GENERAL ELECTRIC

Review

JULY 1958

Research Laboratory

SPECIAL ISSUE

Dislocations

Helium Tunnel

Fusion

Magnetron

Fuel Cells

Patterns of silicon carbide crystals, magnified 1000X, reveal important information concerning the mechanism of crystal growth. The photomicrograph, taken in natural light, depicts the structure's brilliance. For a new technique in the study of crystal structure, **turn to page 9.**

Dr. William W. Piper joined the staff of the General Electric Research Laboratory in 1951, after receiving his Ph.D. in Physics from Ohio State University (1950) and his B.S. from Columbia University (1946). His fields of interest include theoretical and experimental studies of electroluminescence, crystal growth, electrical and optical properties of transparent crystals, and atomic field computations.

Research in electroluminescence

Single crystals led General Electric's Dr. William W. Piper to new understanding of light sources

Electroluminescence, the process in which electrical energy is converted directly into light within a phosphor, has been known for many years. Only in the last decade, however, have scientists obtained detailed knowledge of its characteristics. Early studies were carried out with samples consisting of large numbers of microscopic phosphor particles. The complexity of this experimental system made it difficult to interpret the data obtained in terms of a fundamental explanation of electroluminescence.

Shortly after Dr. William W. Piper joined the staff of the General Electric Research Laboratory, he learned how to grow single crystals of zinc sulfide phosphors. His studies of these single crystals soon led to the successful identification of the means by which electroluminescence occurs in this material.

The improved understanding of the basic processes involved is aiding in the development of new light sources, such as electroluminescent ceiling panels and radar plotting boards, contributing both to a higher level of living and the national defense.

Progress Is Our Most Important Product

GENERAL ELECTRIC

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Review

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SPECIAL RESEARCH LABORATORY ISSUE

All articles in this issue, unless bylined, were prepared by the Research Information staff of the General Electric Research Laboratory.

OPERATION UPTURN:

Excerpts from the report of Ralph J. Cordiner to General Electric share owners:

IN the light of economic circumstances today, what must be done to bring about the resurgence of business and employment that everyone wants? The situation seems ripe for a special effort: consumers have the money to spend, industry is tooled up to deliver as never before, and there are signs that the upturn is trying to get under way.

Opportunities to serve customers better

It seems to me that the most practical and effective course right now is for every business to buckle down and sell goods as never before. I mean a total effort, by every man and woman on the job, to concentrate on giving customers the best service and the best reasons to buy they ever had. King Customer needs some constructive attention. He is willing to do his part, if he is convinced that this is the time to buy. Let's convince him by showing him the best values and by giving him the best service he could ask for.

This may seem like an old-fashioned prescription to those who are shouting for massive government make-work programs and meaningless tax cuts, but we in General Electric are convinced that what happens to the economy in the remainder of this year will be largely determined by what business does to help its customers and itself. This is a do-it-yourself country. Each of us is in some way responsible for a part of the total effort, as a consumer, an employee, an investor, a voter, or whatever roles we play in economic life.

That is not to say that federal, state, and local governments do not have important work to do. There are many constructive measures that would stimulate a sound recovery without sowing the seeds of future inflation. What I am suggesting is that the government must provide the political conditions in which the economy can work its way out of the recession; but the government cannot be expected to cure the recession.

Outstanding values available now

General Electric's three-year, $500,000,000 program of capital expenditures, which was announced in 1955,

Over 3,000 share owners—a typical cross section of the nearly half a million Americans who are owners of General Electric —listen to the president's message by Ralph J. Cordiner at the Annual Meeting held in April at Schenectady, N. Y.

A nation-wide "do-it-yourself" program to help build sales and jobs in 1958

OPERATION up turn — Build sales and jobs in '58 — GENERAL ELECTRIC

is proceeding on schedule. This modernization and expansion program has put the company in an excellent position to give its customers outstanding values and up-to-date products.

The competitive industry prices at which General Electric sells have remained about level, in spite of the continued rise in costs. Customers are getting unusual values at today's prices, and this will help build business volume back up to the normal trend. Looking at the situation realistically, however, such bargain prices cannot be expected to continue indefinitely.

In addition, the company is offering improved credit terms that recognize the problems of the times. More advantageous terms have been made available through the General Electric Credit Corporation, such as the Unemployment Protection Plan to aid customers through periods of unemployment due to sickness or layoff.

A program to accelerate the upturn

This is a moment of opportunity. The slight upturn in some sectors can be turned into a definite trend, and then snowball into a steady recovery, if business will make a fresh, concerted effort.

To this end, the General Electric Company today announces that it is setting in motion a company-wide program of aggressive action in all departments and in all functions to accelerate the upturn in business.

It is known as OPERATION UPTURN. Basically, it is a program to accelerate the upturn in business by bringing extra values and renewed confidence to customers. Its purpose is to build sales and jobs in 1958. All across the country, other companies are announcing their own plans to stimulate sales and renew public confidence. OPERATION UPTURN is part of this exciting national picture of the people of the United States shaking themselves loose from the doubt and confusion of recent months and setting about purposefully to resume the national advance.

Remember, programs such as this, even if they are conducted by all the leading companies in the country, cannot work overnight miracles. But the tide is turning, and this is the time for a massive effort by everyone to keep the economy moving in the right direction. All signs indicate that this country can have its biggest surge of growth in the 1960's.

OPERATION UPTURN...

OPERATION up turn — Build sales and jobs in '58 — GENERAL ELECTRIC

is General Electric's program to help accelerate the upturn in business by bringing extra values and renewed confidence to customers. Its purpose is to build sales and jobs in 1958 through the enthusiasm and participation of more than a quarter million employees, their community friends and neighbors, some 45,000 suppliers, more than 400,000 firms that sell or service the company's products, and nearly half a million share owners. OPERATION UPTURN can help all of us together to contribute more effectively toward our common goals and add confidence and strength to the nation's economy.

Responsibilities for every citizen

In a free economy, economic growth is paced and directed by the decisions of millions of businessmen, consumers, investors, employees — indeed, by every citizen. The faith of our society is that these millions of points of initiative will produce swifter progress, with greater liberty, than any system of centralized control.

Thus, a business recession is really a test of the American people and their form of society. Their decisions — to buy, to invest, to modernize, to work more purposefully, to raise their levels of living — will determine the speed of economic advance. They will also decide whether Russia will, as she has announced, surpass us in the years ahead.

It is my opinion that the American people will bring about the upturn this year and head into a great surge of growth that will leave both the recession and the Russians far behind. This is what we Americans want. And what we want, we are willing to work for. That is all that is needed.

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Industrial Research Stimulates Small Business

Seven specific kinds of action are necessary to insure the continuation of large-scale industrial-research benefits. In doing these things—evaluating the over-all value of research to America—we must keep in mind key aspects of industrial scientific research.

In a recent address. "Large Business as a Source of Technical Assistance for the Small Business. Dr. Guy Suits—General Electric Vice President and Director of Research—stated these seven points in plain terms. He submitted them, in more detail, to the President's Conference on Technical and Distribution Research for the Benefit of Small Business in Washington, DC.

Admittedly *others* do benefit from *your* research. The sponsor, though, expects his research contribution to enable him to be "first" with new and improved products and thus to broaden his opportunities to serve his customers and to deserve an adequate profit. But the new markets will not be served by a single company. Typically, a new market is an opportunity for widespread participation by industrial units large and small, giving full play to the specialized skills of the supplier of materials and component machinery and equipment, as well as the manufacturer of the complete product or product line.

For instance fluorescent lamps, developed by General Electric, now engage eight major manufacturers, who are busy with improvements in the initial new product—improvements to benefit everyone concerned. For example, within the first 10 years after the introduction of fluorescents, the 20-watt fluorescent efficiency was increased by 44 percent, its life was increased 150 percent, and its price was decreased by 62½ percent. Another 24 companies, mostly small, manufacture fluorescent ballasts. An additional 113 firms, again mostly small ones, make fluorescent fixtures.

The following recommendations, then, are necessary to continue the benefits of large-scale industrial research. All seven of these, quoted directly from Dr. Suits's paper, are equally important to both small and large businesses. —EDITORS

TO INSURE CONTINUATION OF THE BENEFITS OF RESEARCH, WE MUST . . .

1. Build up the nation's supply of adequate technical manpower.

Engineers and scientists obviously hold the key to our nation's progress in this swift-moving age. Industry, large and small, can do much to solve the shortage of technically trained people. Working with schools, we businessmen can take an active role in encouraging young people to further their studies and to explore their technical aptitudes and interests. We can awaken students to future opportunities, provide tangible career-guidance material, help teachers become even more effective, and provide financial assistance to colleges in several ways, including that of helping our employees repay their alma maters for their education. Within our own companies—regardless of size—we can give our men and women opportunities to acquire new skills, encourage them to continue their education by establishing cooperative programs with nearby schools and colleges, and provide opportunities for professional training and development.

2. Rejuvenate our patent system.

There is need for a more sympathetic attitude on the part of the courts toward the original concepts and philosophy upon which the patent system is based. We must recognize that the inventor who provides previously unknown ideas, machines, and processes definitely contributes to the progress of our social structure. There also is need for improving the facilities of the United States Patent Office for determining whether the inventions submitted for patenting are new or old. It is apparent that the Patent Office, in common with other components of our technical society, threatens to be overwhelmed by its inability to accumulate, classify, and search—as its responsibilities require—the growing mass of technical literature, including its own, within a reasonable time.

3. Develop new ideas about scientific advances and how they are produced.

We need greater understanding of scientific and technical specialization and their relationship to team effort. We must recognize, in our developing management concepts, the basic character of creative technical work, and we must provide the incentives that stimulate productive effort.

