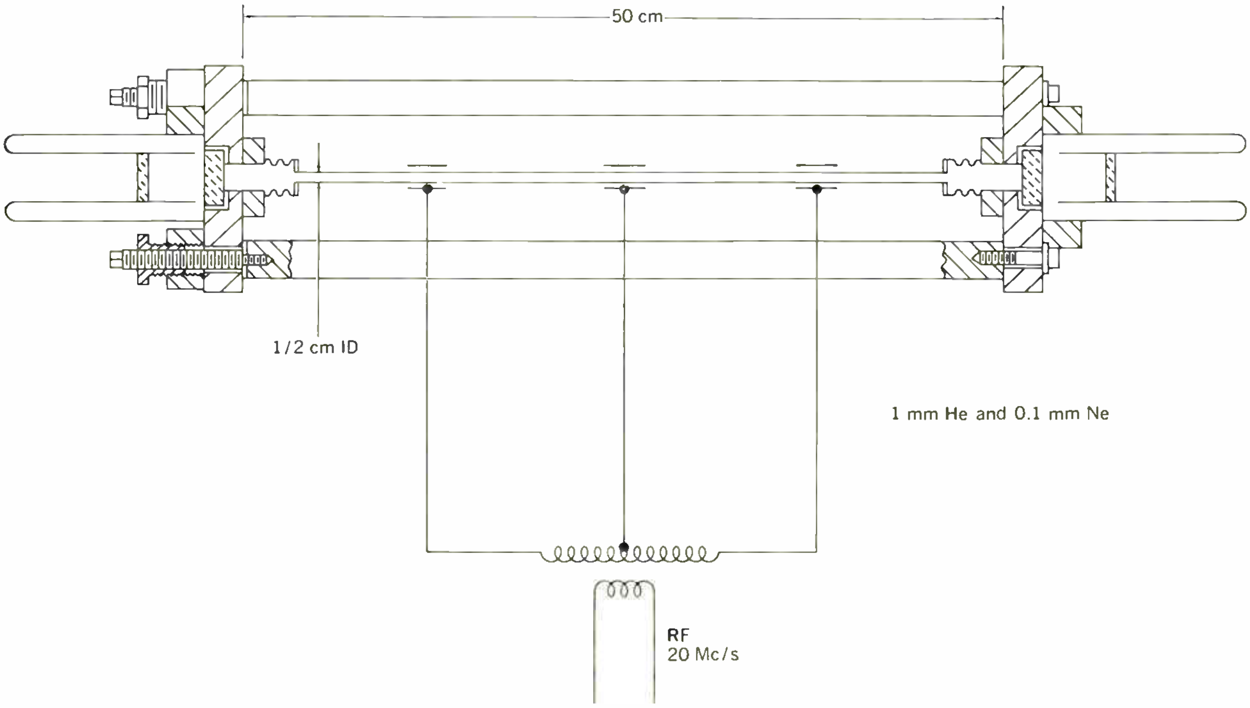
Another class of lasers was initiated through the discovery[37] that a p-n junction of the semiconductor GaAs through which a current is passed can emit near-infrared light from recombination processes with very high efficiency. Hall *et al.*[38] obtained the first maser oscillations with such a system, with light traveling parallel to the junction and reflected back and forth between the faces of the small GaAs crystal. His results were paralleled or followed immediately, however, by similar work in two other laboratories.[39, 40] This type of laser, illustrated in Fig. 5, is of the general size and cost of a transistor. It can be made to oscillate simply by passage of an electric current, and in some cases the radiation emitted represents more than 50 percent of the input electric energy—an efficiency greater than that of other man-made light sources.

There quickly developed a large family of semiconductor lasers, some involving junctions and, recently, some using excitation by an external beam of electrons.[41] They range in wavelength from about 10 microns, in the infrared, to the center of the visible region.

Normal Raman scattering can be regarded as spontaneous emission from a virtual state, as indicated in Fig. 6. Associated with any such spontaneous emission there must be, in accordance with Einstein's relations, a stimulated emission. Javan showed[42] the principles involved in using this stimulated emission for a Raman maser. What is required is simply a large enough number of molecular systems which are sufficiently strongly excited by radiation of frequency greater than some Raman-allowed transition.

One might consider the population of the virtual level in a Raman maser (see Fig. 6) to be greater than that of the first excited state, so that there is no population inversion. On the other hand the initial state, which is the ground state, needs to be more populated than the first excited state. One can quite properly consider the amplification process as a parametric one with the molecular frequency as idler, or as due to a mixture of ground and excited states in which there is phase coherence between the various molecules. This is the second type of loophole through the black-body radiation law mentioned earlier. The ammonia beam maser itself illustrates the case of amplification without the necessity of population inver-

Fig. 4. Schematic diagram of a He-Ne (gas discharge) laser. Electrical excitation can initiate a steady maser oscillation, resulting in an emitted light beam from either end of the gas discharge, where there are reflecting mirrors.



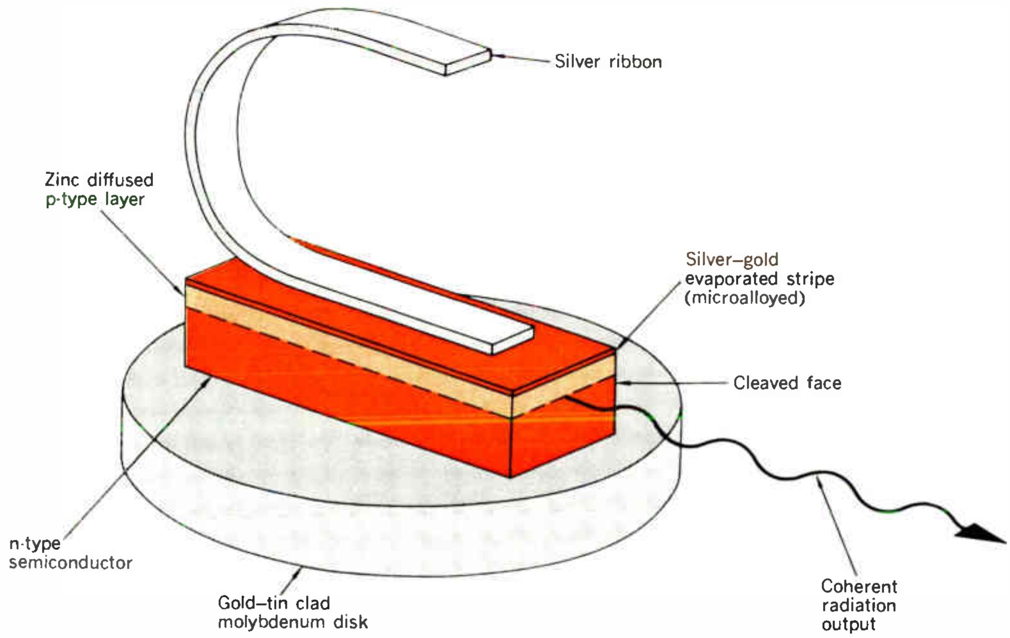


Fig. 5. Schematic diagram of a gallium arsenide (injection, or semiconductor) laser. A small voltage applied between the silver ribbon and the molybdenum disk can produce maser oscillations with resulting emission of coherent infrared radiation.

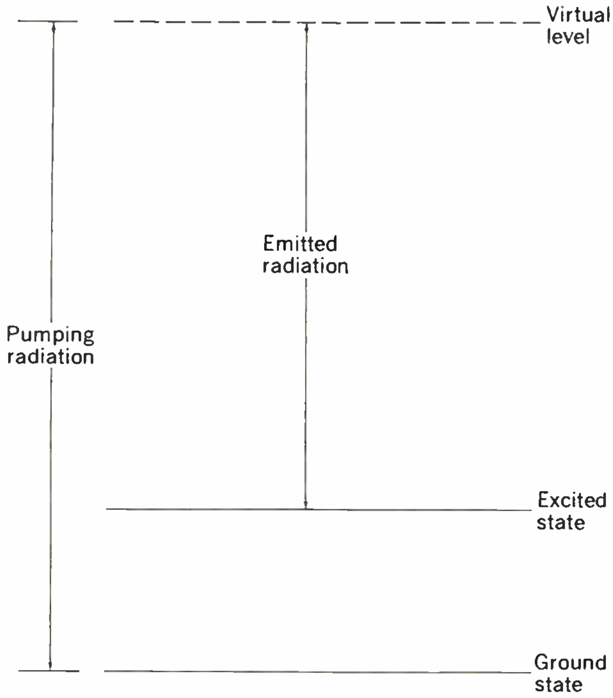


Fig. 6. Representation of energy levels in a Raman maser. This system resembles qualitatively a three-level maser, one of the levels being "virtual," or not characteristic of the molecule, when no field is present.

sion. As the ammonia molecules progress through the cavity and become predominantly in the ground state rather than the excited state, they continue to amplify because their oscillations are correlated in phase with each other, and have the appropriate phase with respect to the electromagnetic wave.

Raman masers were first demonstrated by Woodbury and Ng[43] as the result of excitation of various liquid molecules with a very intense beam from a pulsed laser. They too have now many versions, giving frequencies which differ from the original driving maser beam by some small integer times a molecular vibrational frequency. Their action has been considerably extended by Terhune,[44] and has been treated in a number of theoretical papers.[42, 45]

Present performance of lasers

Where now do we stand in achieving the various theoretical expectations for performance of masers?

First, consider the general extension of the frequency range where we have coherent amplifiers and oscillators. This has been increased by a factor of somewhat more than 1000; there are still additional spectral regions where such techniques need to be developed, but the pace has been quite rapid in the last few years. Maser oscillations in the infrared, optical, and ultraviolet regions have now been obtained in many ways and appear easy; new excitation mechanisms and systems are continually turning up. There are still two frequency regions, however, where such sources of radiation are rare or nonexistent. One is in the submillimeter region or far-infrared. The region has, in a sense, now been crossed and conquered by maser oscillators. But techniques in this spectral region are still rudimentary, and the frequency coverage with masers is spotty. Presumably further work will allow interesting explorations in this region and a very fruitful, high-resolution spectroscopy.

Another region in which coherent oscillators have not yet been developed is that of still shorter wavelengths stretching indefinitely beyond the near-ultraviolet, where the first such oscillators are now available. It can be shown that a rather severe and fundamental limitation exists as one proceeds to shorter wavelengths because of the continually increasing number of electromagnetic modes in a given volume and because of the faster and faster dissipation of energy into them by spontaneous emission.

Consider a cavity resonator of fixed volume, fixed-wall reflectivity, and fixed-fractional frequency width $\Delta\nu/\nu$. Meeting the threshold condition (11) in such a resonator requires that there is power which increases as ν^4 radiated by spontaneous emission into all modes of the system.[15] In the optical region this dissipated power amounts to only a few milliwatts for typical conditions, whereas at 50 Å, in the soft X-ray region, it would be about 10^5 watts. The threshold condition would then be very difficult to maintain. But by the same token, if it is maintained, the coherent X-ray beam produced would contain many kilowatts of power. It seems reasonable to expect, on this basis, that masers eventually will be developed to wavelengths that are somewhat below 1000 Å; however, maser oscillations in the X-ray region will be very much more difficult to realize.

Second, let us examine the monochromaticity that has been achieved. For the ammonia beam maser, the phase variation of microwave oscillations was shown experimentally to agree with the theoretical expression (7) within the experimental precision of about 50 percent. This was done by beating the outputs of two independent ammonia oscillators together and examining their relative phase variations.[46] A similar procedure can be carried out for two optical oscillators by mixing their two light beams together in a photocell and detecting the beat frequency. However, the technical difficulties in obtaining theoretical performance are rather more demanding than in the case of the ammonia maser. Expression (8) for a typical He–Ne laser predicts a frequency spread of about 10^{-2} c/s, or a fraction 3×10^{-17} of the oscillation frequency of 3×10^{14} c/s.

Almost all masers so far oscillating in the optical or near-infrared region require a sharper resonance, or higher Q, of the cavity than that of the atomic resonance. Hence the frequency of oscillation is primarily determined, from (5), by the cavity resonance. The frequency of oscillation thus depends on the separation L between mirrors since, from (12), $\nu = qc/2L$, where q is some integer. If, then, the radiated frequencies are to have a fractional bandwidth of about 3×10^{-17}, such as would come from fundamental noise according to (8), the mirror separation must not vary by more than this fractional amount. For a mirror separation of one meter, the motion allowed would be less than 3×10^{-15} cm—a demanding requirement!

If the mirror separation is held constant by cylindrical rods, L must still vary as a result of thermal excitation of the lowest frequency-stretching modes of the rods. This gives an additional fluctuation, which is usually larger than that from spontaneous emission. It produces a fractional motion[47]

$$\left(\frac{2kT}{YV}\right)^{1/2}$$

where T is the temperature, V the volume of the separators, and Y their Young's modulus.

In order for the monochromaticity of lasers to be examined, two He–Ne systems were carefully shock-mounted in an acoustically insulated wine cellar of an unoccupied and isolated house so that acoustic vibrations would be minimized.[47] Their pairs of mirrors were separated by heavy invar rods about 60 cm long. For this case, the limiting theoretical fluctuations set by thermal motions of the rods corresponded to fractional frequency variations of 5×10^{-15}, or a frequency fluctuation of 2 c/s. Light from each laser was sent into a photodetector, and the beat frequency examined electronically. Under good conditions free from acoustic disturbances or thermal transients in the invar spacers, this experiment showed that variations in the laser frequencies over periods of a few seconds were less than 20 c/s, or about one part in 10^{13}. This was ten times the limit of thermal fluctuations, but corresponded to detection of motions of the two mirrors as small as 5×10^{-12} cm, a dimension comparable with nuclear diameters. Presumably, with great care results still nearer to the theoretical values can be obtained.

The narrowest atomic spectral lines have widths of the order of 10^8 c/s, so that the laser measured was more monochromatic than earlier light sources by a factor of about 10^6. Light of this type can interfere with itself after traveling a distance of about 10 000 km. Hence it could in principle measure changes in such a large distance to a precision of one wavelength of light, if there were any optical path so constant. Interference work has been done in several laboratories with laser light over distances of a few hundred meters, which does not require quite such special elimination of acoustic or other disturbances.

A third property of laser light is its directivity, or the spacial coherence across the beam. As indicated above, certain modes of oscillation should represent approximately a plane wave of cross section comparable with the mirror diameter D. The He–Ne maser seems to easily allow adjustment so that such a mode of oscillation occurs, and its beam has been shown[35,48] to have nearly the expected divergence λ/D due to diffraction.

The spacial coherence or planarity of a laser beam implies that the entire beam can be focused by a microscope to a region as small as about $\lambda/2$, or the resolving power of the microscope. Similarly, it may be transmitted through a telescope in a beam whose angular width is simply determined by the angular resolution of the telescope and hence much less than the angular divergence λ/D as the beam emerges from a small laser. The entire energy is originally created in the ideal laser in a single mode; it can be transmitted into other single modes by optical systems without violating the well-known brightness laws of optics.

This brings us to a fourth important property, the intensity or brightness that can be achieved by maser techniques. As indicated initially, once one has the possibility of coherent amplification there is no firm limit to intensity, because equilibrium thermodynamics and Planck's law no longer are controlling. The only limit is set by the available energy input, heat dissipation, and size of the apparatus used.

If only the one milliwatt of power emitted by a He–Ne laser is focused by a good lens, the power density becomes high because the cross-sectional area of the focused spot would be only about $\lambda^2/4$. This gives a power density of 4×10^5 watts/cm². The effective temperature of such a beam, because of its monochromaticity, is also rather high—approximately 10^{19}°K for the light of 20-c/s bandwidth.

The pulsed systems, such as ruby lasers in particular, emit much greater power, although they do not quite approach the limits of coherence that the gaseous systems do. Ruby lasers emit a few tenths of a joule to a few hundred joules of energy in pulses from about 10^{-3} to 10^{-8} second in length. The power can thus be as great as 10^9 watts or more. Effective temperatures of the radiation are about 10^{23}°K. The actual limit of power density will generally be set by the limit of light intensity optical materials can stand without breakage or ionization. Power of 10^9 watts focused to a spot 10^{-2} mm in diameter produces an electric field strength in the optical wave of about 10^9 volts/cm, which is in the range of fields by which valence electrons are held in atoms. Hence this power ionizes and disrupts all material. The radiation pressure also becomes large, being about 10^{12} dynes/cm², or 10^6 atmospheres, at such a focal point.

Some applications of lasers

It is clear that light in more ideal and in more intense form, which maser techniques have produced, can be expected to find application in wide and numerous areas of technology and of science simply because we find our present techniques of producing and controlling light already so widely applied. Most of these applications are still ahead of us, and there is not time to treat here even those that are already beginning to develop. I shall only mention that in technology, lasers have been put to work in such diverse areas as radar, surgery, welding, surveying, and microscopy. A little more space will be devoted here to discussing three broad areas of science to which optical, infrared, and ultraviolet masers are expected to contribute.

Masers seem to provide the most precise techniques for measurement of the two fundamental dimensions of time and length. Over short periods of time, maser oscillators clearly give the most constant oscillations; for longer times the hydrogen maser also seems to provide the most precise clock yet available. Light from optical masers allows new precision in the measurement of distance, and already seems capable of improving our standard of length. This new precision suggests interesting experiments on certain fundamental properties of our space, as well as the application of higher precision to a variety of physical effects. So far, experiments have been done to improve the precision with which the Lorentz transformation can be experimentally verified.[49,50] It appears that improved precision in measurement of the speed of light can also be expected. If we look some distance in the future, it seems clear that the techniques of quantum electronics will allow direct measurement of the frequency of light, rather than only its wavelength. This can be accomplished by generation of harmonics of a radio frequency, amplification of the new frequency, and further generation of harmonics until the radio region is linked with optical frequencies. This should eventually allow measurement of the velocity of light c to whatever precision we define time and length. Or, it will allow the elimination of separate standards of time and of length because c times a standard time will define a standard length with more precision than we can now achieve.

The power of spectroscopy should be considerably increased by use of masers. In particular, these very monochromatic sources can greatly improve spectroscopic resolution and thus allow more detailed examination of the structure of atoms, molecules, or solids. This advance can be particularly striking in the infrared and far-infrared, where present resolution is far less than the widths of atomic or molecular lines. Already some high-resolution spectroscopy has been done with lasers,[51,52] and still more interesting work of this general type can be expected before long.

A third interesting field for which lasers are important has emerged as a field almost entirely because of the existence of lasers, and is the area where scientific research has so far been most active. This is what is usually called nonlinear optics,[53,54] although it includes some phenomena which might not previously have been described in this way. We have been accustomed in the past to discussing the progress of light through a passive optical material of more or less fixed properties. But in the intense laser beams now available, interactions between the light and the optical medium are sufficiently large that properties of the medium can no longer be regarded as fixed. The medium distorts, its molecules vibrate, and polarization of electrons in its atoms no longer responds linearly to the applied field. One must now also consider the dynamics of both the light and the optical medium, and interactions between their two motions. Some of the new phenomena observed are multiple-quanta absorption, which makes absorption depend on intensity,[55,56] harmonic generation in optical materials and mixing of light frequencies,[57-60] excitation of coherent molecular vibrations and stimulated Raman effects,[42-45] and stimulated Brillouin scattering.[61,62] Only the last two of these will be discussed, partly because they bear on still another kind of maser, one which generates phonons.

The phonon maser

Acoustic waves follow equations that are of the same general form as the equations of light and manifest many of the same phenomena. An acoustic wave can produce an atomic or molecular excitation, or receive energy from it by either spontaneous or stimulated emission. Hence, one may expect maser action for acoustic waves if a system can be found in which molecules are sufficiently coupled to an acoustic field and appropriate excitation can be obtained to meet the threshold condition. The first such systems suggested involved inversion of the spin states of impurities in a crystal in ways similar to those used for solid-state electromagnetic masers.[63] A system of this type has been shown to operate as expected.[64] However, a more generally applicable technique seems to be Brillouin scattering and its close associate Raman scattering, which utilize phase correlation rather than population inversion to produce amplification. This process can also be viewed as parametric amplification.

Light may be scattered by the train of crests and troughs in an acoustic wave much as by a grating. Since the wave is moving, the scattering involves a Doppler shift. The net result, first analyzed by Brillouin,[65] is that the scattered light is shifted in frequency from the frequency ν_0 of the original beam by an amount

$$\nu = 2\nu_0 \frac{v}{c} \sin \frac{\theta}{2} \tag{13}$$

where v and c are the phase velocities of sound and of light, respectively, in the medium, and θ is the scattering angle. The energy lost, $h\nu$, is given to the scattering acoustic wave of frequency ν. If the light is of sufficient intensity, it can thus give energy to the acoustic field faster than it is lost and fulfill a threshold condition which allows the acoustic energy to build up steadily.

For the very high acoustic frequencies (10^9 to 10^{10} c/s) implied by (13) when θ is not very small, the losses are usually so large that interesting amplification cannot be achieved with ordinary light. But with laser beams of hundreds of megawatts per square centimeter, it is quite feasible to produce an intense build-up of acoustic waves by this process of stimulated Brillouin scattering[61,62]—so intense, in fact, that the acoustic energy can crack glass or quartz. This gives a method of producing and studying the behavior of very-high-frequency acoustic waves in almost any material that will transmit light—a possibility which was previously not so clearly available.

Brillouin scattering by spontaneous emission has been studied for some time. But the intense monochromatic light of lasers allows now much greater precision in work with this technique,[52] and it too is yielding interesting information on the propagation of hypersonic waves in materials.

There is no firm limit to the acoustic frequencies that can be produced by stimulated emission, even though (13) indicates a kind of limit, for $\theta = \pi$, of $2\nu_0 v/c$. But in the optical branch of acoustic waves, the phase velocity v can be very high. In fact, stimulated Raman scattering, or the Raman maser mentioned briefly above, represents excitation of the optical branches of acoustic spectra, and generates coherent molecular oscillations. Quantum-electronic techniques can thus allow interesting new ways to generate and explore most of the acoustic spectrum as well as much of the electromagnetic domain.

Concluding remarks

In a few years this brief report will no longer be of much interest because it will be outdated and superseded, except for some matters of general principle or of historical interest. But, happily, it will be replaced by further striking progress and improved results. We can look forward to another decade of rapid development in the field of quantum electronics—new devices and unsuspected facets of the field, improved range and performance of masers, and extensive application to science and to technology. It seems about time now for masers and lasers to become everyday tools of science, and for the exploratory work that has demonstrated so many new possibilities to be increasingly replaced by much more finished, more systematic, and more penetrating applications. It is this stage of quantum electronics that should yield the real benefits made available by the new methods of dealing with radiation.

REFERENCES

1. Pierce, J. R., "Millimeter waves," *Phys. Today*, vol. 3, pp. 24–29; Nov. 1950.

2. Ramsey, N. F., "Thermodynamics and statistical mechanics at negative absolute temperatures," *Phys. Rev.*, vol. 103, pp. 20–28; July 1, 1956.

3. Lamb, W. E., and Retherford, R. C., "Fine structure of the hydrogen atom. I," *Phys. Rev.*, vol. 79, pp. 549–572; Aug. 15, 1950.

4. Purcell, E. M., and Pound, R. V., "A nuclear spin system at negative temperature," *Phys. Rev.*, vol. 81, pp. 279–280; Jan. 15, 1951.

5. Bloch, F., Hansen, W. W., and Packard, M., "The nuclear induction experiment," *Phys. Rev.*, vol. 70, pp. 474–485; Oct. 1 and 15, 1946.

6. Basov, N. G., and Prokhorov, A. M., "Applications of molecular beams to radio spectroscopic studies of rotation spectra of molecules," *J. Exp. Theor. Phys. (U.S.S.R.)*, vol. 27, pp. 431–438; 1954.

7. Weber, J., "Amplification of microwave radiation by substances not in thermal equilibrium," *IRE Trans. on Electron Devices*, vol. PGED-3, pp. 1–4; June 1953.

8. Quarterly Progress Rept., Columbia Radiation Lab., Dec. 1951.

Townes, C. H., *J. Inst. Elec. Commun. Eng. (Japan)*, vol. 36, p. 650; 1953 (in Japanese).

9. Gordon, J. P., Zeiger, H. J., and Townes, C. H., "Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3," *Phys. Rev.*, vol. 95, pp. 282–284; July 1, 1954.

10. Gordon, J. P., Zeiger, H. J., and Townes, C. H., "The maser—new type of microwave amplifier, frequency standard, and spectrometer," *Phys. Rev.*, vol. 99, pp. 1264–1274; Aug. 15, 1955.

11. Serber, R., and Townes, C. H., in *Quantum Electronics*. C. H. Townes, ed. New York: Columbia University Press, 1960, p. 233. See also H. Friedburg, p. 227.

12. Shimoda, K., Takahasi, H., and Townes, C. H., "Fluctuations in amplification of quanta with application to maser amplifiers," *J. Phys. Soc. (Japan)*, vol. 12, p. 687; June 1957.

Muller, M. W., "Noise in a molecular amplifier," *Phys. Rev.*, vol. 106, pp. 8–12; Apr. 1, 1957.

Strandberg, M. W. P., "Inherent noise of quantum-mechanical amplifiers," *Phys. Rev.*, vol. 106, pp. 617–620; May 15, 1957.

Pound, R. V., "Spontaneous emission and noise figure of maser amplifiers," *Ann. Phys. (N.Y.)*, vol. 1, pp. 24–32; Apr. 1957.

13. Townes, C. H., in *Advances in Quantum Electronics*, J. R. Singer, ed. New York: Columbia University Press, 1961, p. 3.

14. Shimoda, K., Wang, T. C., and Townes, C. H., "Further aspects of the theory of the maser," *Phys. Rev.*, vol. 102, pp. 1308–1321; June 1, 1956.

15. Schawlow, A. L., and Townes, C. H., "Infrared and optical masers," *Phys. Rev.*, vol. 112, pp. 1940–1949; Dec. 15, 1958.

16. A correction of a factor of 2 to δ given by references 10 and 15 is demonstrated by P. Grivet and A. Blaquiere in *Proc. 1963 Symp. on Optical Masers*, Polytechnic Institute of Brooklyn.

17. Alsop, L. E., Giordmaine, J. A., Townes, C. H., and Wang, T. C., "Measurement of noise in a maser amplifier," *Phys. Rev.*, vol. 107, pp. 1450–1451; Sept. 1, 1957.

Gordon, J. P., and White, L. D., "Experimental determination of the noise figure of an ammonia maser," *Phys. Rev.*, vol. 107, pp. 1728–1729; Sept. 15, 1957.

18. DePrins, J., and Kartaschoff, P., in *Proceedings of Course XVII, Enrico Fermi International School of Physics*. New York: Academic Press, 1962, p. 88.

19. Goldenberg, H. M., Kleppner, D., and Ramsey, N. F., "Atomic hydrogen maser," *Phys. Rev. Letters*, vol. 5, pp. 361–362; Oct. 15, 1960.

Goldenberg, H. M., Kleppner, D., and Ramsey, N. F., "Atomic beam resonance experiments with stored beams," *Phys. Rev.*, vol 123, pp. 530–537; July 15, 1961.

20. Combrisson, J., Honig, A., and Townes, C. H., "Utilisation de la résonance de spins électroniques pour réaliser un oscillateur ou un amplificateur en hyperfréquences," *Compt. Rend.*, vol. 242, pp. 2451–2453; May 14, 1956.

Feher, G., Gordon, J. P., Buehler, E., Gere, E. A., and Thurmond, C. D., "Spontaneous emission of radiation from an electron spin system," *Phys. Rev.*, vol. 109, pp. 221–222; Jan. 1, 1958.

21. Bloembergen, N., "Proposal for a new type solid-state maser," *Phys. Rev.*, vol. 104, pp. 324–327; Oct. 15, 1956.

22. Basov, N. G., and Prokhorov, A. M., "On possible methods of producing active molecules for a molecular generator" *J. Exper. Theor. Phys. (U.S.S.R.)*, vol. 28, p. 249; 1955.

23. Scovil, H. E. D., Feher, G., and Seidel, H., "Operation of a solid-state maser," *Phys. Rev.*, vol. 105, pp. 762–763; Jan. 15, 1957.

24. Makhov, G., Kikuchi, C., Lambe, J., and Terhune, R. W., "Maser action in ruby," *Phys. Rev.*, vol. 109, pp. 1399–1400; Feb. 15, 1958.

25. Siegman, A. E., *Microwave Solid State Masers.* New York: McGraw-Hill, 1964.

26. Alsop, L. E., Giordmaine, J. A., Mayer, C. H., and Townes, C. H., "Observations using a maser radiometer at 3-cm wavelength," *Astron. J.*, vol. 63, p. 301; Sept. 1958.

Giordmaine, J. A., Alsop, L. E., Mayer, C. H., and Townes, C. H., "A maser amplifier for radio astronomy at X-band," *Proc. IRE*, vol. 47, pp. 1062–1069; June 1959.

27. Epstein, E. E., "Atomic hydrogen in galaxies," *Astron. J.*, vol. 69, pp. 490–530; Sept. 1964.

28. DeGrasse, R. W., and Scovil, H. E. D., "Noise temperature measurement on a traveling-wave maser preamplifier," *J. Appl. Phys.*, vol. 31, pp. 443–444; Feb. 1960.

29. DeGrasse, R. W., Hogg, D. C., Ohm, E. A., and Scovill, H. E. D., "Ultralow noise measurements using a horn reflector antenna and a traveling-wave maser," *J. Appl. Phys.*, vol. 30, p. 2013; Dec. 1959.

30. Fox, A. G., and Li, T., "Resonant modes in a maser interferometer," *Bell System Tech. J.*, vol. 40, pp. 453–488; Mar. 1961.

31. Jacobs, S., Gould, G., and Rabinowitz, P., "Coherent light amplification in optically pumped Cs vapor," *Phys. Rev. Letters*, vol. 7, pp. 415–417; Dec. 1, 1961.

32. Maiman, T. H., "Stimulated optical radiation in ruby masers," *Nature*, vol. 187, pp. 493–494; Aug. 1960.

33. Maiman, T. H., Hoskins, R. H., D'Haenens, I. J., Asawa, C. K., and Evtuhov, V., "Stimulated optical emission in fluorescent solids. II. Spectroscopy and stimulated emission in ruby," *Phys. Rev.*, vol. 123, pp. 1151–1157; Aug. 15, 1961.

34. Collins, R. J., Nelson, D. F., Schawlow, A. L., Bond, W., Garrett, C. G. B., and Kaiser, W., "Coherence narrowing, directionality, and relaxation oscillations in the light emission from ruby," *Phys. Rev. Letters*, vol. 5, pp. 303–305; Oct. 1, 1960.

35. Javan, A., Bennett, W. R., Jr., and Herriott, D. R., "Population inversion and continuous optical maser oscillation in a gas discharge containing a He–Ne mixture," *Phys. Rev. Letters*, vol. 6, pp. 106–110; Feb. 1, 1961.

36. Javan, A., "Possibility of production of negative temperature in gas discharges," *Phys. Rev. Letters*, vol. 3, pp. 87–89; July 15, 1959.

37. Keyes, R. J., and Quist, T. M., "Recombination radiation emitted by gallium arsenide," *Proc. IRE* (*Correspondence*), vol. 50, pp. 1822–1823; Aug. 1962.

38. Hall, R. N., Fenner, G. E., Kingsley, J. D., Soltys, T. J., and Carlson, R. O., "Coherent light emission from GaAs junctions," *Phys. Rev. Letters*, vol. 9, pp. 366–368; Nov. 1, 1962.

39. Nathan, M. I., Dumke, W. P., Burns, G., Dill, F. H., Jr., and Lasher, G., "Stimulated emission of radiation from GaAs p-n junctions," *Appl. Phys. Letters*, vol. 1, pp. 62–64; Nov. 1, 1962.

40. Quist, T. M., Rediker, R. H., Keyes, R. J., Krag, W. E., Lax, B., McWhorter, A. L., and Zeiger, H. J., "Semiconductor maser of GaAs," *Appl. Phys. Letters*, vol. 1, pp. 91–92; Dec. 1, 1962.

41. Basov, N. G., Bogdankevich, O. V., and Devyatkov, A. G., *Dokl. Akad. Nauk SSSR*, vol. 155, p. 783; 1964 (in Russian).

Basov, N. G., and Bogdankevich, O. V., "Excitation of semiconductor lasers by a beam of fast electrons," in *Symp. on Radiative Recombination in Semiconductors.* Paris: Dunod, 1964, pp. 225–233.

Benoit à la Guillaume, C., and Debever, J. M., "Effet laser par bombardement electronique," in *Symp. on Radiative Recombination in Semiconductors.* Paris: Dunod, 1964, pp. 255–257.

42. Javan, A., "Transitions a plusiers quanta et amplification maser dans les systemes a deux niveaux," *J. Phys. Radium*, vol. 19, pp. 806–808; Nov. 1958.

Javan, A., "Description of a Raman-type two-level maser," *Bull. Am. Phys. Soc.*, vol. 3, p. 213; 1958.

Javan, A., in *Proceedings of Course XXXI, Enrico Fermi International School of Physics.* New York: Academic Press, 1964.

43. Woodbury, E. J., and Ng, W. K., "Ruby laser operation in the near IR," *Proc. IRE* (*Correspondence*), p. 2367; Nov. 1962.

Eckhardt, G., Hellwarth, R. W., McClung, F. J., Schwarz, S. E., Weiner, D., and Woodbury, E. J., "Simulated Raman scattering from organic liquids," *Phys. Rev. Letters*, pp. 455–457; Dec. 1, 1962.

44. Terhune, R. W., "Nonlinear optics," *Solid State Design*, vol. 4, pp. 38–46; Nov. 1963.

Minck, R. W., Terhune, R. W., and Rado, W. G., "Laser stimulated Raman effect and resonant four-photon interaction in gases H_2, D_2, and CH_4," *Appl. Phys. Letters*, vol. 3, pp. 181–184; Nov. 15, 1963.

Stoicheff, B., in *Proceedings of Course XXXI, Enrico Fermi International School of Physics.* New York: Academic Press, 1964.

45. Hellwarth, R. W., "Theory of stimulated Raman scattering," *Phys. Rev.*, vol. 130, pp. 1850–1852; June 1, 1963.

Zeiger, H. J., and Tannenwald, P. E., in *Quantum Electronics: Proceedings of the Third International Congress*, P. Grivet and N. Bloembergen, eds. New York: Columbia University Press, 1964, p. 1589.

Garmire, E., Pandarese, F., and Townes, C. H., "Coherently driven molecular vibrations and light modulation," *Phys. Rev. Letters*, vol. 11, pp. 160–163; Aug. 15, 1963.

46. Tolnas, E. L., "Measurement of NH_3 maser oscillator frequency noise," *Bull. Am. Phys. Soc.*, vol. 5, pp. 342–343; 1960.

47. Jaseja, T. S., Javan, A., and Townes, C. H., "Frequency stability of He–Ne masers and measurements of length," *Phys. Rev. Letters*, vol. 10, pp. 165–167; Mar. 1, 1963.

48. Herriott, D., "Optical properties of a continuous helium–neon optical maser," *J. Opt. Soc. Am.*, vol. 52, pp. 31–37; Jan. 1962.

49. Cedarholm, C. P., and Townes, C. H., "A new experimental test of special relativity," *Nature*, vol. 184, pp. 1350–1351; Oct. 31, 1959.

50. Jaseja, T. S., Javan, A., Murray, J., and Townes, C. H., "Test of special relativity or of the isotropy of space by use of infrared masers," *Phys. Rev.*, vol. 133, pp. A1221–A1225; Mar. 2, 1964.

51. Szöke, A., and Javan, A., "Isotope shift and saturation behavior of the 1.15-μ transition of Ne," *Phys. Rev. Letters*, vol. 10, p. 521; June 15, 1963.

52. Chiao, R. Y., and Stoicheff, B. P., "Brillouin scattering in liquids excited by the He–Ne maser," *J. Opt. Soc. Am.*, vol. 54, pp. 1286–1287; Oct. 1964.

Benedek, G. B., Lastovka, J. B., Fritsch, K., and Greytak, T., "Brillouin scattering in liquids and solids using low-power lasers," *J. Opt. Soc. Am.*, vol. 54, pp. 1284–1285; Oct. 1964.

Mash, D. I., Starunov, V. S., and Fabelinskii, I. L., "Determination of hypersonic attenuation in liquids by an optical method," *J. Expt. Theor. Phys.* (*U.S.S.R.*), vol. 47, pp. 783–784; 1964.

53. Akhmanov, C. A., and Khokhlov, R. B., *Problems in Nonlinear Optics, 1962–1963.* Moscow: Academy of Sciences, 1964.

54. Bloembergen, N., *Nonlinear Optics.* New York: W. A. Benjamin, to be published.

55. Abella, I. D., "Optical double-photon absorption in cesium vapor," *Phys. Rev. Letters*, vol. 9, pp. 453–455; Dec. 1, 1962.

56. Giordmaine, J. A., and Howe, J. A., "Intensity-induced optical absorption cross section in CS_2," *Phys. Rev. Letters*, vol. 11, pp. 207–209; Sept. 1, 1963.

57. Franken, P. A., Hill, A. E., Peters, C. W., and Weinreich, G., "Generation of optical harmonics," *Phys. Rev. Letters*, vol. 7, pp. 118–119; Aug. 15, 1961.

Franken, P. A., and Ward, J. F., "Optical harmonics and nonlinear phenomena," *Rev. Mod. Phys.*, vol. 35, pp. 23–39; Jan. 1963.

58. Giordmaine, J. A., "Mixing of light beams in crystals," *Phys. Rev. Letters*, vol. 8, pp. 19–20; Jan. 1, 1962.

Terhune, R. W., Maker, P. D., and Savage, C. M., "Observation of saturation effects in optical harmonic generation," *Appl. Phys. Letters*, vol. 2, pp. 54–55; Feb. 1, 1963.

59. Ducuing, J., and Bloembergen, N., "Observation of reflected light harmonics at the boundary of piezoelectric crystals," *Phys. Rev. Letters*, vol. 10, pp. 474–476; June 1, 1963.

60. Armstrong, J. A., Bloembergen, N., Ducuing, J., and Pershan, P. S., "Interactions between light waves in a nonlinear dielectic," *Phys. Rev.*, vol. 127, pp. 1918–1939; Sept. 15, 1962.

Bloembergen, N., and Pershan, P. S., "Light waves at the boundary of nonlinear media," *Phys. Rev.*, vol. 128, pp. 606–622; Oct. 15, 1962.

61. Chiao, R. Y., Garmire, E., and Townes, C. H., in *Proceedings of Course XXXI, Enrico Fermi International School of Physics.* New York: Academic Press, 1964.

62. Chiao, R. Y., Townes, C. H., and Stoicheff, B. P., "Stimulated Brillouin scattering and coherent generation of intense hypersonic waves," *Phys. Rev. Letters*, vol. 12, pp. 592–595; May 25, 1964.

63. Townes, C. H., in *Quantum Electronics*, C. H. Townes, ed. New York: Columbia University Press, 1960, p. 402.

Kittel, C., *Phys. Rev. Letters*, vol. 6, p. 449; 1961.

64. Tucker, E. B., "Amplification of 9-kMc/s ultrasonic pulses by maser action in ruby," *Phys. Rev. Letters*, vol. 6, pp. 547–548; May 15, 1961.

65. Brillouin, L., "Diffusion de la lumière et des rayon x par un corps transparent homogene," *Ann. Phys. (Paris)*, vol. 17, p. 88; 1922.

Born, M., and Wang, K., *Dynamical Theory of Crystal Lattices.* New York: Oxford University Press, 1954, p. 373.

Atmospheric research and electromagnetic telecommunication—Part I

The broad subject of electromagnetic telecommunication in the United States is examined, with the stress on the importance of atmospheric research to this growing field

H. G. Booker University of California, San Diego
C. G. Little National Bureau of Standards

This report is based on material prepared during 1964 for the Interdepartmental Committee for Atmospheric Sciences, entitled "Atmospheric Research Required to Facilitate Electromagnetic Telecommunication." The authors were chairman and secretary, respectively, of the Steering Committee set up to guide the preparation of the report.

Part I of this report deals with the economic magnitude of electromagnetic telecommunication in the nation, and discusses the interactions between atmospheric science and electromagnetic telecommunication. Part II, to appear next month, will present an analysis of the fiscal year 1964 telecommunication-oriented atmospheric research across the nation, and discusses the balance of this research program relative to the atmospheric research needed to support the nation's telecommunication activities.

Economic magnitude of electromagnetic telecommunication

One hundred years ago Maxwell first described the electromagnetic nature of light. Now, only 63 years after Marconi's first transmission of radio signals across the Atlantic, electromagnetic telecommunication activities comprise several large industries which have a tremendous impact on the way of life of all Americans. It is the purpose of this section to outline briefly the magnitude of these electromagnetic telecommunication industries.

Expenditures, investment, and employment. Table I shows that the 1962 U.S. expenditures on electromagnetic telecommunication through the atmosphere were of the order of $17 billion, or about 3 percent of the Gross National Product.