4. Create a better understanding among our citizens of the necessary relationship between profit and progress.

Research is a high-risk business investment and a very costly one. It is unrealistic to assume that the research activity of private industry can be geared to the demands of technological progress without consideration of adequate profits—demands that provide the incentive for research and literally make it possible. Adequate profits give us the opportunity to maintain the cycle of technological progress: research—new products—jobs—sales—and the profits that permit the cycle to start again. We must reaffirm to people everywhere the basic American belief that profit, instead of being something "left over," is an integral element of the growth of our nation and our society.

5. Create a greater understanding, principally on the part of management and employees, of the significance of new processes and new products.

The human trait of "resistance to change" has kept people in some parts of the world literally in the dark ages. Even in America, individual unwillingness to accept the temporary "inconvenience" associated with innovation is a major deterrent to insuring our defense and improving our living standards. Obviously, I am not suggesting that everything new is necessarily good, nor that all the results of modern scientific research will yield immediate improvements in our products or our way of living. However, it is essential that we all contribute to an atmosphere in which new things can be evaluated objectively, without fear of changes simply because they *are* changes.

6. Continue to urge that a greater proportion of the nation's total research effort be done by industry—large and small—and that the government's research be administered in a way that stimulates the progress, vitality, and independence of business.

Even in the national defense area, private industry would be willing and able to finance a greater proportion of the needed research and development—*if* the procurement policies were to provide the same profit incentives that over the years have been so magnificently productive in the civilian economy. With research and innovation assuming such a tremendously important role in the nation's economy, these elements should most certainly be kept within the framework of the free-enterprise system.

7. Establish a climate of informed public opinion that recognizes the political and economic conditions necessary for encouraging the expansion of industrial technology.

The public as a whole must recognize the importance of large-scale industrial research and its proper role in our economy. Government must not let an emotional fear of "big business" reduce or destroy the contributions that such research can make to the nation's welfare and defense. The management of all American industry must recognize the importance of supporting the kind of fundamental science that provides us with basic new understanding about the world in which we live. And small business must recognize and take advantage of the countless opportunities being made available by large-scale industrial research operating in a free society.

The opportunities presented by today's "technological revolution" are so challenging that America needs the full range of her industrial resources, large and small, each company doing what it can do best, and each drawing strength from the other.

Guest Editorial

Innovations: Nuisance and Necessity

This issue of the GENERAL ELECTRIC REVIEW is the first to be devoted wholly to the work of the General Electric Research Laboratory. In it we have gathered together reports on some of the more interesting and significant programs of investigation now under way. If we can judge by past experience, these efforts will, within the next 10 years or so, result in important new opportunities for technological developments in the Company's engineering and manufacturing operations. Since innovations in any field of human endeavor are not always greeted with open arms, it may be appropriate to consider our attitudes toward such changes.

First, let me say that new ways of doing things in the electrical industry are traditional, axiomatic, inevitable, and desirable; our chief concern is the timetable of progress. Our best and only hope for staying ahead in the intense competition for technological progress that is fundamental to our business is to keep in close touch with the "advance parties" of research—those that explore the frontiers of science and provide us with the identification and appraisal of things to come in our business. Each passing year brings more of these exploring parties to keep in touch with; and the job becomes increasingly complex and expensive.

Our objective is to keep in the van of the march of progress, and we will be able to do so if we realize the magnitude of the job and act accordingly. Particularly, we must realize the importance of an across-the-board approach to scientific research. Large research efforts, delving into a multiplicity of scientific fields, give the advantages of breadth and depth; large-scale research offers the advantages of supporting skills and specialized facilities, without which the modern scientist, necessarily specialized in one field, cannot work.

It is not suggested that everything new is necessarily good, nor that all the results of modern scientific research will yield immediate improvements in our products or services—or our way of living. However, progress requires new technology and thoughtful appraisal of its economic opportunity. We can be certain of one thing in the future: our businesses will be doing things differently. If we are thoughtful about it, we will do things not only differently but also better—better in terms that will be persuasive to our customers at the market place.

To anyone in a currently profitable business, innovation can be a downright nuisance. In our free-enterprise system, however, this nuisance is the lesser of two evils: the greater evil is business extinction. In the electrical industry nothing can substitute for large-scale technical work as a base for technological innovation.

In our own Company, in some years the expenditure for the technical work represented by research and development and engineering has exceeded the net profits. No more difficult problem faces modern management than determining the best balance between short-range and long-range goals—for example, the proper balance between today's profits and research for tomorrow's business. It is difficult to determine both how much is too much and how little is too little—risks lie in both directions. However, one is hard put to assemble a very long list of businesses that have failed because they did too much research. On the other hand, one can cite a long list of businesses that have experienced failure or serious loss of position due to obsolescence of principal products, processes, or services.

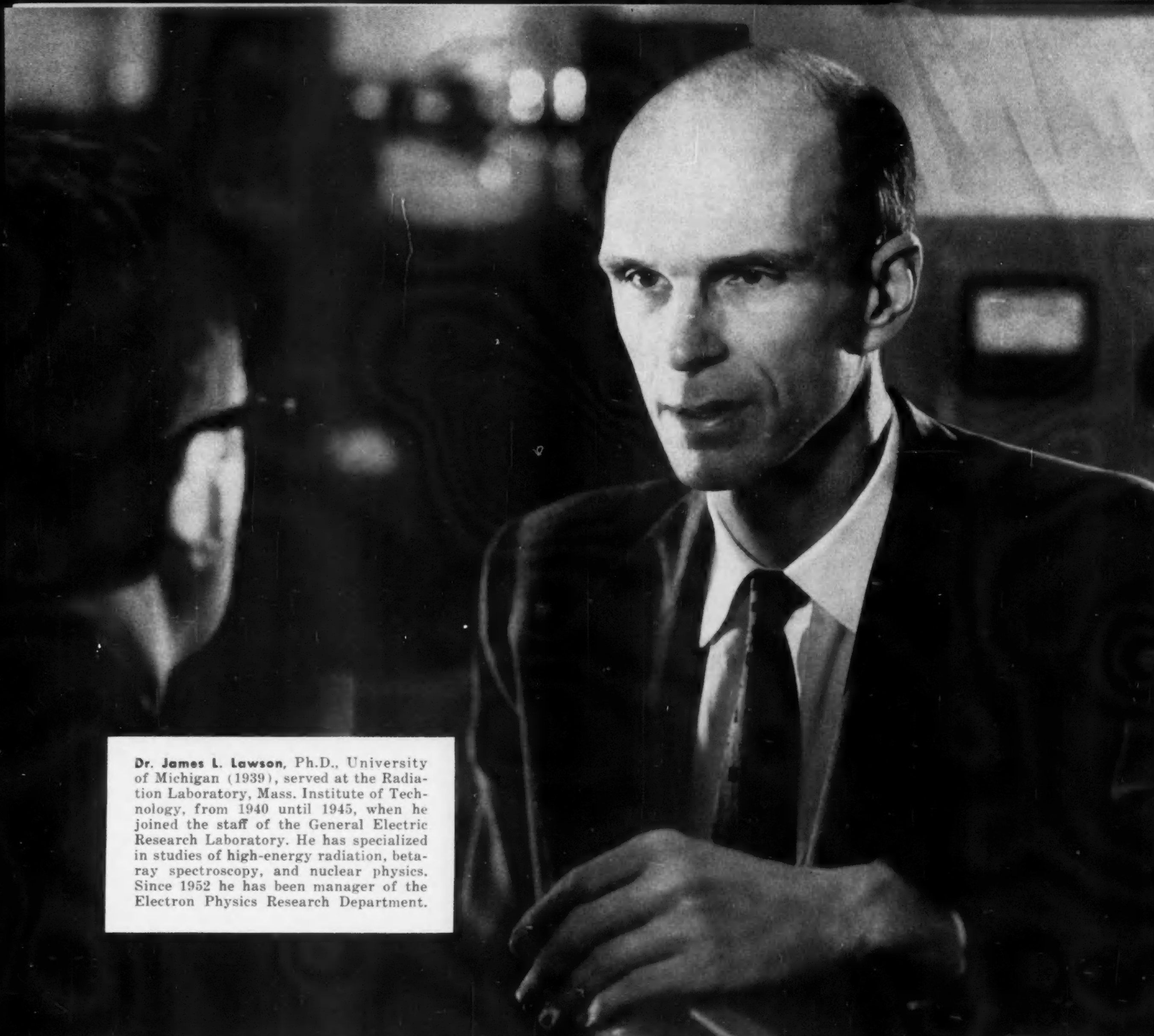
"Innovation," you may say, "is a confounded nuisance." That's true, but business obsolescence may be a disaster.

The nuisance aspects of innovation are more than offset by the abundance of the payoff provided by scientific research. In seeking long-range goals, we stumble across countless unexpected research dividends, and frequently these are directly applicable to the improvement of our present way of doing things.

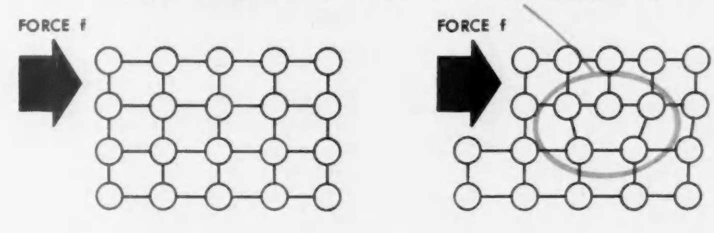
In solving the problems of materials for atomic-powered aircraft, for example, we will solve metallurgical and mechanical problems applicable to other types of heat engines. Fundamental studies of new heating and cooling techniques—required by space missiles and space flight—may be expected to have additional, far less glamorous, and more work-a-day applications. The search for fusion power probably will provide by-products in circuit technology or radiation generation long before the energy of the hydrogen bomb has been controlled for peaceful use.

We can make these predictions confidently because scientific research produces improvements as well as innovations. I firmly believe that the cost of research can be justified to the sponsoring company and its customers on the basis of unexpected payoffs alone. But without the long-range goals, we might never set out on the explorations at all.