Table II estimates $26 billion as the 1963 depreciated U.S. investment in electromagnetic telecommunication systems, equipment, and research and development facilities.

The total impact on the economy is, of course, far greater than that indicated in Table I, both in terms of supporting industries and the "multiplier effect" of the income generated by these expanding activities. Preliminary research by the Office of Business Economics on interindustry sales and purchases indicates that sales of communications equipment to final users have an almost equivalent additional impact on other industries and activities. Every dollar spent on communications equipment requires almost an equal total output from such supporting industries as electronic components, chemicals, fabricated products, plastics, and other materials; services, such as trade, transportation, water and electric power, real estate, etc.; primary metals; mining, and others. Also, before communications equipment can be used, additional expenses are incurred in transportation, distribution, and installation.

The income generated by expanding telecommunication activities and supporting industries has a further economic

I. Estimated annual sales, revenue, or expenditures for electromagnetic telecommunication equipment, operations, or services, 1962

	Millions
Manufacturing (value of shipments at manufacturers' prices)	$ 5 600
Wholesale and retail trade in electromagnetic telecommunication equipment and components (estimated markup or net revenue)	850
Installation and repair services	1 400
Electromagnetic telecommunication operations and maintenance expenditures or revenues	8 350
Research and development expenditures not included in other categories (industry, government laboratories, universities, and other nonprofit organizations)	800
Total	$17 000

II. Estimated U.S. Investment in electromagnetic telecommunication systems, equipment, and R&D facilities, 1963

	Depreciated Value, millions
U.S. Government	
Department of Defense and other National Security Agencies	$ 9 000
Federal Aviation Agency	635
National Aeronautics and Space Administration	250
Treasury (Coast Guard)	450
Commerce (Maritime Administration, Weather Bureau, National Bureau of Standards, etc.)	70
U.S. Information Agency	90
Others, including Atomic Energy Commission, Agriculture, Interior, Justice, Tennessee Valley Authority, Veterans Administration, St. Lawrence Seaway, etc.	75
Manufacturing, net fixed assets	1 000
Non-U.S. Government communications services, facilities, and equipment	
Broadcasting	
Television	370
Radio	260
Common carrier	1 700
Safety and special services, including state and local government	1 500
Research and development, equipment and facilities not reported elsewhere	
Government, industry, and educational and other nonprofit institutions	350
Repair and installation services, and test and measuring equipment and facilities	300
Wholesale and retail trade	450
Consumer electromagnetic telecommunication equipment	
Television receivers	5 500
Radio receivers	4 000
Total	$26 000

III. Estimated employment in electromagnetic telecommunication activities, 1963

	Thousands of Employees
Manufacturing	
Government and commercial telecommunication equipment	270
Television and radio receivers	115
Electronic components	160
Operations and maintenance	
Government	
Department of Defense, including Armed Forces and civilian personnel	400
Other federal agencies	60
Nongovernment	
Broadcasting	100
Safety and special services	140
Common carrier	40
Government facilities operated by private contractors	30
Research and development	
Government, industrial, educational, and nonprofit R&D laboratories, not included elsewhere	40
Wholesale and retail electromagnetic telecommunication equipment distribution	
Television and radio receiver distribution	70
Other: commercial equipment and parts distribution	15
Repair and installation services	
Television and radio repair shops	80
Other: commercial equipment repair and installation services	20
Total	1500

IV. Authorized station count, June 30, 1963

Type of Radio Service	Number of Stations	
Safety and special services		
Amateur	270 838	
Aviation	106 202	
Industrial	107 796	
Land transportation	14 089	
Marine	143 227	
Public safety	43 168	
Citizens	446 590	
Total		1 131 910
Broadcast services		
Standard (AM)	3 997	
Frequency modulation (FM)	1 445	
Television (TV)	757	
Others	9 630	
Total		15 829
Common carrier		6 599
Experimental services		730
Total station count		1 155 068

Source: Federal Communications Commission 29th Annual Report for Fiscal Year 1963.

effect as people spend this income on housing, food, consumer goods, insurance, recreation, and other goods and services. The relatively rapid growth rates of industries and services based on the telecommunication arts have been, and will continue to be, a major factor in U.S. economic growth.

The total employment in electromagnetic telecommunication is estimated to be about 1.5 million persons. The principal categories are shown in Table III.

Authorized transmitter stations. Table IV shows that the authorized station count for civilian transmitters in the United States, as of June 30, 1963, was 1 155 068. After omitting the large amateur radio and citizens' radio usage, the total broadcast, common carrier, experimental, public safety, and special radio services numbered 437 640.

Economic usage by broad spectral region. Table V is an attempt to divide the economic usage of the electromagnetic spectrum into four main spectral regions. These are from 0 to 3×10^7 c/s (primarily involving ground-wave and/or ionospheric propagation); 3×10^7 to 10^9 c/s (primarily tropospheric line-of-sight propagation; 10^9 to 3×10^{12} c/s (primarily tropospheric line-of-sight and beyond-the-horizon propagation); and 3×10^{12} to 10^{15} c/s (infrared and optical line-of-sight propagation).

The distribution of annual expenditures for the different frequency bands for 1962 is estimated as follows:

V. Estimated annual sales, revenue, or expenditures for electromagnetic telecommunication, by broad frequency ranges, 1962 (in millions of dollars)

Activity	Frequency Range, c/s: 0 to 3×10^7	3×10^7 to 10^9	10^9 to 3×10^{12}	Over 3×10^{12}	Total
Manufacturing (value of shipments at manufacturers' prices)	$1 000	$2 750	$1 600	$250	$ 5 600
Government expenditures for installation operations and maintenance	450	2 000	1 800	250	4 500
Nongovernment annual revenue or expenditures					
Broadcasting	620	1 500	—	—	2 120
Common carrier	90	110	430	—	630
Safety and special services	80	1 000	20	—	1 100
Research and development expenditures for electromagnetic telecommunication (industry, government, and nonprofit institutions not reported elsewhere)	50	250	400	100	800
Wholesale and retail trade in electromagnetic telecommunication equipment and components (estimated markup or net revenue)	250	530	70	—	850
Installation and repair services (radio, TV, and commercial)	400	950	50	—	1 400
Totals	$2 940	$9 090	$4 370	$600	$17 000

Fig. 1. Electronic equipment output compared with Gross National Product, 1929 to 1963.

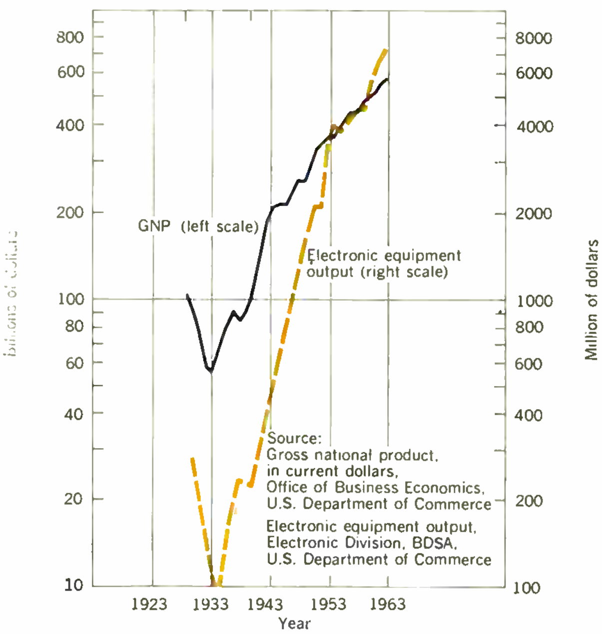
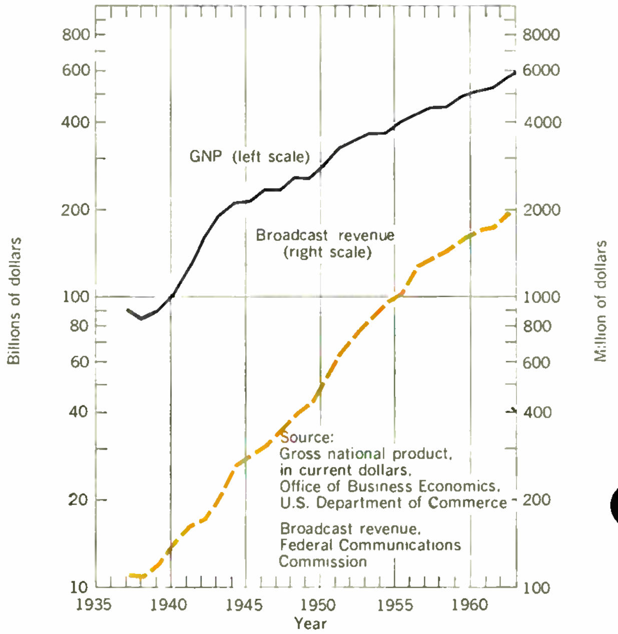


Fig. 2. Growth of total broadcast revenues compared with Gross National Product, 1937 to 1962.



Frequency, c/s	Approximate Expenditure
Below 3×10^7	\$3 billion
3×10^7 to 10^9	\$9 billion
10^9 to 3×10^{12}	\$4.4 billion
Above 3×10^{12}	\$0.6 billion

Growth rates and trends. Now that the large magnitude of atmospheric telecommunication activities has been established, it is important that the growth rates be identified. Common experience shows that the field is still growing; the question, of course, is "how fast?"

Growth of manufacturing. Figure 1 gives dollar figures for the manufactured output of electronic equipment and the Gross National Product for the period 1926–1963, in current dollars. (About 70 percent of the electronic equipment is for telecommunication purposes.) It is noteworthy that in the last 30 years the GNP has increased by essentially one order of magnitude and the electronic equipment output by about two orders of magnitude. As one would expect, the rate of growth of electronic equipment is no longer as fast as it was in the 1940s and early 1950s; nevertheless, over the last ten years the annual growth rate has been about 8 percent per year (in current dollars) compared with an equivalent GNP annual growth rate of 5 percent.

Growth of broadcasting revenues. Figure 2 illustrates the growth of total broadcasting revenues (AM/FM radio and television) over the 25-year period 1937–1962, compared with the Gross National Product. Again the growth of the telecommunication activity has been more rapid than that of the GNP; in this case the annual growth rate (in current dollars) of the broadcast revenue has averaged approximately 10 percent per annum during the last ten years.

Growth of authorized station count. From these two analyses, one of manufacturing, one of telecommunication service revenue, it is clear that the field of electromagnetic telecommunication is still growing rapidly, with an annual growth rate roughly twice as fast as the Gross National Product. This ratio in the growth rates is increased if they are expressed in dollars of constant value, rather than in current dollars. Further evidence of this growth is presented in Table VI, which gives authorized transmitters licensed by the Federal Communications Commission, as of June 30, 1935; June 30, 1959; and June 30, 1963. Here the growth over the four-year period 1959–1963 totals 127 percent.

The trend to higher frequencies. An important feature of this growth is the trend to higher frequencies. As radio telecommunication usage has increased, the International Telecommunication Union has found it necessary to extend specific regulatory control to higher and higher frequencies. The upper limits of the ITU coverage are given in Table VII, in which the figures refer to the frequency assignments for *all* radio services. As an example of the way a particular service has been affected by this trend to higher frequencies, Table VIII gives the band allocations and station counts for public safety services (police, fire, forestry conservation, highway maintenance, local government, state guard) since 1931.

Anticipated growth areas in atmospheric telecommunication. The foregoing discussion has identified the magnitude of the telecommunication activities of the nation, and has shown that the nation's expenditures in this field are still increasing. We believe that these expenditures will continue to grow, both because of the rapid evolution of the technology of telecommunication and because of the rapidly evolving telecommunication demands of our industry and civilization. Examples of the evolving technology include the laser and space telecommunication systems; examples of potential or growing demands for telecommunication capability lie in such areas as

1. Picture phone

VI. Growth of safety and special services in the United States

Radio Service	Authorized Station Count			Percentage Growth
	June 30, 1935	June 30, 1959	June 30, 1963	1959–1963
Marine	2 157	84 947	143 227	69
Aviation	678	77 682	106 202	37
Public safety	298	29 363	43 168	47
Industrial	146	49 697	107 796	116
Land transportation	0	10 625	14 089	32
Citizen	0	49 269	446 590	909
Amateur	45 561	195 776	270 838	38
Totals	48 840	497 359	1 131 910	127

Source: Federal Communications Commission 29th Annual Report for Fiscal Year 1963.

VII. Upper limits of International Telecommunication Union coverage

Year	Maximum Frequency of ITU Allocations, c/s
1927	6×10^7
1938	2×10^8
1947	1.05×10^{10}
1959	4×10^{10}

VIII. Band allocations, public safety services

Year	New Band Added, Mc/s	Total Number of Stations
1931*	1.5 to 3	62
1935	30 to 40	252
1949	152 to 162	5 700
1954	450 to 470	15 697
1963	—	43 168

* Creation of this radio service.

2. Color television
3. Closed-circuit television
4. Educational television
5. Mobile communications
6. Automatic collection of geophysical data
7. Provision of remote access to computer centers
8. Provision of remote access to data-storage centers and libraries
9. Military command and control

The normal expansion of existing services, plus the expansion required to meet new needs such as those suggested above, make it highly probable that the telecommunication activities of the nation will continue to grow appreciably faster than the Gross National Product.

Intangible benefits resulting from telecommunication. The foregoing discussion has been concerned primarily with identifying the magnitude and trends of the national expenditures on electromagnetic telecommunication. There has been no discussion of the benefits obtained by these expenditures, though it is important to recognize that they are so large as to make it appropriate to speak of the 20th century as the Age of Telecommunication. The impact (political, military, sociological, economic, educational, scientific, and historical) of man's ability to communicate over long distances essentially instantaneously is rarely even discussed, let alone measured. Indeed, it does not appear possible to measure quantitatively the many benefits derived by the United States from this use of the electromagnetic spectrum. For example, how would one estimate the total value of television (including international relay) to the nation? What are the military and civilian benefits obtained (say) by the use of radar? How does one measure the worth of the lives saved by the use of radio by the fire and police services (or even how many lives are saved)? To what extent will the use of two-way radio by American industry for instant communication with skilled decision makers increase our ability to compete effectively in worldwide markets? We do not attempt to answer such questions here, since this article is concerned primarily with atmospheric research rather than social science and economics. Instead, we will list the principal uses of telecommunication, leaving it up to the reader (if he wishes) to make his own estimates of the benefits derived from such services. These uses (approximately in descending order of annual expenditure or revenue) are as follows:

1. Military uses for the command, control, and guidance of friendly forces and weapons; for the detection, surveillance, deception, and (if necessary) destruction of hostile weapons, activities, and forces
2. Television broadcast
3. Mobile communication to and from aircraft, ships, and land vehicles
4. Navigation
5. Long-distance radio relay of telephone calls
6. AM and FM broadcast
7. Public safety by law enforcement agencies, fire services, civil defense, etc.
8. Space telecommunication
9. Geodesy
10. Atmospheric research by remote electromagnetic probing
11. Voice of America broadcasts
12. Citizens' band
13. Amateur radio
14. Dissemination of time and frequency standards

Telecommunication capabilities and limitations of the atmosphere

The primary purpose of this section is to review the field of telecommunication by electromagnetic waves, and to indicate across the spectrum the extent to which the atmosphere interacts with and limits telecommunication.

First, we should note that the analysis relates to communication through the atmosphere using electromagnetic waves. We will be concerned with the atmosphere as it affects propagation; we will not, in general, be directly concerned with the details of either the transmitting or the receiving devices.

Second, it is necessary to define telecommunication in the sense used in this article. By telecommunication we mean the use of electromagnetic waves propagating through the atmosphere to convey information (intelligence) of any type. Thus telecommunication must be recognized as including all radar, navigation, broadcast, television, and other systems that involve propagation of electromagnetic waves in the atmosphere.

Third, it is important to recognize the range of frequencies considered here. Although the electromagnetic spectrum has been explored by the physicist over at least the range 10^{-3} c/s to 10^{22} c/s, that part of the spectrum between about 10^4 (very-low-frequency radio waves) and 10^{15} c/s (near-ultraviolet) is potentially the most useful for telecommunication purposes. Among other difficulties, the radiation, modulation, and detection of coherent electromagnetic waves outside this frequency band makes such frequencies unattractive to the communicator. There are however a number of research uses, and even some specialized applied telecommunication uses, of frequencies below 10^4 c/s. Following and extending the terminology of the radio telecommunication engineer, we will describe the different regions of this spectrum by the terms given in Table IX.

Fourth, because of the extremely broad frequency range to be covered, it is important to recognize that very many different propagation mechanisms (i.e., methods by which electromagnetic waves propagate through the atmosphere from a transmitter to a receiver) must be considered. The principal propagation mechanisms which are significantly

IX. Regions of the frequency spectrum

Region	Frequency, c/s	ITU Band Number
Very-low frequencies (VLF)	3×10^3 to 3×10^4	4
Low frequencies (LF)	3×10^4 to 3×10^5	5
Medium frequencies (MF)	3×10^5 to 3×10^6	6
High frequencies (HF)	3×10^6 to 3×10^7	7
Very-high frequencies (VHF)	3×10^7 to 3×10^8	8
Ultrahigh frequencies (UHF)	3×10^8 to 3×10^9	9
Superhigh frequencies (SHF)	3×10^9 to 3×10^{10}	10
Extremely high frequencies (EHF)	3×10^{10} to 3×10^{11}	—
Teracycle radio	3×10^{11} to 3×10^{12}	—
Infrared	3×10^{12} to 4×10^{14}	—
Visible	4×10^{14} to 8×10^{14}	—
Near-ultraviolet	8×10^{14} to 10^{15}	—

affected by the atmosphere may be listed as follows:

1. Geometrical-path (line-of-sight) propagation
   a. Tropospheric line of sight at radio, infrared, and optical frequencies
   b. Earth–space line of sight at radio, infrared, and optical frequencies
2. Propagation mechanisms involving reflection
   a. Earth–ionosphere ducting
   b. Earth–ionosphere reflection
   c. Tropospheric ducting
   d. Tropospheric reflection
3. Propagation mechanisms involving scatter
   a. Ionospheric forward scatter
   b. Meteor scatter
   c. Tropospheric scatter at radio, infrared, and optical frequencies

It should be noted that several other propagation methods exist but have been omitted. Such mechanisms are

1. Propagation mechanisms not discussed because of minor sensitivity to atmospheric effects
   a. Space-to-space line of sight (essentially unaffected by the propagation medium for all frequencies greater than about 10^7 c/s)
   b. The Norton surface (diffracted) wave (a very important propagation mechanism at VLF, LF, and MF and of some importance to about 10^8 c/s, in which the propagation is determined primarily by the electrical characteristics and curvature of the ground, rather than by the atmosphere)
   c. Mountain diffraction and ground scatter (which may be of importance in the range of 10^7 to about 10^{11} c/s, again depending on the characteristics of the ground rather than the atmosphere)
2. Propagation mechanisms not discussed because of limited usefulness except for atmospheric research purposes
   a. Incoherent scatter (3×10^7 to 10^9 c/s)
   b. Hydromagnetic waves, and the whistler mode (10^{-3} to 10^5 c/s)
   c. Magnetospheric ducting (10^6 to 2×10^7 c/s)
   d. Auroral scatter (10^6 to 3×10^9 c/s)

Fifth, for any of these propagation mechanisms, a telecommunicator may well be interested in the following principal parameters of an electromagnetic wave, as well as their space and time dependence. In many cases, the propagation-induced fluctuations in these parameters limit the telecommunication capabilities of the system. These parameters include

1. Amplitude
2. Phase
3. Frequency (time derivative of phase)
4. Polarization
5. Direction of travel
6. Phase velocity
7. Dispersion (the variation of phase velocity with frequency)

Sixth, it should be recognized that the final limit to the information-carrying capability of an electromagnetic telecommunication system is the existence of unwanted signals and noise. These may be man-made or of natural origin; they may originate in the system itself or may be signals that originate elsewhere and are picked up by the receiving system. In any discussion of the effects of the atmosphere on telecommunication systems, the atmospheric noise level in which the system is immersed must therefore be considered.

Seventh, it should be recognized that in many atmospheric telecommunication systems, the signals may propagate to the receiver by more than one propagation mechanism at a time. These may follow somewhat similar paths (such as the two magnetoionic mode paths of an HF communication system), or two very different mechanisms may be involved, as in the case of simultaneous reception of the ground wave and the sky wave at low or medium frequencies.

Atmospheric telecommunication limitations. A detailed discussion of the manner and extent to which each of the significant parameters describing an electromagnetic wave is affected by the several atmospheric regions, across the whole spectrum of interest to the communicator, is clearly beyond the scope of this article. Instead, two figures summarizing this information have been prepared. Figures 3 and 4 present graphically the key aspects of significance, understanding, and predictability of atmospheric limitations to telecommunication as a function of propagation mechanism and frequency. It is important that the reader recognize that the frequency boundaries used in these figures are very arbitrary. In practice, the transition from one propagation mechanism to another, or from one grade to another, occurs over a range of frequencies rather than at a discrete frequency.

The several different uses of a given propagation mechanism will not in general be equally sensitive to changes in propagation; a given change in propagation conditions may be of far greater significance for one telecommunication system than for another. Also, different specialists would undoubtedly grade the telecommunication limitations of an individual propagation mechanism differently, with the standard deviation probably about one grade. The reader should therefore be cautious in using these figures, especially when attempting to apply them to an individual telecommunication circuit instead of to the general state of the art for that propagation mechanism.

Gaps in our understanding of atmospheric effects. In Figs. 3 and 4 the degrees of significance, understanding, and predictability of these atmospheric effects for each of the main propagation mechanisms are summarized. The purpose of the present section is to use this material to identify the major gaps in the understanding of the atmospheric effects on electromagnetic telecommunication. The treatment will be broad and certainly not all-inclusive; however, it is hoped that by identifying the main gaps in our knowledge it will be possible to test the balance of the existing atmospheric research program in support of telecommunication.

For purposes of broad review of the balance of the research effort it is convenient to consider only four main types of electromagnetic propagation paths. These are, respectively, tropospheric line-of-sight paths; tropospheric beyond-the-horizon paths; paths involving ionospheric reflection or scatter; and earth–space line-of-sight paths, involving both tropospheric and ionospheric propagation. The status of understanding of each of these four main types of telecommunication paths will now be considered in turn.

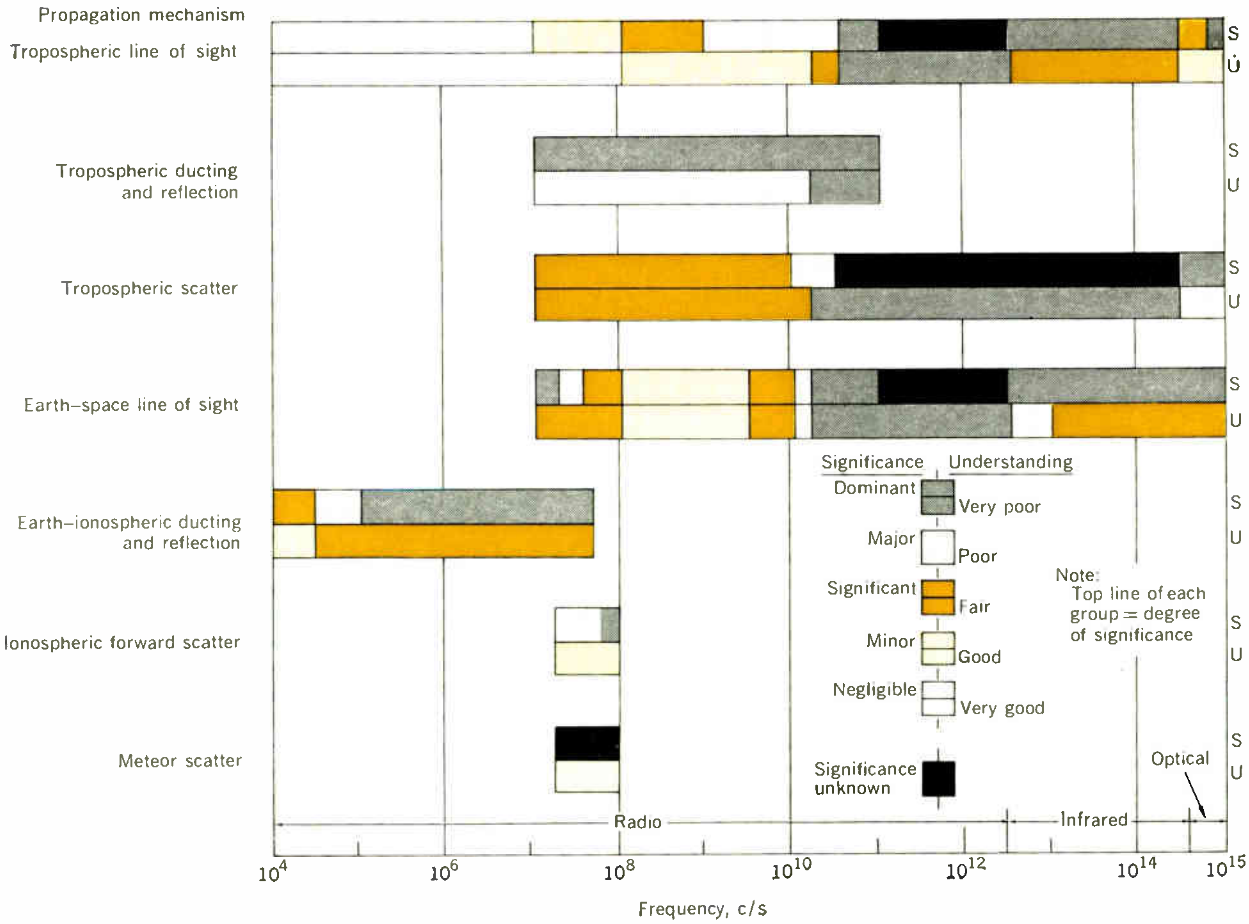
Tropospheric line-of-sight paths. In this most important propagation mechanism (typically limited to distances of a few tens of miles) the degree of understanding is good up to roughly 10^{10} c/s. As the frequency increases from $\sim 10^{10}$ to $\sim 3 \times 10^{12}$ c/s, the degree of understanding changes rapidly to poor or very poor. The history of line-of-sight radio telecommunication is one of constant extension to higher and higher frequencies; it is clear that the pressures for increasing bandwidth are such as to cause this trend to continue. Since atmospheric limitations are of increasing significance at radio frequencies above about 10^{10} c/s, it is clear that considerable research on the radio properties of the troposphere (including especially the absorption of radio waves by atmospheric gases, and their attenuation by clouds and precipitation) will be required to optimize system design and spectrum utilization.

The understanding of line-of-sight propagation at optical and infrared frequencies is rated as fair; again considerable atmospheric research is required before the telecommunication capabilities of the atmosphere at these frequencies is understood. Considerable effort is being devoted to component development in this frequency band; much of it will be wasted unless adequate propagation information is available.

Tropospheric beyond-the-horizon paths. The tropospheric reflection, ducting, or scatter of electromagnetic waves to points beyond the horizon represents an extremely important propagation mechanism applicable (with the exception of some absorption bands) to all frequencies above about 10^7 c/s. The degree of understanding of the atmospheric effects on such propagation paths is typically poor or very poor. For example, although in a favorable case it is possible to predict the *median* transmission loss with a probable error of about a factor of two, the instantaneous transmission loss between single antennas typically varies by at least a factor of one million, in an unpredictable manner. Although the theory of electromagnetic propagation in simplified models of the atmosphere is well advanced, there is no general agreement as to the appropriateness of any of the models, nor even as to the relative amount of time that the received signal should be attributed to tropospheric scatter, reflection, or ducting. It is clear that any further major advances in RF tropospheric scatter communication are dependent upon a better understanding of the radio propagation, and that a much better understanding than now exists of the large- and small-scale variations of atmospheric refractive index will be required.

No systematic studies have been made of beyond-the-horizon propagation of infrared and optical wavelengths; such studies appear to be of high priority, since they may offer completely new telecommunication opportunities. Radio telecommunicators have found the very weak scattering of signals that occur in the troposphere and the

Fig. 3. Degrees of significance and understanding of atmospheric effects on the main electromagnetic propagation mechanisms.



lower ionosphere extremely valuable for beyond-the-horizon propagation; at optical wavelengths the scattered component is orders of magnitude stronger, and so well may provide a valuable telecommunication mechanism.

Paths involving ionospheric reflection or scatter. An examination of Fig. 3 reveals that the degree of understanding of ionospheric propagation is rated from fair to good, being best in the range 10^4 to $\sim 3 \times 10^4$ c/s, and poorest in the range 10^5 to 10^6 c/s. The fact that the degree of understanding is higher for this type of propagation rather than for tropospheric propagation can be attributed to two main factors:

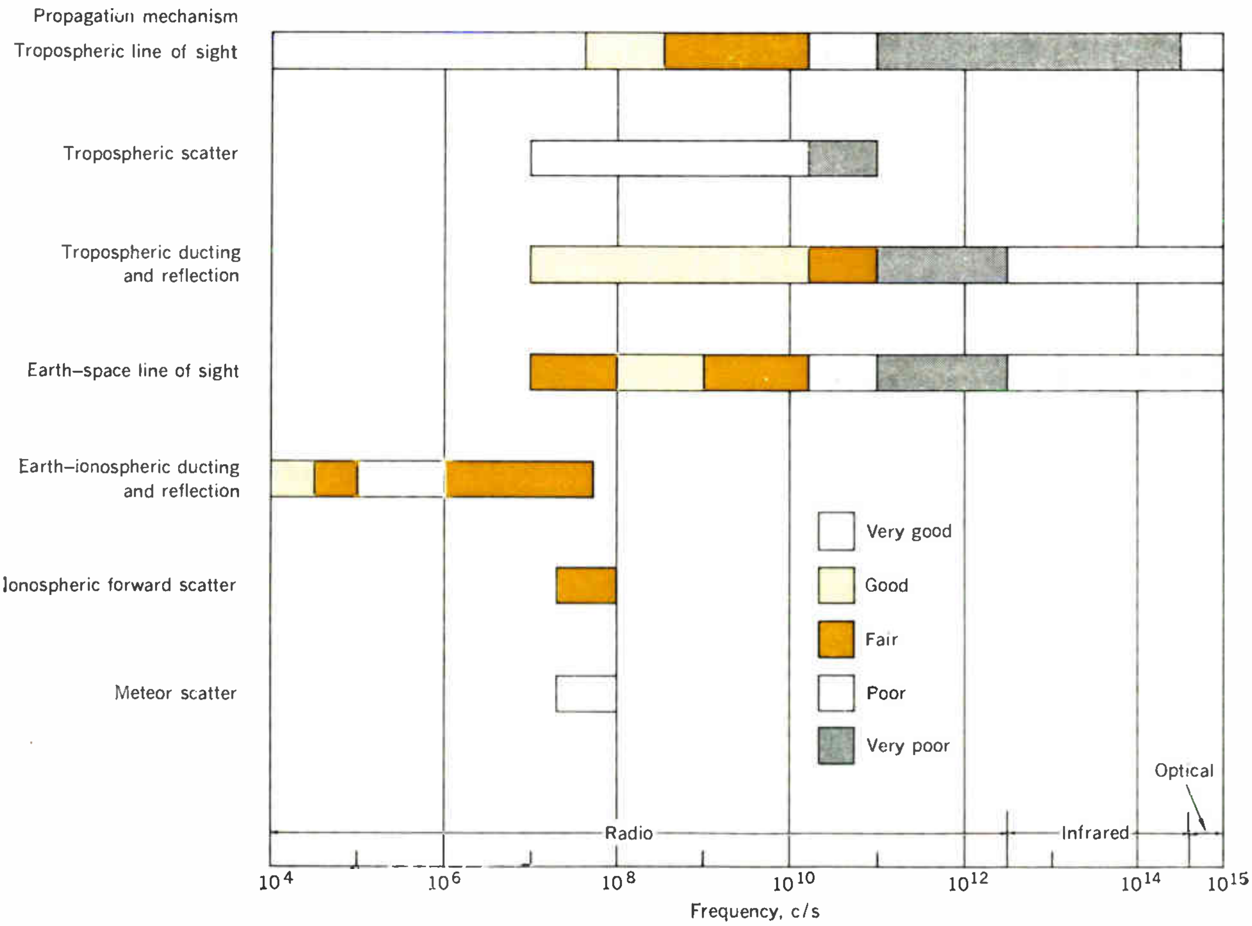
1. The large amount of research (both propagational and atmospheric) that has been conducted in this field, starting almost 40 years ago
2. The major extent to which radio techniques have been used to study the upper atmosphere

The first of these points can be attributed to the dominant importance of ionospheric propagation, which until about 1955 was the only method of communicating far beyond the horizon (except for the important, though then relatively small, use of cables). The second factor is attributable to the inherent simplicity of the remote electromagnetic probing techniques relative to the difficulty of conducting *in situ* studies of the upper atmosphere.

From the point of view of telecommunication, the ionosphere is enormously more variable, both geographically and temporally, than the lower atmosphere. The last decade has seen major improvements in our understanding of the gross temporal variations (diurnal, seasonal, and 11-year sunspot cycle) and the gross geographic and height variations. The present limitations in our understanding of the ionosphere are primarily in terms of the shorter term (disturbance-type) variations, and those of smaller scale (from roughly 1000 kilometers down to scales of tens of meters). These irregular, and at the moment unpredictable, variations have importance comparable to that of the long-term and large-scale variations, and much research must be devoted to increasing our understanding of their role in ionospheric telecommunication.

Earth–space line-of-sight paths. The propagation of electromagnetic waves from the earth's surface to space vehicles involves both tropospheric and ionospheric propagation. Up to frequencies of the order of 10^9 c/s, ionospheric effects (refraction, scatter, polarization, rotation, and absorption) are the most important; above about 10^9 c/s the tropospheric effects become more significant, especially at low angles of elevation. The present trend is to use frequencies of the order of 2×10^9 to 10^{10} c/s for most earth–space telecommunication; for this reason the atmospheric research required to support this type of telecommunication is tropospheric in nature.

Fig. 4. Degree of predictability of atmospheric effects on the main electromagnetic propagation mechanisms.



Three main types can be identified:

1. Because many of the present allocations for earth-space telecommunication are on a shared-use basis, it is important to study the effects of tropospheric scattering, ducting, and reflection, which may result in unacceptable interference between services operating on the same frequencies.

2. Studies of earth-space propagation at radio frequencies above 4×10^{10} c/s (the highest frequencies currently assigned by the ITU) should be made in order to investigate the possibility of their use for space telecommunication.

3. The potential importance of earth-space propagation at infrared and optical frequencies should also be investigated.

Atmospheric noise levels. Since all telecommunication systems are ultimately limited by the effects of unwanted noise and interference, it is important that appropriate studies of atmospheric noise levels be made. Across the spectrum, the major research needs may be identified as follows.

Up to about 10^9 c/s, the principal noise limitation is not atmospheric in origin, but due to unintentional and often unnecessary radiation of energy from electric machinery, motor vehicles, neon lights, power lines, etc. At higher radio frequencies, particularly above about 2×10^{10} c/s, thermal noise due to atmospheric absorption becomes dominant. With the advent of ultralow-noise receivers, atmospheric noise (including ground noise scattered into the antenna beam by precipitation) is becoming a serious limitation. Studies of atmospheric absorption as a function of frequency and elevation angle are required at frequencies up to and including the infrared frequencies. At optical frequencies a considerable body of unorganized data exists; it is clear that there is a need for studies of the background illumination levels as a function of (optical) frequency, angle of elevation, climatic conditions, etc., before optical telecommunication systems can be designed in an optimum manner.

Interference noise levels. As the use of the electromagnetic spectrum increases, the problem of cochannel interference becomes more serious. Eventually, noise of natural origin ceases to limit the sensitivity of telecommunication systems, and instead the limit becomes one of interference from other competing man-made signals. Because the received strength of these unwanted signals is often determined largely by the atmosphere, there exists an important need for atmospheric research directed toward the interference problem. (These studies differ from normal atmospheric telecommunication studies. Usually the telecommunicator designs his system to cope with the periods of weakest received signal strength. In decisions concerned with mutual interference—e.g., frequency-allocation problems—the telecommunicator must consider the *strongest* signal strengths that will be received from the interfering source.) This problem is currently of critical concern in the HF band, in the VHF mobile bands, and in connection with frequency sharing between earth-space and ground-ground systems at ultrahigh and superhigh frequencies. However, across the whole of the spectrum it forms an essential part of the information required by any civilian or military frequency-allocating body. Since errors or uncertainties in the magnitudes of these interference fields impose a serious limit on efficient spectrum utilization, it is clear that much study (including atmospheric research) should be devoted to this problem.

Modification and control of the telecommunication capabilities of the atmosphere. One important goal of atmospheric research in support of electromagnetic telecommunication is to be able to modify the propagation limitations and capabilities of the atmosphere. The progress to date has been limited. However, it is now clear that man can modify the electromagnetic propagation characteristics of his environment in several ways, though with difficulty and usually only in a very transient and localized manner; for example:

1. Temporary, localized disturbances in electron density capable of scattering or reflecting radio waves have been produced by artificial seeding of the ionosphere by suitable chemicals.

2. The production of extra ionization in the middle and high atmosphere by high-altitude nuclear bomb explosions has been studied on a number of occasions. Under many circumstances the ionization is produced sufficiently low in the atmosphere to cause major disruption in radio communication because of the high absorption associated with the high electron collision frequency. Atmospheric nuclear bomb explosions can also have major propagation effects on infrared and optical telecommunication systems.

3. A third way to perturb the propagation medium is the controlled use of electromagnetic waves (radio, infrared, or optical) to heat the medium, the resultant change in temperature of the atmospheric gases or electrons changing the refractive index, and hence the propagation characteristics of the medium. This method, when applied to the lower ionosphere, results in the so-called Luxembourg or radio-wave interaction.

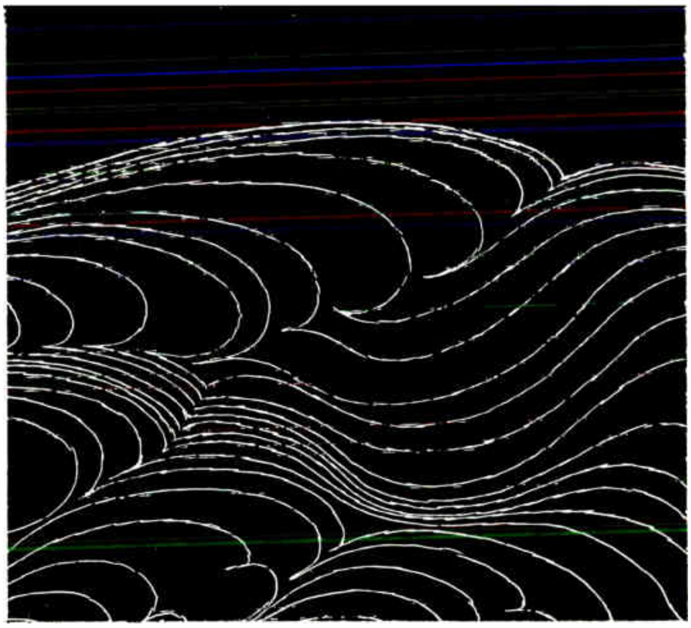
4. The production of ionized regions by shock waves from supersonic objects (artificial meteors, re-entry vehicles) results in the production of a transient, localized, and often undesired perturbation of the electromagnetic properties of the atmosphere.

5. Electromagnetic propagation through the atmosphere may also be modified by the introduction of passive metallic material capable of scattering electromagnetic waves—e.g., chaff, balloons, Project Westford needles, etc.

6. The telecommunication capabilities of the atmosphere may be modified by changing the noise environment in which the telecommunication system works, rather than the propagation medium itself. Examples of such man-made perturbations are the weak increases in background noise level at radio frequencies due to synchrotron emission from energetic electrons resulting from the high-altitude bomb explosion of July 9, 1962, or at optical and radio frequencies from the Westford needles. More dramatic, but shorter-lived, changes in noise level can occur across the whole telecommunication spectrum in the moments following an atmospheric nuclear bomb explosion.

Although a great deal has been learned by studying these phenomena—including, for example, techniques for the remote detection of nuclear bomb explosions—it does not appear that the telecommunication properties of the atmosphere are likely to be controllable in the immediate future.

(*This article will be concluded in the September issue.*)



Science and the salty sea

Man's dream for centuries has been to turn the oceans into sweet water. Today we know that this dream will be fulfilled tomorrow for the vast arid regions from the Mojave Desert to the Sahara, where human prosperity—and survival—depend upon new sources of fresh water

Gordon D. Friedlander *Staff Writer*

"Water, water, every where,
And all the boards did shrink;
Water, water, every where
Nor any drop to drink."

Samuel Taylor Coleridge
The Ancient Mariner

Back in 49 B.C., Julius Caesar attempted to convert salt water to fresh water during the siege of Alexandria. In 1963 A.D., in the United States, President Kennedy said: "If it can be done inexpensively, it will dwarf any other scientific accomplishment." And he directed that a maximum effort be made during his administration to achieve a major breakthrough in increasing water supplies by low-cost water desalting and purification. Today, this program has been greatly accelerated, and Federal funds for this effort have doubled the previous appropriations.

The world problem

Large areas of the globe are presently short of pure, fresh water. During the next four decades—unless alternative sources are found—the shortage will become critical.

In the United States, it was expected, until recently, that our natural supply would exceed the demand for many years to come. But unforeseen and prolonged drought in watershed areas that previously had adequate rainfall has changed this optimistic outlook. Also, our water resources are not uniformly distributed. An excess of demand over supply by 1980 is predicted for five of our 22 major resource regions. Poor water quality, either from natural alkalies or industrial pollution, considerably affects our present-day supply. Further qualitative diminution could bring critical shortages before 1980.

A United Nations' study of 75 emerging nations reveals that more than 130 million people depend upon water sources that are inadequate, or unsafe, or a combination of both. And this alarming estimate is expected to increase by 300 percent by 1980, unless sweeping technological changes and advances are achieved.

An international program. As an international approach to the overall problem, 50 nations are pooling their efforts this year for a long-range study project, sponsored by UNESCO, to be called the International Hydrological Decade. The participants in this project realize, as their basic premise, that with sufficient ingenuity, financing, and experimentation, man can almost always obtain fresh water from some nearby or remote source. But economics must invariably be the controlling element. For example, a cost differential of one penny per 1000 gallons increases to prodigious proportions when required quantities are measured in billions of gallons.

At first glance, water desalination may seem to be a remote subject for the pages of an electrical and electronics engineering publication. But its relevance and close relationship is apparent when one realizes that a number of the present desalination methods, especially the evaporative processes, are being used in the design and construction of close-coupled, dual-purpose plants, in which exhaust steam from the turbine cycle of nuclear generating plants is used to operate the water plants. This promising application, in areas where shortages of both electric power and fresh water are critical, will be explored in more detail later in this article.

Large-scale single- and dual-purpose plants are already under construction in the United States, Israel, on the island of Bahrein in the Persian Gulf, and at the U.S. Naval Base at Guantanamo Bay, Cuba.

The four methods of obtaining water

Four principal methods of supplementing local water supplies are in use today.

Transporting water. Fresh water from inland lakes, streams, and reservoirs can be conveyed great distances by aqueducts, a method in use since the days of ancient Rome. But this is a costly method and entails many associated problems.

For example, in California, surface waters will be impounded from abundant watershed sources in the Sierra Nevada range by the world's largest earthfill dam, which will be built on the Feather River at a cost of $457 million. Water will be carried by aqueduct, across deserts and through mountains, for a distance of 400 miles to the south. An additional 638 miles of canals, conduits, and tunnels will be required to distribute the water to coastal farms and towns. The cost of the entire project will involve billions of dollars. The construction of the aqueduct system alone is estimated at $1.3 billion.

But beyond the initial investment costs, the transportation of fresh water from one place to another creates a "vicious circle" in that the population of former arid lands invariably soars as fresh water becomes available, thereby requiring ever-greater quantities in the future. This situation will inevitably deplete the reserves of the distant sources.

Desalting sea water. Our oceans and inland seas contain 92.7 percent of the earth's water. This water can be made potable if its saline content is reduced from about 35 000 parts per million to 500 ppm or less. The desalination of sea water can be accomplished by various distillation or evaporative methods, by electrodialysis, or by the newer experimental processes of reverse osmosis, direct contact freezing, and propane hydrate.

But even at the present state of the art, to attain only a moderate economy in operation, distillation plants for a large population must be of huge size. The domestic requirements of one million people are approximately 150 Mgpd (million gallons per day), and in a distillation plant of such capacity, the cost to produce fresh water would range from 35 to 45 cents per 1000 gallons at the distribution centers.

A major disadvantage is that costs per 1000 gallons do not decrease markedly even with much greater production. A distillation plant capable of meeting the full requirements of the city of London—about nine million people—would produce 1350 million gallons per day at a cost of 25 to 30 cents per 1000 gallons at the plant. But since such plants must be situated on the sea coast, aqueduct and pumping costs to inland cities and towns must be added.

Sea water can be efficiently desalted by electrodialysis, but because of the high saline content, present costs are too great. It is expected that substantial reductions of these costs may ultimately be achieved from R & D programs now under way.

Electrodialysis of brackish waters. During the Devonian period of the earth's formation, a vast sea covered most of the midwestern prairies of the United States. Over the millions of years of geological time, this sea receded, but left as its residue the surface waters of the Great Salt Lake in Utah, the alkali wastes of the South Dakota "bad lands," and huge underground "aquifers" of brackish waters (see Fig. 1 map). By definition, brackish water consists of between 1000 and 10 000 ppm of alkali salts.

Of the total rain that falls on the land, 70 percent either evaporates or is transpired by plant life and returns to the atmosphere. The remaining 30 percent falls into catchment or watershed areas from which it eventually reaches rivers through surface runoff. But about one quarter of this 30 percent percolates into the ground to augment the supply of the existing aquifers. This water is recoverable, mainly by electrodialysis, and many hydrologists believe that the brackish underground supplies are one of the world's great untapped natural resources. Vast quantities of such water can be found in almost every country of the world. The brackish waters contain far less salt than sea water does, and hence can be more easily converted to fresh water. And equally important, the brackish water sources are frequently situated close to the point of intended use.

Essentially, in electrodialysis, electric power removes salts from the water by drawing them through membranes. When salts and minerals are dissolved in water, their atoms acquire positive and negative ionic charges in the solution. Common salt, or sodium chloride, splits into positively charged sodium ions and negatively charged chloride ions. We will discuss electrodialysis in detail later in this article.

Water reuse and reclamation. The fourth method of assuring a continuous supply of fresh water is reuse—after purification and desalination. This method can be used wherever central sewers are installed.

The reuse of waste and sewage waters can virtually perpetuate the existing supply of a community. The contaminants in sewage effluent include organic material, detergents, and biological materials. As water passes through a municipal system, the dissolved mineral content also increases by 300-400 ppm. Conventional sewage treatment systems remove the organic and biological contaminants, but do not remove dissolved minerals. After the water is purified, however, it can be demineralized by electrodialysis at a relatively low cost (see Fig. 2). It is forecast that for direct municipal use on a scale of 50 Mgpd, the cost by this method could eventually be 10 cents per 1000 gallons.

Wrightsville Beach—Government-sponsored 'proving ground'

To implement the crash program of new water conversion processes and techniques, the Office of Saline Water (OSW), of the U.S. Department of the Interior, has established a single, consolidated test site at Wrightsville Beach, N.C. Here, R & D work is carried out under contracts and grants administered by the OSW,[1] which

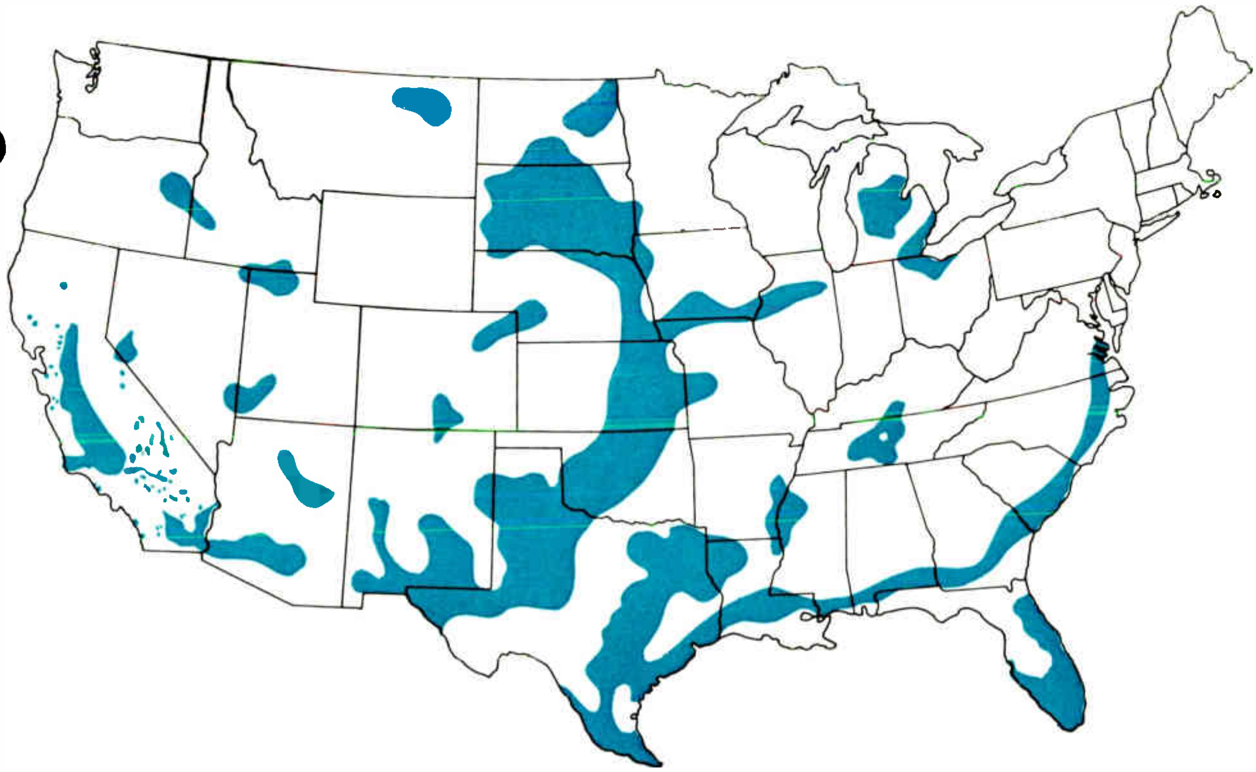
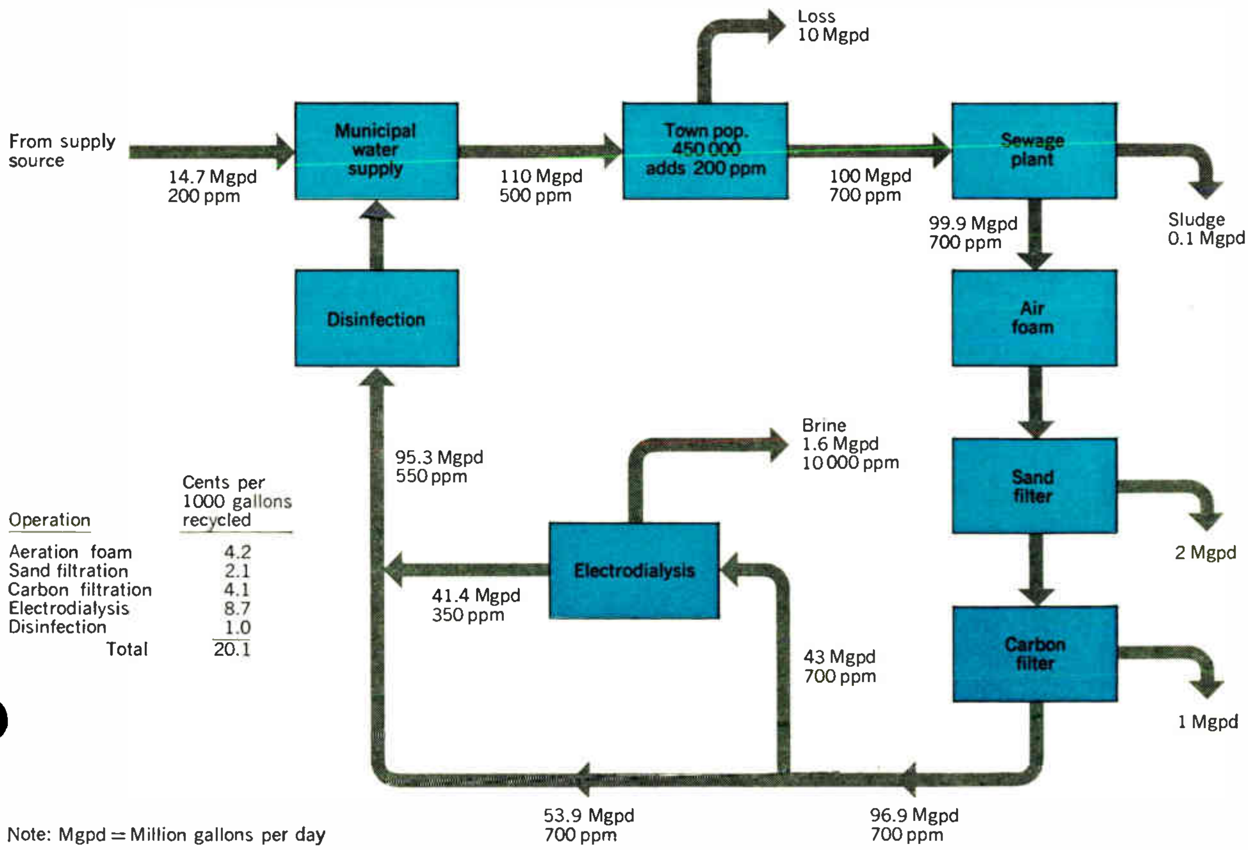


Fig. 1. Map showing brackish underground aquifers which could be purified economically by a number of desalination processes.

Fig. 2. Typical sewage reclamation process, showing representative costs.



Operation	Cents per 1000 gallons recycled
Aeration foam	4.2
Sand filtration	2.1
Carbon filtration	4.1
Electrodialysis	8.7
Disinfection	1.0
Total	20.1

Note: Mgpd = Million gallons per day

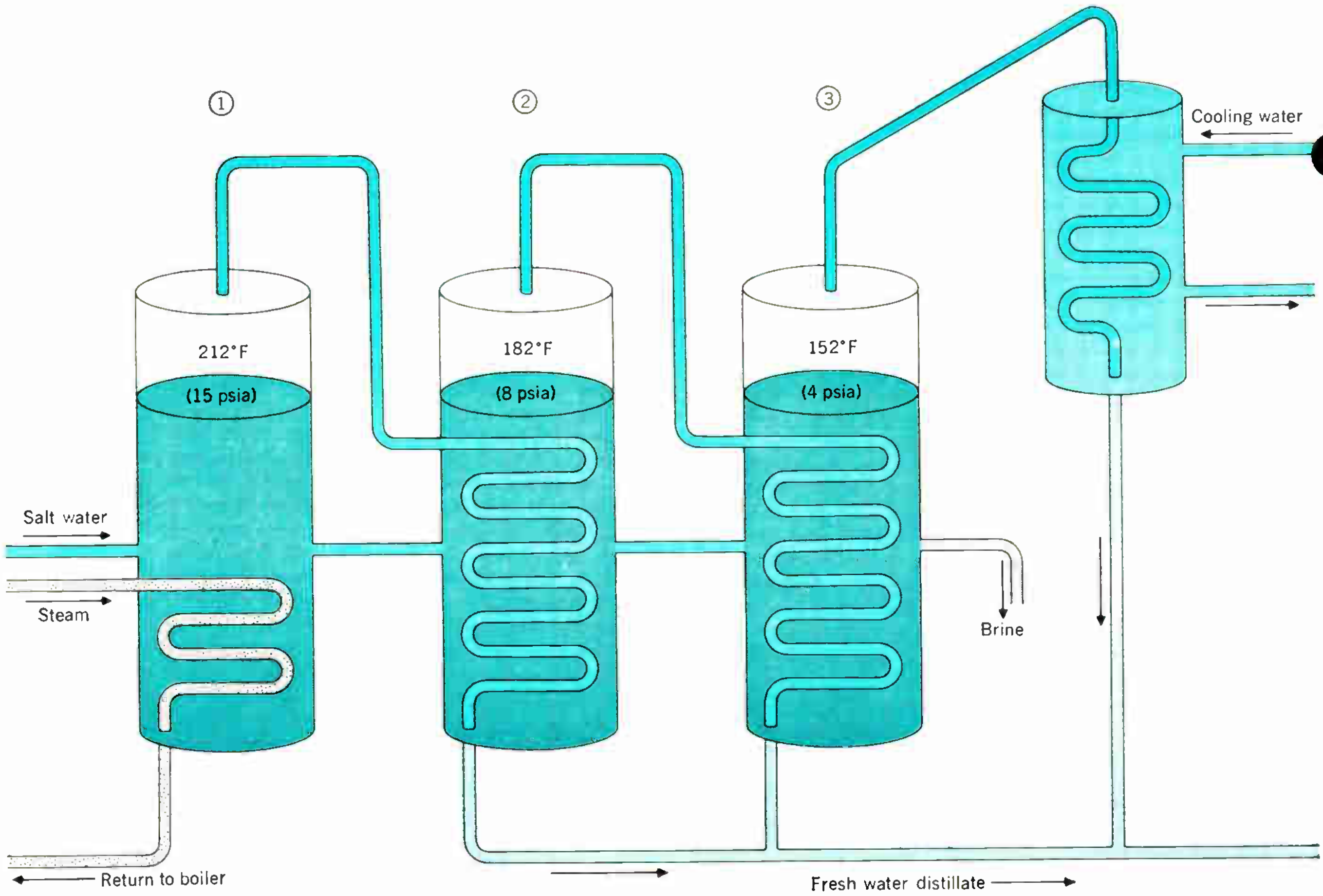
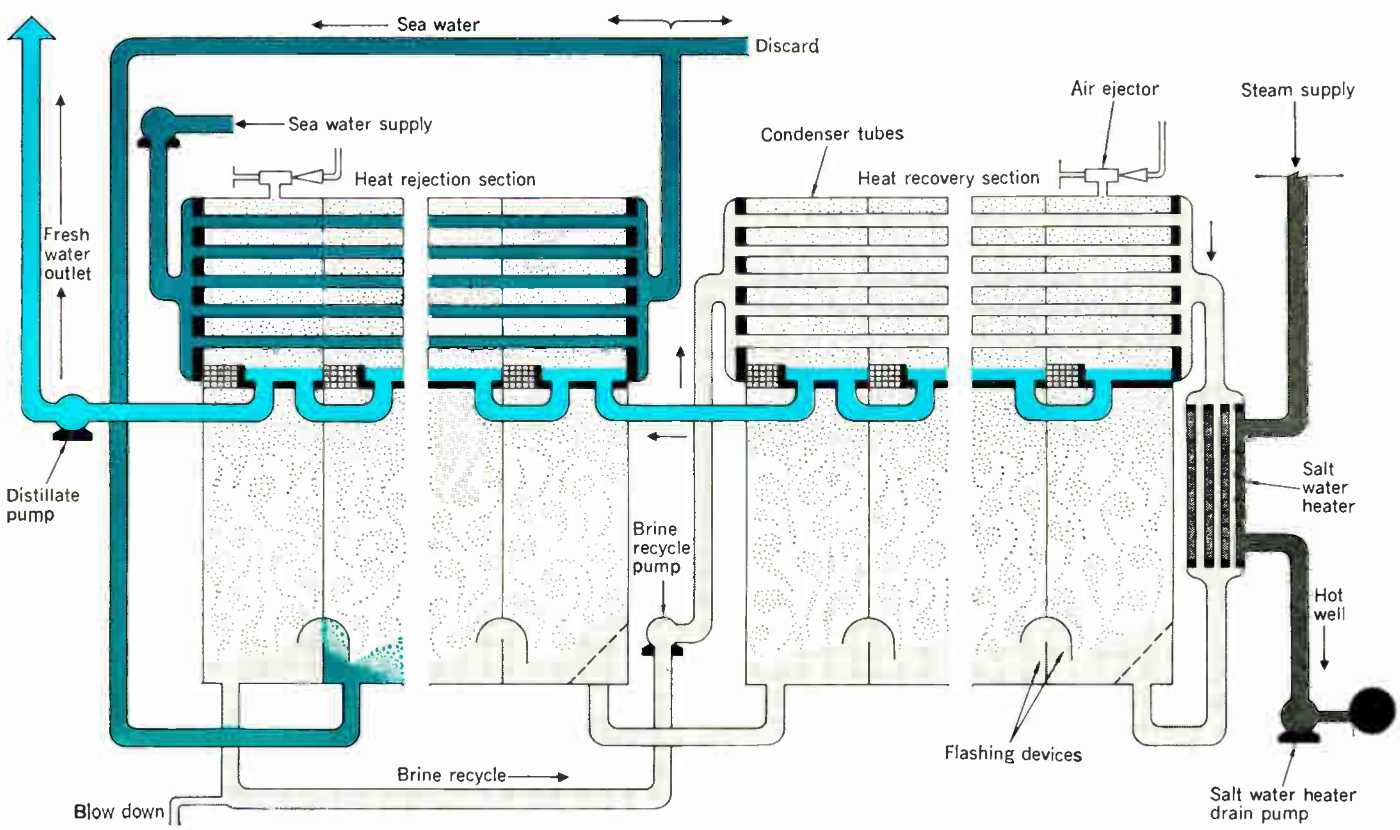


Fig. 3. Flow diagram of a triple-effect distillation system that is commonly used to produce boiler makeup feed.

Fig. 4. Diagram displaying the fundamental principles of a flash evaporator system that is similar in process operation to a one-Mgpd plant under construction in Israel.



must evaluate the hundreds of ideas that come from universities, industry, and private individuals.

The projects reviewed may range from pure research studies to commercial-scale demonstrations of advanced processes.

One vital effort in the R & D program is to translate fundamental data into a complete and practical process for testing on a pilot plant scale. The pilot plants are designed at the smallest workable scale for the determination of both method feasibility and economic practicality.

Physical facilities of test station. As originally designed, the test station, which was completed in January 1963, provided for ten pilot plant sites. Each site is furnished with all necessary utilities, such as high- and low-pressure steam, electricity, sea water and fresh water connections, compressed air for plant and instruments, and propane gas for laboratory experimentation. The reinforced concrete "test pads" also have overhead crane facilities for the installation or removal of heavy equipment.

At present, the Koppers Company of Pittsburgh, Pa., operates and maintains the station facilities under contract license to the OSW. By terms of the contract, personnel are available to operate the central station boilers, machine shop and repair installation, and chemical laboratory, and to maintain all necessary station appurtenances.

Nucleus of the program. The basic purpose of the Wrightsville Beach program is the testing that is being performed in the nine individual pilot plants. The plants function by the various processes, both operational and experimental, that will be described next in this article.

The basic evaporation process

Multiple-effect distillation. In this early method of sea water conversion[2] the vapor produced in one evaporator of a series (Fig. 3) is used as the heat source for the following evaporator. The pressure in the next adjacent evaporator is lowered so that the solution will boil, with the latent heat of condensation of vapor as its heat supply. For example, in the first stage shown in the diagram, sea water is evaporated to steam at atmospheric pressure or higher. As the steam passes to coils in the second evaporator, it condenses and is collected as distilled water. In condensing, the steam releases latent heat and evaporates the sea water in that vessel—and so on through a number of successive stages. Essentially this is the process used in marine installations to provide boiler feed water. It is limited in its output and it is expensive in terms of cost per thousand gallons.

Long-tube vertical evaporators. In the long-tube vertical evaporator process (LTV), sea water is fed into the inside of the tubes, from whence it precipitates in a falling-film pattern. In this configuration the water vapor condenses on the outside of the tubes, and the sea water is boiled on the inside.

The oldest operating pilot plant sponsored by the OSW at Wrightsville Beach, is the LTV evaporator that was designed by W. L. Badger Associates, Inc. The one-Mgpd demonstration plant at Freeport, Tex., was designed on the basis of information obtained from the pilot unit. This plant contains a 12-effect system of evaporators of the falling-film type, with a maximum operating temperature of 250° F.

At the present time the pilot plant is used principally to develop methods of increasing the efficiency of the process, and the main emphasis is directed toward finding ways to control scale formation on heat transfer surfaces at high temperatures.

Multistage flash distillation. In the multistage flash distillation process, sea water is progressively heated and then introduced into a large chamber, wherein pressure just below the boiling point of the hot brine solution is maintained. When the brine enters this chamber, the reduced atmospheric pressure immediately causes part of the liquid to boil, or "flash," into steam. The remaining brine is then passed through a series of similar chambers at successively lower pressures where the flash process is repeated at progressively lower temperatures.

Figure 4 shows the Baldwin-Lima-Hamilton Corporation's configuration of a multistage flash distillation plant that is similar in process operation to a one-Mgpd 30-stage flash plant nearing completion in Eilat, Israel.

In operation, sea water is pumped from a water intake through the condenser tubes of the heat rejection stages. Here, the sea water is heated and most of it is returned to the sea, but a portion of this water is treated for scale prevention, deaerated, and then flashed into one of the lower flash chambers as makeup.

The brine is recycled from the lowest pressure stage through the tubes of the heat recovery stages. This brine is heated in each stage by vapors from the flashing brine steam in the heat recovery section of the shell. After the brine has passed through all of the stages, it has received more than 90 percent of the heat required for producing water. As shown in the Fig. 4 diagram, the additional heat required is obtained from an external source in the brine water heater where the temperature is raised to the maximum desirable value.

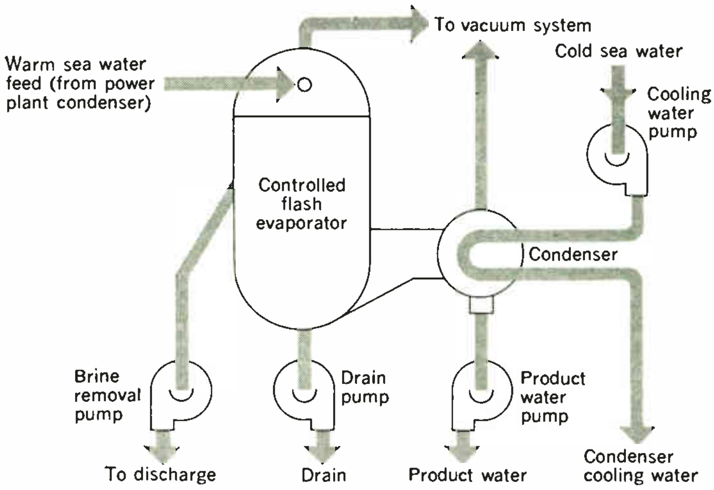
The brine is then piped into the first-stage shell where the pressure is maintained slightly below the saturation pressure at the brine temperature. This permits a portion of the brine to flash into steam and attain thermal equilibrium. The remainder of the brine passes into the successively lower stages where the process is sequentially repeated.

The vapor generated in each of the stages passes up from the brine surface, through suitable demisters, into the condenser shell. It is condensed on the tubes and gives up its heat to the incoming brine.

Finally, the condensate drops from the tubes into a collection trough which transports this water through successively lower pressure stages. The distilled fresh water is continuously removed from the lower stages.

Vapor compression distillation. The fourth basic evaporation method is that of vapor compression distillation. Essentially, the vapor produced in the evaporator is compressed and therefore can be used as the heat supply to heat the solution in the evaporator tubes. When returned to the evaporator, the compressed vapor condenses at its higher temperature and thus gives up sufficient heat to boil more saline water. Actually, this is an application of the heat pump since the energy required for evaporation is that supplied to the vapor compressor. A pump is included in the system to circulate the sea water within the system so that it really is a forced-circulation, vapor compression distillation system.

The largest vapor compression unit in operation is the one-Mgpd demonstration plant built by Aqua-Chem,



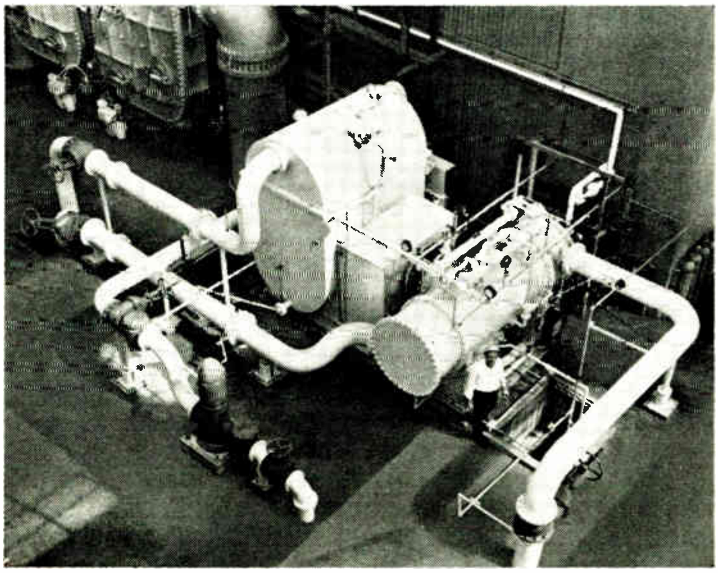


Fig. 5. (top) Diagram showing the configuration of the controlled flash evaporator process that is patented by the Saline Water Corp. (bottom) View of the 14 400-gpd controlled flash evaporation unit installed for the production of high-purity boiler makeup water at the 165-MW Palo Seco power station in Puerto Rico.

Inc., at Roswell, N. Mex. A unique horizontal tube arrangement, with condensation of the compressed vapor inside the tubes, is used for this unit. The gravitational pull of condensate to the bottom of a tube, plus the surface tension effects, tend to produce a thin film for heat transfer at the top of the tube, and sea water is sprayed over the tubes to complete the thin film effect. Higher heat transfer coefficients may be achieved by this arrangement, and it is expected that the pumping power requirements will be less than those for the standard, forced-circulation vapor compression units in operation today.

Controlled flash evaporation. The flash and condensing spaces in a conventional, open tray flash evaporation plant occupy the same space. When a warm brine solution is injected into the much cooler interior of the condenser, a violent flashing occurs because of the pressure differential, and vapor molecules are accelerated at random in all directions. In the controlled flash evaporation process, each evaporation zone is defined by a narrow space between multiple, parallel wood or Fiberglas plates. A thin film of flowing water is constantly maintained over these vertical plates, each of which is separated by an open tapered space of about ½ inch maximum spacing from the next adjacent plate. The plates can be as large as 2 feet in depth by 20 feet in length, and, depending upon the volume of product water required, this series of closely spaced plates may be as much as 50 feet in edge width.

The proper spacing and configuration of the plates produce uniform differential flash temperatures along the channels formed by the plates. This eliminates violent bubbling at one point and fresh water is evaporated evenly over the entire surfaces of all the plates in the series. Finally, the vapor is partially recompressed in a diffuser section and it is drawn off by a discharge trough system.

In this system the correct spacing of adjacent plates has a great influence on the efficiency of the process. If the channels are too wide, flash throttling is negligible, and if the channels are too narrow, the quantity of vapor which can flow through it is very small under existing differential pressures.

When the plates are spaced for a fixed flow and pressure differential, brine will enter without flashing, and, by properly shaping the channel, vapor production within it can be modified so that the total available pressure drop—and the corresponding temperature drop—of the brine are evenly distributed along the entire channel. In this way equal quantities of vapor are produced by each incremental channel segment. And because the evaporation surface can be made as large as desired, the vapor release per unit can be kept very small. Thus flash evaporation is actually transformed into a diffusion process.

Figure 5 shows a schematic diagram of the controlled flash evaporation process, which is patented by the Saline Water Conversion Corporation, an affiliate of Burns & Roe, Inc. Also shown is the 14 400-gpd (gallon per day) controlled flash evaporation unit that has been installed for the production of high-purity boiler makeup water at the 165-MW Palo Seco generating station in Puerto Rico.

The company is presently designing units, based upon the principle of this pilot plant, that will have a fresh water production capacity of 3.5 Mgpd per module, and up to 50 Mgpd per unit.

Electrodialysis in detail

An electrodialysis cell consists of a set of electrodes, Fig. 6(A), between which are a large number of closely spaced plastic membranes. Some of the membranes are permeable to positive ions (anions) and relatively impermeable to negative ions (cations), while others are permeable only to cations.

When a direct current is passed through the water, the ions with positive charges (sodium) move toward the cathode, and the negatively charged ions (chloride) move toward the anode. With the application of electric current to the cell in Fig. 6(B), salts are removed from the saline water in alternate compartments between the membranes by transferring ions to adjacent compartments

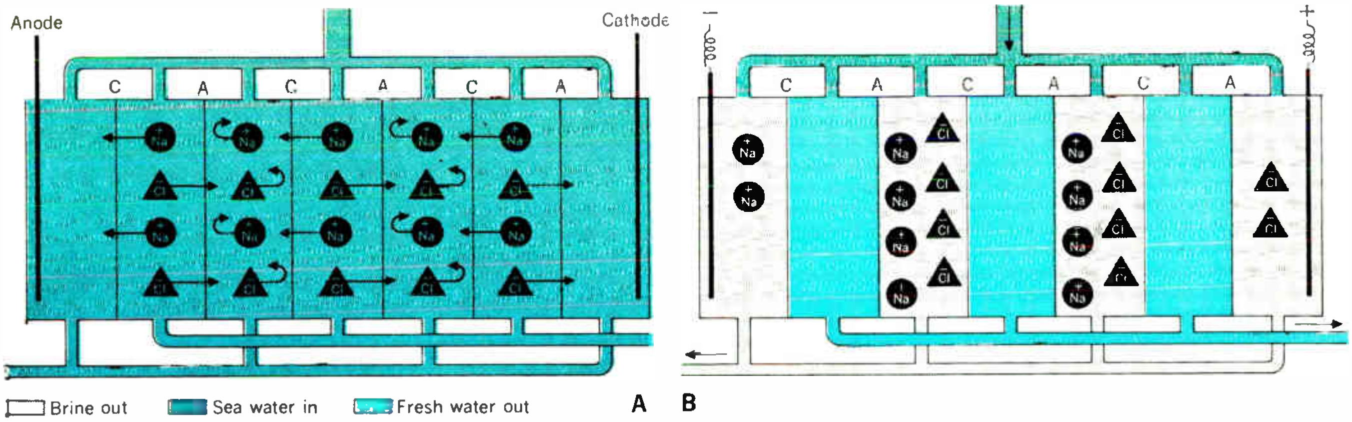


Fig. 6. Sectional view of electrodialysis cells, showing the ion dissociation of sea water.

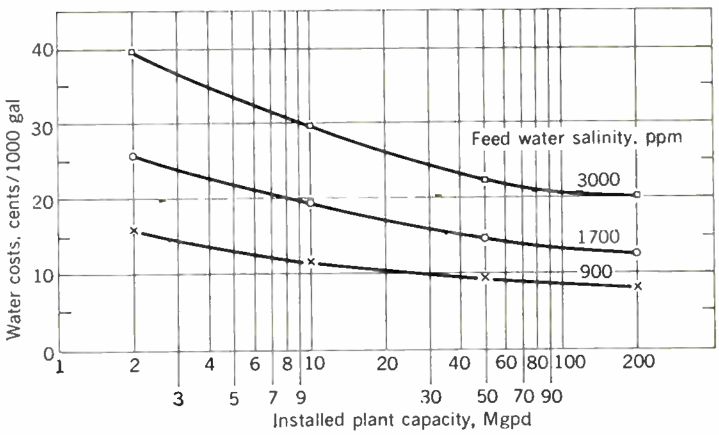


Fig. 7. Graphic plot of costs, based on current technology, for the electrodialysis of brackish water.

where they are trapped because the membrane halts further migration of the respective ion. Thus the water flowing through the alternate spaces between the membranes consists, respectively, of water depleted of salt, and an enriched brine. In short, when a current is applied, equivalent amounts of anions and cations will migrate from alternate compartments through opposite walls. One half of the compartments will become less concentrated in salt, and the other half will become more concentrated in salt after the current is applied.

One basic unit for this process, that of Ionics, Inc., is a *membrane stack*, with alternating cation and anion membranes. Each pair of membranes is separated by a spacer which confines the liquid in the stack, directs the flow of liquid between the membranes, and allows for the separation of the compartments. When the desired purity is attained, the fresh water is pumped out for use.

Comparison with distillation. Since salts are being removed in electrodialysis, the total costs are related to the quantity of salts to be removed from the water. Thus, the lower the initial concentration, the lower the costs will be. In distillation, the aqueous component of the solution is separated and collected, and becomes the fresh water fraction. Total costs are therefore dependent upon the volume of water to be processed and are essentially independent of the concentration of salts.

Depending upon plant size, the costs of the two processes are approximately equal for saline waters in the range of 10 000 to 15 000 ppm. In the normal brackish water range of 1000 to 10 000 ppm, however, electrodialysis is considerably cheaper than distillation.

An electrodialysis plant with a capacity of 10 Mgpd (Fig. 7), processing brackish water of 1700–3000-ppm salinity, will produce enough fresh water for all the domestic needs of 60 000 people, at a cost of 20–30 cents per 1000 gallons.

Reverse osmosis. Another promising approach to saline water conversion is reverse osmosis. Osmosis is a process that takes place in all living cells and plants. It is the diffusion which proceeds through a semipermeable membrane, typically separating two solutions, or a solvent and a solution, and tends to equalize their concentrations. For example, osmosis may be observed in a vertical tube that contains sugared water, the lower end of which is closed with an organic membrane and immersed in plain water. The sugar is hindered from passing through the membrane and more plain water particles pass inward than outward. Thus the volume of liquid in the tube increases and osmotic pressure is produced. The net movement in osmosis is the diffusion of solvent into the more concentrated solution.

The osmosis phenomenon also occurs in the human body, wherein nutriments pass through the intestinal wall (acting as a membrane) into the blood stream.

Figure 8(A) illustrates a simple osmotic system in which diffusion proceeds through a semipermeable membrane that separates solutions of sea water and fresh water, and tends to equalize the concentrations of dissolved materials on both sides. A semipermeable membrane is one which permits the passage of the solvent—in this case, water—but does not allow the passage of the salt ions in the solute. Thus the net movement in osmosis is the diffusion of the solvent (fresh water) into the more concentrated solution (sea water).

However, when pressure is applied to the more concentrated solution, the rate of back diffusion is increased and the pressure at which there is no net flow (equilibrium), as shown in Fig. 8(B), is called the *osmotic pressure*. This is about 375 lbf/in^2 for sea water, and about 200 lbf/in^2 for brackish water that contains 2000 ppm of dissolved solids.

When a pressure is applied on the salt solution that is in excess of the osmotic pressure, reverse osmosis, as indicated in Fig. 8(C), occurs. This condition causes a net water flow from the more concentrated salt solution through the membrane, thereby leaving a solution even more concentrated in salt. But since no semipermeable membrane is entirely efficient, some salt passes through the membrane with the water. However, laminated cellulose acetate film membranes are available that can reject from 95 to 98 percent of the monovalent salt ions and practically all of the higher valence ions.

To obtain reasonable water flow rates and an economic balance between capital investment and the cost of pumping power, the reverse osmosis systems are operated at pressures several times higher than the osmotic pressure. This economic optimum is about 1500 lbf/in² for sea water, and about 1000 lbf/in² for brackish water.

Process description. A simplified process flow diagram of the system developed by the General Atomic Division of General Dynamics[3] is shown in Fig. 9. The plant comprises five major subsystems:

1. Raw sea water preparation system—intake, filtration, and acid treatment units.
2. Main system pumps.
3. Reverse osmosis units—membranes, support structure, and piping.
4. Power recovery turbines for plants of 0.5 Mgpd, or larger.
5. Product water and concentrated brine discharge systems.

The energy input to the system is mechanical and may be in the form of an electric, motor-driven pump.