VICE PRESIDENT AND DIRECTOR OF RESEARCH



Dislocations moving inside a crystal allow it to deform plastically. Scientists can watch them move by means of etch pits—tiny square pits gouged out of a crystal's surface by etching reagent. Each etch pit locates a dislocation line.



Plasticity of Solids Explored by New Technique

Direct observation of dislocation motion in crystals leads toward stronger metals through more efficient forging, rolling, and machining methods.

By DR. JOHN J. GILMAN

Modern industrial society with its extensive use of the forge, the rolling mill, and machine cutting tools depends on the plasticity that metal crystals exhibit. By way of contrast, the consumer of fabricated products usually wants as much strength, or lack of plasticity, as possible. For both conditions, the crucial properties depend on tiny imperfections in the metal's crystal structure. These flaws in the alignment of the atoms are called *dislocations*. Our growing knowledge of their nature and behavior constitutes one of the most challenging and potentially rewarding fields in modern science.

Basic Mechanical Properties . . .

The great importance of this subject to the engineer becomes clear when we consider the four fundamental mechanical properties of engineering materials: the elastic modulus; the yield stress, or elastic limit; the strain-hardening rate, or plastic modulus; and the fracture stress.

. . . Elastic Modulus . . .

All these mechanical properties depend on the properties of dislocations, with the exception of the elastic modulus, which is determined by the bonding forces between the atoms of a crystal.

. . . Yield Stress . . .

The yield stress is proportional to the stress at which dislocations begin to move in the crystals of a material. In engineering tests, considerable dislocation motion occurs before yielding can be detected.

By ordinary means it is difficult to measure plastic strains smaller than about 10^{-6}; that is, one microinch per inch. But by watching the individual dislocations move in crystals of lithium fluoride, it is possible to detect strains at least as small as 10^{-12}.

These very small strains define the true yield stress of a material. They represent the very beginning of plastic deformation, or the very first departure from completely elastic behavior.

The interesting fact is that comparisons of the stresses needed to cause dislocations to move with the stresses that cause yielding on the engineering scale have shown that the two are proportional. Therefore, the yield stress can be thought of as simply the stress needed to move dislocations in a material.

Crystals exhibit an enormous range of resistance to dislocation motion. If we take a soft crystal like talc as the unit of resistance, then the resistance of diamond to dislocation motion is about 100 million times larger! Between talc, so soft it does not scratch milady's face, and diamond, so hard it scratches anything, there are many crystals with widely different plastic resistances.

The resistance of crystals to dislocation motion depends on the atomic pattern that forms the basis of their construction and also on the strength of the bonds between adjacent atoms in the structure. Zinc crystals illustrate this point well. In zinc the atoms are packed together in layers. And the bonds between the atoms within each layer are stronger than the bonds between two layers. Therefore, gliding occurs more easily between the layers than on planes that cut across the layers. At 250 C and the same rate of glide, the stress needed to cause glide on the planes that cut across the layers is 50 times as great as the stress for glide between the layers.

Each kind of crystal has a certain intrinsic resistance to plastic deformation, depending on the strength of the bonds that bind its atoms together. However, other factors exert a strong influence on its plastic resistance. And one of the most important factors is impurities. Impure crystals always resist deformation more than pure crystals—sometimes with very pronounced effects. Some impure crystals are 10 to 100 times as resistant as pure crystals, the

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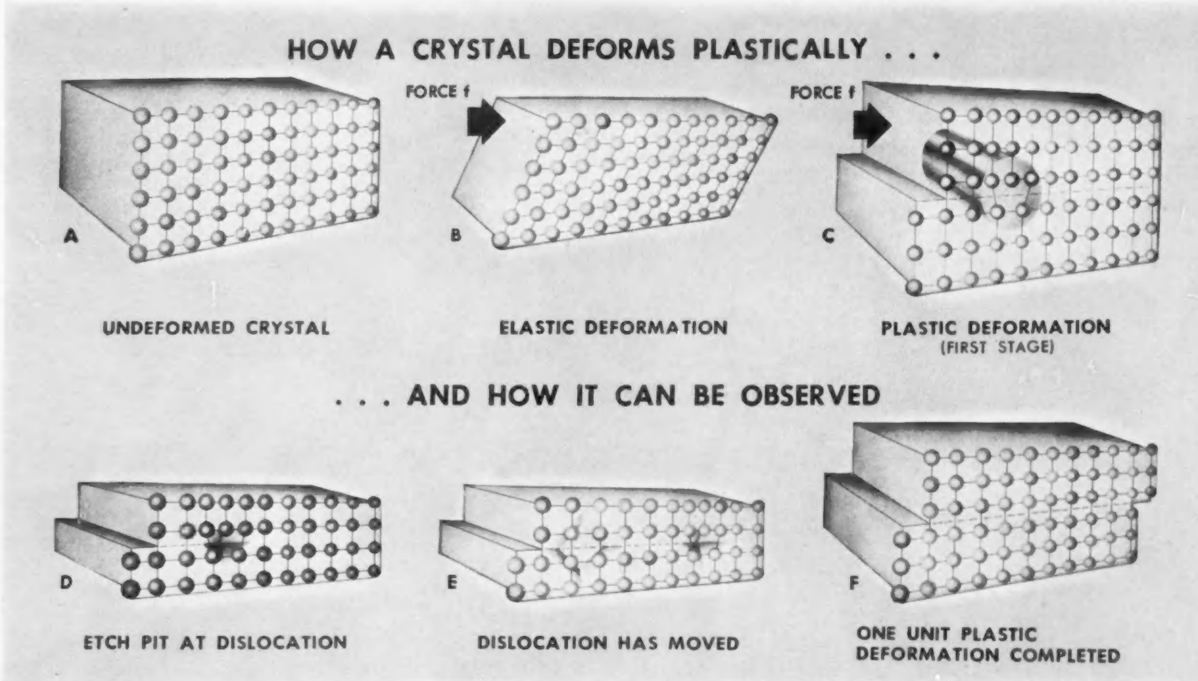
Dr. Gilman—metallurgist, Physical Metallurgy Section, Metallurgy and Ceramics Research Department, General Electric Research Laboratory, Schenectady—has been with the Company six years. He does research on the fundamental basis of plastic deformation and fracture and last year received the A. H. Geisler Award from the American Society of Metals for his contributions to the metallurgy profession. This past May he visited Russia to attend the international Conference on Mechanical Properties of Solids held at Leningrad.



DISLOCATION MOTION inside a crystal permits plastic deformation. Acid easily attacks the crystal where the dislocation line intersects the crystal surface, forming etch pits. These follow the dislocation line as it moves through the crystal, under force.

reason being a matter of impurity size. The impure atoms, which replace a few of the normal atoms, are either slightly smaller or larger than the normal atoms. This causes some distortion of the normal crystal pattern and impedes dislocation motion.

Intense radiation, such as neutron bombardment, also raises the plastic resistance of a crystal. The radiation knocks some of the atoms out of the crystal, leaving holes inside about the same size as the knocked-out atoms. These holes act in a manner similar to impurities, distorting the crystal pattern slightly and making plastic deformation more difficult.

Still another impediment to dislocation motion is provided by small hard particles that can sometimes be precipitated at numerous places inside a crystal. When these particles lie on glide planes, they act as "keys" which prevent the planes from sliding over one another. Then to have dislocations move between the planes, they must move through the particles. If the particles are hard, dislocations move through them with difficulty, and dislocation motion is impeded.

This kind of hardening is used extensively to make aluminum resistant to deformation. Pure aluminum is soft and thus unsuitable for airplane structures, but it can be hardened markedly by precipitating small particles of a copper-aluminum compound along its glide planes.

It is a familiar fact that solid materials become stiffer when they are cooled to low temperatures. Crystals are no exception. As the atoms of a crystal vibrate less and less with decreasing temperature, it becomes more and more difficult for dislocation motion to occur. This makes crystals like germanium and sapphire hard and brittle at low temperatures but pliable at high temperatures. Other crystals like aluminum, lead, and cadmium are soft at most temperatures, becoming somewhat harder at very low temperatures. Because dislocations can still move in them at temperatures as low as one degree absolute, they do not become too brittle to be useful at very low temperatures.

. . . Strain-Hardening . . .

If a crystal has been strained somewhat, then it is difficult to deform it further. This phenomenon, known as strain-hardening, has occasionally been used to trick the uninitiated. A crystal of copper in the form of a round bar as much as ½ inch in diameter can easily be bent *once* to the shape of a horseshoe. Pity the victim who tries to straighten it out! After the first bend, the copper crystal is at least 10 times stronger than originally. This hardening results from the mutual interference between dislocations that meet while trying to move in different directions through a crystal. Dislocations that were moving on one set of planes are blocked by dislocations on an intersecting set of planes. The glide on each plane interferes with the glide on the intersecting plane so that a "traffic jam" results, which makes further glide very difficult.

The hardness due to strain increases with increasing strain. The reason is that the increased numbers of dislocations that accompany increased strains cause more frequent meetings between dislocations that are moving in different directions.

Hardening similar to strain-hardening is caused when two or more crystals are connected together to form a polycrystalline aggregate. When a stress is applied to the aggregate, each crystal deforms by gliding along its glide planes. But the glide planes of the various crystals do not match up; so there is interference between the gliding in adjacent crystals, and hence much resistance to deformation.

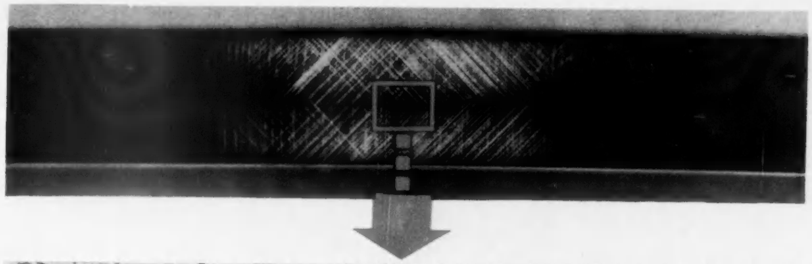
Advantage is taken of this phenomenon when a metal is forged. During forging, the crystals of the metal are hammered to break them down into small crystals; by thus increasing the amount of interference to glide in the aggregate, the metal is made harder and tougher.