Since the principal component of the reverse osmosis

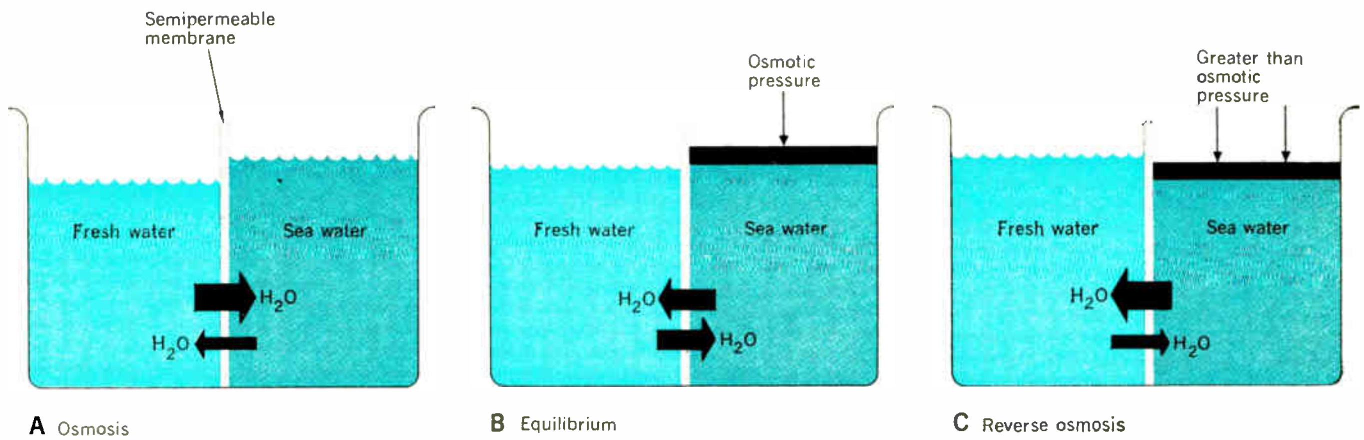
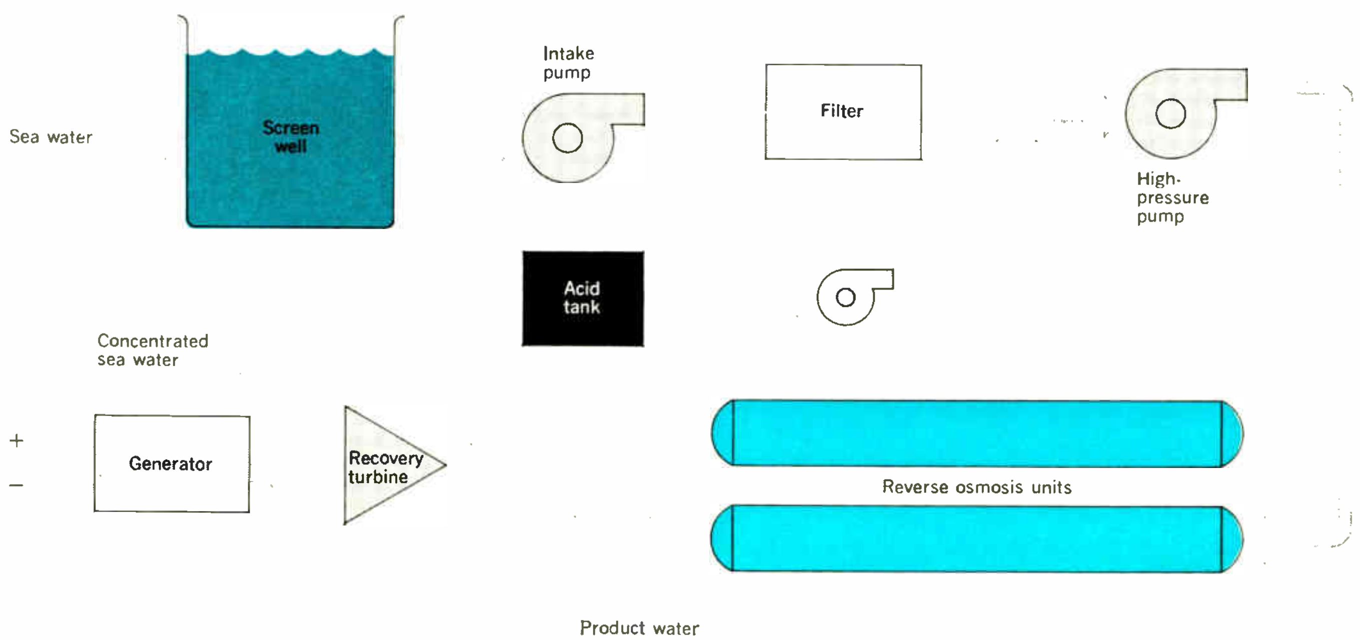


Fig. 8. A—Illustration of a simple osmotic system in which diffusion proceeds through a semipermeable membrane that separates solutions of sea water and fresh water. B—An equilibrium condition exists when pressure equal to the osmotic pressure is applied to the more concentrated solution. C—When pressure greater than the osmotic pressure is applied on the salt solution, reverse osmosis occurs.

Fig. 9. Typical flow diagram in a reverse osmosis plant.



system is the semipermeable membrane, considerable R & D is being devoted toward the investigation of known membrane materials, the practical assembly methods for the use of these materials, and the establishment of quantitative relationships among various parameters that affect the performance of the process.

At present it appears that modified cellulose acetate films of a type developed at the University of California in Los Angeles are the best membranes available for reverse osmosis. The membranes are manufactured in continuous, two-layer sheets that are about 0.005 inch thick; one layer comprises 99.8 percent of the volume, is highly porous, and is permeable to water and salt. The layer in which the salt–water separation occurs is only 10 millionths of an inch thick.

At a typical water flow of 10 gal/ft^2 of membrane per day, a fresh water production rate of 3000 gpd per cubic foot of pressure vessel volume seems possible. Thus it is estimated that a 100-Mgpd plant could be accommodated (exclusive of intake, discharge, and water storage facilities) on a one-acre site.

Power requirements and economics. Representative power requirements for a single-stage reverse osmosis system, operating at 1200 lbf/ft^2 and using a recovery turbine, are about 20 kWh per 1000 gallons. Therefore, a plant of this type, with an output of 100 Mgpd, will need a system load of about 80 000 kW. To translate this pragmatically, consider that the present water consumption of the city of San Diego (population 700 000) is about 100 Mgpd, and the just-stated power requirement is approximately 10 percent of the electrical load for this city.

Reverse osmosis plants do not have to be closely integrated with a generating plant as is the case with desalination plants that use the evaporative processes. These plants are operationally flexible to rapid changes in load demand, and can be started up or shut down in a matter of seconds. Finally, the reverse osmosis system is adaptable to automated control and unattended operation.

The freezing processes

Among the newer processes under development, there are—

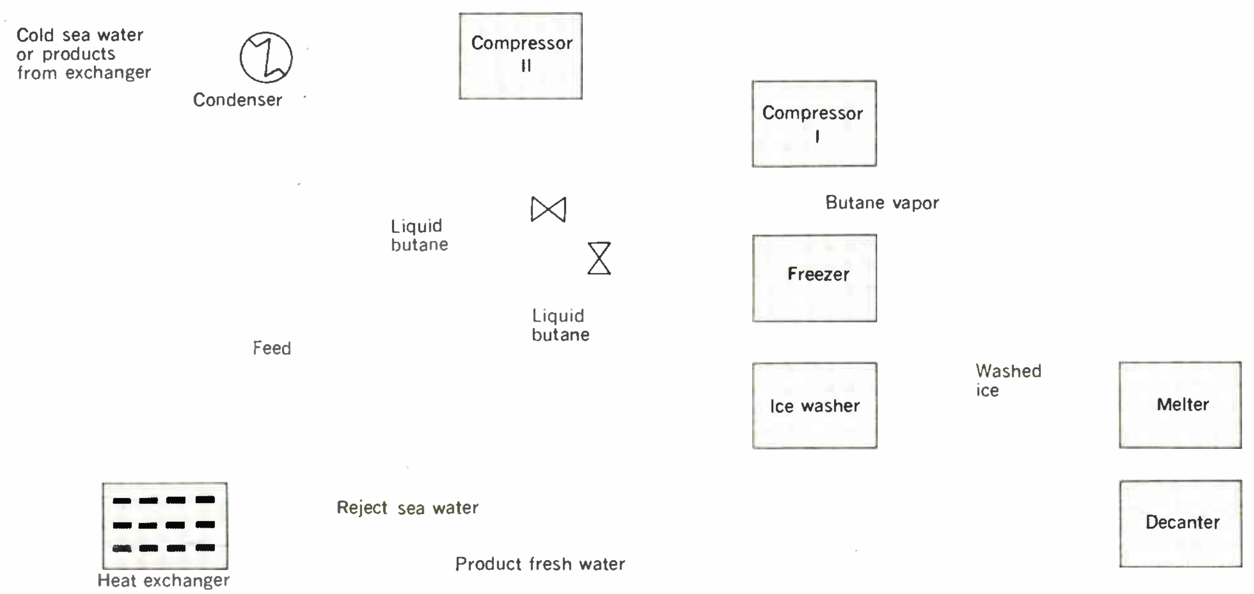
Direct freezing. In the direct freezing process, the ice crystals generated by freezing saline water that is washed free of entrained salt can be melted to produce fresh water. The flash evaporation of precooled sea water at 3- to 4-mm Hg pressure produces an ice–brine mixture from which the brine is separated and the ice crystals are washed countercurrently to remove the occluded salt. The water vapor is either compressed and condensed on the ice to melt the ice, or it is absorbed by an absorbent and the heat of absorption is utilized to melt the ice to produce water.

A variation of this process (Fig. 10) is that of vaporizing an immiscible hydrocarbon refrigerant (usually butane) in direct contact with precooled sea water to produce an ice–brine mixture. After washing the ice crystals free of occluded salt, the refrigerant vapor is compressed and condensed on the ice to produce fresh water. The immiscible liquid refrigerant is separated from the water product by decantation, and the traces of refrigerant that remain in the water are removed by suitable degassing techniques.

Propane hydrate process. The propane hydrate process consists of combining propane and water to form insoluble clathrate crystals that have the approximate composition of 17 mols of water for every mol of propane. The crystals are separated from the mother liquid, washed, and then decomposed to form immiscible layers of salt-free water and propane. This is the only chemical process presently being developed for the production of large quantities of potable water.

Liquid propane is introduced into a reactor where it both combines with the water to form a hydrate and vaporizes to remove the heat of formation of the hydrate crystals. In condensing, the propane supplies the heat required to decompose the hydrate crystals to water and liquid propane. After decantation, the liquid propane is recycled to the reactor.

Fig. 10. Direct freezing process, using butane, is under development by the Blaw-Knox Co.



The dual-purpose plant

During the past year, there has been a major emphasis on dual-purpose plants[4] for the simultaneous production of electricity and fresh water, in which the conversion is effected by the multistage flash, or other distillation systems.

For the utilities serving regions of existing or potential water shortage, these plans and programs are of vital concern since any of the methods of desalination under consideration can be viewed ultimately as either large blocks of electric energy consumption or as alternative blocks of additional generating capacity for which the utilities will become responsible.

It is now apparent that nuclear power can compete economically with fossil-fuel power in many geographical areas of the United States, and parallel studies on the technology and economics of sea water conversion have indicated the feasibility of dual-purpose plants. These developments have paved the way for the consideration of large-scale plants that can supplement both the electric energy and fresh water requirements of large urban complexes near the sea coast.

Why dual purpose? The primary advantages of a dual-purpose facility are the economic gains that result from a "scale-up" in plant size and the improved utilization of energy in a combination plant. Capital cost savings are realized from the low incremental cost for larger unit heat sources and from the sharing of common plant facilities. Operational and maintenance savings may also result by the pooling of supervisory and operating personnel.

The engineering logic supporting the consideration of dual-purpose plants is also apparent. In a typical combination plant, steam from the turbine system is exhausted from either a back-pressure or extraction turbine to the brine heater of the distillation system, from whence the condensed steam passes to the feed water system. This close integration of the water plant and the electric generating plant achieves the following thermodynamic and economic advantages:

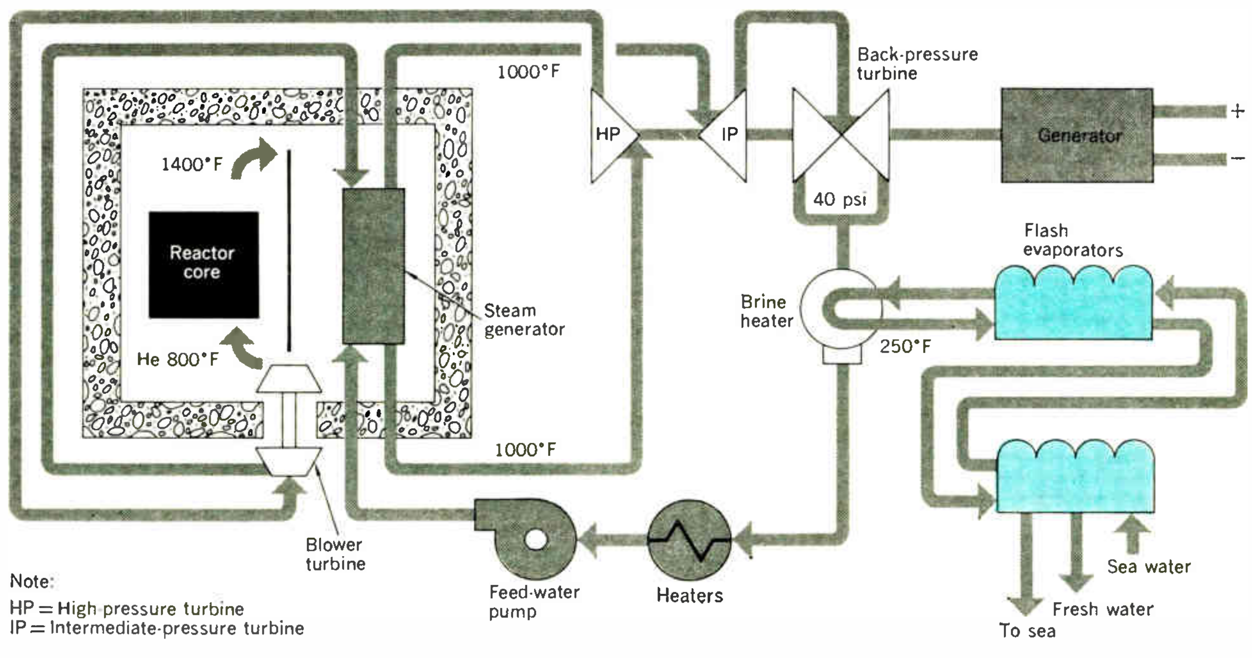
1. The overall capital investment is reduced since the thermal rating for a dual-purpose plant is less than the total requirements for two single-purpose plants that have the same net outputs of electric energy and fresh water.
2. The thermal rating of the steam generating components of the dual-purpose plant is larger than it would be for either of the separate plants.
3. Some plant components can serve dual functions; the brine heater can be used as a condenser, and common structures may be utilized for sea water intake and discharge.
4. The combined operating cost for the integrated plant would be less than for two single-purpose plants that produce comparable quantities of electricity and fresh water.
5. The advantages just mentioned would lead to a reduction in the capital expenditures for the overall plant, and would achieve lower unit cost for electricity and water.

The principal disadvantage of the dual-purpose plant may be in the fact that, for maximum efficiency, it must be situated in an area where there is a definite need for both additional electric energy and fresh water. It is apparent, therefore, that if the urgent requirement is either for power or water, a single-purpose plant would be more suitable.

Nuclear plant processes

Essentially, there are about four types of nuclear reactors: the presently established light water reactor (LWR); the high-neutron-economy heat sources represented by the heavy water, organic-cooled reactor (HWR); the

Fig. 11. Flow diagram for a high-temperature gas-cooled reactor (HTGR) dual-purpose plant, in which sea water conversion is a by-product of power generation.



fast-breeder reactor (FBR); and the high-temperature gas-cooled reactor (HTGR).

Because of space restrictions, the writer cannot present a detailed description of the various nuclear reactors, relative economies, and their advantages and disadvantages.

An excellent description of the boiling water reactor (BWR), the pressurized water reactor (PWR), and the applications of nuclear reactors in dual-purpose desalting plants may be found in the article, "Nuclear Power Today and Tomorrow," by Schwoerer and Witzig (IEEE SPECTRUM, July 1964, pp. 120–130).

HTGR process. This is an advanced type of nuclear power system—a flow diagram for a dual-purpose plant is shown in Fig. 11—which employs helium as the primary system coolant, graphite as the neutron moderator, and uranium–thorium as the fuel. As helium is chemically inert, it is a logical choice as a coolant in high-temperature operation. It neither becomes radioactive nor does it parasitically absorb neutrons in the core of the reactor, and its use permits a range of temperature and pressure selectivity for the primary coolant system.

Referring to Fig. 11, we see that the helium passes through the reactor core and absorbs sufficient nuclear heat to raise its temperature to about 1400° F. Next, the high-temperature gas passes to the steam generators, or boilers, to produce superheated steam at temperatures of 1000° F, or higher. This steam then flows to a conventional high-, intermediate-, and low-pressure turbine system. As indicated in the diagram, the cold reheat from the high-pressure turbine element passes to a blower turbine drive for the helium circulators prior to reheat. Full exhaust from the back-pressure turbine to the heater section of the evaporator plant is assumed.

The steam condition enthalpy that is available today from an HTGR system offers advantages for use in dual-purpose plants which include:

1. Low fuel cycle costs that are possible because of the effective use of neutrons in the reactor core.
2. High thermal efficiencies.
3. The achievement of a higher ratio of net electric power to a given water production.
4. Advanced design concepts that will use prestressed concrete reactor vessels to permit the consideration of single-unit plants of 8000 MW or larger.

Performance and economy. Table I indicates typical theoretical performance data for a very large HTGR, dual-purpose plant. The power and water output balance is predicated upon a turbine system that rejects the full steam flow at 40 psia to the brine heater of a multistage flash evaporation plant. The performance of the evaporation plant is based on the present maximum brine temperature (250° F) and a sea water temperature of 65° F, thereby giving an energy requirement of approximately 80 Btu per pound of fresh water. Thus each increment of 100 Mgpd of water production capacity is accompanied by a net salable electrical capacity of about 285 MW.

The Fig. 12 graph shows typical water costs that may be anticipated from large HTGR combination plants that have the performance characteristics indicated in Table I. The cost curves assume a divided ownership situation in which a private electric utility operates the power plant and a municipality, or other agency, owns and operates the desalination plant. A split ownership

I. Typical performance, HTGR dual-purpose plant

Overall dual-purpose plant	
Thermal power	1000 MW(th)
Electrical output	254 MW(e)
Water plant capacity	90 Mgpd
Ratio, mgd/MW(e)	0.28 Mgd/MW(e)
Power plant	
Throttle steam conditions	2400 psia @ 1000° F, reheat to 1000° F
Back-pressure turbine exhaust	40 psia
Electrical output, gross	287 MW(e)
Electrical output, net	279 MW(e)
Water plant	
Maximum brine temperature	250° F
Sea water temperature	65° F
Concentration ratio	2.0
Performance index	80 Btu/lb of product

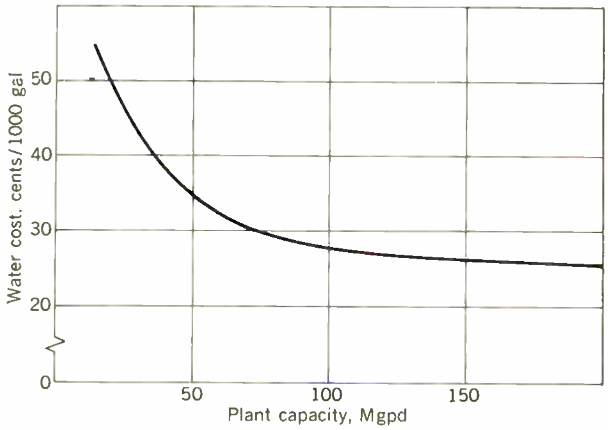


Fig. 12. Graph showing the estimated water costs for a HTGR dual-purpose plant. Mixed plant ownership, an 80 percent capacity factor, full back-pressure turbine, and 250° F brine temperature are assumed.

has also been assumed for the structural or equipment components that serve both functions of the dual-purpose plant.

A fixed charge rate of 12.5 percent for the generating plant and 7 percent for the desalination plant is used along with a concurrent 80 percent capacity factor.

Figure 13 is an architectural rendering of a typical dual-purpose sea water conversion complex. The nuclear reactor which supplies heat for the desalting process is shown in the center foreground, and the power generating facility is at the left. The multiflash evaporating unit tower is shown at the right.

Large-scale projects that are pending

The experience gained from the Guantanamo Bay, Cuba, and Point Loma, Calif., evaporating plants has convinced many equipment manufacturers and Government officials that there is presently no technical limitation on plant size. These people believe that it is feasible to build desalting plants with capacities from 50 to 150 Mgpd—or larger—with a life expectancy comparable to that of power plants.

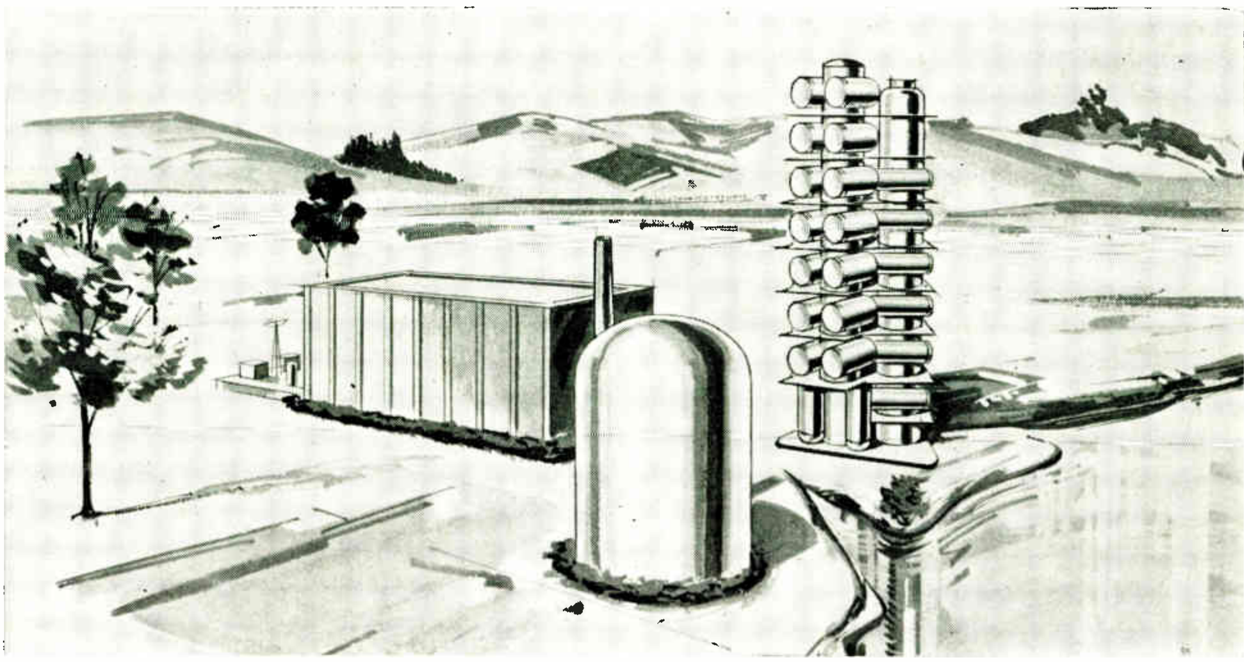


Fig. 13. Architectural rendering of a typical dual-purpose sea water conversion complex. In the foreground is a nuclear reactor which supplies heat for the desalting process. At the left is the power station, and the multistage flash evaporating unit is shown at the right.

John Simpson, a vice president of the Westinghouse Electric Corporation, in testifying before a subcommittee of the Senate Interior and Insular Affairs Committee, stated that ". . . the pioneering research work has been done. What remains to be done is a vigorous engineering effort. . . Today's cost of about $1 per 1000 gallons in a one-Mgpd plant could be reduced, we estimate, to 30 to 35 cents in a plant of 50-Mgpd capacity based on like conditions. . . Building the big plant now is, we believe, a crucially important step in the advancement of water conversion technology."

Simpson also recommended that the OSW continue and expand its research efforts of methods for water desalination.

At the recent annual meeting of the Southern California Edison Company shareholders, it was disclosed that three electric utilities in southern California have offered to join with the Metropolitan Water District, the principal water agency in that area of the state, in a huge, nuclear-fueled desalting project. The president of Southern California Edison, Jack K. Horton, said:

"Recently completed feasibility studies by our engineers indicate that two, large-scale nuclear generating units, operating in conjunction with a sea water desalination plant, could produce 150 Mgpd of fresh water per day at a cost less than 30¢ per 1000 gallons. . ." He further stated that ". . . these encouraging estimates and other data" were the basis for submitting a proposal to the Metropolitan Water District, setting forth conditions and principles for the joint construction of such a facility.

According to the proposal, two large commercial-type, nuclear steam generating units, one owned jointly by Southern California Edison and San Diego Gas & Electric Company, and the other by the Los Angeles Department of Water and Power, would supply steam to a multistage flash evaporator plant owned by the Metropolitan Water District. The proposal further stated that the estimated cost of power to Southern California Edison would be less than 5 mills/kWh.

Necessity is the mother of expedition

The scope of the subject of this article is a vast and ever-expanding technology. And the description of the various desalination processes—both operational and in the R&D stages—cannot claim to be more than a comprehensive outline. *The Desalination Research Conference Proceedings*, published by the National Academy of Sciences in 1961, in itself contains more than 450 pages devoted to process descriptions and research theory.

In areas of marked climatological change in which prolonged drought has replaced normally adequate precipitation patterns, the need for large-scale desalination plants is becoming urgent. Add to this exigency the worldwide population explosion, and the industrial pollution of streams, rivers, and lakes, and one can appreciate the dramatically critical fresh water shortage that confronts the civilized world.

The time for deliberation and debate has passed; the time for expeditious action is now.

REFERENCES

1. Hahn, W. J., and Barnes, W. L., Jr., "New water conversion processes & techniques are developed and proved," *Power Eng.*, pp. 26–29, Jan. 1965.

2. Strobel, J. J., "Saline-water-conversion processes," *Proc. 1961 Desalination Research Conf.*, pp. 86–106.

3. Bray, D. T., and Johnston, T. A., "Approaches to the conversion of sea water to fresh," presented at the American Power Conf., Chicago, Ill., Apr. 27–29, 1965.

4. Siegel, S., Golan, S., and Falcon, J. A., "Application of nuclear energy to large-scale power and desalting plants," presented at the American Power Conf., 1965.

Physical electronic phenomena in ion propulsion engines

The ion engine offers one of the most promising techniques for long-duration space propulsion, for missions ranging from the prime propulsion of manned interplanetary vehicles to the control of earth satellites

George R. Brewer

Hughes Research Laboratories

As we look ahead to the more ambitious missions that man will wish to accomplish in space—the missions requiring longer times and therefore greatest propulsion energy—we seek a reaction rocket with a high propellant exhaust velocity. This high velocity allows the generation of thrust with relatively less consumption of propellant, with significant advantage to the mission in the additional payload capability of the spacecraft as less propellant is required. The only way presently known to obtain propellant exhaust velocities significantly higher (by a factor of 10 to 100) than those of current chemical rockets is by means of the acceleration of charged particles. In principle, electrical acceleration can provide essentially any exhaust velocity, by proper choice of the particle mass and the accelerating voltage. In practice, however, the engines that have reached the highest state of development and currently show the greatest promise use heavy ions (having atomic masses of approximately 100 to 200) as the propellant, accelerated through 3000 to 10 000 volts.

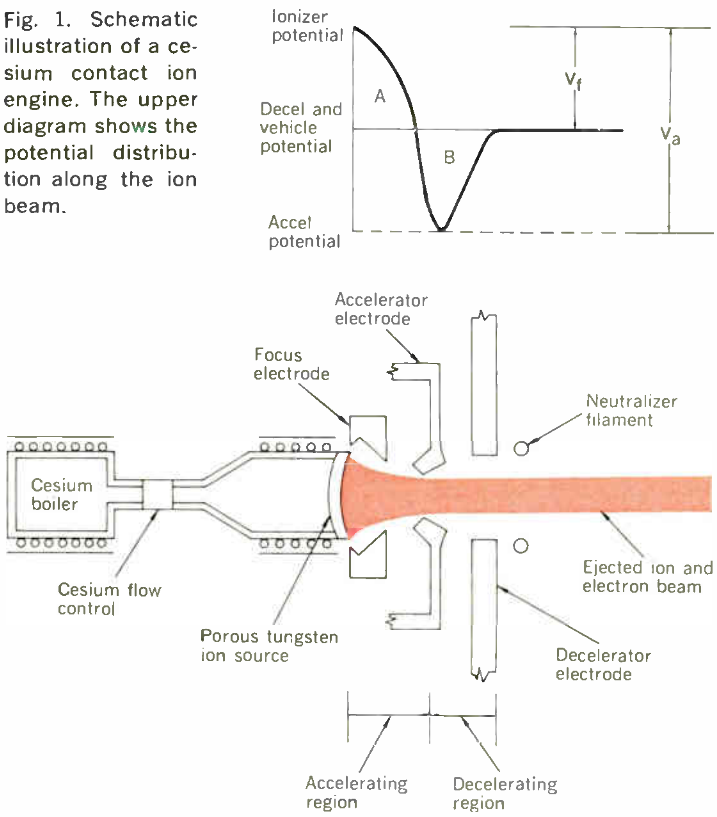
In concept, of course, the electrical acceleration of ions is quite simple. A number of different types of sources and propulsion engines have been built and demonstrated. The details of engine design and performance will not be discussed here; the reader is referred to other sources for this subject.[1,2] Rather we will review in some detail a number of very interesting physical electronic phenomena that occur in ion engines, including, for example, the ion source, electron emission enhancement due to adsorbed films, and charge-exchange ion creation and erosion. Some of these effects were not known or anticipated at the inception of the work on ion engines and it is only within the past year or two that an understanding has been obtained; others were known many years ago but their importance in ion engines has just been recognized. New measurements on the characteristics of materials were needed in order to understand certain phenomena observed in operating engines.

Some of the phenomena that will be described form real and fundamental limitations on the life and performance of an ion engine and are therefore of crucial importance to the engine developer; others are more in the nuisance category and can be eliminated by proper engine design. Much information on these subjects has come to the designers of these new propulsion devices from the electronics field—for example, from work on thermionic energy converters. Similarly, some of the data generated in electric propulsion research may be of value in electronics technology. One of the purposes of this article is to provide a degree of cross coupling of these technologies.

The ion engine

There are two classes of electrostatic or ion engines currently under development, differing principally in the method of creation of the ions. In the electron bombardment engine[3] the ions are created by electron impact in a Penning-type discharge and are extracted from the resulting plasma by means of a set of accelerator grids

Fig. 1. Schematic illustration of a cesium contact ion engine. The upper diagram shows the potential distribution along the ion beam.



placed at one end of the discharge chamber. In the contact ion engine, ions are created by contact ionization of the propellant (cesium) with a hot ionizer electrode and are accelerated in a geometry of electrodes roughly similar to conventional electron guns used in traveling-wave tubes.

Let us first look briefly at the operation of a cesium contact ion engine, as illustrated in Fig. 1. This figure shows the basic configuration of elements that form an engine, with emphasis on the ionizer and accelerating electrode system. This engine employs a porous refractory ionizer, heated to approximately 1400°K by an electric resistance heater, through which cesium atoms diffuse from the reservoir onto the frontal surface, where they are evaporated predominantly as ions. The ions are accelerated and formed into a collimated beam by means of electric fields, which result from the negative potential on the accelerating electrode.

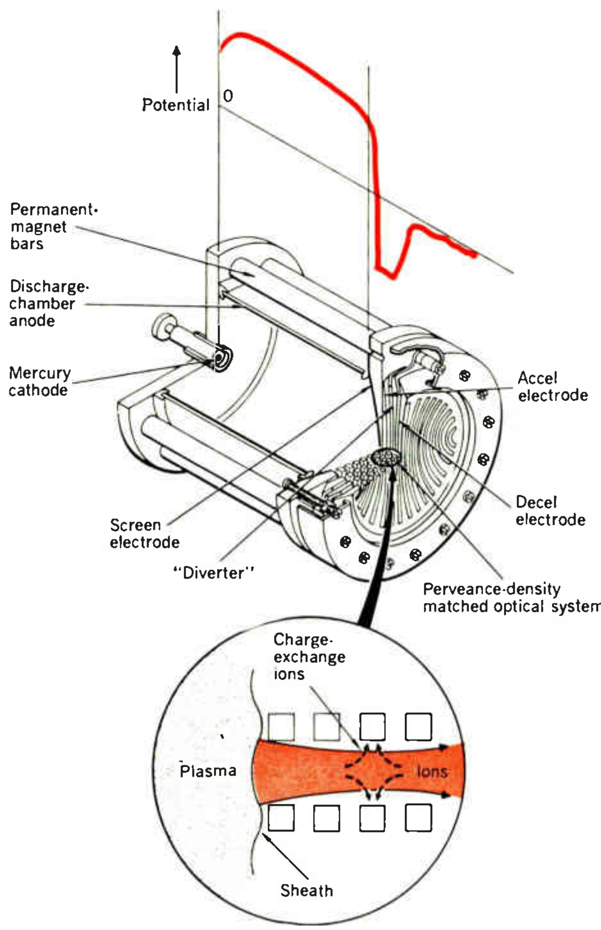
After acceleration, the ions are usually decelerated by fields created in the decelerating region. The ions thus leave the engine with a velocity corresponding to the potential difference between the ionizer and the decelerating electrode, which is held at spacecraft ground potential. The acceleration of the ions of course results in an opposite force on the engine electrodes, transmitted by means of the electric fields; this force is the thrust produced by the engine. Electrons must be injected into the ion beam in equal numbers to the ions, in order to effect neutralization of the space charge of the injected beam. In the accelerating region, it is imperative that very few ions strike the electrodes, so as to prevent bombardment erosion. It is also desirable that the current density distribution across the ionizer be reasonably uniform in order to insure that all possible particles will be drawn off as ions rather than evaporated as neutral cesium particles. These objectives can be met by proper control of the ion-optical characteristics of the accelerator system—that is, by careful design of the electric field configuration in this accelerating region through the use of techniques such as those developed originally for the design of high-perveance electron gums.[4] The focus electrode shown in Fig. 1 helps to shape the electric fields in such a way that these objectives will be achieved.

The second important class of electrostatic ion engines employs a fundamentally different type of ion source, in which the propellant gas is ionized by electron impact. This electron bombardment engine is shown schematically in Fig. 2. The ionization chamber is composed of a cylinder, with the propellant introduced into one end and the ions extracted from the other end. The center portion of this cylinder is maintained at a positive potential with respect to the two end plates, so that the electrons emitted by the cathode are injected through the plasma sheath into a potential well, which varies with both radius and axial distance. The application of an axial magnetic field prevents the electrons from going directly to the other cylinder. In this crossed electric and magnetic field configuration, the electrons will spiral around the axis and oscillate longitudinally. As the electrons strike the atoms of the propellant gas, the particles will be ionized and the electrons will lose energy and eventually reach the other cylinder, where they are collected.

Since, for any reasonable geometries and practical densities, the mean free path for ionization (of the order of meters) is much larger than the dimensions of the ionization chamber, it is evident that the efficiency of such a source depends upon maintaining a long mean lifetime of the primary electrons. This long lifetime is accomplished by the use of the magnetic and electric fields arranged as described, to trap electrons and thus increase the ionization probability to a reasonable value. The ionized particles thus form a neutral plasma, which essentially fills the discharge chamber. At the screen electrode, located at one end of the discharge, there is created a scalloped plasma sheath from which the ions are accelerated away from the plasma by the negative potential on the accelerator grid (see inset in Fig. 2). The ejected beam of positive ions thus produces the thrust of the engine.

To a first order, the process of acceleration, deceleration, and neutralization of the ion beam from this type of source is very similar to that discussed for the cesium contact engine; one merely imagines the substitution of a shaped plasma sheath for the shaped ionizer surface of the contact engine. The interception of ions on the accelerating grid, however, is a function of the shape of this plasma boundary near the screen. Since the shape of this plasma boundary is a function of the current density drawn, the electron and ion temperature in the plasma, etc., the ion-optical properties of this accelerator may

Fig. 2. Electron bombardment type ion engine. The potential distribution through the discharge and acceleration regions. The inset shows how the ions are extracted from the plasma source.



vary with operating conditions. In principle, this discharge mechanism can be used to ionize any gas; in practice, cesium, mercury, and xenon have been used most frequently as the propellant.

Ionization and emission phenomena

In ion engines there are several classes of physical electronic phenomena that involve the ionization of neutral atoms and the emission of ions and electrons from electrode surfaces. Most of the effects to be described result from the fact that the ion source is not a perfect ionizer but, depending on the conditions, the neutral efflux from the source may consist of 85 to 99 percent ions and 1 to 15 percent neutral atoms. These neutral atoms will be present in the accelerating (ion flow) region with a density of roughly 10^{11} atoms/cm^3, and will stream away from the source with a flux of approximately 10^{15} atoms/cm^2·s, to result (for example in the case of cesium) in a coating on the electrodes with a surface density of roughly 10^{14} atoms/cm^2. The way in which these atoms interact with the ions and the engine electrodes depends on the type of atom. The two most popular propellants, cesium and mercury, have certain features in common, such as charge-exchange ion creation. The more chemically active cesium can also produce certain qualitatively different effects, such as surface work function change.

The following effects are illustrated in Fig. 3 and will be described individually:

1. Ions are created by charge-exchange collision with the atoms in the accelerating region.
2. Electron emission, enhanced by the Schottky effect, can take place from the negative accelerator electrode to the more positive electrodes of the engine when the work function of this negative electrode has been lowered by an adsorbed cesium layer.
3. Cesium ion emission can take place from a hot focus electrode to the more negative accelerating electrode.
4. Photoelectric emission can occur from a low-work-function accelerating electrode; however, this current is small compared with the thermionic emission.
5. Secondary electron and negative ion emission can come from the accelerating electrode; this effect is also of negligible importance.

In addition to the above effects due to atoms between and on the electrodes, we will discuss also

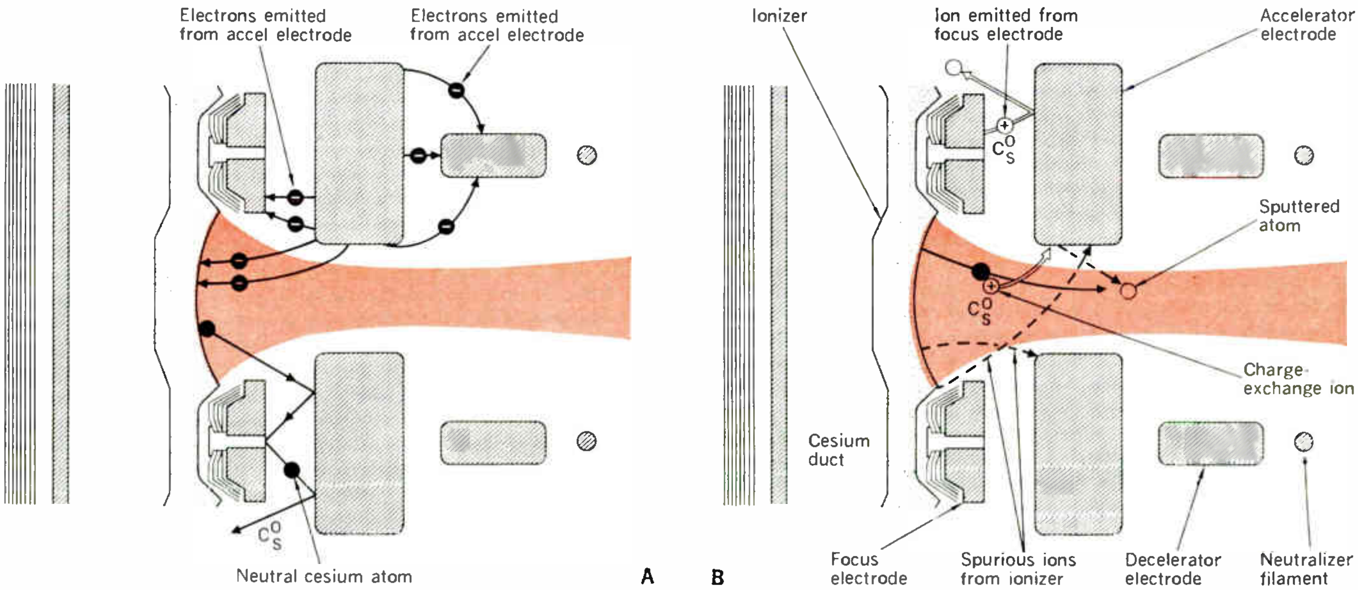
6. The ion and neutral emission characteristics of the ion source.
7. The sputtering characteristics of the electrodes due to ion bombardment.
8. The processes involved in the neutralization of the exhaust ion beam by electrons.

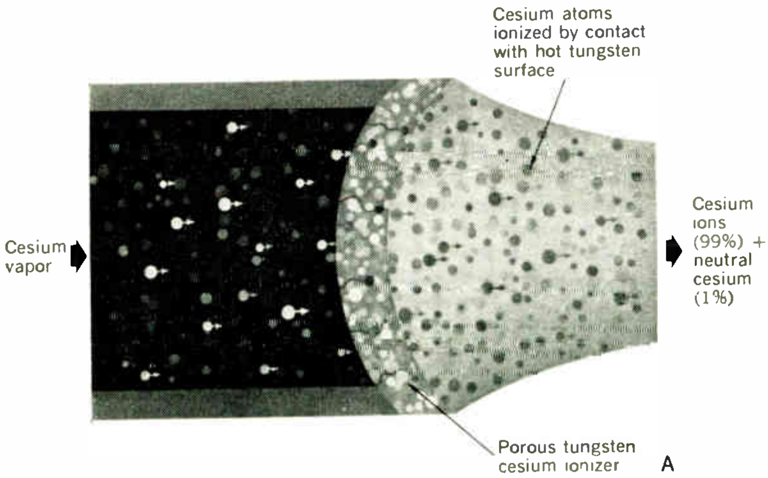
Most of these effects involve the neutral atom component of the efflux from the ion source, and would be largely absent if there were no neutrals from the source. It is, therefore, important to understand first those characteristics of the contact and plasma sources which give rise to neutral efflux.