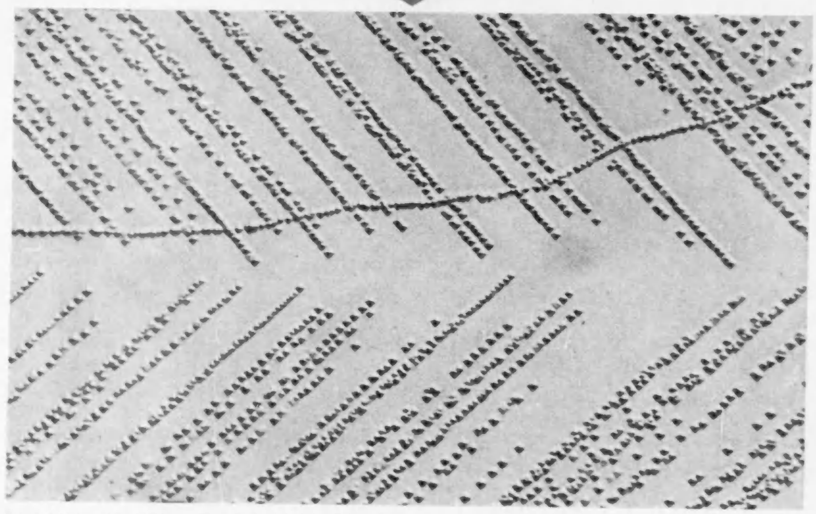
. . . and Fracture

The fracture of solids is a subject in itself, and so I will not discuss it in detail. But I should like to mention that the fracture stress of a material such as mild steel is largely determined by the behavior of dislocations in it. It is the stress concentrations that result when dislocation motion is blocked in mild steel that leads to its failure by fracture.

Phenomenon of Dislocation

Now that we have considered some of the significance of dislocations, let us examine the phenomenon itself. The two photomicrographs at the top of this page show the side of a lithium fluoride crystal that was plastically bent and then etched by immersing it in acid. It is covered with tiny square pits that were gouged out of the surface by the etching reagent. The long lines of pits make a definite angle of 45 degrees with the sides of the crystal. These etch pits are much more numerous in the plastically deformed parts of the crystal than elsewhere. They would simply be interesting scientific curiosities if it were not that each pit locates a dislocation line in the crystal. When a lithium fluoride crystal is immersed in the proper etching reagent, etch pits appear on the surface wherever such a line intersects the crystal surface. As we have already seen, the motion of dislocations inside a crystal is what allows it to deform plastically. And by means of the etch pits, we are able to track the dislocation-line movements that occur during the plastic deformation of crystals. Using special stressing methods, Dr. W. G. Johnston and I have watched dislocations move as slowly as a few atomic distances per second and as fast as 10^{12} atom distances per second—almost the speed of sound.





PLASTICALLY BENT CRYSTAL is etched in acid: one area (color inset) magnified 600 X (below) discloses long lines of etch pits that occur only in plastically deformed portion.

MOTION OF DISLOCATION is revealed in an actual crystal by flat-bottomed pit (left) at initial position and by sharp pit at position of dislocation after stress has moved it.

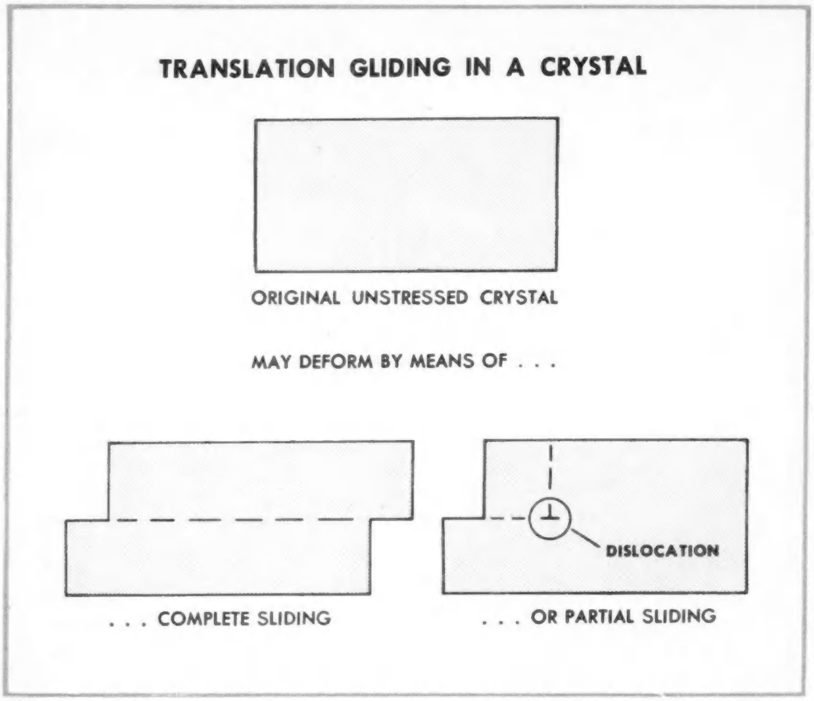
The meaning of the term dislocation-line can be understood by studying the illustration. Note that *A* is a schematic drawing of a crystal, and *B* is the same crystal shown with an *elastic* distortion. If force *f*, which causes the elastic distortion, is removed, the crystal will recover its original shape. Next, *C* represents the first stage in the *plastic* distortion of the crystal. At the left end of the crystal, the applied force has caused a shift of the top half of the crystal by one atomic distance with respect to the bottom. At the right end, no shift has yet occurred. The boundary between the shifted and the unshifted region is indicated by a cylindrical tube. This tube encloses what is known as a dislocation-line in the crystal.

Near the dislocation-line you can see a severe disturbance of the regular geometric array of atoms. This disturbance of the crystal structure makes it easy for an acid to attack the crystal where the dislocation-line meets the surface. Therefore, if the crystal is immersed in the proper acid, an etch pit will form, as in *D*.

Further application of a force may cause the dislocation-line to move; that is, the shifted region of the crystal grows larger, making the unshifted region smaller. Hence the boundary between the two regions—the dislocation-line—moves to the right, and the crystal looks as it does in *E*.

Now if the crystal is immersed in acid, a new etch pit forms at the new location of the dislocation-line. The old pit stops getting any deeper, because a disturbed structure is no longer at its bottom. It continues to grow sidewise, however, and so it develops a flat-bottomed shape. This sequence of events is shown for a real crystal in the lower photo (above).

Finally, the shifted region moves entirely across the crystal until there is no longer a dislocation present. However, the shape of the crystal has changed to



TRANSLATION GLIDING permits crystal deformation without destroying the crystal pattern. Partial sliding overcomes crystal resistance by moving a dislocation through the crystal.

that shown by *F*. The new shape is the result of a shift of the top half of the crystal by one atomic distance with respect to the bottom half.

Now the function of the etch pits becomes clear. They "premagnify" a structure that is only atomic in size. After this premagnification, the structure can be observed with an ordinary microscope.

Multiplication of Dislocations

Because each dislocation that moves across a crystal causes a displacement of only one atomic distance, an enormous number of dislocations must move through a crystal to make a strain of the size that is familiar in everyday engineering. For example, suppose you have a ½-inch cube of some crystal and you want to shear it by 10 percent—that is, to shear the top of the cube 1/20 of an inch with respect to the bottom half. Then it will be necessary for about 5-million dislocations to move from one side, through the crystal, and out the other side.

Actually, during a plastic deformation, dislocations do not usually travel distances as large as one-half inch, or 100-million atomic distances. Before they can move such a large distance, they usually suffer some mishap. They hit either some obstacle in the crystal—such as a precipitate particle—or a dislocation coming the other way and become annihilated. Therefore, the average distance traveled might be more like 1/1000 of an inch instead of ½ inch. This means that several billion dislocations, each moving 1/1000 inch, would be required to cause a 10 percent shear of the ½-inch crystalline cube.

The large numbers of dislocations needed to yield large deformations can be created through multiplication of a few dislocations that are originally present in a crystal. The atomic mechanism by which this multiplication occurs is not yet understood. It is one of the mysteries of plastic deformation presently being studied.

Why Dislocations?

A natural question is, Why does plastic deformation occur in this way? Why does it occur by means of dislocations—why not something else? To answer these questions, let me first point out that there are not very many ways to deform a crystal and yet retain the crystal as a crystal. If a deformation simply destroys the crystal, then fracture has occurred instead of plastic deformation. The only way of not destroying the pattern of a crystal, during a permanent deformation, is to glide one part of it over the rest by one complete unit of the pattern. This is called *translation gliding* (illustration).

The two possible ways of accomplishing translation gliding are by complete sliding and by partial sliding. If partial sliding occurs in a crystal, then by definition a dislocation moves through the crystal.

Crystals prefer to deform by partial sliding instead of complete sliding. You can appreciate the reason for this if you have ever attempted to move a large rug simply by pulling on one side of it. The friction between the rug and the floor is simply too large to be overcome. No doubt you solved your problem by simply making a small hump (dislocation) in the rug and then moving the hump along. When the hump came out the other side, you had moved the rug by an amount equal to the size of the hump.

The situation is much the same with crystals. The resistance of a crystal to deformation is much too great to allow the occurrence of complete sliding. But, if a dislocation (hump) is made in a crystal, then deformation is easy to accomplish.

Rapid Progress Anticipated

I have attempted to show how and why dislocations and their motion in crystals account for plastic behavior. The etch-pit technique is a powerful tool for studying the motion of dislocations in crystals. A detailed knowledge of these motions is essential to any real understanding of the many plastic phenomena that I have discussed. Because these phenomena occur whenever solid materials are formed into useful shapes, this information will eventually find useful application in making the complex arts of forging, rolling, and machining more efficient.