The ion source

The cesium ionizer. An illustration of a typical cesium contact ionizer is shown in Fig. 4(A). Typically, it is composed of tungsten grains compressed and sintered together to form a porous matrix. In order to provide a uniform pore distribution, the tungsten grains are spherodized and separated into narrow size fractions, of the order of 2 to 4 microns in diameter.[5] The resulting

Fig. 3. Some physical electronic effects that can take place in a cesium contact ion engine. A—Effects of electrons, that is, emission from the cesium-coated accel electrode. B—Effects of ions, that is, sputtering caused by ion emission from the focus electrode, ions from charge exchange, and direct interception by the accel electrode of improperly focused ions from the ionizer. Certain of these effects are characteristic of the propellant used; others are common to all types of ion engines.





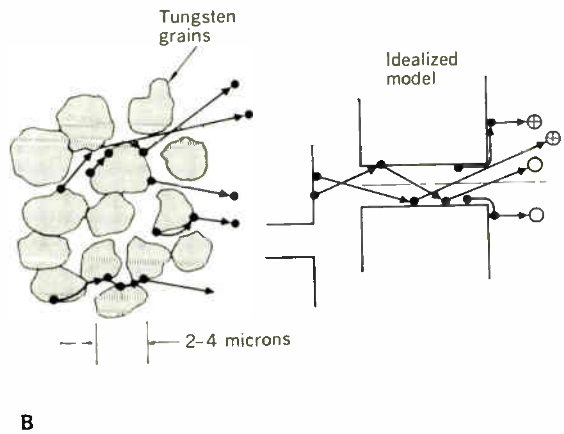


Fig. 4. Cesium contact ionizer, formed of porous refractory metal. A—Typical configuration. B—Surface diffusion and molecular transport mechanisms resulting in ion and neutral atom evaporation from the pore and the surface, using the actual granular structures and an idealized model composed of cylindrical pores.

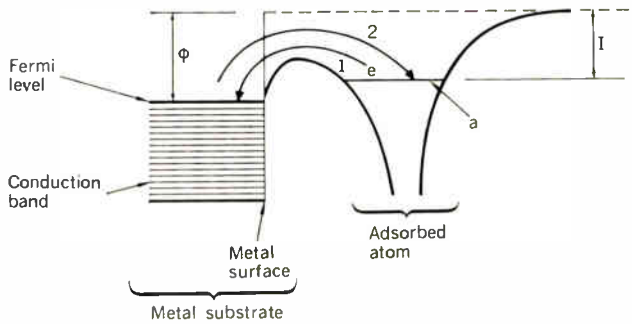


Fig. 5. Simplified illustration of the energy levels involved in adsorption of an atom onto a metal surface. For a cesium atom there are two states into which an electron from the metal can go in the adsorbed atom, depending on the electron spin.

compact is sintered to a density of roughly 80 percent and the regions between the grains provide narrow channels through which the cesium can flow. The cesium can flow through the ionizer by two mechanisms: surface diffusion along the grain surfaces, and molecular flow by continuous evaporation and condensation. Under typical operating conditions the latter flow mechanism is predominant. These processes are illustrated in Fig. 4(B). Here the mechanisms of molecular flow and surface diffusion are shown, with atom and ion evaporation directly from the pores as well as surface diffusion of the cesium onto the top surface. The cesium is evaporated from either place as ions or neutral particles. Since the ion and atom evaporation characteristics of the porous ionizer reflect the characteristic of cesium adsorbed on the refractory surface, let us examine in some detail the adsorption and evaporation characteristics of cesium on tungsten.

While the exact details of this surface adsorption and emission process are still somewhat controversial, the following, somewhat oversimplified picture will suffice for this discussion. The energy diagram for a low-ionization-potential atom, such as cesium, adsorbed on a high-work-function metal surface, such as tungsten, is shown in Fig. 5. Before adsorption the atom will contain a valence electron in the outer shell, in an energy level marked a. An amount of energy I (the ionization potential) will be required to ionize this atom by removing this electron to infinity. Likewise, an electron from the top of the conduction band of the metal requires an energy φ (the work function) to remove it to infinity. When the atom is adsorbed on the surface the valence electron can arrive at a lower energy state by moving to the conduction band of the metal; the particle is then adsorbed as an ion. Since the electrons in a hot metal possess a (Fermi) distribution of energies, there exists a probability that such an electron can move over the surface barrier into level a of the adsorbed ion, to transform it into an adatom. The relative density of electrons in level a and at the Fermi level—i.e., the relative surface density of adsorbed atoms to ions—is given by the Maxwell law:

$$\frac{n_a}{n_i} = 2 \exp -\left(\frac{\varphi - I}{kT}\right) \tag{1}$$

where the factor two is the ratio of statistical weight of the normal states of the cesium atom to that of the ion. If we consider that the adsorbed particle is evaporated in the state in which it is adsorbed, the ratio of evaporation rates of atoms to ions is also given by (1). The ratio of evaporation rate of ions ν_i to the cesium atom arrival rate $\mu = \nu_a + \nu_i$ is therefore given by

$$\frac{\nu_i}{\mu} = \frac{1}{2 \exp [(I - \varphi)/kT] + 1} \tag{2a}$$

The corresponding evaporation rate of atoms ν_a is

$$\frac{\nu_a}{\mu} = \frac{2 \exp [(I - \varphi)/kT]}{2 \exp [(I - \varphi)/kT] + 1} \tag{2b}$$

which is the Saha–Langmuir equation.[6] As the concentration of adsorbed atoms (the field from each of which lowers the work function of the surface) increases, the composite surface work function decreases. A decrease in surface work function results in an increased ratio of atom-to-ion surface concentration and, therefore, evaporation. From this reasoning we can see that an increased surface concentration of cesium will result in increased atom evaporation compared with the ion evaporation and that the rates will be approximately equal when the work function and the ionization potential are approximately equal. This equality will take place for a surface coverage slightly less than 10 percent.

It is seen also from (2) that the substrate work function very strongly influences the rate of atom evaporation, a high substrate work function being desirable for low neutral efflux. If the vacuum work function of the substrate is used for φ in (2), the resulting ion (or atom) evaporation found will be valid for very low surface coverage; as the surface coverage depresses the work function, the composite value must be used. This property of low neutral evaporation with high ion flux from the ion source is the most important characteristic of the source that affects engine life and performance. This equation also shows clearly why cesium was chosen as the propellant in the contact-type ion engine; of the acceptable elements it has the lowest ionization potential.

Typical ion and atom evaporation characteristics of cesium from tungsten as determined by Langmuir[7] is expressed in the graph in Fig. 6 plotted as a function of the fractional surface coverage by cesium. It is seen that at a constant surface temperature, say 1500°K, the number of atoms that can be evaporated from the surface per cm² per second (expressed by the solid light line) increases rapidly with the surface coverage. The number of ions that can be evaporated is seen to increase with surface coverage to approximately 2 percent and decrease rapidly at higher coverage levels. The sum of these two curves expresses the total evaporation rate and is drawn as the solid heavy line in Fig. 6. It is seen that this latter curve passes through a maximum, at which ion evaporation is predominant, and a minimum value before increasing again with increasing surface coverage, where the atom evaporation is predominant. It can be shown that the region marked in Fig. 6 is unstable, so that under the effect of a constant arrival rate of atoms onto the surface (expressed by the horizontal solid line) the ionizer surface can exhibit two stable conditions expressed by points *A* and *B*, which are, respectively, points of low and high atom evaporation. Of course, operation at points such as *A* is the desirable operating condition for an engine ionizer.

This cesium–tungsten system exhibits an interesting behavior as a function of surface temperature. If we allow the cesium atom arrival rate on on the surface to be constant (as indicated by the horizontal line) and gradually raise the surface temperature from 1300°K, at which the surface coverage will be approximately 20 percent, it is seen that the atom evaporation rate will increase and the surface coverage will decrease (in such a way that the total evaporation rate is always equal to the arrival rate) until a point *B* is reached. If the temperature is increased further the evaporation rate is increased above the arrival rate and the surface coverage will decrease again until a stable point *A* is reached.

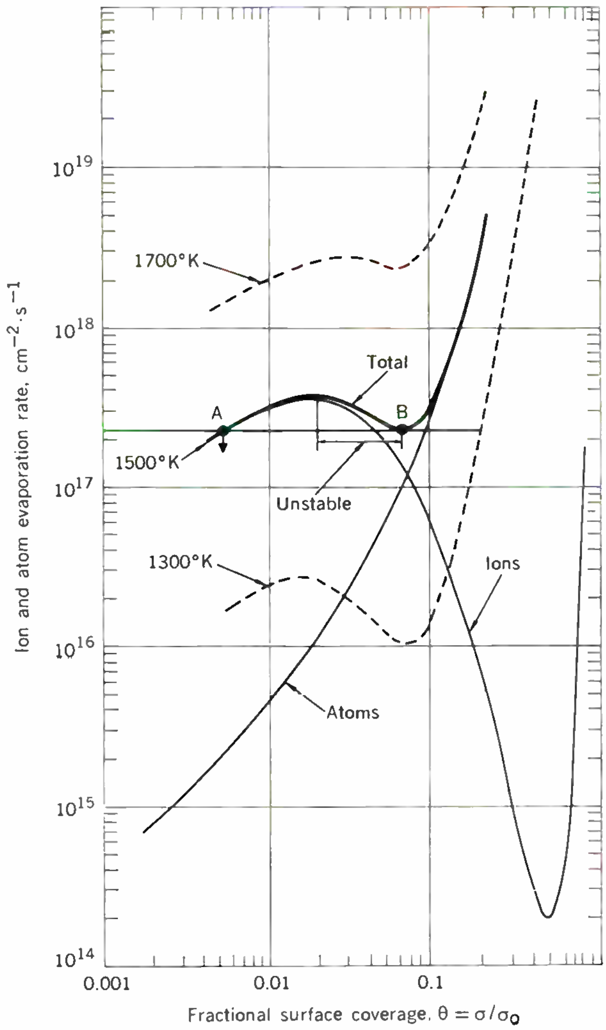


Fig. 6. Rate of cesium atom and ion evaporation from a tungsten surface vs. adatom surface coverage, for three surface temperatures. Heavy line shows total (ion + atom) evaporation rate for 1500°K. (From Langmuir and Taylor[7])

This last change in surface coverage will occur with a very small change in temperature. At this temperature the evaporation suddenly changes from one in which atoms predominate to one which consists mostly of ion emission; this temperature is called the critical temperature.[8] Since operation along the left branch of this curve is always desirable, it is essential that the ionizer always be operated above this critical temperature value.

The ion evaporation rate from the tungsten as determined from data such as Fig. 6 (expressed in terms of the current density) is shown as a function of surface temperature in Fig. 7. As described above, it is seen from the heavy solid line in Fig. 7 that increasing the surface temperature results in a very rapid increase in current at the critical temperature until essentially all of the atoms that can be ionized on the surface are being drawn off as ions, giving rise to the saturation level shown. The heavy dashed curve shows the corresponding decrease in neutral evaporation rate. The critical temperature for the particular cesium arrival rate at the ionizer surface illustrated here is shown by the vertical line marked T_c. The envelope of such curves for different surface arrival rates is shown by the heavy line marked "porous tungsten." Such a curve shows the maximum ion current that can be drawn from a porous tungsten ionizer as the temperature is varied. Similar critical temperature envelope curves for other substrate metals are also shown.[5,9] It is seen also that an adsorbed layer of oxygen on the tungsten will bind the cesium to the tungsten more tightly and require higher temperature for ion desorption. As the current density drawn from the surface is increased, higher cesium surface density and ionizer temperature are required. The higher surface density will depress the work function and, as indicated from the Saha equation, these effects will result in a higher ratio of atom to ion evaporation. This effect is shown in the curve plotted at the right in Fig. 7 expressed as the neutral evaporation fraction versus current density. As we will see later, this neutral cesium evaporation characteristic is of extreme importance to engine lifetime.

It is seen from Fig. 7 that the ionizer must be operated at a relatively high temperature (at least 1350°K) in order to evaporate ions from tungsten at a rate of 10 mA/cm². This hot ionizer will radiate heat, which is essentially waste power. Thus a certain amount of energy is required to create each ion, given in this case by the ionizer power divided by the ion current, usually expressed in electron volts per ion. Since the ion current increases rapidly with temperature, the energy loss per ion decreases rapidly as the ion current density is increased. Typical values are 850 eV/ion at 10 mA/cm² and 350 eV/ion at 30 mA/cm². Thus the efficiency of the engine increases with current density; the neutral fraction forms the upper limit on tolerable current density, as we will see later.

The Saha equation is plotted in Fig. 8 for a constant temperature of 1400°K. It is seen that the neutral efflux fraction (NF) is essentially unity (that is, all particles are evaporated as atoms) until a work function of approximately 3.8 volts is reached, above which evaporation of neutrals decreases very rapidly. The bare function of a number of metals is indicated on this curve; the neutral efflux calculated in this way would of course be valid only for very low surface coverages, where the adsorbate has not altered the work function. It is seen that smooth tungsten will exhibit a neutral fraction of approximately 1 percent but that a number of other refractory materials, such as rhenium, rhodium, iridium, etc., exhibit higher work functions and therefore potentially lower neutral fractions. Thus it appears possible to evolve ionizers with considerably superior characteristics to those of tungsten. The cesium–tungsten system was studied many years ago; the characteristics of other cesium–refractory metal and alloy systems are only now beginning to be

Fig. 7. Cesium-ion current density at the critical point vs. the corresponding critical temperature, for several materials. Behavior of the ion current and neutral flux (curves A and B, respectively) is shown as a function of temperature for one value of cesium arrival rate at the ionizing surface. The dashed curve portion (C) of the ion current curve shows the effect of a carbon contaminant. The curves at the right show the corresponding increase in neutral cesium efflux as current density is increased, together with the reduced neutral evaporation fraction from a higher-work-function material (rhenium).

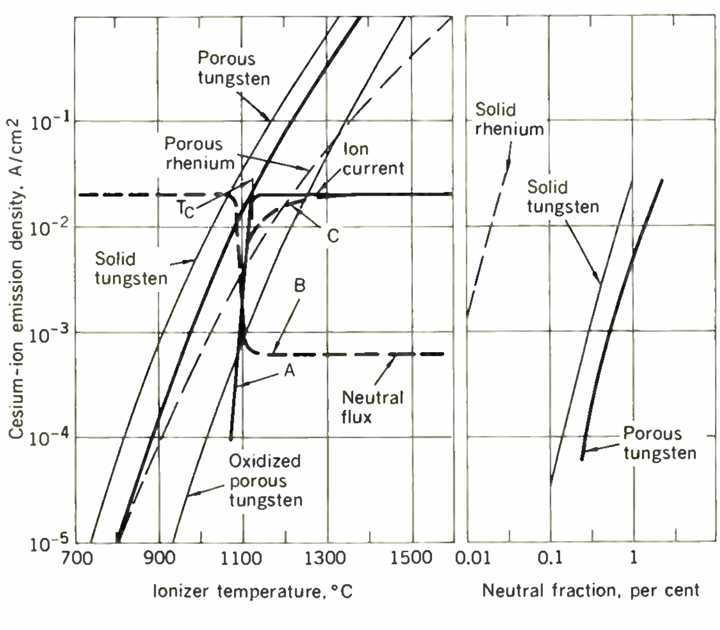
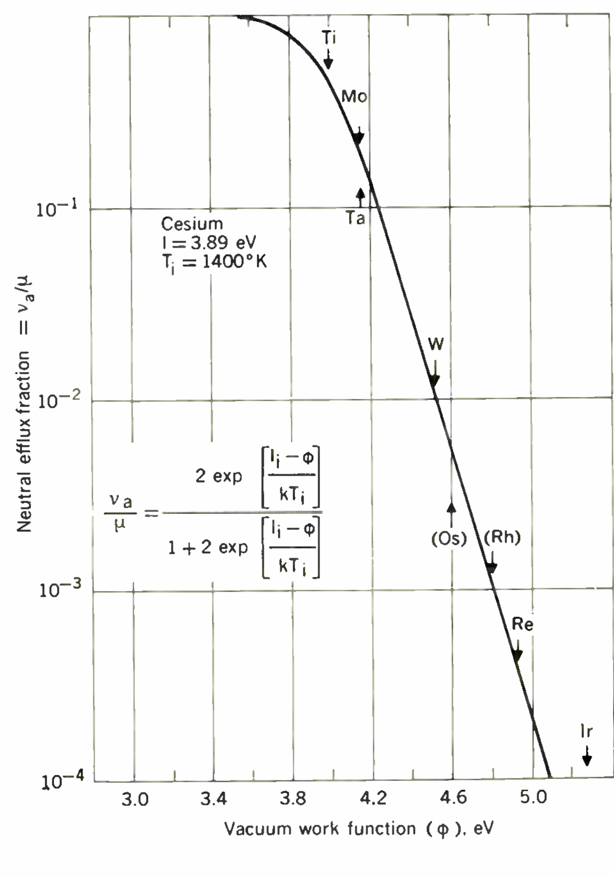


Fig. 8. Cesium neutral efflux fraction vs. surface work function plotted from the Saha–Langmuir equation. The bare work function values for several materials are indicated by the arrows.



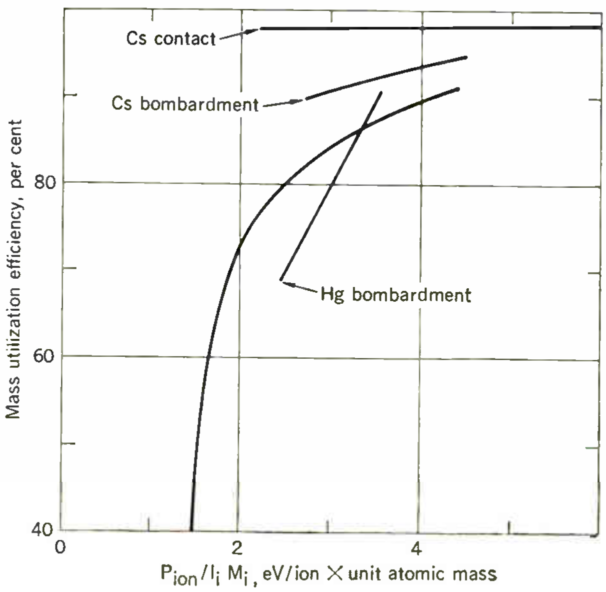
understood as a result of current research. Studies of the emission properties of other materials of potential use in ion engines have contributed new data on the behavior of cesium on nonrefractory metals, on insulators, and on some reportedly low-work-function compounds.[9]

The plasma ion source. As mentioned earlier, the ion source of the electron-bombardment-type ion engine is a plasma created by electron impact ionization of the propellant atoms in an arc-discharge chamber. This ionization produces a plasma of density roughly 10^{11} ions/cm^3, from which ion current densities of 5 to 10 mA/cm^2 for cesium and mercury can be drawn. This ionization process is not amenable to as complete an analytical treatment as the contact ion source, and such quantities as neutral fraction must be determined by experimental measurement. Typical data of propellant utilization efficiency (η_m = 1 − NF) are shown in Fig. 9 as a function of the energy required for ion creation. The ion creation energy in this source is the power expended in the arc discharge divided by the ion current extracted. It is seen that higher propellant utilization (that is, lower neutral efflux) results from the expenditure of larger amounts of energy for ion creation. This effect is the result of the greater arc current (that is, more ionizing electrons) necessary to achieve a higher degree of ionization in the plasma.

Charge-exchange ion effects

The fact that the ion source is not perfect, but evaporates a mixture of ions and neutral atoms, has a number of serious implications in the operation of ion engines. Perhaps the most important of these effects, from the point of view of limitation on life expectancy of the engine, results from the creation of new ions throughout the beam flow region by charge-exchange collisions.

Fig. 9. Typical curves of propellant utilization (η_m = 1 − NF) vs. normalized ion creation energy for three types of ion engines. (Sources: Cs contact, Husmann[5]; Cs bombardment, 3rd Quarterly Rept. on Contract NAS 3-5250, Electro Optical Systems; Hg bombardment, Kaufman[3])



In the region of the accelerator through which the ions are focused, neutral propellant atoms are present with a density of roughly 10^{11} atoms/cm^3. Some of these atoms will exchange an electron with a traveling ion, to result for each such collision in a relatively stationary ion where the atom used to be and an atom traveling with the velocity which the ion had before the collision. These newly created ions are of most concern, since they will be largely attracted to the most negative electrode of the engine; in the usual configuration of electrode potential this will be the "accel" or accelerating electrode. These ions will give rise to sputtering erosion of the accel electrode and provide a limitation on the life expectancy. This problem is particularly serious, since relatively little can be done in the structural design of the engine to reduce this effect substantially. Improvement will come about principally by increasing the ionization efficiency of the source; for example, in the contact source the use of higher work function materials for the ionizer will yield lower neutral efflux, as seen in Fig. 8.

Figure 1 shows also a potential diagram for the usual accel–decel ion engine system. It is clear from energy considerations that any ion created without significant initial velocity in region B will oscillate in this potential well until the transverse fields in the accel aperture eventually attract it to the accel electrode; that is, all ions created in region B will be collected at the accel electrode. Ions created in region A can, in principle (from energy considerations), escape from the engine. It is clear, however, that not all of these ions will escape from the engine, but the transverse electric fields in the region between the ionizer and the accel electrode will deflect the charge-exchange ions toward the accel electrode. That is, the ion optical design of the accelerator system is made to focus through the accel aperture the ions that were created at the ion source; this same field configuration will not, in general, focus as well those ions created throughout the beam flow region. This effect is common to both the contact and the bombardment types of ion engine.

The number of charge-exchange ions created per second ($\dot{n}_{CE} = I_{CE}/e$) which go to the accel electrode is given by

$$I_{CE} = GI_iQn_al = GI_iQl\frac{\dot{n}_aF}{v_a} \qquad (3)$$

where I_i is the ion current flowing from the source, Q the cross section for charge-exchange collision, n_a the density of neutral atoms through which the ion beam flows, and l the length of the interaction region. The neutral atom density can be expressed in terms of the atom efflux rate $\dot{n}_a$ and the mean thermal velocity of the atoms v_a. G is a factor to account for the fraction of charge-exchange ions created which go to the accel electrode ($G \approx \frac{1}{2} - \frac{2}{3}$, depending on the accel-to-decel ratio) and F is a factor relating to the reflection of atoms from the electrodes, which influences the atom density. F depends on the geometry of the accelerator region of the accelerator region of the engine under study; in a typical case it varies along the axis of the beam, from 2.5 near the ionizer to 0.5 near the decel electrode. In terms of neutral efflux fraction the atom efflux density is $\dot{n}_a$ = NF × J_i/e. Thus, on a per-unit-area basis the charge-exchange current is proportional to

$$I_{CE} \approx J_i^2 Q l \, \text{NF} \qquad (4)$$

For a typical accelerator structure

$$\frac{I_{CE}}{I_i} \cong 3J_i \, \text{NF}$$

for NF = 1 percent, J_i = 0.015 A/cm², the charge-exchange current to the accel electrode is $4.5 \times 10^{-4} I_i$. The collision cross-section values for various atoms is shown in Fig. 10 as a function of ion energy. It is seen, for example, that within the ion energy range of interest (1000–10 000 volts) the cross section for cesium is about four to five times as great as that for mercury.

In order to obtain a realistic analysis of the behavior of the charge-exchange ions in an engine, a study[15] was carried out in which a family of trajectories of ions created by charge-exchange collision was plotted by the use of an electrolytic tank automatic trajectory tracer. Figure 11 shows that the ions created by charge exchange in the negative potential region of the engine go to the accel electrode. These ions are attracted preferentially to the center of the inner face of this electrode, to result in the erosion pattern shown by the dashed lines. It is seen also that some charge-exchange ions do strike all faces of the accel electrode and at different angles with respect to the surface. This behavior has been demonstrated at least qualitatively by experimental observation of accel electrodes run for extended periods of time in operating engines.

Some typical photomicrographs are shown in Fig. 12 in which we see three characteristic types of erosion patterns. The first, in which the erosion is by means of ions created by contact ionization on the focus electrode impinging normally on the accel surface, produces a deep hole and a column pattern as shown at region A. This class of ion erosion results from a hot focus electrode, which will emit ions directly to the accel electrode. This undesirable effect can be eliminated by proper engine design. Those charge-exchange ions striking the ionizer side of the accel electrode do so with a grazing incidence, and give an erosion pattern as shown in region B. The indentation caused by the charge-exchange ion erosion on the inner face of the accel (similar to that shown in Fig. 11) is shown in region C. It is clear that such severe erosion (region C) of a critical electrode will adversely

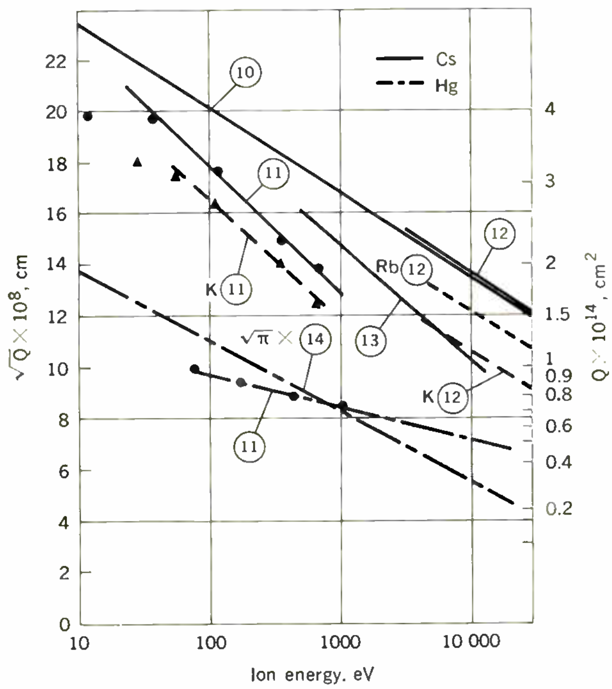
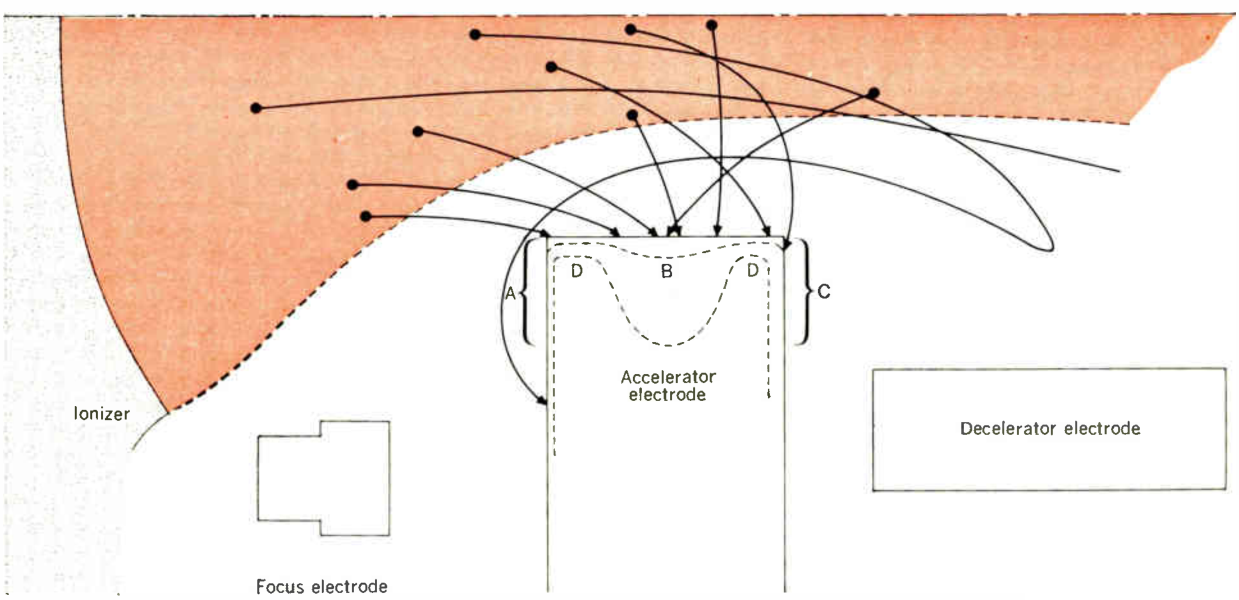


Fig. 10. Plot of values of cross section for charge-exchange collision Q vs. ion energy for several ions. The circled numbers are the reference numbers of the data sources. The data of Ref. 11 are shown multiplied by $\sqrt{\pi}$ to correct what appeared to be an error.

Fig. 11. Plots of typical trajectories of ions created in the beam-flow region (at the origin of each trajectory) by a charge-exchange collision. Accel-to-decel ratio = 2.



affect the structural and ion–optical characteristics of the engine, eventually resulting in failure. If necessary, a modification in the trajectories can be made so that they do not strike the accel electrode, by inserting a third electrode, which is somewhat more negative than the accel electrode. This new electrode would serve to divert the charge-exchange ions to itself, and would of course be eroded. However, the engine can be designed in such a way that the operation is less sensitive to the shape of this electrode.

The graphs in Fig. 13 show the sputter yield for cesium (or xenon) and mercury ions normally incident onto several materials.[16,17] The yield values form the usual periodic behavior with atomic number of the target atom. The sputter yield values in Fig. 13 are shown for illustrative purposes; the values for cesium and mercury in the voltage range of interest are roughly 304 times those indicated. Thus, for example, about seven copper atoms are sputtered away for each incident cesium ion. The volume of electrode material eroded per impinging ion is proportional to MY/σ, where M = atomic mass of electrode atom, Y = sputter yield, and σ = density. Thus, an important criterion for selection of accel electrode material for long engine life is the minimization of this ratio. In order to obtain the lowest rate of electrode sputtering one is tempted to use a material of low sputter yield, such as molybdenum, tantalum, titanium, etc. Although such refractory metals are suitable for use in the bombardment-type engine, as we shall see later, in the case of the contact engine the sputtered atoms of these metals can have serious adverse effects on the ionizer, so metals that are not evaporated rapidly from the ionizer must be avoided. This latter consideration narrows the choice of usable accel electrode materials in the contact engine to copper and possibly nickel, titanium, or iron.

From the erosion rates, which are determinable from knowledge of the charge-exchange and engine parameters, the approximate expected lifetime of a given electrode structure can be calculated as a function of ion current density and neutral fraction. Such lifetimes are shown plotted in Fig. 14 (light diagonal lines) calculated for the contact engine with nickel electrode material, for two fixed values of neutral efflux, as a function of current density from the ion source. Curves are also shown for

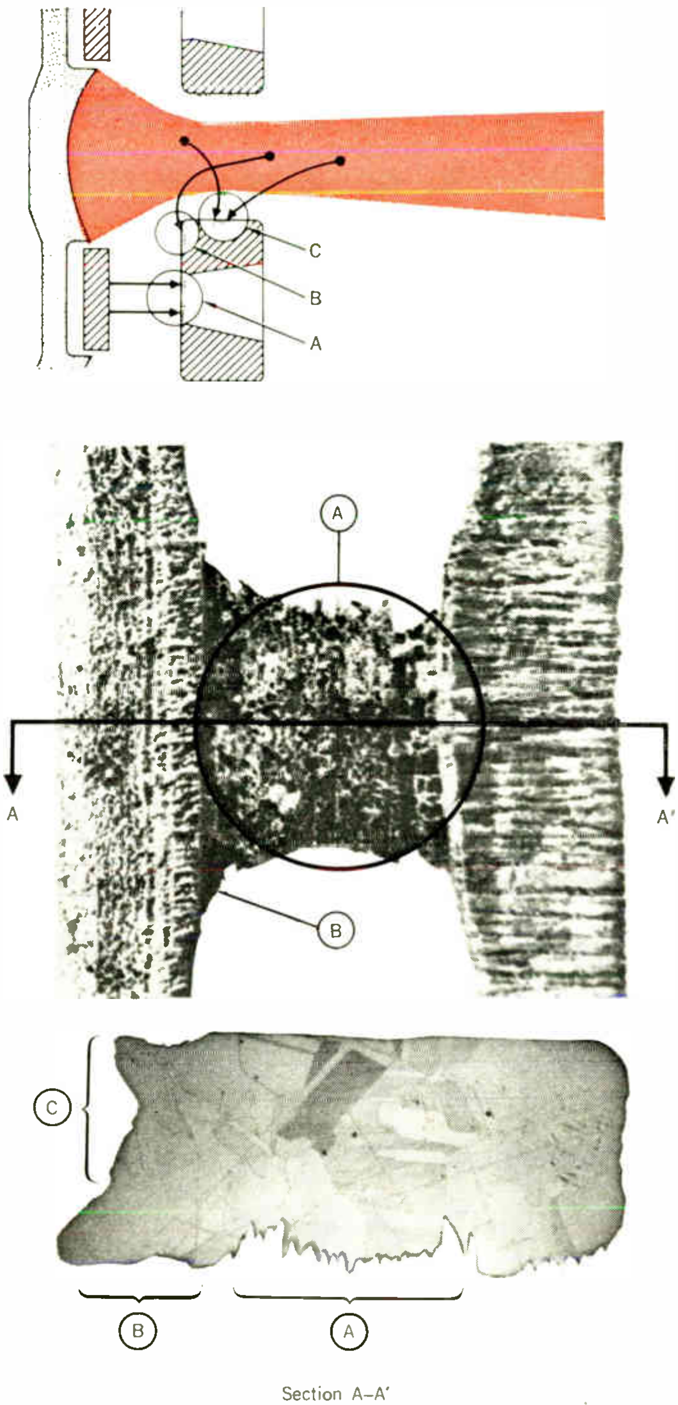


Fig. 12. Photomicrographs of the surface of an accel electrode from a contact ion engine after long-duration operation in which significant charge-exchange erosion has occurred. Region A shows deep pitting by normally incident ions from the focus electrode; region B shows the effect of charge-exchange ions that struck at grazing incidence; region C is the typical indentation on inner face of the accel electrode, showing the concentration of charge-exchange ions at this point (see Fig. 11).

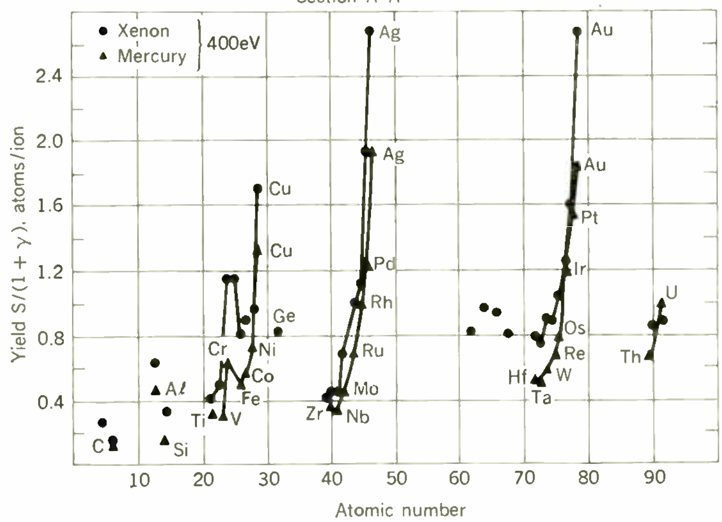
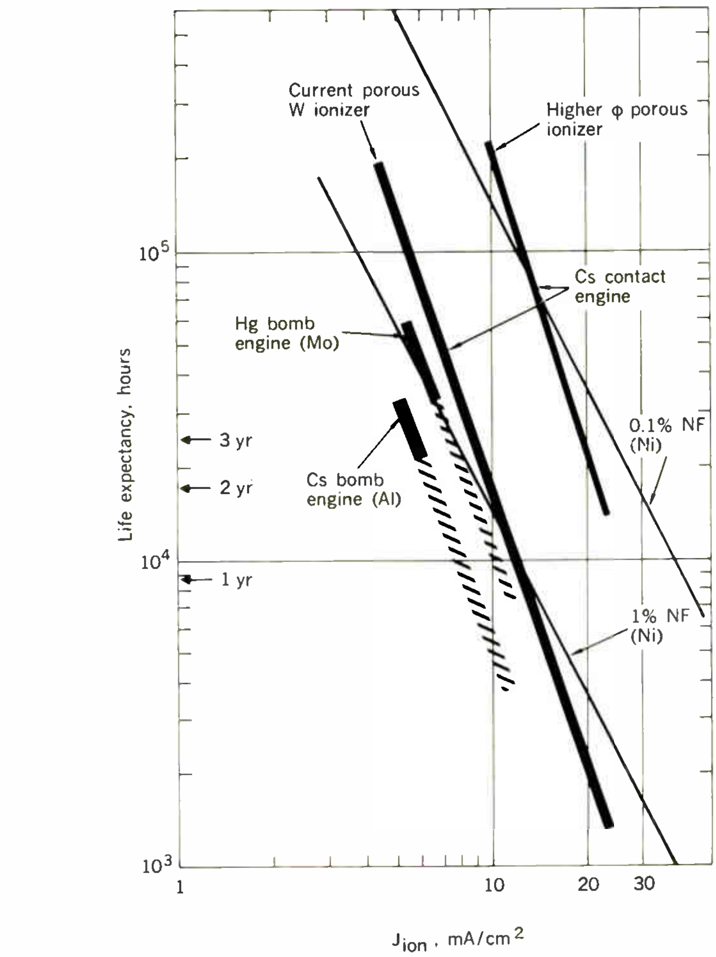
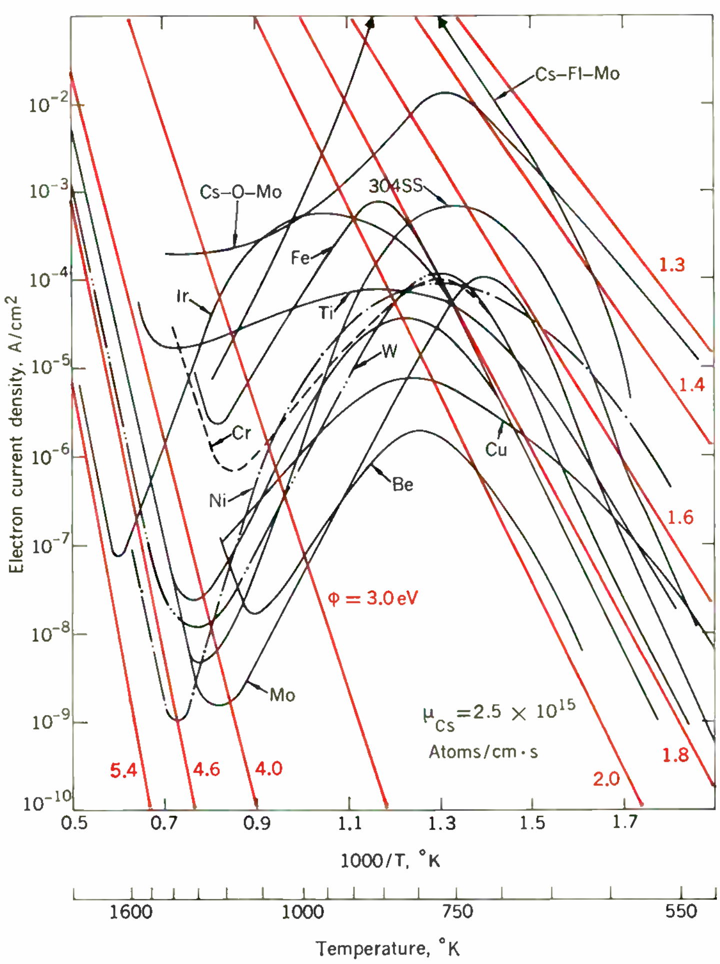


Fig. 13. Sputter yield of xenon (similar to cesium) and mercury ions onto a number of metals. (Data from Wehner[16] and Stuart[17])





values of neutral efflux ratio corresponding to typical ionizers, taking into account the variation of neutral efflux with current density, as shown in Fig. 7. Curves for the bombardment engine with cesium and mercury propellant are also shown in Fig. 14. The lifetime criterion here was somewhat arbitrary, determined by allowing about 30 percent of the accelerating electrode to be eroded away before either the optical or structural characteristics of the accelerator would be very seriously affected.