The strength of a crystalline material can be increased by making it difficult for dislocations to move in it, but the factors that determine how easily a dislocation can move in a crystal are not properly understood at present. Direct observations of dislocation motion should enable rapid progress to be made toward understanding these factors. Scientists and engineers trying to meet the clamor for materials with high and still higher strengths will then be able to proceed more systematically than is now possible. Ω

The Future of Science and the Liberal Arts

If science and the liberal arts are to survive in this ever-widening technological age, then these two great areas in our culture must begin immediately to replace their self interests with a strong mutual interdependence.

By DR. GLENN W. GIDDINGS

In a very literal sense, both science and the liberal arts are on trial for their lives. This is my main thesis. Let me defend it.

Arnold of Rugby is reputed to have said that no man should meddle with a University who does not know it very well and love it very dearly. Now some of the things I have to say may be interpreted as meddling; so before I say them, let me outline my qualifications as a meddler.

I am sure that I qualify on Arnold's second count, for I have a deep and abiding affection for educational institutions. When I left education, after nearly 20 years of continuous association, I know that I left a part of my heart on the campus.

Science and Society

When I was a teacher, I used to be concerned about some of the anomalies in education. I still am. But I have developed an even deeper concern about some of the long-range implications of education in our society, such as the reciprocal relationship between science and society. We all accept as a truism the cliche, "We live in a scientific age," for certainly our society depends upon science. We give very little thought, however, to the converse idea that our science depends upon society.

Basis of Modern Science

Modern science had its origin in Western Europe in the 17th century, just 300 years ago. Particularly noteworthy were the beginnings in England. Sociologist R. K. Merton has pointed out that in Puritan England, "The deep-rooted religious interests of the day demanded in their forceful implications the systematic, rational, and empirical study of Nature for the glorification of God in His works and the control of the corrupt world."

The combination of rationalism and empiricism characteristic of the Puritan ethic forms the basis of modern science. The basic assumption of modern science is that nature is orderly. The scientist assumes that nature is an intelligible order and that by properly asking questions of nature, he may elicit intelligent answers.

In our generation we have witnessed a striking culmination of the reciprocal effect between science and society in a favorable social climate. Most of our comforts and conveniences have stemmed from the work of a relatively few scientists, almost all of them in the past 300 years, the majority in the past 150 years. These scientists worked for the most part not for gain but simply for the joy of exploring and knowing and understanding. They believed that "It is good to know even if just for the knowing."

They could not possibly have foretold the technological applications of their scientific work, nor were they interested in them. Only recently have scientists become concerned with applications of their work, for only recently have the streams of science and invention merged to form the basis of our own technological society.

The technology of such a society always feeds upon science. As the technology advances, it must be supported by a continuing stream of new scientific knowledge—for which there must be a continuing supply of competent scientists. There is no other way.

Meaning of the Liberal Arts

Let me speak now for a moment about the humanities, "the branches of polite learning" as Webster calls them—those studies that are designed not to produce a better living but a better *life*. Without arguing terminology let me use the broader term "the liberal arts," which in the modern curriculum is usually interpreted to include the basic sciences. (It is worth while for the devotees of liberal education to recall sometimes that among the Romans the liberal arts were the higher arts that only the free men, the *liberi*, were permitted to pursue.) In our time we take a liberal education so much for granted that sometimes its proponents and practitioners cannot clearly define either its means or its ends. One of the finest statements I have ever read appears in an issue of the College of Wooster Bulletin titled *Adventure in Education*. It is worth remembering. Here is part of one paragraph from it . . .

> Liberal studies should do more than furnish a quality in men and women. They should generate action. They should emerge into the activity of a responsible citizen. Free to choose because he knows what the choices are, the liberally educated person can assist in those discriminations and value judgments that are the very life of a state.

Both Areas on Trial

With this introductory background, now, on science and the liberal arts, let me pursue my main thesis: Both science and the liberal arts are, in a very literal sense, on trial for their lives.

The scientist says, "I have only sought the truth." The humanist says, "I have only tried to preserve the values of the past." But of course almost everyone—including even some scientists—believes that science and the scientists are culpable for having invented engines of war—horrible bombs

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Dr. Giddings—Manager, Research Personnel at the General Electric Research Laboratory in Schenectady—came with the Company in 1945. During World War II, he was Technical Aide to the Director of the Radiation Laboratory at the Massachusetts Institute of Technology. Prior to the war, he served on the faculty of DePauw University—as Professor of Physics for 12 years and also Assistant Dean of Men in his last few years there. His work in the Company has been chiefly with technical personnel, including recruiting of scientists at the Doctoral level, and personnel administration in the Research Laboratory. Interested particularly in liberal arts colleges—having graduated from one, Cornell College in Iowa, and taught at another—he has maintained active contacts with education at all levels. His article is based on an address delivered at the College of Wooster, Wooster, Ohio.

"To be truly literate one must have an appreciation for the values

and bacteria that may destroy mankind. And almost everyone knows that the humanities are impractical and useless, if not downright dangerous! Now how has all this come about?

Plight of Science

In their lonely search for truth—and the truth of nature is the only true objective of science—scientists have not taken the trouble to interpret to the lay public either the spirit of science or its results. They have not helped the public to understand that every discovery may be used for good or for evil. The surgeon's scalpel may become the assassin's knife. Is the man who invented steel a culprit?

Scientists, both individually and collectively, have been content to be inarticulate as far as the public is concerned. It is part of the philosophy of the scientist to be objective in everything relating to his science, and this has precluded his being an active protagonist for science, particularly for his own work.

A British scientist, Dr. J. Bronowski, says of scientists . . .

> They have enjoyed acting the mysterious stranger, the powerful voice without emotion, the expert and the God. They have failed to make themselves comfortable in the talk of people in the street; no one taught them the knack, of course, but they were not keen to learn . . . . And now they find the distance which they enjoyed has turned to distrust, and the awe has turned to fear, and people who are by no means fools really believe that we should be better off without science.

Many honest people truly believe this, even though our modern way of life owes its very existence to science and to its offshoot, technology—the industrial applications of science.

Science has obviously become the scapegoat for the helplessness that people always feel in times of crisis. An active anti-intellectualism against science and scientists has developed, although the intellectual climate has improved in recent months. Science and the scientist are really so far removed from the public that the attitude toward them is not unlike that of the untutored tribesman toward the witch doctor: mingled awe and fear plus a decided belief that he possesses supernatural, or at least superhuman, powers.

The image of the scientist in the popular mind is very important. The present image is a caricature, but most scientists do not seem deeply concerned about it. In a recent issue of *Science*, Margaret Mead and Rhoda Metraux describe a study on the image of the scientist among high school students. Here are some excerpts . . .

> The scientist is a brain. He spends his days indoors, sitting in a laboratory, pouring things from one test tube into another. His work is uninteresting, dull, monotonous, tedious, time consuming, and, though he works for years, he may see no results or may fail, and he is likely to receive neither adequate recompense nor recognition. He may live in a cold-water flat; his laboratory may be dingy . . . . He neglects his family—pays no attention to his wife, never plays with his children. He has no social life, no other intellectual interest, no hobbies or relaxations. . . .
>
> He is always reading a book. He brings home work and also bugs and creepy things. He is always running off to his laboratory.

This image of the scientist is not a very pretty picture.

Flaws in the Liberal Arts

And now that I have discussed the plight of science, what are the charges against the humanities and the liberal arts? Let me quote first from Professor Joel H. Hildebrand, a distinguished former Dean of the College of Letters and Science at the University of California. Speaking on the subject "Knowledge and Power" in the Bampton Lectures at Columbia University, Professor Hildebrand said . . .

> Some seek salvation in a movement "back to the humanities," although just what it is that we are to go back to is not very clear. It often seems to consist in a prescribed number of so-called "units" of courses offered by departments which call themselves "the humanities," with little critical scrutiny of their humanistic content and purpose. The so-called "humanities" have had their opportunity ever since the Renaissance to improve mankind, but all the while racism, religious intolerance, extreme nationalism, and war have continued as usual. I see nothing particularly alluring to go back to.
>
> A revealing discussion of this matter took place at a meeting of the American Council on Education in October 1954. Its vice-chairman, Clark Kerr, Chancellor of the University of California in Berkeley, said, in part: "If the humanities are dying, I am not convinced that it is a case of murder or that the administrators are the most likely suspects. It seems to me that in a good many departments, in a good many universities, it is a case, rather, of attempted and as yet not entirely successful suicide.
>
> "Now, it seems to me that one of the troubles with the humanists is that they are trying very hard to be something that they cannot be. They are trying to be scientific. And they turn with a vengeance to history and develop all sorts of unimportant facts about unimportant poets, or they develop pseudoscientific criticism, and I have wondered a bit why this was so frequently true, and wondered whether this wasn't an effort to get the prestige that goes along with science and also the protection that goes along with developing an independent discipline, which nobody else understands, and thus nobody else can properly criticize . . . ."

Those are hard words, coming as they do from distinguished educators.

A Warning to Liberal Arts Colleges . . .

Thus far I have been speaking about science and the liberal arts in general. Let me now particularize regarding the independent liberal arts college. It is no secret, I am sure, that in addition to the general problems facing all educational institutions, chiefly problems of finance and faculty, the liberal arts colleges have their own special problems.

Consider the matter of numbers alone. As a body the independent liberal arts colleges, for sound educational reasons, plan to grow very little in size in the next decade or two. It seems pretty certain that college enrollments nationally will at least double during this period and that the public institutions will take most of the increase. By simple arithmetic, then, the liberal arts colleges will be reduced to one half, relatively, in the postion they occupy in the educational system.

Whatever they may have to offer that is valuable or unique will become available to a smaller and smaller fraction of the total group. Unless they really do have something to offer that is valuable and unique and unless they are articulate about it, the independent liberal arts colleges will likely disappear as a potent factor in American education.

Officials of a sizable number of independent colleges appear to believe that they can best perform their function by concentrating upon increasing quality rather than by providing for increasing numbers of students. They look forward to becoming more selective in their enrollments. To have a quality college, however, there must be high quality in both student body and faculty. Fortunately, great emphasis is currently being given to the problem of faculties.

The second report to the President of the so-called Josephs Committee on

and modes of thought of the sciences as well as the humanities."

Education Beyond the High School is forthright in its conclusions and recommendations . . .

The most critical bottleneck to the expansion and improvement of education in the U. S. is the mounting shortage of excellent teachers. Unless enough of the Nation's ablest manpower is reinvested in the educational enterprise, its human resources will remain underdeveloped, and specialized manpower shortages in every field will compound. Unwittingly the United States right now is pursuing precisely the opposite course. Demands for high quality manpower have everywhere been mounting, but colleges and universities have found themselves at a growing competitive disadvantage in the professional manpower market.

The Committee believes that in order to make the teaching profession competitive financially with other professions, the salaries of college teachers will have to be raised by 100 percent or more by 1970. Bluntly the Committee asserts . . .

The plain fact is that the college teachers of the United States, through their inadequate salaries, are subsidizing the education of students, and in some cases the luxuries of their families, by an amount which is more than double the grand total of alumni gifts, corporate gifts, and endowment income of all colleges and universities combined. This is tantamount to the largest scholarship program in world history, but certainly not one calculated to advance education.

At a recent meeting of the American Council on Education, as reported in the *New York Times*, there was much discussion of the financing of higher education while maintaining quality, as the number of students increases nationally. To the question, "Can quality be maintained?," the educators answered: "Not unless the public finally realizes that education is more than a luxury item. As long as more money is spent for highways than for schools, just so long will education take a back seat." Less than one percent of our Gross National Product goes into higher education.

. . . and Their Unique Opportunity

Thus far I have painted a pretty dark picture of the present situation and of current trends. Had I believed the future is wholly dark, however, I should not have spoken at all. I believe that the faculty and students of the independent liberal arts colleges are in a strategic position to counteract some of the present trends. The liberal arts colleges have a unique opportunity, if they will only grasp it.

In outlining what is needed I can do no better than to quote from an address "Science and the Educated Man" by Dr. J. A. Stratton, Chancellor of the Massachusetts Institute of Technology . . .

Whatever its short-comings, education in science and engineering is on the move. I see no grounds for an equal confidence in the present state of the liberal arts. From the nontechnical colleges will come that body of educated men whose judgment and understanding must largely temper the public attitude toward science. Yet in a world that increasingly will be dominated by science and its products, it appears to me that liberal education has failed to keep pace with the changing character and expanding needs of the society which it should be designed to support.

Let me distinguish sharply between the ideals of liberal education and its current practice. These ideals are indigenous to western civilization; they do not alter with the times. A liberal education is designed to enlighten, to impart a love of knowledge and wisdom. Its essence, according to Whitehead, is an education for thought and for esthetic appreciation. It purports to deal with human values, with problems that are timeless. It undertakes to prepare the student to read, to listen, to see all that is lasting of man's works in art, music, literature, and thought.

But a liberal education must also be relevant to time and circumstance. It is an education for cultivated men in every walk of life and it should fit them to perceive and comprehend the great issues of our times, the forces that are shaping our destiny. It is my belief that modern man must take full account of the role of science and technology.

There is one great, unifying force working in our age, and that is science. We must turn to science for the lingua franca of modern men and find in science the vehicle of modern thought.

All the outer forms and even the inner forces of our contemporary civilization are molded and controlled by science and technology, and yet we have failed to make the understanding of science a part of our common culture. Anti-intellectualism, as it is called, the thinly veiled hostility to the "egghead," is the inevitable symptom of a distrust of the unknown . . . . We must allow no gulf to grow between scientists and the great body of educated people. The education of scientists and engineers is now too serious a matter to remain wholly the concern of the profession itself. The liberal education of all people is a matter of equal moment to us as scientists. In our generation the classical tradition has lost meaning and relevance. It contained values and standards that we must preserve in the new tradition of scientific learning that is now in the making. The age in which we live may provide man's greatest epic. We have in our hands the power to destroy ourselves or to survive in unity, in peace, and prosperity.

Writing in the *Atlantic Monthly* on "Scientist and Humanist," Professor I. I. Rabi, distinguished Nobel Laureate in Physics and Chairman of the President's Scientific Advisory Board, stated . . .

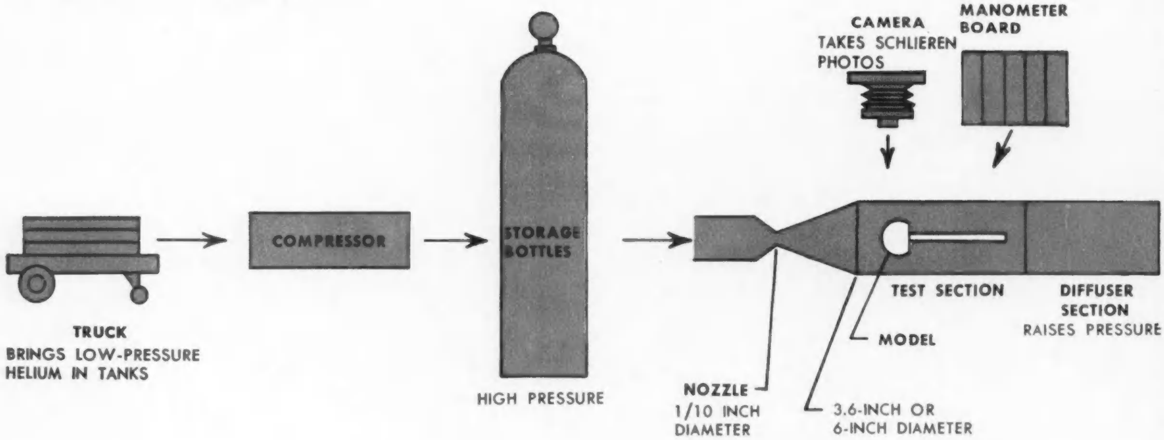
Anti-intellectualism has always been endemic in every society, perhaps in the heart of every human being. In times of stress this attitude is stimulated, and people tend to become impatient and yield to prejudice and emotion just when coolness, subtlety and reason are most needed . . . How can we hope to attain wisdom, the wisdom which is meaningful in our time? We certainly cannot attain it as long as the two branches of human knowledge, the sciences and the humanities, remain separate and even warring camps.

Integrating Science into Our Culture

Making science a part of our culture is a worthy objective for a college of liberal arts. Whether we like it or not, we do live in a technological civilization founded upon science, a civilization that will rise or fall as science and liberal education prosper or as they fail. To be truly literate, one must have an appreciation for the values and modes of thought of the sciences as well as of the humanities.

Too often in the past the humanists have exhibited a prideful illiteracy in science, and technical men have been notoriously illiterate in the humanities and the arts. It need not be so—in fact it must not continue to be so if we are not to succumb to the rising hysteria and anti-intellectualism of our times. Ω

HELIUM FLOW CHART . . .



Helium Tunnel Tests High-Speed Models

The Research Laboratory now operates what is believed to be the largest and fastest helium wind tunnel in the world. Helium, the same gas that fills slow-moving blimps, is being used in studies of problems associated with the ultrahigh-speed flight of satellites, missiles, and meteorites.

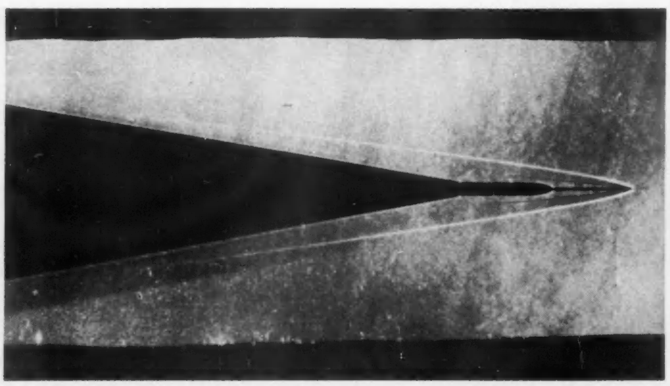
Highest Supersonic Speeds

With helium serving as a "stand-in" for air, the new facility has produced the highest Mach numbers ever attained in a wind tunnel, reaching velocities in helium corresponding to Mach number 28—28 times the speed of sound. According to Dr. Guy Suits, Vice President and Director of Research, the attainment of these record-breaking Mach numbers represents progress toward better understanding of the problems of high-speed flight.

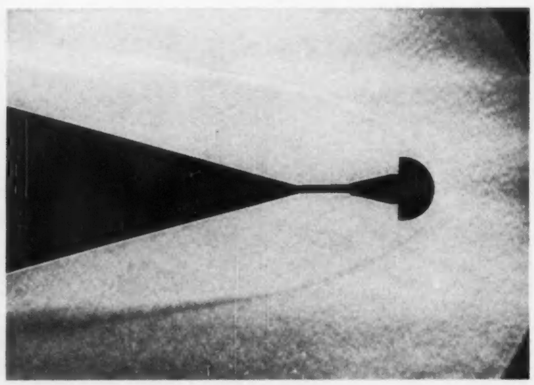
The launching of the first U.S. satellite, *Explorer I*, required speeds corresponding to a Mach number of approximately 25 in air. A Mach number of 35, based on sea-level sound velocity, would be necessary for an object to escape the earth's gravitational field. Mach numbers in this region may be reached in future experiments.