It is seen, for example, that with nickel accel material the lifetime of a contact engine accel electrode would be approximately 20 000 hours for a current density of 20 mA/cm^2 with a low-neutral-efflux ionizer. The use of a lower sputter yield accel electrode possible in the bombardment engine should result in a life of 20 000 to 40 000 hours. These lifetimes are quite adequate to perform most useful interplanetary missions with the desired margin of safety. It is seen that the life, and therefore the reliability for performing a given mission, decreases quite rapidly as the current density is increased. This is due, of course, to the combination of more ions with which charge-exchange reactions can occur and more neutral particles (which increase as the current density increases), as seen from Eq. (4). Although cesium current-density values as high as 40 mA/cm^2 have been obtained from porous tungsten ionizers, the more conservative design, leading to higher reliability levels, can be achieved by operating at current densities in the range of 15–30 mA/cm^2. The higher current densities result in an increase in engine power efficiency, particularly at the lower values of specific impulse. However, since a design based on very high current densities can result in short life, operation in this range is undesirable until the higher current densities can be obtained with very low values of neutral efflux. It can be shown also that the life can be extended even further without significant sacrifice in engine efficiency, down to a level of approximately 7 mA/cm^2.

The graph in Fig. 14 shows clearly that significant increase in lifetime is possible as the neutral efflux of

Fig. 14. Calculated life expectancies of three types of ion engines when lifetime is limited by charge-exchange ion erosion of the accel electrode, plotted vs. the current density from the ion source. The lifetime of the contact engine for constant values of neutral efflux is shown by the light lines. Expected lifetimes with current and improved contact ionizers are shown by the heavy bands. It is seen that lifetimes measured in years are possible from all three types of engines.

Fig. 15. Typical "S" curves of electron emission density from several metals with adsorbed cesium, vs. emitter temperature. The cesium arrival rate is constant in these curves (2.5×10^{15} atoms/cm^2·s). The effects of surface impurities and the influence of the substrate metal are shown clearly by the curves. If possible, the accel electrode material in a cesium engine should be closer for minimum electron emission. (Data from Refs. 7 and 18)

the ion source is reduced. This fact places great importance on the improvement of contact ionizers through the use of higher work function surfaces. Current research directed toward the development of such higher work function ionizers gives encouraging results. Studies on the arc discharge of the bombardment engine should yield improvement in neutral efflux from this source as well.

These lifetime calculations are based on only the mode of failure due to charge-exchange ion erosion of the accel electrode. Although this is currently felt to be the most likely long-term limitation, other failure modes may be shown by long tests to be of significance. For example, cathode erosion by ion bombardment in the electron bombardment engine could be a limitation unless this electron-emitting surface is continually replenished as it is eroded away. Cathodes having this replenishment feature are now under development.

Electron emission

In bombardment and contact ion engines that use cesium propellant, the efflux of neutral cesium atoms from the ion source will result in a continuous cesium condensation on, and evaporation from, the electrodes of the engine. For typical ion current densities the neutral cesium arrival rate onto the accel electrode will be approximately 10^{15} atoms/cm^2·s, which for typical accel electrode temperatures (500 to 1000°K) will correspond to a coverage on copper of about one third to two thirds of a monolayer. The presence of these alkali ions on the accel electrode surface will reduce the work function, and thereby allow significant electron current to flow to the more positive electrodes. The resulting thermionic electron emission from the accel electrode will be temperature limited and will obey the Richardson–Dushman equation:

$$J_s = A_0 T_a^{\,2} \exp -\left[\frac{e\phi}{kT_a}\right] \exp\left[\frac{0.44\sqrt{E}}{T_a}\right] \qquad (5)$$

If the accel electrode were a clean metal, the current density could be found by the use of the work function appropriate to this metal in the above equation. In engines using cesium, however, the work function can be much lower than this bare-metal value. The emission from a partially cesium-covered electrode is usually expressed by means of an S-shaped graph of current density versus reciprocal temperature. A group of these graphs, for different metals and a constant arrival rate of cesium at the electrode surface, is shown in Fig. 15, together with two curves illustrating the effect of contaminants on the metallic surface.[18] It is seen that, in the normal range of parameters, the electron emission from a clean metal exhibits a maximum as a function of electrode temperature, giving rise to values of the order of 10^{-5} A/cm^2 for cesium on copper.

Different metals exhibit rather striking differences in emission characteristics, and the effect of a contaminant on the surface (much more realistic in actual engine operation) is quite significant. For example, the presence of a monolayer of oxygen on the clean metal surface will cause the cesium atoms to adhere more tenaciously to the surface and so result in a higher cesium surface coverage at a given temperature and therefore in a lowered work function. The cesium oxide–metal double layer thus can give rise to a several-order-of-magnitude increase in electron emission (compare the molybdenum and molybdenum–oxygen curves in Fig. 15). Another criterion for selection of accel electrode material in cesium engines is therefore to minimize this electron drain current of potentially acceptable metals. Iron, molybdenum, titanium, nickel, and copper (in order of decreasing emission) exhibit the lowest cesiated electron emission in the temperature range of interest.

The presence of an electric field between the accel electrode and ionizer lowers the work function still further and allows increased electron emission. At field values of $E = 10^6$ volts/cm or higher, this Schottky effect becomes significant. In the presence of such a field, the Richardson equation is modified to include the Schottky term, which is the right-hand exponential expression in (5). The electric field normally used in this equation is the average between focus and accel electrode. It has been observed experimentally that considerably greater fields (enhanced by a factor of 20 to 40) result from sharp protrusions from the electrode surface, due to surface scaling, "whisker" growth,[19] etc. The electron current in such cases has been observed experimentally to vary linearly with exp $\sqrt{E}$.

This electron current will be typically 1 to 5 percent of the ion-beam current, will consume some power, and may increase the temperature of any electrodes to which it is drawn, but it is essentially in the "nuisance" category when compared with the serious erosion which can result from ion bombardment of electrodes. The electron current from the accel electrode can be limited by controlling the temperature of this electrode or reducing the cesium arrival rate by the use of an ion source with lower atom flux. As seen by the S curves of Fig. 15, operation at temperatures away from the emission peak—i.e., around 600°K or 1000°K—is desirable to minimize the electron emission. The higher of these temperatures has been found to be preferable, to reduce condensation of oxide impurities and the formation of "whiskers," both of which increase the electron emission. The general behavior as shown by these S curves has been verified experimentally in the operation of ion engines.[20]

Focus-electrode emission

The focus electrode in a cesium contact engine can also be a source (by contact ionization) of undesired ions, which will be attracted directly to the accel electrode to produce severe erosion. However, there are three techniques of focus design that can be used to reduce this spurious ion bombardment. These involve (1) the use of a focus electrode that is reduced in temperature below that at which surface contact ionization can occur, (2) the use of a material on the surface of the electrode that will not result in contact ionization of cesium even if the temperature is quite high, and (3) design of the focus electrode so as to cause essentially all ions created on the surface to flow out through the aperture with the ion beam.

It was shown earlier that cesium can be ionized by contact with most metals, but each metal exhibits a critical temperature below which such ionization will not occur. Thus, the cooling of the focus electrode below its critical temperature for ionization forms a straightforward and controllable approach to the reduction of

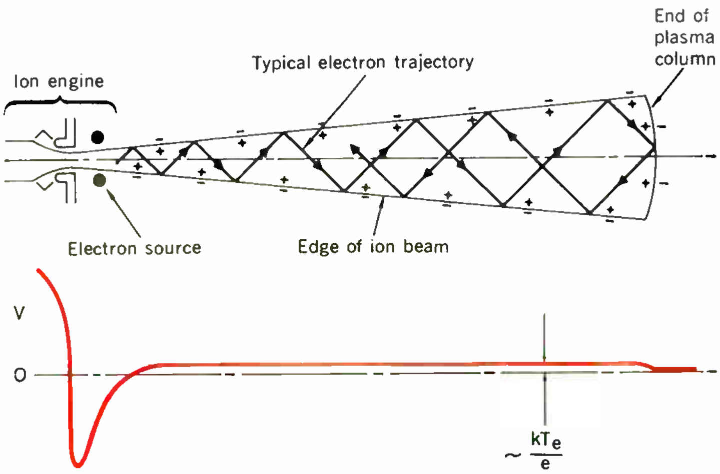
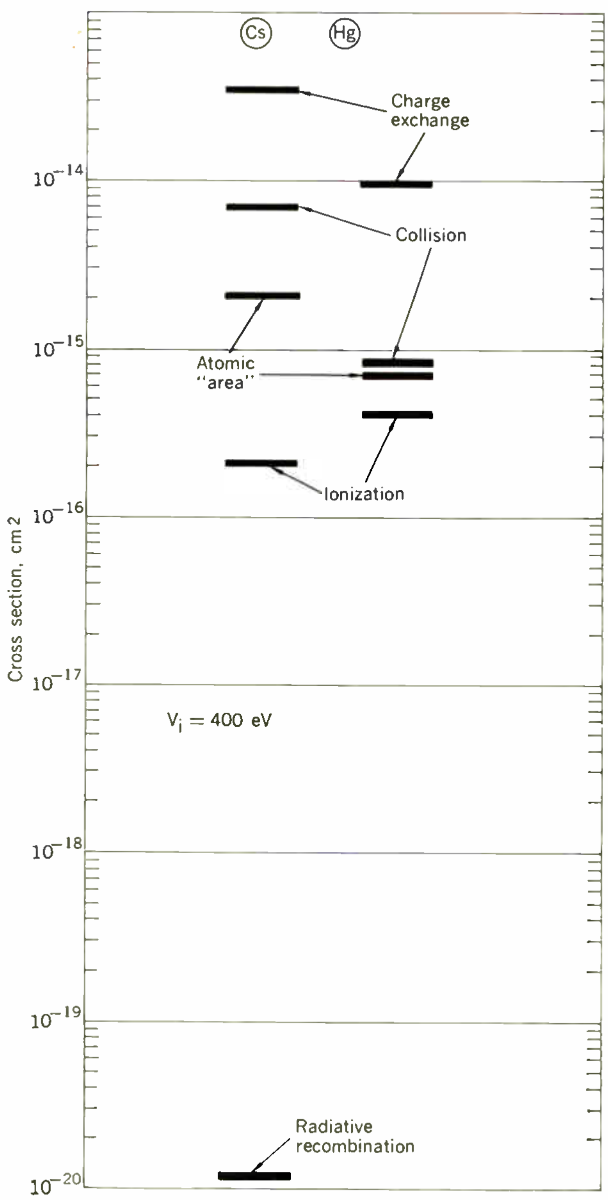


Fig. 16. Diagram of neutralization of an ion beam by electrons. Expected potential diagram is at the bottom.

Fig. 17. Magnitudes of several cross-section values representing interactions of interest in the ion engine.



ionization. Also, experiments with a number of other materials have indicated that it may be possible to achieve a satisfactory coating of the focus electrode to prevent ionization, while still operating this electrode at a high temperature. The most satisfactory coating material, from the point of view of ion emission suppression, that has been found to date is alumina.[9]

Alumina is normally thought of as an insulator, but at high temperatures it can conduct enough current to act as an emitter of either electrons or ions. The ion emission, however, at 1400°K is one or two orders of magnitude lower than that from metals. In the third method, designs have been made of sharp-edged focus electrodes in which essentially all ions from the surface are focused away from the accel electrode. It is seen that, fortunately, the focus electrode as a possible source of ions can be controlled by proper design of the engine, so that this particular problem need not form a life-limiting factor.

Ion-beam neutralization

As we have seen, the electrostatic ion engine is characterized by the separate acceleration of positive and negative charges. This class of electric engines also has the common requirement for neutralization of the exhaust ion beam by the injection of charged particles of the opposite polarity. In practice, electrons are always used as the negative particle to be ejected along with the ions, because of the great difficulty of generating negative ions in sufficient quantity. The ejection of an equal number of electrons and ions from an isolated space vehicle is, of course, essential to prevent charge build-up on the vehicle, with consequent creation of fields that would retard the ions and therefore decrease the thrust; in an extreme case, these fields could cause the complete turnaround and return of the ion beam to the space vehicle.

The simplest form of electron ejection into the ion beam, which has been found in tests in both ground-based vacuum chambers and in an actual space test, involves the arrangement of an electron-emitting filament in close proximity to the ion beam so that the positive charges of the beam can attract electrons into the beam. The electrons then move around inside of the beam, being prevented from leaving by the plasma sheath potential. The electrons trapped within the beam can oscillate both transversely and longitudinally, somewhat as shown in Fig. 16. The potential "hill" at the engine side of the beam, which results from the usual accel–decel mode of potential in the engine, prevents the electrons from being attracted from the beam toward the ion source. In the absence of an explicit decel electrode as part of the engine, biasing of the electron emitter positive with respect to the accel electrode can also result in a sheath potential at the engine which effectively prevents electron loss from the beam. Even though the electron velocity is considerably greater than the drift velocity of the ions, a simple analysis[2,21] shows that the electrons will be reflected from the beam edges in such a way as to give rise to a double streaming motion, the average or drift velocity of which will be just equal to the ion velocity.

Numerous ground-based tests over the past several years have shown that effective neutralization of such an ion beam can be achieved. The earliest of these tests[22] used simply the transverse expansion of the beam under space-charge forces as a criterion of neutralization, and it was found that when neutralization took place the beam did not expand. More sophisticated measurements involving probing, including electron and ion beam probes,[23] to measure the potential and electron flow in the beam have shown the existence of counter-streaming electrons and that neutralization was achieved. The net charge of the ion beam passing through a circular hoop into which charge was induced showed a zero net charge in a traveling pulse of ions when neutralization was effected.[24] In July 1964 the SERT-I (Space Electric Rocket Test) flight test of an engine by NASA showed that neutralization in space, where the equipotential metallic walls of the ground-based test chamber are, of course, absent, was equally effective, and the engine performance was in all measurable respects identical to that achieved in ground tests.[25] Although some details of the neutralization process in space still remain to be answered, there is no real concern at present as to whether ion-beam neutralization can be achieved in space. Several years ago this question was of considerable concern when it was felt that the lack of ability to neutralize the beam could prevent the use of electric propulsion.

It is emphasized that by "neutralization" we mean that equal electron and ion currents are ejected from the vehicle and that the drift velocity of ions and electrons in the beam are equal. The actual recombination of neutralizing electrons with the ions is extremely improbable. The radiative recombination cross section is so low[26] (10^{-20} cm^2) that a typical ion beam of density 10^{10} ions/cm^3, containing an electron cloud with an energy of approximately one half volt (typical of measured electron temperatures in an ion beam), will decrease to $1/e$ of its initial ion density value in a distance considerably greater than 10^{10} cm, or roughly the distance from the earth to the moon! The recombination effect is therefore negligible. A neutralized ion beam is thus analogous to a directed neutral plasma of high directed energy. The potential nonpropulsive uses of such a beam of charged particles have not even begun to be investigated.

Figure 17 shows in graphical form the cross-section values for the several atomic processes that can take place throughout the volume occupied by ions, and provides perspective on the several types of collision of importance in ion engines. It is seen that the charge-exchange cross section is the highest, when compared with the somewhat more familiar collision and ionization (by electrons) cross-section values.

Environmental effects

Since many of the phenomena considered here involve electron and ion emission from electrode surfaces, the detailed surface characteristics of which determine the emission to a great degree, these effects can be strongly influenced by the particle environment in which the engine is operated. Certain of these environmental effects are the result of the imperfect vacuum and the finite-sized test chamber in which ion engines are operated in the laboratory, and certain other of the effects will still be present during operation in space.

We have seen previously (Fig. 15) the effect that electronegative gases (for example, oxygen and fluorine) can have on the electron emission from the cesiated surface. It was found that such gases can result in a two-order-of-magnitude increase in electron current. The adsorption of oxygen on the accel electrode certainly occurs in an operating ion engine and can, in a ground-based test chamber, occur partly as a result of the imperfect vacuum. The effect of an adsorbed layer of oxygen on the ionizer of a contact engine was also shown (Fig. 7) where it was seen to cause a significant increase in the critical temperature. The effects of oxygen, however, are not felt to be particularly serious, inasmuch as it is easily removed from the vacuum chamber and, after engine outgassing, this element will not be present in space.

However, effects of other gaseous contaminants found in vacuum test chambers, particularly the carbon-bearing gases (such as CO, CO_2, CH_4, etc.), can have extremely deleterious effects on the contact ionizer. These contaminants can, in fact, result in a severe limitation to the life of the ion engine when tested in the usual vacuum chamber, a limitation that could prevent ground life tests from providing a representative indication of the life of the engine in space. Carbon-bearing gases can result from the vacuum pumps, outgassing of O-rings, etc. Upon impinging on the hot ionizer surface, a carbon-gas molecule will have a probability[27] of roughly 10^{-3} of reacting to leave a carbon atom on the surface. This carbon atom can diffuse into the interior of the tungsten grain so as to maintain the surface concentration of carbon at a relatively low level. As the grain saturates with carbon, however, the surface concentration will build up, lower the surface work function, and raise the neutral cesium, thus resulting in premature engine failure due to charge-exchange ion erosion. These effects are illustrated graphically[28] in Fig. 18, in which the change in work function due to the adsorbed surface layer of carbon (and the corresponding neutral efflux) is plotted as a function of operating time for various partial pressures of carbon-bearing gases. It is seen, for example, that a partial pressure of CO equal to 10^{-7} mm of mercury will begin to depress the work function after about ten hours, and after an operation between 100 and 1000 hours the neutral efflux would have risen to an intolerable level. A partial pressure of approximately 10^{-11} is necessary in order to secure uncontaminated operation for 10 000 hours. This requirement imposes restrictions on the design of the test chamber and suggests that more reliable, long-duration testing may be obtained in space.

Another contaminating effect on a contact ionizer can result from the deposition of metallic atoms onto the ionizer surface, which causes changes in the surface work function. Such atoms may come as a result of sputtering from the accel electrode due to charge-exchange ions or from the ion beam collector in a vacuum test chamber. The effect of selected adsorbed metallic atoms on a tungsten ionizer is shown in Fig. 19, where the calculated[20,29] composite work function is plotted as a function of the arrival rate of the contaminating atom. The parameter on these curves is the equilibrium surface coverage. It is seen that materials, such as platinum, nickel, and palladium, that exhibit a higher work function than tungsten will result in an increased composite work function; other materials, such as manganese, beryllium, and copper, will lower the work function to a value below that of tungsten. The curves drawn here represent the effects due to an equilibrium surface coverage resulting from the given arrival rate and the evapora-

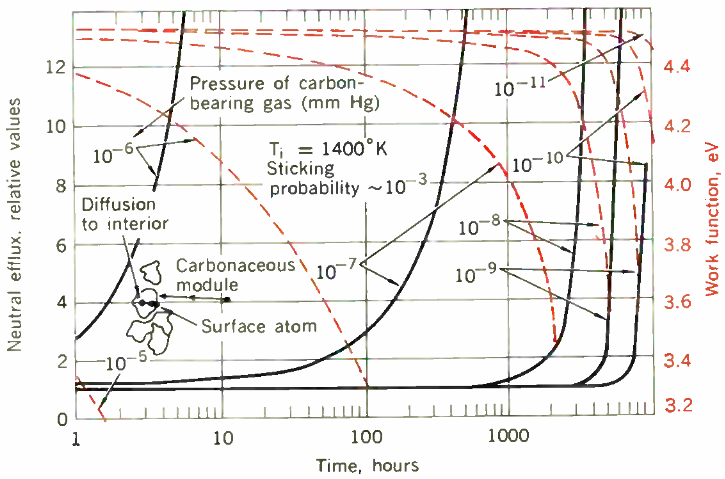
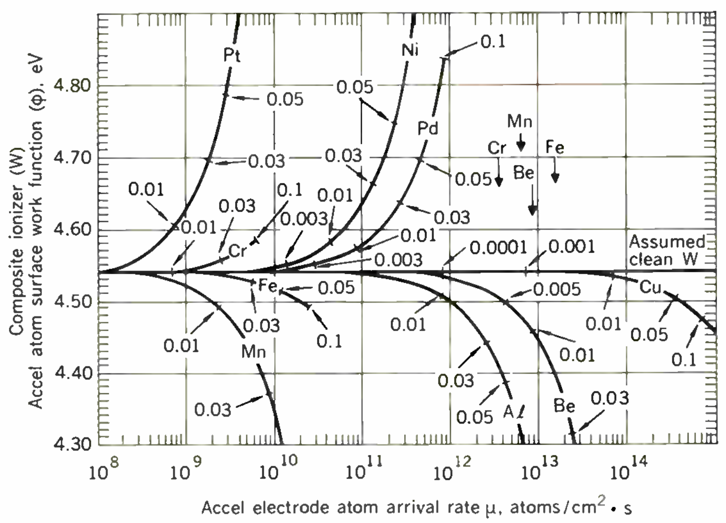


Fig. 18. The effect of a carbonaceous atmosphere on the work function and neutral efflux of a tungsten ionizer, vs. time of exposure of the tungsten to the carbon-bearing gas, with partial carbon gas pressure as parameter.

Fig. 19. Change in work function of tungsten, due to adsorption of several metallic atoms, vs. the arrival rate of these foreign atoms. Ionizer temperature = 1400°K. Arrows indicate expected arrival rates due to sputtering of an accel electrode under typical operating conditions. An accel electrode for the contact engine should be chosen so that the expected sputtering due to charge-exchange ions will not lower the work function of the ionizer.



tion rate of the atoms from tungsten. It is seen, for example, that copper, with its lower vaporization temperature, can arrive onto the ionizer at a much higher rate without producing a significant effect than can (for example) manganese. Since metallic atoms can arrive at the ionizer as a result of charge-exchange ion sputtering of the accel electrodes, the consideration of ionizer contamination by accel material is very important in the choice of this electrode material. Also, the sputtering of copper atoms from the ion-beam collector can give rise to an arrival of approximately 10^{14} atoms/cm²·s onto the ionizer. It is seen from the graph that this level is just barely tolerable. This condition necessitates great care in the design of the test chamber and collector assembly in order to maintain the level of copper arrival below this upper limit.

Those who have experienced the "poisoning" of an electron-emitting cathode can appreciate these effects. In seeking the best ion and electron emitters, we work at opposite ends of the work function spectrum, the lowest work function providing the best electron source and the highest work function the best ion source. Thus almost any adsorbed atom will poison either surface.

The electron-emitting cathodes (particularly the oxide type) used in electron bombardment engines can suffer degradation as a result of deposition of sputtered particles or by the residual gas in a test chamber. Over long periods of time, sputtered material can change the thermal characteristics of an engine by altering the emissivity of radiating surfaces. Here we see additional situations in which the testing environment can have an adverse effect on engine life and, unless great care is taken in the design of the test chamber, ground-based tests may provide an unduly pessimistic estimate of the life potential.

The graphs in Fig. 19 illustrate a recent significant advance in the understanding of surface characteristics as related to particle emission. Based on the theory of Levine and Gyftopoulos,[30] analytical expressions have been developed to allow calculation of the effect of any adsorbed film on almost any substrate, using only known or measurable physical parameters. These theories have provided an invaluable guide to design of experiments and greater insight into the effects of adsorption.

Miscellaneous emission

The light radiated from the hot (1400°K) ionizer in a contact engine will produce photoelectric emission from a low-work-function (cesium-coated) accel electrode. Typically this photoelectric current density will be of the order of 10^{-10} to 10^{-11} A/cm², which is seen to be negligible compared with the thermionic emission from this electrode. If this surface were irradiated with ultraviolet light, the yield would be greater but probably still of small effect.

Ions striking the electrodes of an ion engine can liberate secondary electrons or negative ions. The secondary electron yield from cesium-covered copper or molybdenum is roughly 1.5 at 8 kV. Negative copper ions can be produced from cesium ion bombardment of a cesium-covered copper surface. The yield is roughly 2 percent for bare copper and as high as 20 percent for cesium-covered copper. Since the only ion current to the electrodes should be from charge-exchange-created ions, these secondary currents will also be of negligible importance.

Conclusions

The ion engine is a relatively new type of space propulsion device. Although the first serious proposals for its use and method of design were put forth around 1954, it has been in active experimental development for only the past five years. During this time much has been learned about its characteristics as a propulsion engine, research studies have contributed needed knowledge on the design and materials selection, and preliminary system operation and long-duration tests have shown its potential for space propulsion. Currently the engine development is in the phase of long-duration reliability testing, where time-dependent failure modes are being uncovered and corrected. The causes of some of these failure modes have been described in this article. The life tests to date, however, have been carried out for only a few hundred hours, while demonstrated lifetimes of 10000 to 20000 hours are necessary to assure its reliability for the intended applications. All present data indicate that the engine is capable of such lifetimes. The ion engine has the potential for further significant improvement and offers one of the really attractive techniques for long-duration space propulsion, over a wide range of missions from prime propulsion of manned interplanetary vehicles to the control of earth satellites.

This article has concentrated on several of the physical electronic phenomena that occur in the ion engine. In addition to aiding in the development of longer-life ion engines with lower spurious electron currents, studies such as those described can also make improved electronic devices possible. Today's deeper understanding of emission from metals and insulators with adsorbed films contributes to such electronic technologies as thermionic energy converters, electron-emitting cathodes, ion sources, and others. A considerably greater insight into the formation of low-work-function surfaces, patch effects, etc., is being obtained and can result in the evolution of cathodes with increased emission capability at lower temperature, anode surfaces for energy converters, etc. Improved knowledge of ion–solid interaction processes and development of ion sources with higher current densities will make possible the research and development of a broad class of new devices utilizing ions and atoms impregnated into metals and semiconductors. Such problems are receiving intensive study throughout the world; it is hoped that research on ion engines will contribute to these new technologies.

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

Data from many sources have been used in the preparation of this article. In addition to those sources indicated by the references, much help has been received by the author from his colleagues, especially R. G. Wilson, H. L. Garvin, H. J. King, and M. R. Currie.

REFERENCES

1. Stuhlinger, E., *Ion Propulsion*. New York: McGraw-Hill, 1964.

2. Brewer, G. R., Currie, M. R., and Knechtli, R. C., "Ionic and plasma propulsion for space vehicles," *Proc. IRE*, vol. 49, pp. 1789–1821; Dec. 1961.

3. Kaufman, H. R., *Advanced Propulsion Concepts*, vol. 1. New York: Gordon and Breach, 1963, pp. 3–17.

4. Brewer, G. R., "Formation of high-density electron beams," *J. Appl. Phys.*, vol. 28, pp. 7–15; Jan. 1957.

5. Husmann, O. K., and Turk, R. R., "Characteristics of porous tungsten ionizers," AIAA Paper 64-691, American Institute of Aeronautics and Astronautics, Sept. 1964.

Husmann, O. K., "A comparison of the contact ionization of cesium on tungsten with that of molybdenum, tantalum, and rhenium surfaces," *AIAA J.*, vol. 1, pp. 2607–2614; Nov. 1963.

6. Langmuir, I., "Vapor pressures, evaporation, condensation and adsorption," *J. Am. Chem. Soc.*, vol. 54, pp. 2798–2832; July 1932.

7. Langmuir, I., and Taylor, J. B., "The evaporation of atoms, ions and electrons from caesium films on tungsten," *Phys. Rev.*, vol. 44; Sept. 15, 1933. Also in *The Collected Works of Irving Langmuir;* vol. 3. New York: Pergamon, 1961.

Zandberg, E. Ya., and Ionov, N. I., "Surface ionization," *Soviet Phys. Usp.*, vol. 67, no. 2, pp. 255–281; Mar.–Apr. 1959.

8. Becker, J. A., "Thermionic and adsorption characteristics of caesium on tungsten and oxidized tungsten," *Phys. Rev.*, vol. 28, pp. 341–361; Aug. 1926.

9. Garvin, H. L., and Wilson, R. G., "Electrode materials for cesium contact ion engines," AIAA Paper 64-484, Sept. 1964.

10. Marino, L. L., Smith, A. C. H., and Caplinger, E., "Charge transfer between positive cesium ions and cesium atoms," *Phys. Rev.*, vol. 128, pp. 2243–2250; Dec. 1, 1962.

11. Kushnir, R. M., Palyukh, B. M., and Sena, L. A., "A study of resonance neutralization in monatomic gases and metal vapors," *Izv. Akad. Nauk SSSR*, vol. 23, no. 8, pp. 1007–1011; 1959 (in Russian).

12. Chkuaseli, D. V., Nikoleishvili, U. D., and Guldamashvili, A. I., "Resonance charge exchange of positive alkali metal ions," *Izv. Akad. Nauk SSSR*, vol. 24, p. 970; 1960 (in Russian).

13. Speiser, R. C., and Vernon, R. H., "Cesium ion-atom charge exchange scattering," ARS Preprint 2068, American Rocket Society (now American Institute of Aeronautics and Astronautics), Oct. 1961.

14. Popescu Iovitsu, I., and Ionescu-Pallas, N., "Resonant charge exchange and the kinetics of ions," *Soviet Phys.—Tech. Phys.*, vol. 4, pp. 781–791; Jan. 1960.

15. Brewer, G. R., "On the nature of leakage currents in cesium contact ion engines," Research Rept. 281, Hughes Research Laboratories, Aug. 1963 (unpublished).

16. Wehner, G. K., "Physical sputtering," *Proc. 5th Internat'l Conf. on Ionization Phenomena in Gases*, Munich, Germany, 1961.

17. Stuart, R. V., "Sputtering yields at medium and low energies," *1961 Trans. 8th Vacuum Symp. and 2nd Internat'l Congress.* New York: Pergamon, 1962.

18. Wilson, R. G., "Electron and ion emission from cesiated nonrefractory metals," *Proc. 1965 Physical Electronics Conf.*, M.I.T., Cambridge, Mass., Mar. 1965.

Aamodt, R. L., Brown, L. J., and Nichols, B. D., "Thermionic emission from molybdenum in vapors of cesium and cesium fluoride," *J. Appl. Phys.*, vol. 33, pp. 2080–2085; June 1962.

Heil, H., Hughes Research Laboratories, private communication.

19. Brodie, I., "Studies of field emission and electrical breakdown between extended nickel surfaces in vacuum," *J. Appl. Phys.*, vol. 35, pp. 2324–2332; Aug. 1964.

20. Brewer, G. R., Zimmerman, R. L., Berman, D., and King, H. J., "Design criteria and performance of a cesium contact ion engine," AIAA Paper 64–710, Aug. 1964.

21. Wadhwa, R. P., *et al.*, "Analysis of electron ion mixing in ion engines," Repts. on Contracts NAS 3-2503 and NAS 3-5757, Litton Industries, San Carlos, Calif.

22. Brewer, G. R., Etter, J. E., and Anderson, J. R., "Design and performance of small model ion engines," ARS Paper 60-1125, May 1960.

23. Hubach, R. A., "Analytic and experimental studies to develop ion engine ground testing techniques," AECD-TDR-64, Mar. 1964.

Sellen, J. M., and Kemp, R. F., "Cesium ion beam neutralization in vehicular simulation," ARS Reprint 61-1778, June 1961.

24. Ward, J. W., and Hubach, R. A., "Neutralization of ion beams from engines of annular geometry," *ARS J.*, pp. 1730–1731; Nov. 1962.

25. Cybulski, R. J., *et al.*, "Results from SERT-I ion rocket flight test," NASA TN D-2718, Mar. 1965.

26. Wada, J. Y., and Knechtli, R. C., "Measurements of electron-ion recombination in a thermal cesium plasma," *Phys. Rev. Letters*, vol. 10, pp. 513–516; June 15, 1963.

27. Husmann, O. K., Jamba, D. M., and Denison, D. R., "The influence of the residual gas atmosphere in space chambers on the neutral efflux and critical temperature of tungsten ionizers," AIAA Paper 64-693, Sept. 1964.

28. Calculated by D. Berman, Hughes Research Laboratories.

29. Wilson, R. G., "Electron and ion emission from cesiated nonrefractory metals," *Proc. 1965 Physical Electronics Conf.*, M.I.T., Cambridge, Mass.

30. Levine, J. D., and Gyftopoulos, E. P., "Adsorption physics of metals partially covered by metallic particles. II—Desorption rates of atoms and ions," *Surface Sci.*, vol. 1, pp. 225–241; 1964.

Trends in EHV transmission equipment

The winds of change accelerating the growth of electric power in the United States are no longer blowing gently. Basic factors affecting the loading capacity of overhead lines (a common index of electrical capability) are herein examined

G. W. Alexander, I. B. Johnson, A. J. McConnell,
H. O. Simmons, Jr. *General Electric Company*

Before the turn of the century, ac polyphase transmission had been firmly established in the transportation of electric energy. Doubling approximately every ten years, the growth rate in the production and consumption of electric power has been more than twice that for the Gross National Product, and much faster than the rate of increase in the population.

Figure 1 shows the key trends in generation capacity and transmission characteristics. The year 1979 will mark the 100th anniversary of the first use of electric energy for commercial purposes. And by that year, it is anticipated that several trillion kWh of energy annually will be produced by a generation capability of the order of 500 000 MW, utilizing transmission facilities operating at maximum voltages approaching one million volts.

The electrical capability of ac transmission is often expressed by the loading capacity of the overhead lines. Figure 1 illustrates that as systems have grown in size, the transmission line loading capability has grown at a rate comparable to the growth rates in energy production and generating capability. However, the growth rate of system voltages has been lower and tends to follow a linear increase in voltage with the passing years.

For distances of 200 miles or more, the design of the components and system to achieve surge impedance loading is justified. For shorter distances, higher loads are transmitted on many lines and magnitudes of 1.5 to 2 times surge impedance loading are realized. However, with a surge impedance loading of approximately one million kW for a 500-kV line, the transportation capacity of even a single circuit becomes enormous.

To realize maximum loadings there are a number of other basic factors in addition to voltage level. Among these are series capacitors, intermediate switching stations, fast relaying and circuit-breaker switching times, high-speed reclosing, large-size ratings in generators, transformers, and breakers; lower than normal terminal reactances, kvar control; increased interconnections; integrated operating procedures; fast responding generator excitation and regulation; reduced line, station, and equipment insulation; and automation of operating procedures. A number of these items are discussed herein.

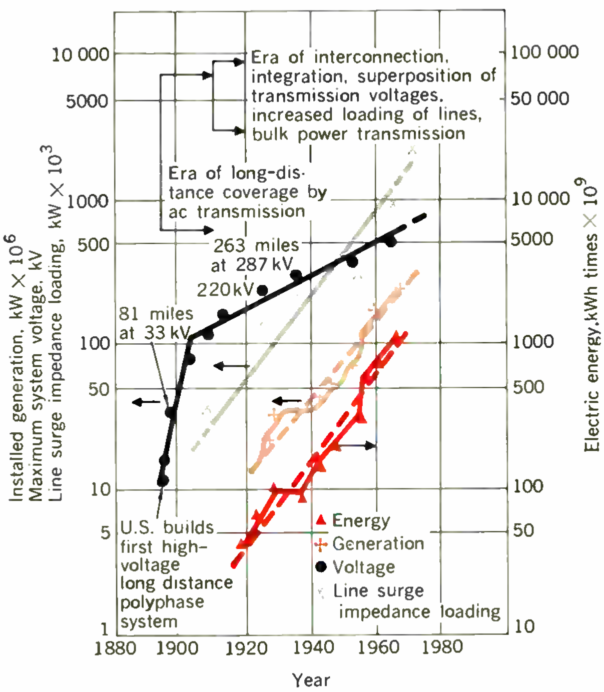
In summary, it may be stated that the winds of change no longer blow gently, but have become increasingly forceful and startling; and that accelerated growth and the consequences thereof continue as a fundamental aspect of the electric utility industry.

Power transformers and reactors

Transformers. A key role in the generation, transmission, and utilization of energy is played by the power transformer. Without the transmission of energy at higher voltages there could not be the vast increase in consumption of power which has occurred since the inception of the electric utility industry. Thus, the transformer must expand in capacity, voltage level, and reliability, along with the other components of the electrical system.

As each decade has passed, this challenge has been met.

Fig. 1. Growth patterns in the electric utility industry of the United States.



The historical trend of maximum sizes is shown in Fig. 2, which also demonstrates the increasing complexity of manufacture, assembly, testing, and shipment of EHV units. Factory assembly and testing assure the reliability needed in the super sizes now foreseen. Therefore, field assembly should be resorted to only as a last alternative. This requirement will establish a trend to single-phase units in these EHV sizes.

The role of testing in establishing reliability will expand. In recognition of this factor, a corona measurement and a switching surge test are now available which are more severe than present standards require.

The corona measurement limit for radio noise within the transformer is 1000 μV during the induced voltage test. A value above this limit will not be passed. This insures against insulation deterioration taking place during the induced voltage test.

The switching surge test must rise to crest in not less than 100 μs, be above 90 percent of the transformer's switching surge strength for not less than 200 μs, and have a duration longer than 1000 μs. Several 500-kV units have recently passed these tests (see Fig. 3). Thus, these tests and others are necessary as EHV systems employ still larger units to effect system economies.

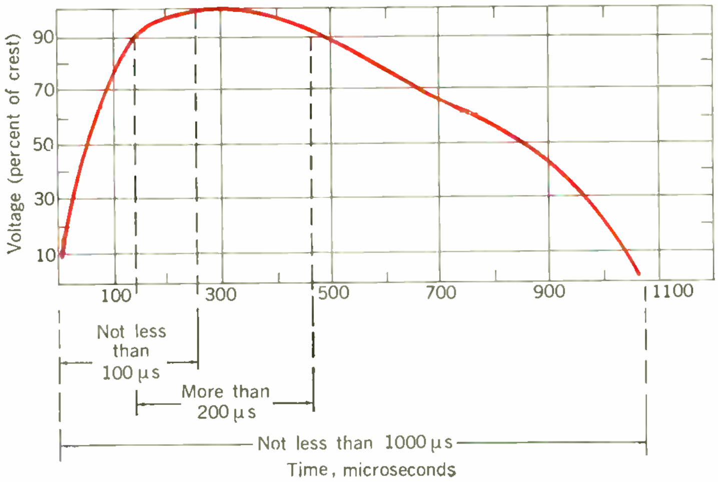
There is a trend to lower BIL ratings on EHV transformers and reactors. The line-side reactor normally has a higher BIL than the station transformer. Typical values for transformer BIL are 1050 kV for 345-kV systems, 1425 kV for 500-kV systems, and 2175 kV for 700-kV systems. These range from 2 to 3.5 steps down in insulation levels from those once contemplated.

The EHV transformer equipments are essentially of two types: generator step-up transformers and transmission tie autotransformers. Figure 2 shows that the two-winding transformer will be approaching 1100 MVA by 1970, because of the growth in size of turbine-generator units.

Figure 2 shows that even as the generator step-up units are gaining in size, the transmission autotransformer is more than keeping pace. By 1970 its output will exceed 1200 MVA. It plays the key role in transforming bulk energy from EHV to transmission network voltages.

Autotransformers will increasingly be examined for the need to include tertiary windings. The decision as to whether or not to specify a tertiary winding will often be dictated by the necessity for establishing an effectively grounded system or by the requirement that EHV voltage control be located on the tertiary winding.

Fig. 3. View of 500-kV transformer and graph of applied switching surge test wave.



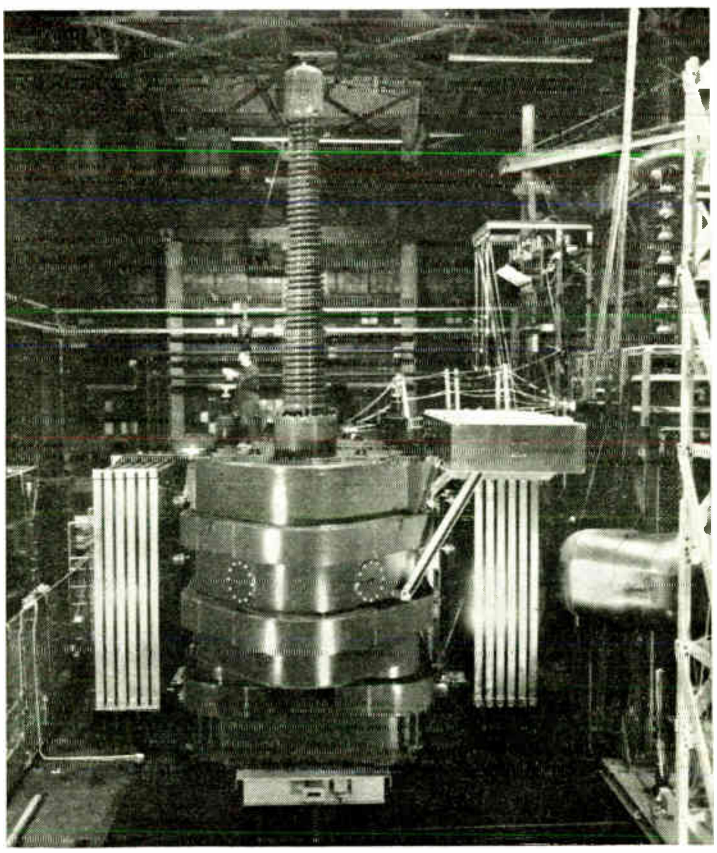
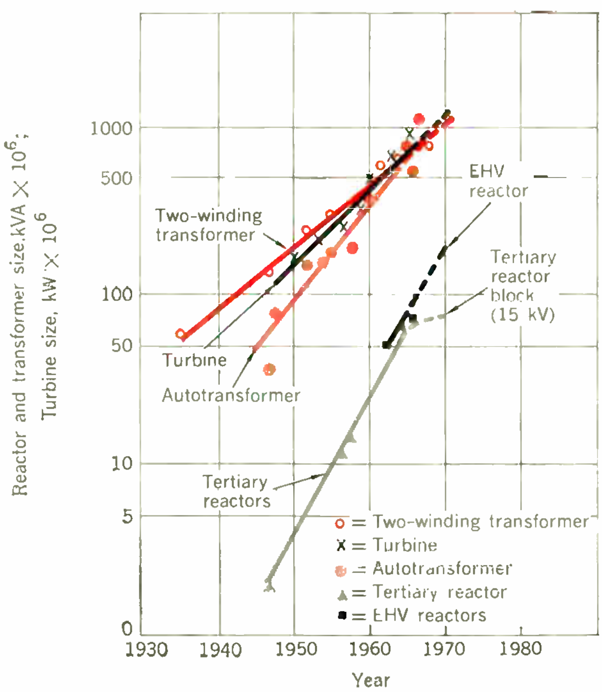


Fig. 2. Power transformers and reactors—historical trend of growth in maximum rating.