Studies at the Laboratory, partly sponsored by the U.S. Air Force, make use of a metal tube in which helium flows past a model that may represent, for example, a missile or its nose cone. In most conventional wind tunnels, huge compressors send a stream of air past the model being studied. But in this new helium tunnel, the compressed gas is stored in tanks and then allowed to escape through a nozzle into the test section, where a near-vacuum is maintained.

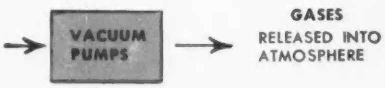
Then as the expanding gas rushes down the tube past the model, very high velocities—together with very low temperatures and pressures—are produced.

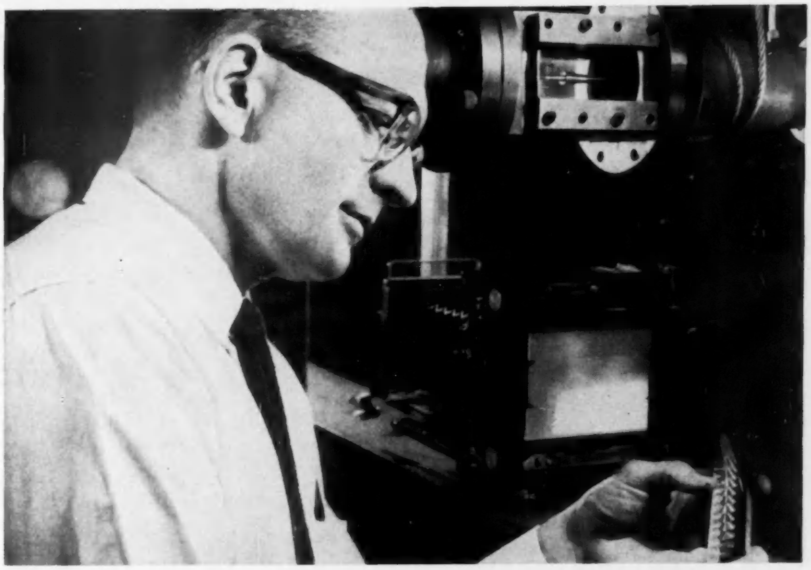


RAZOR BLADE is held in helium stream at Mach 22. The white line represents shock wave; the dark inside line marks the boundary layer.

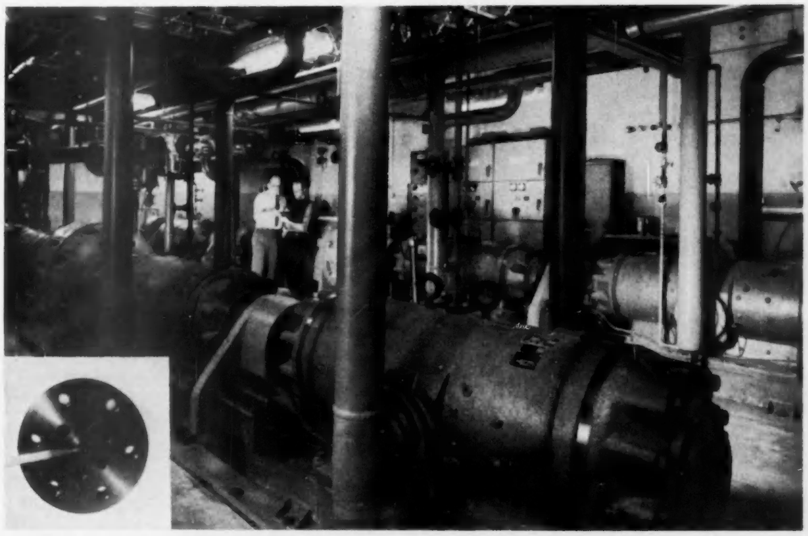


HELIUM FLOW forms shock-wave pattern around a ½-inch hemispherical model in tunnel at Mach 28.





CONE-SPHERE MODELS used in experiments relating to the very-high-speed flight of missiles are examined. Model is visible inside tunnel's test section (above schlieren camera).



VACUUM PUMPS for helium tunnel fill an entire room and maintain a vacuum in the test section of the tunnel. Helium flows through a 1/10-inch orifice (inset).

Static temperatures only two or three degrees above absolute zero have been obtained at the Laboratory during runs lasting from seconds to minutes.

More Research

"The growing interest of the General Electric Company in very-high-speed flight has resulted in a pressing need for a greater understanding of the flow of air above Mach number 20," stated Robert H. Johnson, mechanical engineer conducting the helium-tunnel experiments in the Laboratory's recently completed $1.2-million Gas Dynamics Facility.

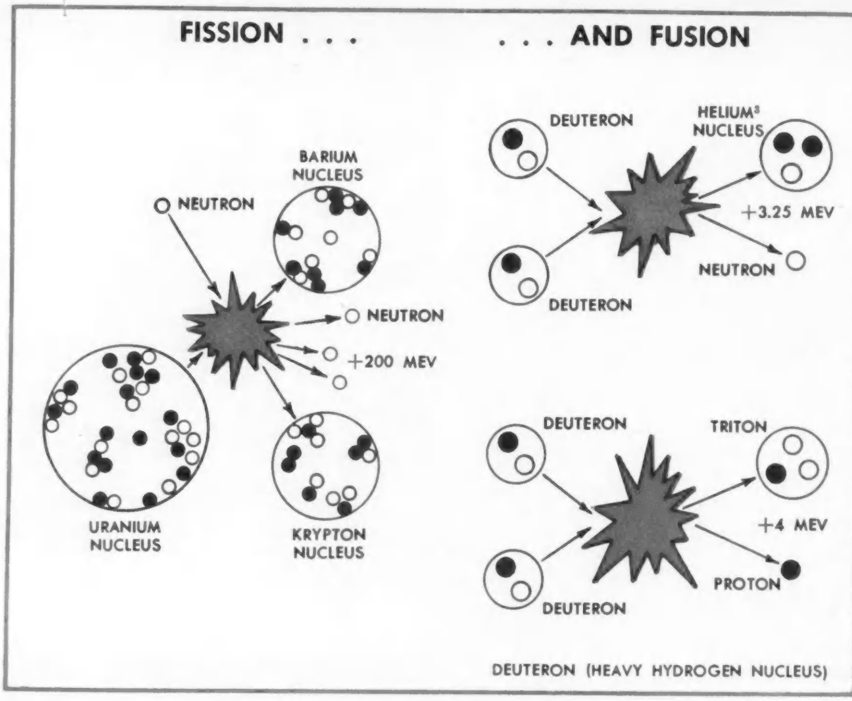
"This interest in the mechanics of fluids is not, however, a recent development for General Electric," Johnson added. "It began with the cut-and-try methods of the early days of the steam turbine and the oscillating wall fan. Today this empirical approach has matured into sophisticated theories that make possible continued improvements in the design of steam and gas turbines, as well as the acquisition of new knowledge in the field of very-high-speed flight."

Helium is used in the tunnel in order to avoid some of the complexities that face the researcher studying high-speed flight in air. At extremely high speeds, air breaks down into an assortment of elements, compounds, and ionized particles that bear almost no resemblance to the air we breathe. Helium, however, the stablest substance in the universe, is not subject to the great changes that occur in air's properties and composition. Additionally, helium has an extremely low liquefaction temperature, which ensures that it will not liquefy, as air would, when it passes through the tunnel passages and through the shock waves that occur in front of the model.

As a result of helium's more tractable behavior, it is possible, by analogy, to obtain information on the dynamic and viscous behavior of air at very high Mach numbers. This information, together with data from complementary research tools, such as shock tubes, contributes to a better understanding of the complex actual behavior of air under similar conditions.

Test sections with diameters of either 3.6 or 6 inches can be used in the tunnel, depending upon the Mach number desired. Models up to one inch in diameter can be studied, with data taken by means of manometer-board readings and schlieren photographs. The latter make visible the differences in pressure by means of variations in the refraction of light. Ω

While the fission process uses neutron bombardment to initiate splitting of a very large nucleus, fusion depends on a high-velocity collision of two light nuclei. About 0.1 percent of the nuclear mass is converted to energy either way.



The Problems of Mastering Thermonuclear Power

Controlled fusion could release power from deuterium in a gallon of water equal to energy from 350 gallons of gasoline—swelling man's fuel reserve immeasurably.

By DR. HENRY HURWITZ, JR.

Many people, laymen as well as scientists, regard the control of the fusion process to produce useful power as the most challenging problem faced by modern technology. Indeed, it has been said that the progress toward a controlled thermonuclear reaction announced recently by American and English scientists has more important bearing on the future of mankind than the launching of earth satellites.

The aspect of thermonuclear power most striking to the imagination is that it offers the possibility of fulfilling civilization's power needs for a virtually unlimited time. Perhaps I can most vividly express the magnitude of the energy reserves that would become available to us with its successful development by telling you that one gallon of ordinary water contains enough heavy hydrogen, or deuterium, to provide energy equivalent to 350 gallons of gasoline. This is despite the fact that the deuterium constitutes only about one part in 6000 of the hydrogen in ordinary water. Separating the deuterium from the ordinary water can be done at a nominal cost—only a few pennies per gallon of water processed.

Our excitement about this potentially vast source of energy must be somewhat tempered by the knowledge that we in the United States have fossil fuels that would last us for many decades if we were willing to burn them up rather than to reserve them for more important chemical processes. Then, too, the use of the fission process for fulfilling our power needs is rapidly approaching technical maturity, and our supplies of the raw materials needed for fission power is large indeed. Even with our rapidly expanding use of power, the fission process would suffice for many generations.