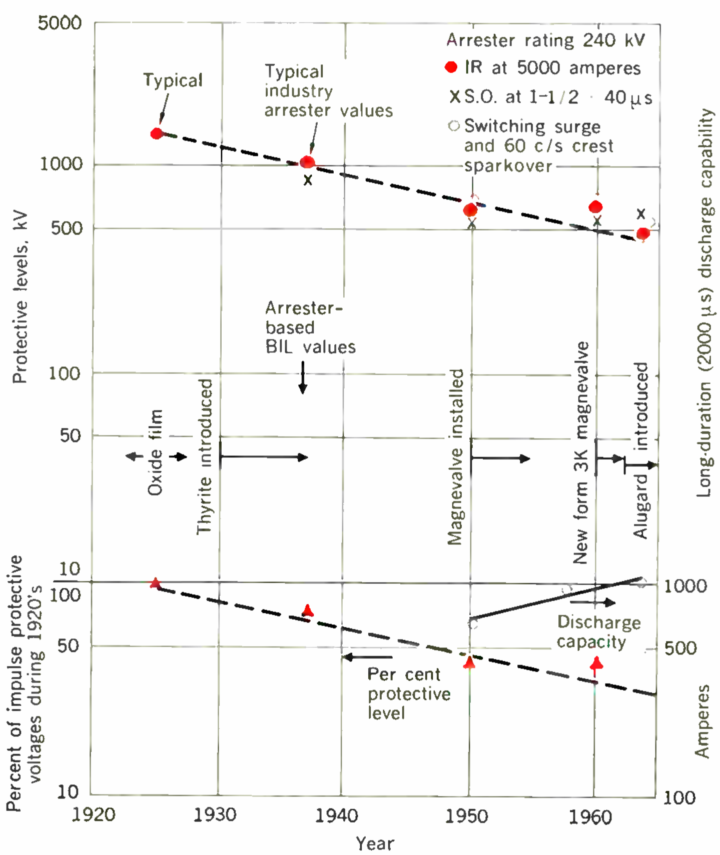
Voltage control will be accomplished by using switched shunt reactors and capacitor blocks at tertiary voltages. This practice provides a coarse control to compensate for the rise and fall of EHV voltage levels with line loading fluctuations.

This does not imply that load tap changing equipment on EHV transformers is obsolete. Such equipment will find continued use but must meet the challenge of larger transformer sizes. There are several methods of accomplishing LTC control; each has its area of application and effectiveness. For example, the use of a neutral LTC for regulation of the low-voltage bus will advantageously increase the reactive compensation of tertiary reactors during light loadings on EHV systems. This occurs because the tertiary voltage rises when the neutral LTC acts to hold voltage at rated value for the lower voltage system.

Reactors. The present average size of the tertiary reactor block is 25 Mvar at 13.8 kV. This allows switching of unit blocks to obtain suitable voltage steps for present systems. As autotransformer sizes and voltage levels increase, these sizes will grow as in Fig. 2. The trend will be toward tertiary voltage levels of 34.5 kV, and large EHV transformers might have five such blocks on their tertiaries before this decade is over.

It is often necessary, however, to include part of the reactive compensation on the EHV side of the autotransformer. This is particularly true in long EHV lines, especially in the initial stage. These EHV reactors are switched with line sections and are sized accordingly. Compensation for line charging might total 100 percent, of which 20–40 percent might be EHV oil-filled reactors. The saturation curves for these units will be linear to 125 percent voltage. The size of the EHV reactor might vary from 50 Mvar at 345 kV to several hundred Mvar at 700/765 kV. Figure 2 shows that a line section could contain 100-Mvar reactors by 1966 while the reactor size might reach 200 Mvar by 1970.

Fig. 4. Arresters—protective levels and discharge capacity.



Lightning arresters

There are three compelling reasons for lightning arrester selection and application, particularly for EHV systems. These are (1) huge investment in terminal equipment, (2) high load capacity per circuit, and (3) need for high reliability of circuit continuity.

The implementation of insulation coordination in power systems has saved utilities literally millions of dollars annually. The savings at 500 kV and 765 kV are of increasingly greater magnitude than at the lower voltages. And in the overall cost, arrester protection is but a fraction of the total.

One important feature of arrester development over the years has been the progressive improvement in protective characteristics. This is illustrated by the trend curves of Fig. 4 for sparkover voltages and *IR* discharge voltage drops for protection against lightning surges, and for sparkover voltages for protection against switching surges. Efficient station lightning arresters for solidly grounded neutral service can now, with adequate margin, protect BIL values three basic steps lower than those published by the industry in 1941. The reductions are, for example, from 1550 BIL to 900 BIL at 345 kV, from 1050 BIL to 650 BIL at 230 kV, and from 650 BIL to 350 BIL at 138 kV. In today's arrester the impulse protective voltages stand at 30 percent of those obtainable in the 1920 decade.

Also shown in Fig. 4 is the growth in another major facet of arrester design: available discharge capacity. The discharge capability is one of the most important differences between arresters applied on low-voltage systems and those to be applied at 500 kV or above. Because of higher voltage, larger capacitance per unit of line length, lower line surge impedance due to conductor bundling, and generally lower lines with increasing voltage, the potential surge energy in switching a 500-kV circuit is over twice that at 345 kV; at 700 kV it is over four times that at 345 kV.

Since adequate discharge capability is probably the key requirement of EHV arresters, the evaluation of this characteristic is an important one. Work has been in progress in the industry to revise and update the long-duration discharge test, which up to the present has been a rectangular wave of specified current magnitude and time duration. The new test parameters include length of transmission line, surge impedance, and switching surge voltage of the line to be discharged.

To provide for satisfactory protection against lightning surges and switching surges on the highest EHV system voltage of 765 kV, 678-kV station arresters have been selected. Figure 5 shows the first arrester ever designed for this highest of voltage ratings, following the successful completion of initial tests.

Power circuit breakers

The ever-increasing demands of power system growth and expansion on circuit-breaker requirements is reflected in Fig. 6. Higher interrupting and continuous current requirements, faster operating speeds, and new requirements for switching-surge control, insulation, and materials are particularly evident at the higher transmission voltage levels.

On the other hand, phenomenal growth in such factors as circuit-breaker interrupting ability has occurred not only with increases in transmission voltage but also for a given voltage level. For example, since 1940, the maximum interrupting capacity of the 230-kV breaker has increased from 2.5 million kVA to today's 20 million kVA rating. During the same period, the 230-kV breaker weight has been reduced from an early oil design of 195 000 pounds to the present air-blast breaker weight of 41 000 pounds.

Larger turbine-generator sizes and the economies of higher line loadings have created the need for higher continuous current ratings of transmission circuit breakers. The trend will continue. Table I indicates the need for continuous current ratings of 3000–3500 amperes for transmission voltage levels of 138 kV through 700 kV during the next ten years. The need for higher ratings has been recognized in recent industry investigations, resulting in new ASA standards which permit higher contact temperature and more efficient use of materials. Still further advance in this area is needed.

Progress in breaker speeds and total fault clearing time is illustrated in Fig. 6. The 1961 introduction of the two-cycle ATB breaker represented a "breakthrough" in power circuit breaker design; this permitted higher line loadings and contributed to the development of economic EHV systems.

Early in the planning of 500-kV transmission systems, it was recognized that large savings could be made in transmission circuit cost through the control of energization and reclosing transients. As a result, a new demand has been placed on the power circuit breaker and new systems at this voltage level call for breakers equipped with closing resistors and contact timing control. Aside from economic considerations alone, the technical feasibility of still higher voltage systems may well depend on the resistor preinsertion design innovation. As a secondary benefit of this development, the economics of resistor preinsertion have already extended to line switching at 345 kV and, in some instances, low-side

I. Future continuous current requirements for power circuit breakers (3000–3500-ampere range)

System Nominal Voltage Level, kV	Larger Unit Sizes: Turbine Rating, MW	Larger Unit Sizes: Breaker Amperes*	Heavier Line Loadings: Breaker Amperes†
138	600	3010	2100
161	800	3450	2200
230	1000	3010	2400
345	1500	3020	2500
500	2000	2780	2800
700	2000	1980	3300

* Ratio of transformer output MVA/turbine rating MW = 1.20.
† Taking into account economic circuit load levels and distance for particular voltage considered and considering current through breaker during contingency.

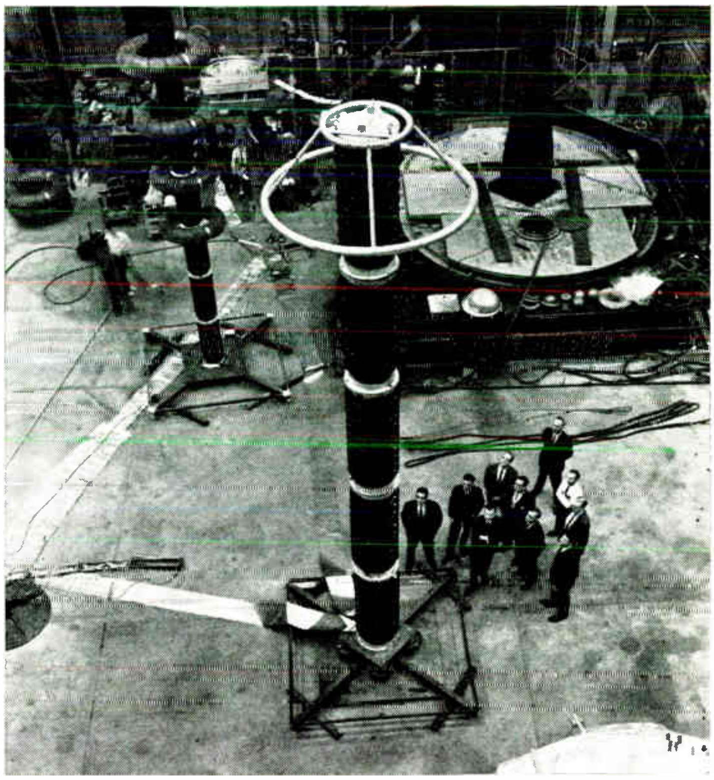
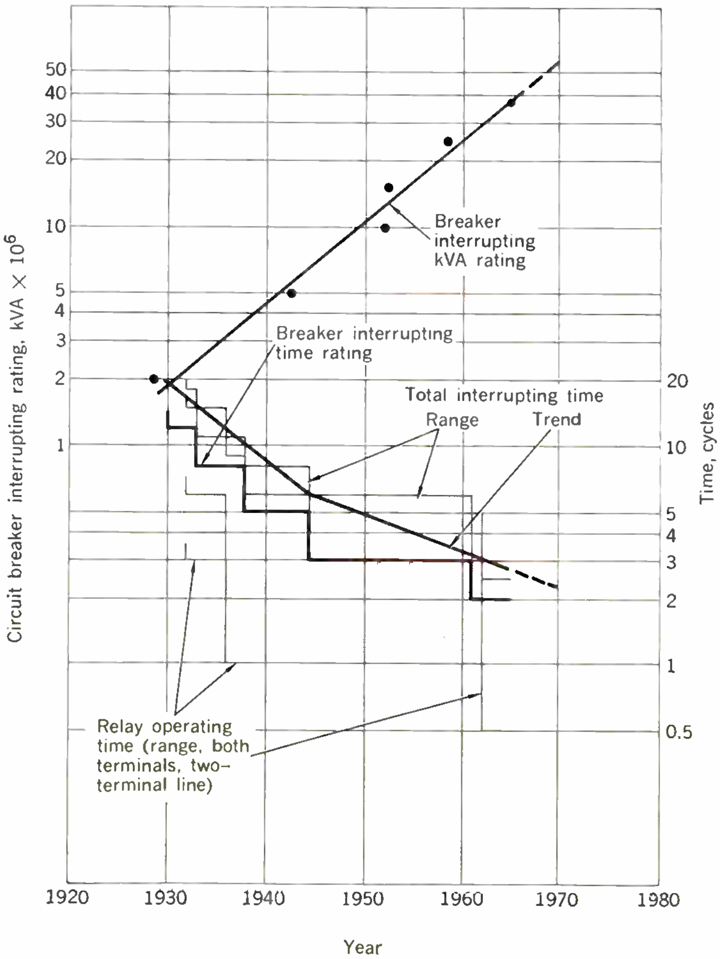


Fig. 5. View of arrester for 765-kV system in test.

Fig. 6. Power circuit breakers and relays—interrupting ratings and time.



switching of EHV transmission lines with 115-, 138-, and 230-kV breakers. Furthermore, preliminary estimates would indicate the use of this feature for reduced line insulation possibilities on future 230-kV systems.

Essential to the development of power circuit breakers and absolutely vital to EHV designs is the modern high-capacity development laboratory. Facilities such as those available at the General Electric Switchgear Laboratory in Philadelphia permit demonstration of breaker capabilities required to meet severe "in-service" conditions.

The recent compound test circuit facility addition to the Philadelphia laboratory (Fig. 7) permits equivalent full-scale testing of a 550-kV-rated maximum voltage breaker to ratings up to 73 million kVA. Duplication of recovery voltages resulting from the "short line" transmission faults, precise timing of recovery voltage with respect to the instant of circuit interruption, and control of source impedance to enable precise representation of circuit configurations under study, including response to post-arc conductivity, are outstanding benefits of the compound circuit facility.

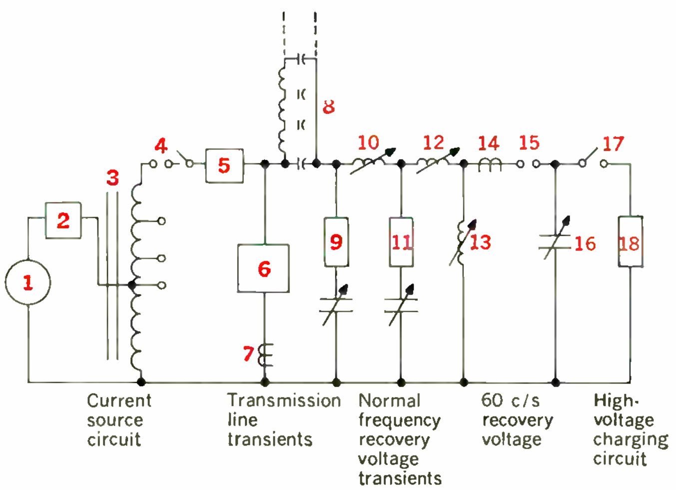
Oilless-type breaker developments have resulted in high-speed, lightweight designs that are outstandingly efficient, pushing aside technical and economic barriers to EHV apparatus and systems. Air-blast and gas-interrupting mediums have virtually displaced traditional dead-tank oil designs at the upper voltage levels. Vacuum interrupters, now proving highly successful as reclosers and breakers at the distribution voltages, show extremely high promise for higher voltage breaker ratings.

Capacitors

Series capacitors. Low capacitor costs, coupled with high costs of rights of way, longer distances, and higher system capabilities, have resulted in series capacitors becoming more competitive for increasing system stability and line loading capability. Bank sizes are increasing from the order of 35 000 kVAc (kilovars capacitive) in the initial installations at 230 kV to the average of 500 000 kVAc per bank in proposed 500-kV lines. The total rating of series capacitors under consideration points to maintaining the established trend in series capacitor usage.

The effectiveness of series capacitors in improving the stability limits of a long line as a function of fault interrupting time is illustrated in Fig. 8. Unlike the case of the uncompensated line where there is a saturation in line-

Fig. 7. Drawing showing power circuit breaker compound test circuit facilities.



1. Generators
2. Gen. breaker
3. Autotransformers
4. Sync. closing switch
5. Isolation breaker
6. Test breaker
7. Current measuring
8. Transmission line
9. Wave shaping bank
10. Tuning reactor
11. Wave shaping bank
12. Tuning reactor
13. Shunt reactor
14. Series breaker
15. Triggered gap closing switch
16. High-voltage capacitor bank
17. Isolation switch
18. Kilovolt rectifier

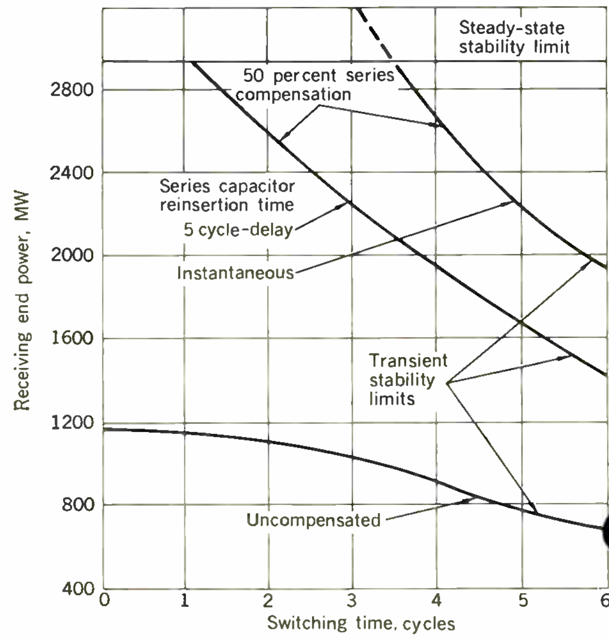
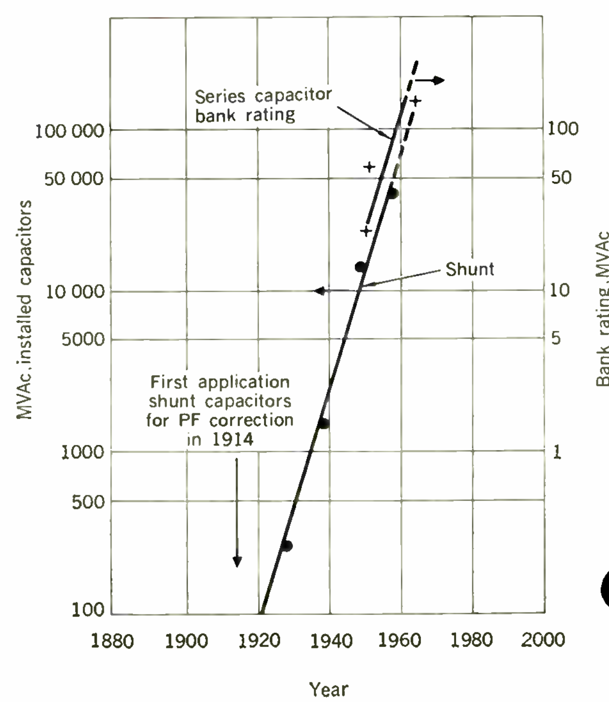


Fig. 8. Increased EHV line loadings with series capacitors.

Fig. 9. Series of shunt capacitor banks—installed capacity.



The modern hospital is one place where heavy clerical burdens, consisting of a constant exchange of information among nurses, patient service, and administrative stations, could be relieved by a computer-based information handling system. What is needed in such a system is an efficient manual information entry terminal for receiving and entering medical data. F. J. Minor and G. G. Pitman (IBM, Endicott, N.Y.) described a simulation study of computer entry devices for use by nurses in a hospital. The nurse, a focal point for information gathering and processing in the hospital routine, must receive requests from physicians, request tests, patient services, etc., and make decisions regarding patients' progress. She communicates and records these decisions through a computer teletype. Speed and accuracy measurements were made with several special teletype consoles and associated command coding schemes. One of the findings of this study was that a terminal consisting of an array of buttons, each associated with some term, instruction, etc., is more suitable for the data entry task than a typewriter terminal.

J. R. Cornog (National Bureau of Standards, Washington, D.C.) and J. C. Craig (U.S. Post Office Department, Washington, D.C.) reviewed field trials conducted by the Post Office Department with various keyboards and coding systems used for sorting mail in post offices. The quantity of mail being handled suggests that tremendous savings can be effected even by very small improvements in coding and handling techniques. Thus, one major goal of Post Office mechanization schemes is a reduction in the number of times a piece of mail is handled.

For those who worry about the usefulness of the Zip Code, Dr. Cornog gave some inside-dopester information. "It really works," she confided, "you get your mail a day earlier."

R. Rosenberg (M.I.T., Cambridge, Mass.) described a computer-based system for teaching the fundamentals of physical dynamic systems (electrical, mechanical) to college undergraduates. The system uses a special form of coding between physical elements, called Enport, which was developed by H. M. Paynter of M.I.T., and which has a format superficially like chemical bond graphs (see Fig. 1). The great advantage of Enport for computerized teaching is that the student can synthesize systems on a teletypewriter and ask questions about their behavior in a language that is isomorphic with the system differential equations.

Human control behavior

Specific mathematical models for human operators acting as control elements in closed-loop feedback control systems were discussed in a session on computer simulation and control.

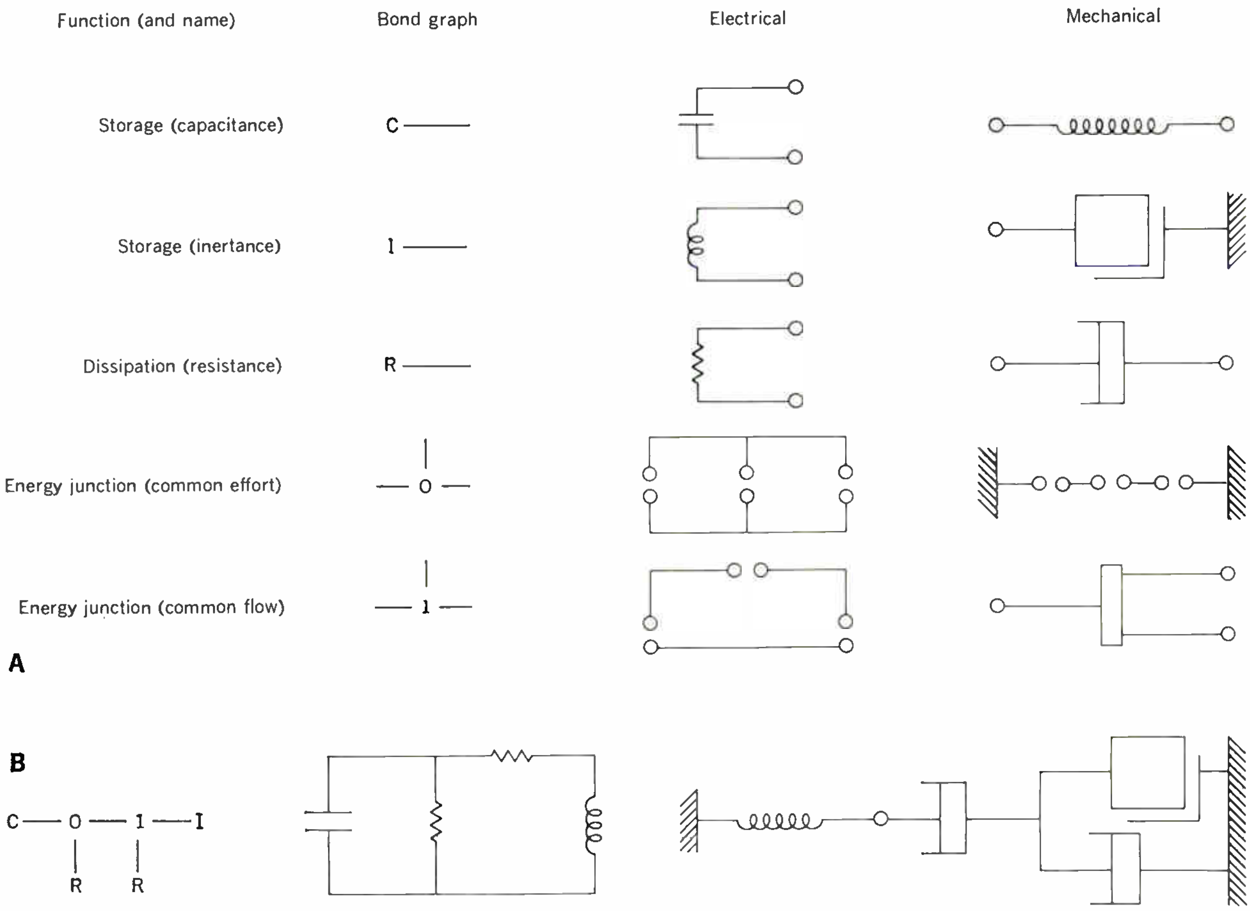


Fig. 1. Bond graphs, which can be used to describe lumped parameter systems that obey the law of conservation of energy, are composed of nodes and bonds. Nodes describe particular types of energetic behavior (such as dissipation or storage); bonds indicate an energy transfer link between two incident nodes. A—Some bond graph elements with their electrical and mechanical interpretations. B—A simple system in bond graph language.

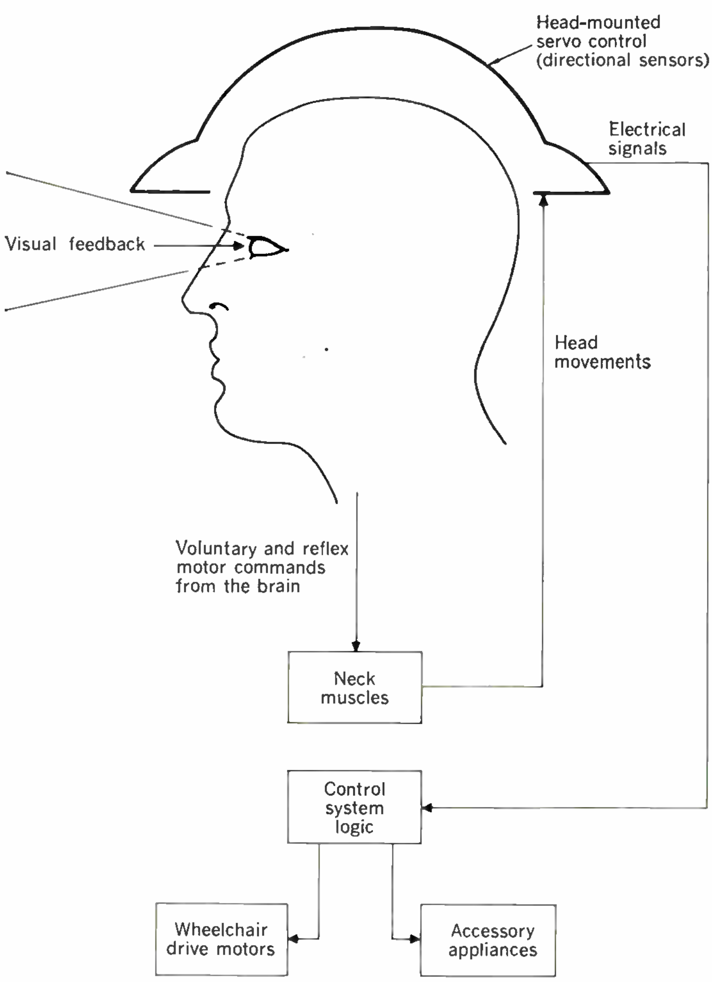
G. L. Teper and H. R. Jex (Systems Technology, Hawthorne, Calif.) described analysis methods and human response models used in the design of manual controls for a booster of the Saturn V Class. The possible roles of the pilot as a parallel element to an automatic system, as a monitor of an automatic system, and as the sole controller of the booster system were described. Teper gave quantitative criteria for "minimal" and "good" control.

In all, STI analyzed four basic pilot-booster systems based on human pilot describing functions. A separate study by NASA based on simulation studies considered three. The two studies, when compared, were strikingly similar in their conclusions, even though they had been developed wholly independently and through fundamentally different methods. In effect, the more conventional NASA methods validated the STI technique, and paved the way for greater acceptability of such analytical methods in the future. It has been estimated that analytical studies could result in very significant reductions—on the order of 40 to 60 percent—of the time and effort required for similar simulation studies.

Continuing from a previous study of the human operator as a two- and three-state relay controller of a pure inertial system, R. W. Pew (University of Michigan, Ann Arbor) characterized human response as a sequence of discrete decisions that represent switching lines in the phase plane. He showed that humans use target velocity to determine these switching lines, and that switching criteria are dependent also upon the type of display used—that is, upon the way in which target velocity is displayed.

A third paper in this session (W. W. Wierwille and Gilbert A. Gagne, Cornell Aeronautical Laboratory, Buffalo, N.Y.) presented a deterministic method for characterizing the time-varying dynamics of human operators. Their method is unlike statistical techniques, which involve finite time averages or methods using steepest descent parameter tracking. This technique gives a best estimation of the time-course of parameters for various levels of relative trade-off between time resolution and amplitude uncertainty.

Fig. 2. Closed-loop bioelectronic servo system, shown here schematically, is a rather straightforward solution to a challenging human-factors problem—namely, the development of a portable, practical, and inexpensive transducer-control system to enable a quadriplegic with normal head mobility to drive himself about in a motorized wheel chair and to operate accessory devices such as tape recorders.



Human extensions

A session on remote manipulation, sensing, and robotry dealt with a very important field of research aimed at the functional extension of man to compensate for physical impairment, to permit manipulative activity in hostile or remote environments, or even to enhance his natural capacities.

A controller worn on the head with which a paraplegic can guide a motorized wheel chair was described by Donald Selwyn (Oakland, N.J.). Applicable in various contexts, the device uses inertial sensors to detect discrete head movements and translates these into electric pulses that govern appropriate servos (see Fig. 2). The handicapped person who uses it daily has found the discrete control easy to use and very effective.

Head motions, which would normally direct the gaze of an observer, can also generate signals to direct the "gaze" of a remote television camera. If the human operator is also equipped with a TV monitor that moves with his head, a highly "compatible" remote viewing system is created, according to William Bradley (Institute for Defense Analysis, Washington D.C.). The ability to look about in a remote environment using the same movements that would be appropriate to local observation is especially suited to remote manipulation.

At very great distances, such as those arising in space exploration, the projection of a human operator's motor and sensory capabilities into the remote environment is made more difficult by the delay due to round-trip signal transmission time. William R. Ferrell (M.I.T.) reported studies of remote manipulation. With delays of 0.3 second or more, operators tend to adopt a strategy of performing as much as they can without feedback; they then pause for one delay time, following which correct positional feedback is obtained. This tactic is repeated until the task is accomplished. The method permits complex and difficult manipulation tasks to be performed without instability.

Because of very long delays or other barriers to communication, systems to extend man's functions will, in the future, rely less on the operator's controlling from within the loop and more on his supervision of an "intelligent" manipulator that can process information and make decisions itself. The process of learning to recognize features of the environment is, for animals, a cooperative enterprise of "hand" and eyes. Louis Sutro (M.I.T.) reported on efforts toward development of a system, based on animal functioning, using both visual and tactile inputs in a coordinated manner, able to become familiar with and to recognize objects.

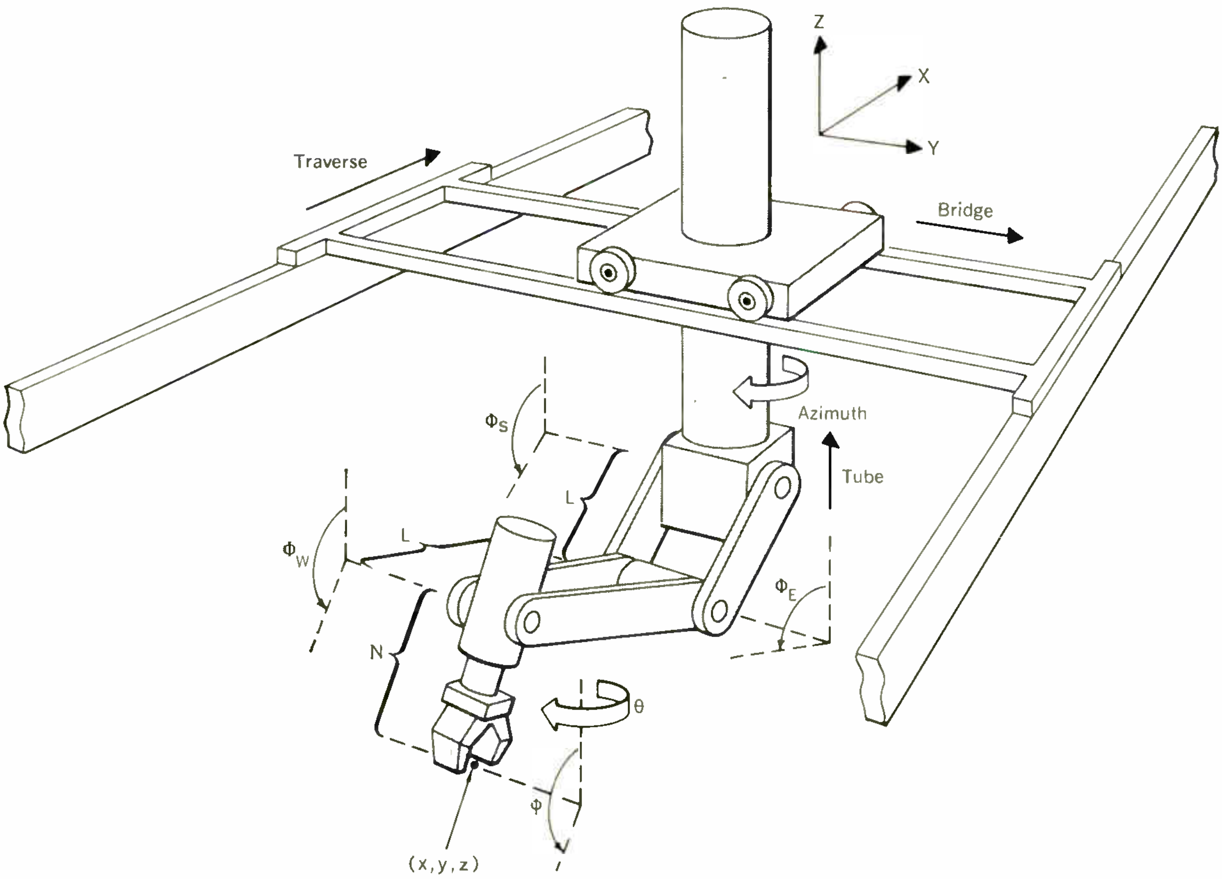
Development of an exoskeletal brace that can be programmed to provide a variety of useful motions for a paraplegic has led investigators at the Case Institute Design Center to look extensively into the question of computer-aided manipulators. The philosophy underlying this research is that an operator need only specify the destination or desired position for the hand of the manipulator, and the control computer will generate the required motions to reach that destination. However, the problems involved in generating such movements are not as simple as might first appear, as an examination of the movement possibilities of the remote manipulator suggests (see Fig. 3). Development of criteria and programs to decide how kinematically indeterminate arm structures should be moved to obtain point-to-point hand movements was discussed by Peter Hammond. He reported on a path optimization scheme, jointly developed with Harold W. Mergler, which minimizes the instantaneous momentum in the arm.

Amplification of man's functional capacity through manipulators will require feedback loops involving the terminal devices but not directly including the operator, according to Edwin G. Johnson (AEC/NASA Space Nuclear Propulsion Office). Such localized loops, which can range from simple protective devices to recognition and decision-making systems, will free the operator from routine information processing and can potentially give him a more effective role in monitoring system behavior.

Man–computer operations

A session on joint man–computer operations for on-line management and command planning consisted of four papers. The first, by J. C. Emery (M.I.T.), presented a theoretical and analytic model of organizational planning developed from the viewpoint of information processing within management structure. Three papers, presented by E. L. Lafferty and E. M. Bennett (The MITRE Corporation, Bedford, Mass.), dealt with case studies of three joint man–computer systems currently operational at varying levels of completeness. These systems are meant to facilitate management and command planning. The first of these described the current U.S. Air Force Headquarters Operations Planning System; the second reported on an on-line data manage-

Fig. 3. Remote manipulator can be pivoted about the axis of the tube, and has pivots with horizontal axes at the shoulder, elbow, and wrist. Thus, the manipulator has seven degrees of freedom, while the position of the "hand" can be described by five coordinates (x, y, z, azimuth, and elevation).



ment system currently in use by the U.S. Strike Command; and the third reported on a prototype display-oriented on-line planning system currently operating in the MITRE Corporation's Systems Design Laboratory. All three studies described the capabilities of the various systems and showed photographic records of the man-computer interface that characterized each.

Design of computer consoles

Console design problems both in the U.S. and abroad were discussed in the session on computer operator and maintenance consoles. D. H. Keene (Electronics Associates, Princeton, N.J.) described the problems of grouping controls and indicators on the Electronics Associates 8800 computer. J. C. Jones (Manchester College of Science and Technology, Manchester, England) discussed the systematic design of the computer-operator interface on the British AEI-1010 computer, emphasizing the use of matrix graphical aids for recording and referring to functional interactions in the process of design. W. H. Brandenberg (United Air Lines, Chicago, Ill.) pointed out the excessive emphasis on processors and memory systems as compared with input-output devices, implying that there are great gains to be made by small improvements in the latter. R. S. Hirsh (IBM, Los Gatos, Calif.) gave specific examples of this in terms of various keyset configurations for computer systems.

Man-computer communication

One of the most popular sessions was on the use of engineering languages for on-line man-computer communication. The topic was discussed by a panel of experts, including J. C. R. Licklider and F. D. Skinner (IBM, Yorktown Heights, N.Y.), D. B. Yntema and J. Weizenbaum (M.I.T.), C. Weissman (Systems Development Corporation, Santa Monica, Calif.), G. Shaw (Rand Corporation, Santa Monica, Calif.), and B. F. Green, Jr. (Carnegie Institute of Technology, Pittsburgh, Pa.). There were live demonstrations on computer consoles tied in with the M.I.T. Project MAC (Machine Aided Cognition or Multiple Access Computer), BBN's time-shared computer, the Dartmouth College-General Electric time-sharing system (the computer being located at Phoenix), and Systems Development Corporation's computer in Santa Monica. A banquet speech by Project MAC's director, Robert Fano, complemented this session by pointing to the promise of the time-shared computer in teaching and research applications.

Information-processing models

Models for monitoring and information processing in man was the theme of the final session. Three papers dealt with the sampling of information from many external sources—characteristic of human behavior in real life but neither well investigated in the laboratory nor included in the descriptions we have for man based upon laboratory research. L. T. Gregg (General Dynamics/Astronautics, San Diego, Calif.) hypothesized that man scans visually (and periodically) over a number of display functions until an out-of-limit indication is reached. The "Logical Model for Logical Man" then acts to correct the out-of-limit condition. The behavior of the model can be specified by a set of Boolean functions. Predictions by the model compared very well with laboratory data gathered from human subjects who monitored many meters.

J. D. Gould and Amy Shaffer (IBM, Yorktown Heights, N.Y.) pursued a similar line and produced results that showed how the number of correct responses in a multichannel error detection experiment declined as the number of channels increased and as the available observation time per display decreased. A third closely related paper, but in an auditory instead of visual context, was presented by H. M. Kaufman, R. M. Glorioso, T. L. Booth, and R. M. Levy (University of Connecticut). They carried out experiments in which they varied signal-to-noise ratios (S/N) and clipping thresholds (T). Results indicated that human operators can maintain a consistently high detection performance level over the range of S/N and T studied; the number of trials to reach a decision followed the theoretical optimum predicted by analytical studies.

Human factors and the automobile

The following two papers, in a somewhat different context, developed mathematical models to describe how the human operator (of an automobile, aircraft, etc.) uses information that can be previewed before a response to it is appropriate.

T. B. Sheridan (M.I.T.) showed how the ability to preview the input course, along with the high-speed computation of an optimal trajectory, can effect great savings of effort and error over what is possible with a conventional servomechanism. Empirical results corroborated the model's predictions.

J. W. Senders (Bolt Beranek and Newman, Cambridge, Mass.) presented a model—and the results of some corroboratory experiments—for the information processing behavior of an automobile driver. The driver in the experiments was permitted only brief periodic views of the road ahead. The model assumes a fading memory for the information available during the view and an input uncertainty rate in terms of bits per unit length of roadway. The predictions of the model and the data from the first experiment are in good agreement.

In the closing hour of the Boston meeting,* John Senders, Chairman of the Symposium Committee, in an artfully droll yet serious disquisition, pressed home the point that a great deal of human-factors research is needed in relation to the automobile, in view of the massive death rate from its use. It is a field virtually untouched, yet (from accident statistics alone) demonstrably one that should awaken the gravest concern among human-factors engineers. Both the automotive and information revolutions are having a profound effect on individuals and society. The impact of the automobile is not only metaphorical. While information processors may do away with jobs, automobiles often bring even greater griefs.

The fact that two final papers at this meeting dealt with questions relating to the use of automobiles may presage more urgent action among human-factors engineers and psychologists. Perhaps an entire human-factors symposium should soon be devoted to the automobile, and to the technical and social problems that it has forced upon us.

* I had nothing to do with the writing from this point on. JWS.

Special Conference Report

Power Industry Computer Application Conference

J. H. Blanchard *Florida Power Corporation*

"The need to get the maximum use from existing computer systems" was stressed at the opening session of the three-day Fourth Power Industry Computer Application Conference at the Jack Tar Harrison Hotel in Clearwater, Fla.

L. John Rankine, manager of public utilities for the International Business Machines Corporation, made the comment, and said its realization would depend on management getting the best out of the new computer systems. He also urged the elimination of the "barriers that exist between your company's various functions," and an inspection of "the engineering and construction sides of your operation to see if they can use the systems already serving your commercial departments."

Rankine stressed that the "hardware" present in utilities firms has much greater capability and putting this capability to use is "one of your challenges." According to Rankine, most of the digital computer systems installed in power companies have been, essentially, a mechanization of clerical-type drudgery, to perform accounting, billing, payroll, and other similar functions. He also felt that the utilities industry has made almost as much use of digital systems as the aerospace industry has. Computers are now being wired into power plant systems to monitor the system, measure its operation, and advise the operators on actions they should take.

Rankine said that the present major technological breakthrough is the ability to make use of large mass data storage centers from outlying terminals. This can enable the power industry to give service never available before.

He concluded by observing that every new touch-tone telephone, which is "dialed" by pushing buttons, is a potential terminal device which can be connected to data storage systems to get information in an instant.

The luncheon speaker, Dr. Louis T. Rader, Vice President and General Manager for the Industrial Electronics Division of the General Electric Company, discussed "Stepping Stones and Stumbling Blocks on the Road of Automation." Rader observed that the market for computers and peripheral hardware in the United States already equals the market for all generation, transmission, and distribution equipment purchased by U.S. industry in 1964. And by 1970, the *overseas* market will be as large as the domestic market is now, while the U.S. market will have grown by half again. Therefore, the question is not whether or not we will have computers, but rather: how can we make the best and most intelligent use of them?

Dr. Rader also said that: "In the electric utility business, as in most manufacturing industries, the accounting function was the first to be automated, because its logic has been solidly worked out and is quite universally understood by all its practitioners.

"However, the step from here to the application of a process computer to the complexities of power plant control and system operation is a giant one, and while it must be made, it is not made without a good deal of faith and vision. It is to the great credit of the industry that you have begun to take this step with the resolution of which these meetings are symbolic."

Dr. Rader noted the stumbling blocks by saying: "One to beware is . . . *computer myopia*. The utility executive who is automating, as well as the company selling automation equipment, must be able to think far beyond the installation of a computer. Expressed in automation machinery, today's automation encompasses data-processing equipment of several kinds, including computers, as well as instruments, controls, sensing devices, and several kinds of communications equipment—both microwave and carrier current—not to mention the actual generation, transmission, and distribution equipment itself. The computer is often profitable only to the extent it is applied knowledgeably to the management of the system, and this requires the integration of many kinds of equipment and many kinds of application, knowledge, and experience. It is a team effort."

Rader believes that another stumbling block may be "the product of some human problems," and at the core of these, the executive managers who must be sold on computer proposals.

Fifty-five technical papers were selected for presentation at separate simultaneous sessions on the general topics of Network Analysis, Power Plant Control and Performance Computers, and Statistical and Forecasting Techniques.

This fourth biennial meeting of PICA witnessed a substantial increase in the number and scope of technical papers. More than twice as many papers were presented

I. Conference papers from abroad

Subjects	Authors and Affiliations	Country of Origin
Short-circuit analysis for large systems	M. A. Laughton, M. W. Humphrey Davies, Queen Mary College	United Kingdom
New method of calculating simultaneous faults by means of digital computer	Jun-Ichi Baba, Shigeo Hayashi, and Tetsuya Kishi, Mitsubishi Electric Corp.	Japan
On the resolution of equations arising in load-flow problems	J. P. Aubin, P. A. Raviart, Électricité de France	France
Theory of convergence of digital load-flow solutions by Ward and Hale method	T. A. T. Norimatsu, Hitachi Wire and Cable, Ltd.	Japan
Digital load-flow studies of the overcompensated system with series capacitors	J. Nagamura, H. Sato, Electrotechnical Laboratory	Japan
Optimization of the overrelaxation factor in the digital study of short-circuit current or load flow	H. Sato, Electrotechnical Laboratory	Japan
An improved method for the calculation of transients on transmission lines using a digital computer	R. Murray-Shelley, University of Wales	United Kingdom
French power system control	N. Steinberg, J. Siroux, Électricité de France	France
An application of the maximum principle to the most economical operation of power systems	I. Hano, Y. Tamura, and S. Narita, Waseda University	Japan
Computational aspects of adaptive reservoirs control process	T. Fukao, Electrotechnical Laboratory	Japan
Determining the operation and equipment of electric power distribution on networks	P. Gaussens, D. Calvet, Électricité de France	France
The long-term design of electrical power distribution systems	J. V. Oldfield, T. Lang, University of Edinburgh	United Kingdom
Computer uses in the Central Electricity Generating Board	A. G. Oughton, Central Electricity Generating Board	United Kingdom

on the program than were included during the 1963 meeting, and this represented a continuing proof of the rapidly mounting interest and technological advancement in the application of computers to power system problems.

Glenn W. Stagg, the program chairman, summed it up well by saying that "the principal aim of the 1965 PICA Conference is to focus attention on the present state of the application of computers to power system planning, design, and operation."

An unusual feature of the conference was the presentation of $50 cash awards for the best-written conference paper and for the best presentation of a paper.

The award for the best-written paper was presented to Dr. Richard Baumann, Munich (Germany) Institute of Technology, for his paper, "Some New Aspects on Load Flow Calculation. Part I—Impedance Matrix Generation Controlled by Network Topology."

Baumann's paper observed that while there are many satisfactory solutions, such as the matrix approach and the nodal iterative approach—all well-adapted to the load flow problem in a high-voltage power transmission system—there are several questions still to be answered. For instance, the amount of numerical work in establishing the driving point and transfer ratio impedance matrix of a given system from the branch impedances—as well as from the node admittance matrix—depends upon how the steps of the algorithm uses are ordered. Thus, for a building algorithm and for an elimination procedure, it is really a problem to find the optimal ordering in accordance with the topological properties of the system.

Baumann believes that the impedance matrix of a given system will possibly be generated much more quickly by topology-controlled elimination applied to the node admittance matrix than by a building algorithm that uses the branch impedances immediately.

A. Doyle Baker, of the Kentucky Utilities Company, Lexington, took the award for the best presentation with his paper, "Breaking the 'All-Digital' Barrier in System Operations Computers."

Baker contended that "no prophet is required to note the inexorable advance in programming techniques and computer hardware, and to project forward to a time in the immediate future when virtually all new generation control computers will be incorporated into a comprehensive, all-digital operations computer system. These will encompass control, economic, analytical, and appropriate accounting functions." Baker went on to describe in detail the all-digital system that was designed and installed "amid dour predictions" at Kentucky Utilities. The system has been in successful operation for nine months.

Highlights of the three-day conference included inspection tours of the Tampa Electric Company's System Operation and Dispatching Center and the Florida Power Corporation's Digital Computer Controlled Dispatching Center in St. Petersburg.

The PICA Conference was attended by more than 420 engineers from the United States and 12 foreign countries, and a number of interesting papers were presented by the overseas representatives. These papers are listed by subjects, authors, and country of origin in Table I.

Information for IEEE authors

An author should familiarize himself with the following information before he prepares and submits a manuscript to any of the more than 30 journals published by the IEEE. Review and editorial processing of a manuscript are facilitated if it is in the proper form.

These instructions are for the guidance of authors preparing papers to be considered for publication in the following:

1. IEEE SPECTRUM, a monthly technical magazine received by all IEEE members, except students, which contains technical articles on the wide variety of subjects of interest and importance to its diverse readership. Included are tutorial articles and articles reviewing the state of the art in specific fields.

2. The PROCEEDINGS OF THE IEEE, a monthly research-oriented journal containing fundamental papers of broad significance and long-range importance to electrical science and technology. In addition to contributions describing original work, the PROCEEDINGS publishes papers which are high-level reviews of specific areas of current interest.

3. The various IEEE TRANSACTIONS, published by each of the IEEE Groups at frequencies ranging from two to 12 times a year. Each of the TRANSACTIONS is devoted principally to specialized papers relevant to the field of interest of the sponsoring group.

4. The IEEE STUDENT JOURNAL, a publication for all undergraduate IEEE Student members, which contains technical and nontechnical material intended to assist them with their career decisions.

Anyone may submit a paper for consideration for an IEEE publication; membership in the IEEE is not a requirement. A manuscript should be submitted exclusively to a single IEEE journal, should not have been published before, and should not be under consideration for publication elsewhere.

These instructions have been divided into two sections: "General Information" and "Information for Specific Publications."

General Information

Preparation of text

Manuscripts should be typewritten, using *double* spacing,* on one side of the sheet. Allow ample margins of at least one inch or 2.5 cm on each side. Number all pages, illustrations, footnotes, and tables. All illustrations should be referred to in the text.

Units

Metric units are preferred for use in IEEE publications in light of the non-national character of the IEEE, the international readership of its journals, and the inherent convenience of these units in many fields. In particular, the use of the International System of Units (Système Internationale d'Unités, or SI Units) is advocated. This system includes as a subsystem the MKSA units, which are based on the meter, kilogram, second, and ampere.

If an author expresses quantities in English units, he is urged to give the metric equivalents in parentheses, for example, a distance of 4.7 inches (11.9 cm); however, this practice may be impractical for certain industrial specifications, such as those giving drill sizes or horsepower ratings of motors.

Symbols and abbreviations

The use of unit symbols and other abbreviations is optional. They should be employed only when desirable for brevity.

The IEEE "Standard Symbols for Units" (IEEE No. 260) should be followed; details are given in the Appendix. Avoid other abbreviations except those that are generally accepted or are listed in Table II of the Appendix. Abbreviations and symbols used on illustrations should conform to those used in the text.

*Manuscripts to be submitted to the TRANSACTIONS of the Power Group and the Applications and Industry Group should be typewritten using single spacing for possible photoreproduction.

Mathematical notation

To prevent errors by the printer, subscripts, superscripts, Greek letters, and other symbols should be clearly identified (by means of a note in the margin, if necessary). In particular, a clear distinction should be made between the following:

1. Capital and lower-case letters, when used as symbols.
2. Zero and the letter "o."
3. The small letter "el," the numeral one, and a prime sign.
4. The letters "k" and kappa, "u" and mu, "v" and nu, "n" and eta.

Care should be observed in using the solidus (slant), radical sign, and parentheses and brackets to avoid ambiguities in equations.

To facilitate the reading of numbers and to eliminate confusion from differing uses of the comma and period in various parts of the world, IEEE editorial practice is to separate the digits by a space into groups of three, counting from the decimal sign toward the left or right. In numbers with four digits, the space is not necessary. If the magnitude of a number is less than unity, the decimal sign should be preceded by a zero. Examples are: 12 531 7465 9.2163 0.102 834

References

References should usually be footnotes at the bottom of the pages on which they are cited, but extended bibliographies may be placed at the end of the paper. References should be complete and in the form below.

For a periodical: J. A. Rich and G. A. Farrall, "Vacuum arc recovery phenomena," *Proc. IEEE*, vol. 52, pp. 1293-1301, November 1964.

For a book: J. D. Kraus, *Antennas*. New York: McGraw-Hill, 1950, pp. 100–108.

References should be to commonly available publications and books; references to reports of limited circulation should be avoided.

Illustrations

Finished drawings in black ink on white paper or tracing cloth, or photographic prints of original drawings, should be provided for all journals, with the exception of SPECTRUM. Photographs should be glossy prints not exceeding 8½ by 11 inches (21.6 by 27.9 cm). Most illustrations are reduced in size to a 3½-inch (8.9-cm) column width when printed, so it is important that all letters, numbers, and lines be so drawn as to remain legible after reduction. Letters and numbers should be at least 1/16 inch (1.6 mm) high *after* reduction to be readable.

All information to be reproduced on illustrations should be lettered in ink, not typewritten. Graphs should be drawn with only the major coordinate lines showing, since a chart containing a large number of closely spaced lines will not reproduce legibly. Short "ticks," extending a short distance from the axes, may be provided for convenience in reading intermediate values.

Captions

All captions, with figure numbers, should be listed on a separate sheet. The captions should be self-explanatory, not merely labels. If also included on the drawing itself, a caption should not appear within the area to be reproduced.

Organization

IEEE papers usually consist of five parts: title, abstract, introduction, body, and conclusions. Two additional divisions, a glossary of symbols and an appendix, are sometimes desirable. SPECTRUM and the STUDENT JOURNAL papers may be less formally organized than those for the PROCEEDINGS and the TRANSACTIONS.

The *title* should clearly indicate the subject of the paper as briefly as possible. Since a paper is indexed by significant words in the title, and many readers select papers to read on the basis of the title, it should be chosen with considerable care.

An informative *abstract* of less than 200 words is needed for all PROCEEDINGS and TRANSACTIONS papers. It should state concisely, but not telegraphically:

1. What the author has done.
2. How it was done (if that is important).
3. The principal results (numerically, when possible).
4. The significance of the results.

The abstract should be informative, *not* merely a list of general topics that the paper covers, because it will probably appear later in an abstract journal.

The text of a paper can sometimes be simplified by following the abstract with a *glossary of symbols* if the paper contains equations in which many symbols are used.

The *introduction* orients the reader with respect to the problem and should include the following:

1. The nature of the problem.
2. The background of previous work.
3. The purpose and significance of the paper.

Where applicable, the following points may also be included:

4. The method by which the problem will be attacked.
5. The organization of the material in the paper.

The *body* contains the primary message of the paper in detail. The writer should bear in mind that his object is to communicate information efficiently and effectively to the reader. Even workers in the same field appreciate clear indications of the line of thought being followed, and frequent guideposts are essential for nonspecialists who want to understand the general nature and significance of the work. The use of trade names, company names, and proprietary terms should be avoided.

The *conclusions* should be clearly stated, and should cover the following:

1. What is shown by this work and its significance.
2. Limitations and advantages.

Where applicable, the following points should also be included:

3. Applications of the results.
4. Recommendations for further work.

Mathematical details which are ancillary to the main discussion of the paper, such as many derivations and proofs, may be included in one or more *appendixes*.

Information for Specific Publications

IEEE SPECTRUM

A SPECTRUM article should be written with a very general audience in mind, as the magazine's circulation is more than 100 000. The subject should have broad significance and appeal, and should be presented so that it is understandable to the "average" engineer. SPECTRUM articles are often revised by the IEEE editorial staff to enhance their readability; alterations appear on the galley proofs that authors receive prior to publication.

Because all drawings are redone, final inked drawings are not necessary; legible sketches will suffice. Biographies and photographs of authors are required for publication.

Three copies of manuscripts intended for SPECTRUM should be sent, with an identifying letter, to IEEE SPECTRUM, 345 East 47th Street, New York, N.Y. 10017. Because many articles are written for SPECTRUM in response to invitation, it is recommended that prospective authors inquire in advance concerning their proposed subject.

PROCEEDINGS OF THE IEEE

Papers for this journal should be of significance and interest to a broad cross section of research-oriented engineers. A rough guide is that a PROCEEDINGS paper should be important to specialists in two or more Groups. It should be written so as to be intelligible to workers not engaged in the immediate field of the paper.

The PROCEEDINGS also publishes letters announcing new research results, for which fast publication is desirable. Length is limited to approximately four double-spaced typewritten pages, with each illustration counted as a half page. To avoid delay, the author should indicate that his letter is intended for the PROCEEDINGS; he should provide illustrations suitable for reproduction; and he should follow the instructions accompanying the proof he will receive if his letter is accepted.

Three copies of manuscripts intended for consideration for the PROCEEDINGS should be sent, with an identifying letter, to PROCEEDINGS OF THE IEEE, 345 East 47th Street, New York, N.Y. 10017. Biographies and photographs of authors of papers, but not of letters, are required for publication.

IEEE TRANSACTIONS

A paper or letter for one of the TRANSACTIONS should be submitted to the Editor listed on the inside front or back cover of the TRANSACTIONS, or in the April and October issues of SPECTRUM. If there is uncertainty as to whom to address the copies of a manuscript, they should be sent to the IEEE Managing Editor for forwarding to the appropriate TRANSACTIONS Editor. Most TRANSACTIONS require three copies of the manuscript and author photographs and biographies.

IEEE STUDENT JOURNAL

An article for the STUDENT JOURNAL should be of interest and importance to undergraduate students of electrical engineering and technology, and it should be written so that it is comprehensible, useful, and appealing to them. It is advisable for a prospective author to write to the SJ Editor for comments and suggestions prior to preparing an article.

Three copies of manuscripts intended for the STUDENT JOURNAL should be addressed to IEEE STUDENT JOURNAL, 345 East 47th Street, New York, N.Y. 10017. Biographies of authors are required for publication.

Appendix

Unit symbols

The IEEE Standard entitled "Standard Symbols for Units" (IEEE Standard No. 260, dated January 15, 1965) lists symbols that may be used in place of the names of units. Symbols from this Standard for some important units, together with other common abbreviations, are given in Table II. Their form is the same for both singular and plural usage, and they are not followed by a period. The distinction between upper-case and lower-case letters should be carefully observed.

When a compound unit is formed by the multiplication of two or more units, its symbol consists of the symbols for the separate units joined by a raised dot, e.g., $N \cdot m$ for newton meter. When a compound unit is formed by division of one unit by another, its symbol consists of the symbols for the separate symbols either separated by a solidus (slant) or multiplied using negative powers, e.g., m/s or $m \cdot s^{-1}$ for meter per second.

Prefixes

Prefixes indicating decimal multiples or submultiples of units and their symbols are given in Table I. Compound prefixes, such as "micromicro" for "pico" and "kilomega" for "giga," are discouraged.

Abbreviations

In general, most abbreviations of technical terms are capitalized, but there are notable exceptions such as ac, dc, and rms. In addition to the unit symbols, Table II lists many common technical abbreviations in their standard IEEE editorial forms. Note that periods are not used, and that the abbreviation is the same regardless of whether it is used as a noun or an adjective. A symbol which is new or not generally accepted should be defined when first used.

I. Recommended prefixes

Multiple	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

II. Recommended abbreviations

Unit or Term	Symbol or Abbreviation
alternating current	ac
American wire gauge	AWG
ampere	A
ampere-hour	Ah
ampere-turn	At
amplitude modulation	AM
angstrom	Å
antilogarithm	antilog
atomic mass unit (unified)	u
audio frequency	AF
automatic frequency control	AFC
automatic gain control	AGC
automatic volume control	AVC
average	avg
backward-wave oscillator	BWO
bar	bar
barn	b
beat-frequency oscillator	BFO
bel	B
billion electronvolts*	BeV
binary coded decimal	BCD
British thermal unit	Btu
calorie	cal
candela	cd
candela per square foot	cd/ft^2
candela per square meter	cd/m^2
cathode-ray oscilloscope	CRO
cathode-ray tube	CRT
centimeter	cm
centimeter-gram-second	CGS
circular mil	cmil
continuous wave	CW
coulomb	C
cubic centimeter	cm^3
cubic foot per minute	ft^3/min
cubic meter	m^3
cubic meter per second	m^3/s
curie	Ci
cycle per second	c/s
decibel	dB
decibel referred to one milliwatt	dBm
degree Celsius	°C
degree Fahrenheit	°F
degree Kelvin	°K
degree (plane angle)	...°
degree Rankine	°R
degree (temperature interval or difference)	deg
diameter	diam
direct current	dc
double sideband	DSB
dyne	dyn
electrocardiograph	EKG
electroencephalograph	EEG
electromagnetic compatibility	EMC
electromagnetic unit	EMU
electromotive force	EMF
electronic data processing	EDP
electronvolt	eV
electrostatic unit	ESU
erg	erg
extra-high voltage	EHV
extremely high frequency	EHF
extremely low frequency	ELF
farad	F
field-effect transistor	FET
foot	ft

Unit or Term	Symbol or Abbreviation
footcandle	fc
footlambert	fL
foot per minute	ft/min
foot per second	ft/s
foot poundal	ft·pdl
foot pound-force	ft·lbf
frequency modulation	FM
frequency-shift keying	FSK
gallon	gal
gallon per minute	gal/min
gauss	G
gigacycle per second	Gc/s
gigaelectronvolt	GeV
gigahertz	GHz
gilbert	Gb
gram	g
henry	H
hertz	Hz
high frequency	HF
high voltage	HV
horsepower	hp
hour	h
inch	in
inch per second	in/s
inductance-capacitance	LC
infrared	IR
inside diameter	ID
intermediate frequency	IF
joule	J
joule per degree	J/deg
joule per degree Kelvin	J/°K
kilocycle per second	kc/s
kiloelectronvolt	keV
kilogauss	kG
kilogram	kg
kilogram-force	kgf
kilohertz	kHz
kilohm	kΩ
kilojoule	kJ
kilometer	km
kilometer per hour	km/h
kilovar	kvar
kilovolt	kV
kilovoltampere	kVA
kilowatt	kW
kilowatthour	kWh
lambert	L
liter	l
liter per second	l/s
logarithm	log
logarithm, natural	ln
low frequency	LF
lumen	lm
lumen per square foot	lm/ft^2
lumen per square meter	lm/m^2
lumen per watt	lm/W
lumen second	lm·s
lux	lx
magnetohydrodynamics	MHD
magnetomotive force	MMF
maxwell	Mx
medium frequency	MF
megacycle per second	Mc/s
megaelectronvolt	MeV
megahertz	MHz
megavolt	MV

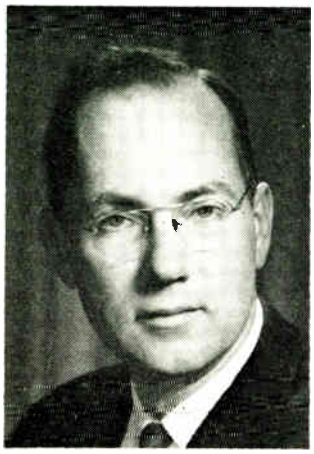
Unit or Term	Symbol or Abbreviation
megawatt	MW
megohm	MΩ
metal-oxide semiconductor	MOS
meter	m
meter-kilogram-second	MKS
mho	mho
microampere	μA
microfarad	μF
microgram	μg
microhenry	μH
micrometer	μm
micromho	μmho
micron†	μ
microsecond	μs
microsiemens	μS
microwatt	μW
mil	mil
mile per hour	mi/h
mile (statute)	mi
milliampere	mA
milligram	mg
millihenry	mH
milliliter	ml
millimeter	mm
millimeter of mercury, conventional	mmHg
millimicron‡	
millisecond	ms
millisiemens	mS
millivolt	mV
milliwatt	mW
minute (plane angle)	...′
minute (time)	min
nanoampere	nA
nanofarad	nF
nanometer	nm
nanosecond	ns
nanowatt	nW
nautical mile	nmi
neper	Np
newton	N
newton meter	N·m
newton per square meter	N/m^2
oersted	Oe
ohm	Ω
ounce (avoirdupois)	oz
outside diameter	OD
phase modulation	PM
picoampere	pA
picofarad	pF
picosecond	ps
picowatt	pW
pound	lb
poundal	pdl
pound-force	lbf
pound-force foot	lbf·ft
pound-force per square inch	lbf/in^2
pound per square inch§	psi
power factor	PF
private branch exchange	PBX
pulse-amplitude modulation	PAM
pulse-code modulation	PCM
pulse-count modulation	PCM
pulse-duration modulation	PDM
pulse-position modulation	PPM
pulse-repetition frequency	PRF

Unit or Term	Symbol or Abbreviation
pulse-repetition rate	PRR
pulse-time modulation	PTM
pulse-width modulation	PWM
radian	rad
radio frequency	RF
radio-frequency interference	RFI
resistance-capacitance	RC
resistance-inductance-capacitance	RLC
revolution per minute	r/min
revolution per second	r/s
roentgen	R
root-mean-square	rms
second (plane angle)	...″
second (time)	s
short wave	SW
siemens	S
signal-to-noise ratio	SNR
silicon controlled rectifier	SCR
single sideband	SSB
square foot	ft^2
square inch	in^2
square meter	m^2
square yard	yd^2
standing-wave ratio	SWR
steradian	sr
superhigh frequency	SHF
television	TV
television interference	TVI
tesla	T
thin-film transistor	TFT
transverse electric	TE
transverse electromagnetic	TEM
transverse magnetic	TM
traveling-wave tube	TWT
ultrahigh frequency	UHF
ultraviolet	UV
vacuum-tube voltmeter	VTVM
var	var
variable-frequency oscillator	VFO
very-high frequency	VHF
very-low frequency	VLF
vestigial sideband	VSB
volt	V
voltage controlled oscillator	VCO
voltage standing-wave ratio	VSWR
voltampere	VA
volume unit	vu
watt	W
watthour	Wh
watt per steradian	W/sr
watt per steradian square meter	$W/(sr \cdot m^2)$
weber	Wb
yard	yd

* Deprecated; use gigaelectronvolt (GeV).
† The name micrometer (μm) is preferred.
‡ The name nanometer is preferred.
§ Although the use of the abbreviation psi is common, it is not recommended. See pound-force per square inch.

Reprints of these instructions are available on request from the Editorial Department, Institute of Electrical and Electronics Engineers, Inc., 345 East 47th Street, New York, N.Y. 10017.

Authors



Charles H. Townes (F), provost of the Massachusetts Institute of Technology, was awarded the Nobel Prize in 1964 for his role in the invention of the maser and laser. He is also internationally known for his research in the field of microwave physics.

He received the B.A. and B.S. degrees from Furman University in 1935, the M.A. degree from Duke University in 1937, and the Ph.D. degree from the California Institute of Technology in 1939. A member of the staff of Bell Telephone Laboratories from 1939 to 1947, Dr. Townes worked extensively during World War II in the design of radar bombing systems. From this he turned to microwave spectroscopy, which he foresaw as a new analytical tool for the study of atoms and molecules and a potential technique for controlling electromagnetic waves. At Columbia University, where he was appointed to the faculty in 1948, he continued research in microwave physics. In 1951 he conceived the idea for the maser. He was executive director of the Columbia Radiation Laboratory from 1950 to 1952 and chairman of the Physics Department from 1952 to 1955. He was a Guggenheim Fellow and Fulbright Lecturer during 1955 and 1956. Before receiving his present appointment at M.I.T. in 1961, he served as vice president and director of research of the Institute for Defense Analyses.

H. G. Booker (F) received the B.A. degree in 1933 and the Ph.D. in 1936 from Cambridge University, England. He joined the faculty of Christ's College, Cambridge, where he conducted research in radio wave propagation and taught applied mathematics and theoretical physics. In 1937 he was a visiting scientist at the Department of Terrestrial Magnetism, Carnegie Institute of Washington. During World War II he was in charge of theoretical research at the radar research establishment of the RAF. After the war he returned to Cambridge. In 1948 he became a professor of electrical engineering and engineering physics at Cornell University, where he built up research in propagation of electromagnetic waves in the earth's atmosphere. From 1959 to 1963 he was director of the School of Electrical Engineering and associate director of the Cornell Center for Radiophysics and Space Research. He then became IBM Professor of Engineering and Applied Mathematics. He joined the University of California, San Diego, in July 1965.

C. G. Little (M) received the B.Sc. in physics in 1948 and the Ph.D. in radio astronomy in 1952, both from the University of Manchester, England. From 1950 to 1952 he served as an assistant lecturer in physics at the University of Manchester while conducting research on radio star scintillations. In 1954 he joined the Geophysical Institute of the University of Alaska, where he served as deputy director, head of the Radio Physics Division, and professor of geophysics, and was engaged in research on the auroral zone ionosphere. He joined the staff of the U.S. National Bureau of Standards in 1958 as a consultant in radio astronomy, ionospheric physics, and radio wave propagation. In 1960 he was appointed chief of the Bureau's newly formed Upper Atmosphere and Space Physics Division, and in 1962 became chief of the Bureau's Central Radio Propagation Laboratory, Boulder, Colo.

He is a Fellow of the Royal Astronomical Society and a member of the American Geophysical Union.

George R. Brewer (F) has been manager of the Ion Propulsion Program at the Hughes Aircraft Company since the program's inception in 1959. Since joining Hughes in 1958 he has been engaged in research, development, and technical direction in microwave electron tubes, with primary emphasis on the generation and focusing of high-density electron beams used in traveling-wave tubes. More recently, he has applied this background to the problems of ion propulsion. Earlier positions include that of research associate at the University of Michigan's Engineering Research Institute, and staff positions with the Naval Research Laboratories and the M.I.T. Radiation Laboratory.

He received the B.S. degree in E.E. in 1943 from the University of Louisville, and the M.S. degree in E.E. in 1948, the M.S. degree in physics in 1949, and the Ph.D. degree in E.E. in 1951, all from the University of Michigan. Dr. Brewer is the author of 18 papers on electron guns and beams and on ion propulsion and holds 15 electron optics patents.

G. W. Alexander (SM) received the B.S. degree in electrical engineering from the State University of Iowa in 1949. Following his graduation from Iowa he joined the General Electric Company. After completion of the company's test course he worked for four years in installation and service engineering in the upper Midwest, and for 11 years served as a utility application engineer in the Chicago and Minneapolis offices of General Electric. This experience covered the broad aspects of electric power distribution, transmission, and generation, as well as system planning work. At the present time he is located at Schenectady, N.Y., where he is engaged in various projects connected with the General Electric Company's Electric Utility Engineering Operation.

Mr. Alexander is a member of Eta Kappa Nu and Tau Beta Pi, and is a registered engineer in the State of Illinois.

I. B. Johnson (SM) received the B.S.E.E. degree in 1937 and the M.S.E.E. degree in 1939, both from the Polytechnic Institute of Brooklyn. He joined the General Electric Company in 1939; after several test assignments, he was employed as a laboratory engineer in the High-Voltage Engineering Laboratory. As a development engineer from 1943 to 1945 he worked on high-altitude ignition systems for military aircraft. After the war, he returned to the field of electric utility systems as an application engineer in the Central Stations Operation. From 1950 to 1958 he served as manager, power systems engineering, Analytical Engineering Operation; from 1958 to 1961, as manager, transmission and distribution analytical engineering, Electric Utility Engineering Operation; and from 1961 to the present, as manager, advanced system design, Electric Utility Systems Research Operation.

Mr. Johnson is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi.

A. J. McConnell (F) received the E.E. degree from Cornell University in 1928, and then joined the General Electric Company as a test engineer. Following the test assignment he became a relay design engineer at the GE switchgear plant at Philadelphia. In 1941 he transferred to the Central Station Engineering Department (now the Electric Utility Engineering Operation) in Schenectady. While in design work he was principally concerned with induction relays. His reduction to practice of the eight-pole induction cylinder design resulted in about 30 relay lines and modifications thereof, most of which are still in production. In the application area, he conceived six carrier-current relaying schemes, all in active use today. He holds 18 U.S. patents and has been author or coauthor of numerous papers and articles, including 11 AIEE or IEEE papers.

Mr. McConnell is a member of the National and New York State Societies of Professional Engineers, Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi.

H. O. Simmons, Jr. (SM) is a 1943 graduate of Union College, from which he received the B.S. degree in electrical engineering. He is now a power transmission engineer with the General Electric Company, Schenectady, N.Y. Prior to his present position, which he has held since 1955, he worked in steam turbine-generator design, general office utility sales, and electric utility application engineering. He has authored and coauthored several papers dealing with the subjects of system stability, kilovar supply, conductor economics, energy transportation, transmission influence on generation reserve requirements, system requirements for power circuit breakers, and other related power transmission topics.

Mr. Simmons is a member of the IEEE Switchgear Committee, Power Circuit Breaker Subcommittee, IEEE System Engineering Committee, and System Planning Subcommittee. He is a licensed professional engineer.

Gerald Salton (M) received the B.A. and M.A. degrees in mathematics from Brooklyn College. Since 1952 he has been a staff member at the Computation Laboratory of Harvard University, first writing computer programs for Air Force research problems on the Harvard Mark IV and later working on a variety of nonnumeric computer applications. In 1958 he received the Ph.D. degree from Harvard and became an instructor in applied mathematics; since 1960 he has been an assistant professor of applied mathematics. He spent most of 1963 as a Guggenheim Fellow in Western Europe, where he studied nonnumeric computer work in several countries. He has twice been a NATO lecturer in automatic documentation, and is now serving as a national lecturer for the Association of Computing Machinery. He is a consultant on information science and computation to several organizations. Dr. Salton is a member of Phi Beta Kappa, Sigma Xi, ACM, the American Documentation Institute, and several other organizations.

Classified Advertising

Positions Open

The following positions of interest to IEEE members have been reported as open. Apply in writing, addressing reply to address given or to Box Number, c/o IEEE Spectrum, Advertising Department, 72 West 45th St., New York, N.Y. 10036.

Classified Advertising Rates for this column: $6.00 per line. No advertising agency commission is granted. Copy must be received by the 2nd of the month preceding date of issue.

Electrical Engineer. Chicago international consulting engineering firm needs electrical engineer experienced in all phases of electrical design of hydroplants. Salary commensurate with experience. Some relocation costs and fringe benefits. Submit resume including salary requirements to the Personnel Manager. Harza Engineering Company, 400 West Madison Street, Chicago, Illinois 60606. An equal opportunity employer.

Electrical Engineers. Professional growth opportunities available with consulting engineering firm. EE graduates will be employed for permanent positions involving design engineering, system planning or specifications writing. Diversified activity involves both U.S. and overseas engineering. Please send resume, including availability and salary requirements, to Personnel Director, Stanley Engineering Company, Muscatine, Iowa 52761. An Equal Opportunity Employer.

Electrical Engineer. International consulting engineering firm needs Chief Distribution Engineer for overseas assignment in family status. Must be capable of training foreign nationals and eventually assuming responsibility for complete charge of distribution department. Salary commensurate with experience. Fringe benefits. Please send complete resume including salary requirements to the Personnel Manager, Harza Engineering Company, 400 West Madison Street, Chicago, Illinois 60606. An Equal Opportunity Employer.

Ph.D. faculty member needed for teaching and research. Good publication record essential. Write: Head, EE Department, University of Tennessee, Knoxville, Tennessee 37916.

Two openings for research-oriented electrical engineers in antennas, propagation, materials science, electronic devices, microwaves, etc. Ph.D. or equivalent required. New building and excellent equipment. Light teaching loads. Active graduate program. Toledo has no smog and no traffic jams. Salary and rank according to qualifications, with superior fringe benefits. Start September or February. Write: R. A. Chipman, Chairman Electrical Engineering, University of Toledo, Toledo, Ohio 43606.

The Miller Company, manufacturer of commercial and industrial, fluorescent and incandescent lighting fixtures, has unique opportunity for lighting sales engineer, primarily to call upon architectural and engineering firms in New York City in behalf of Company's Sales Engineers throughout the United States. Send resume to Box 6044.

Electrical Engineer, BSEE. Permanent position with large Southern Michigan mineral processing industry. Interest and ability required in the application, operation and maintenance of motors, controls, and modern electronic instrumentation. Salary dependent on experience. An equal opportunity employer. Please send complete resume including salary requirements to Box 6046, IEEE Spectrum.

Electrical Engineering faculty members for teaching and research in the fields of computer sciences and communications. Ph.D. degree required, as well as other evidence of productivity in scholarly research. Rank and salary commensurate with qualifications. Reply to Box No. 6047.

Electrical Engineer. A world leader in offshore construction and marine engineering has an opening in their New Orleans office for an electrical engineer, age 35 to 45, with ten years or more experience. Engineering contracting firm or utility company experience is preferable. Applicants should be able to take full responsibility for the electrical part of projects in oil and gas industry construction. The man selected will be required to give guidance to younger engineers and draftsmen. Foreign travel of short duration will be required. This is a permanent position with advancement possibilities and full-range company benefits. Salary will be commensurate with experience. Send complete resume to J. Ray McDermott & Co., Inc., Second Floor, Saratoga Building, New Orleans, La. 70112. An equal opportunity employer.

Control Design Engineer. Experience in circuit design of switchboards & metal clad switchgear as applied with A-C generators & motors. Some experience desirable, but not required, with static regulators & exciters. Send resume to R. Green, Electric Machinery Mfg. Company, 800 Central Avenue, Minneapolis, Minnesota 55413. An equal opportunity employer.

Electrical Design Engineers. Synchronous, induction, or D.C. machine design. Experience in programming rotating machine design for computer desirable, but not required. Send resume to R. Green, Electric Machinery Mfg. Company, 800 Central Avenue, Minneapolis, Minnesota 55413. An equal opportunity employer.

Instrumentation Engineer. Graduate E.E. or Physicist. Advanced degree desirable. Must be an innovator, interested in challenge to conceive and carry out new operational control concepts. Must be management minded and production oriented. Salary commensurate with experience and ability. Please write in confidence to Mr. G. E. Morrison, Personnel Department, Kellogg Company, Battle Creek, Michigan. An Equal Opportunity Employer.

Senior Project Engineer, Electrical Apparatus. Graduate EE or ME to direct development of electrical apparatus products. Require 10 years experience in development and design of outdoor air break switches, vacuum and other types of load and fault interrupters, and circuit reclosers as used on electric utility transmission and distribution circuits. Experience with power fuses, cutouts, and automatic circuit switching also helpful. Knowledge of industry standards and test requirements necessary. Modern engineering research center has excellent high-voltage and short circuit test facilities. Pleasant living in small community with top-rated school system, and only 25 miles to state university. Within easy driving distance of St. Louis, Kansas City, and Lake of the Ozarks. Annual cash bonus, profit sharing, and major medical insurance plans. Send resume including age, education, experience, and salary to B. J. Smith, A. B. Chance Company, Centralia, Missouri.

Electrical Engineers. Positions available for electrical engineers in design and consulting engineering work on power systems and large industrial facilities. Philadelphia or Chicago location. Full benefits, profit sharing, moving allowance, professional development and advancement. Send complete resume to R. F. Matthiessen, Administrative Assistant—Engineering. United Engineers & Constructors Inc., 1401 Arch St., Philadelphia, Pa. 19105. An equal opportunity employer.

Electrical Engineer (BS Degree)—One of 100 largest U.S. Corporations, manufacturer of agricultural and industrial equipment with multi-plant operations in U.S. and overseas, needs an electrical engineer. Work involves electrical design construction and installation follow-up of high, medium, and low frequency induction heat treating equipment, machine sequence controls, electro-plating and other related work. Some induction experience preferred. Position in Mid-west location. An equal opportunity employer. Box 6048.

Positions Wanted

Classified advertising Rates for "Positions Wanted" column: $6.00 per line per insertion. 50% discount for members of IEEE (please supply membership number with copy). Copy must be received by the 2nd of the month preceding date of issue. Address replies to Box Number given, c/o IEEE Spectrum, Advertising Department, 72 West 45th St., New York, N.Y. 10036.

Electronic Engineer, BEE '59, MSEE '64, six years' industrial experience, digital circuits, techniques, systems, and microelectronics as applied to radar. Desires position which will allow and aid in obtaining doctorate. Prefer Northeast. Box 8043.

Electrical Engineer, power, P.E., 16 years design, coordination, liaison, supervision, evaluation of industrial power, control systems, facilities, and utility power plant control. Prefer South, S.W., West. Box 8045.

Product or Project Manager. Extensive experience in all phases of power and control for industrial, military and marine. Heavy in systems, drives, and power supplies. Design experience A.C. & D.C. including electrical engineering Dept. Mgr.; mfg. experience in methods & layout & supervision; marketing experience in research & sales. Management experience in coordinating all 3. Skill in anticipating & developing new products to meet market needs. BSEE plus advance work on MS. Age 38. Will start in design, marketing or manufacturing. Box 8046.

Seeking position in Niagara Falls area. 11 years consulting electrical engineering experience. Heavy on design of electrical power systems for industrial plants including lighting, motor control, etc. Will consider plant engineering position or electrical consulting engineering. Box 8047.

Electrical Engineer, MS in EE, age 42, aggressive, of Greek descent, with experience in all phases of management, construction, military projects, top level contract negotiations, sales and distribution, manufacturing, seeks responsible assignment with American International Corporation in Greece. Willing to participate financially in establishing operation of subsidiary to cover Greece and Middle East. Will relocate within reasonable time. Please reply to Box 8048.