Advantages of Fusion Over Fission

But it is not necessarily true that the use of thermonuclear power would be deferred until our reserves of fissionable material were exhausted, any more than the use of fission power is awaiting the depletion of our reserves of chemical fuels. Indeed, we foresee certain advantages of the fusion process that would make us wish to utilize it at a relatively early date. For example, in a thermonuclear power plant the problem of radioactivity would be significantly less severe than in a fission power plant. Although some radioactivity would be associated with a thermonuclear plant, the worst actors—the long-lived fission products—would be absent. Also, ther-

Dr. Hurwitz—Manager, Nucleonics and Radiation Section at the Research Laboratory for the past 1½ years—joined General Electric in 1946. For 10 years he served on the staff of the Knolls Atomic Power Laboratory. Prior to that he was a physics instructor at Cornell University, and he worked at the Los Alamos Scientific Laboratory in Dr. Edward Teller's group on problems related to the hydrogen bomb. An outstanding reactor physicist, Dr. Hurwitz was named by *Fortune* in 1954 as one of 10 leading scientists in industry.

"Scientists seek methods never applied in nature—let alone by man."

monuclear power is particularly suited to directly converting some of the heat energy to electricity without the use of conventional turbines and generators.

Not yet knowing what all the practical problems of a thermonuclear plant would be, we cannot be sure that these plants, though technically feasible, would replace fission plants. But it seems unlikely that fission plants will be made obsolete by thermonuclear plants in the immediate future. Our interest in the long-range problems of fusion power must therefore not cause us to hesitate in the more immediate problem of developing the fission power industry.

To scientists, the quest for thermonuclear power has a great fascination even aside from the tremendous practical stakes. Fusion research leads us to the creation and study in the laboratory of conditions that exist only in the stars or, very transiently, in atom and hydrogen bombs.

We unfortunately do not have available to us the vast size and gravitational forces which lead to thermonuclear conditions in the stars. Although it has been seriously suggested that thermonuclear power be obtained from confined hydrogen bomb explosions, this brute force approach is, in many respects, less attractive than a fully controlled thermonuclear reaction.

Scientists who are trying to control the thermonuclear reaction are therefore forced to seek out methods that, as far as we know, have never been successfully applied in nature—let alone by man. Before describing these methods, I should like to discuss some of the fundamental properties of thermonuclear processes.

How Fusion and Fission Differ

First, let me clarify the difference between the fission and fusion processes (illustration). The fission process corresponds to the splitting of a very large nucleus, initiated by neutron bombardment. The fusion process, on the other hand, corresponds to joining two light nuclei, initiated by causing these nuclei to collide at high velocity. The somewhat paradoxical fact that both of these processes can liberate energy is explained by the circumstance that the neutrons and protons in nuclei of intermediate size are more strongly bound together than in either the lightest or the heaviest nuclei. Although only about one-tenth percent of the nuclear mass is turned into energy in either reaction, this relatively small conversion is nevertheless more than a million times greater than that typical in chemical reactions.

In addition to the deuteron-deuteron (D-D) fusion reactions, a fusion reaction can occur between deuteron and triton —heavy-heavy hydrogen. This deuteron-triton (D-T) reaction, in addition to liberating about five times the energy of the deuteron-deuteron reactions, occurs much more rapidly. Unfortunately, the hydrogen isotope tritium does not occur in nature, so that although it could be produced artificially by neutrons emitted from the fusion process, this added requirement would considerably complicate the operation of a thermonuclear power plant.

The experimental observation of the D-D reaction was first reported by Oliphant, Harteck, and Rutherford in England in 1934. Although only four years elapsed between the discovery of fission in 1938 and the first successful chain-reacting pile in 1942, scientists have already had a quarter of a century in which to consider ways to obtain useful power from fusion.

You may well ask, why has controlling the fusion reaction proved to be such a hard nut to crack? The answer is that we do not have the services of the neutron, which plays so remarkable a role in the fission chain reaction. The key to the neutron's effectiveness is that it has no electric charge and so can easily penetrate into the uranium nucleus and cause it to split. In the fusion reaction, on the other hand, both of the particles that participate have a positive electric charge, and so they repel each other because of the electrostatic force between two like charges. They can only come close enough to react if one of them is shot toward the other with high enough velocity to penetrate the barrier.

Energy Balance

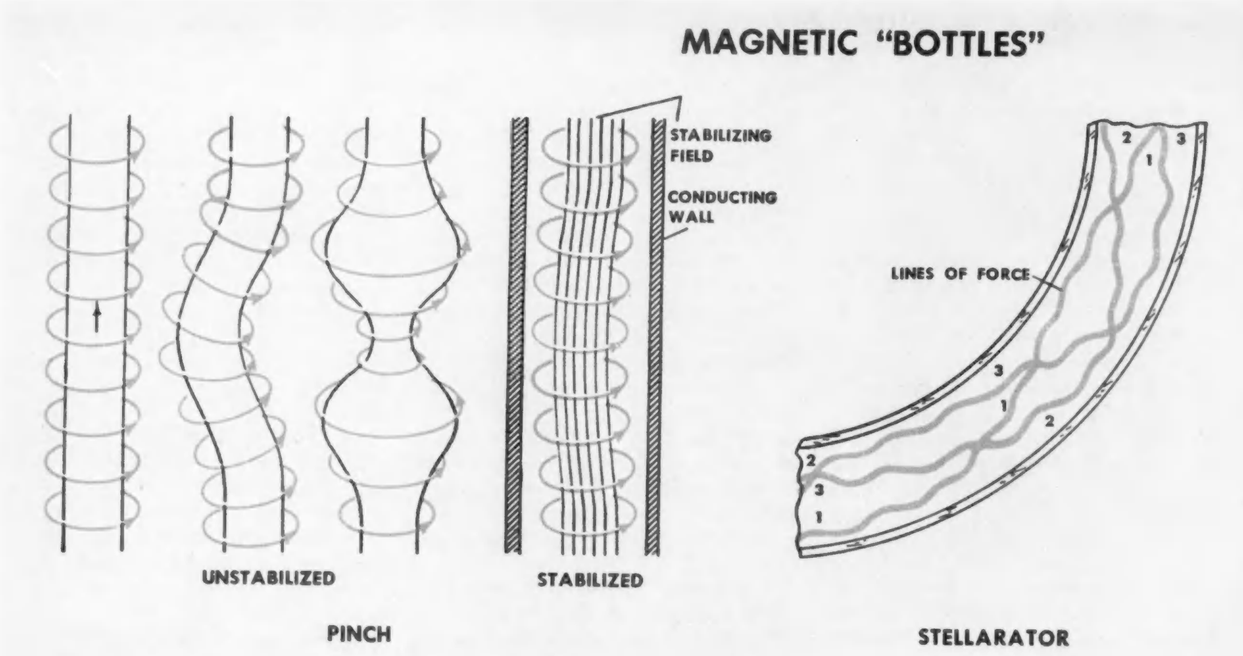
Fortunately, in the fusion reaction the energy required to produce the reaction, though large, is small compared with the energy liberated in the reaction. For example, the reaction "cross section" (a measure of probability of the reaction) becomes large when the relative energy of the reacting particles is a few tens of kilovolts, whereas the energy yield for the D-D reaction is about 3.5 Mev. (An Mev—the energy attained by an electron on falling through a potential of a million volts—is 1.6×10^{-6} ergs.)

Again, you may ask, why can't power be generated by simply accelerating a beam of deuterons and firing it into a deuterium target? (This is essentially how the reaction was discovered in the first place.) And again, the rub lies in the Coulomb force between charged particles. A long-range force, it acts over large distances, causing many more scattering collisions than actual nuclear reactions. These scattering collisions provide an effective means of energy sharing between particles by the billiard-ball effect. Hence, if a high energy deuteron is shot into a target, it will very quickly give up all its energy to the target particles, and only rarely will a nuclear reaction ensue. The nuclear reactions that do occur provide a slight contribution to target heating beyond that due to the kinetic energy of the incident beam alone. But the infinitesimal gain in energy cannot be effectively used to produce net power output, because this gain is much smaller than the losses inherently associated with converting heat back to electricity.

Many otherwise ingenious schemes for obtaining energy from the fusion process have foundered upon the fact that the energy exchange between charged particles by Coulomb collisions is so large. A careful study of the relevant numbers forces the conclusion that there is little likelihood of finding any scheme, however clever, that will produce a net energy yield under conditions in which the temperatures of the various types of charged particles are not of comparable magnitude.

Because energy loss by radiation requires a relatively long time, we can envisage a situation in which the particle temperatures are high and the radiation temperature is low. This is most fortunate. For at the temperatures at which the fusion reaction begins to take place at a significant rate, the pressure and heat flux of thermal radiation would be entirely too large for terrestrial mechanisms to handle.

The major process by which a hot, fully ionized gas can radiate is the acceleration of the electrons as they collide with the ions. The rate of radiation varies directly as the square root of the temperature. On the other hand, the rate of the fusion reaction increases



Confining Gas Plasma at stellar temperatures has been attempted with current-carrying gases that rely on the stabilized made with the recently announced stellarator and mirror devices, which use current in ex-

exponentially with temperature in the relevant range. Because the energy production increases more rapidly than does the radiation loss, we can define an ignition temperature for a thermonuclear reaction above which the energy production exceeds the radiation loss. This temperature is 35 kv, or 350-million degrees Kelvin (K), for the D-D reaction, but only 4 kv, or 40-million degrees, for the D-T reaction. The ignition temperature provides a lower limit to the temperature at which a thermonuclear power plant must operate, because a gas heated to a temperature below the ignition point will cool off before much fusion energy has been generated.

The quoted ignition temperatures are based on the assumption that the reacting gases are pure. Because the radiation losses are drastically increased by small impurities of high atomic weight, the purity of the reacting gas is an important prerequisite to the successful achievement of a self-sustained thermonuclear reaction.

Magnetic Containment—Key Concept

The key concept that scientists hope to employ in maintaining a gas at the phenomenally high temperatures required for the thermonuclear reaction is that of magnetic containment. This concept is applicable because in the temterature range of interest the gas is completely ionized—an assembly of free electrons and bare nuclei and an assemblage of charged particles customarily referred to as a *plasma*, a term introduced by Langmuir. The practical use of a magnetic field to control the orbits of charged particles dates back to the work of Dr. A. W. Hull on the magnetron in 1921.

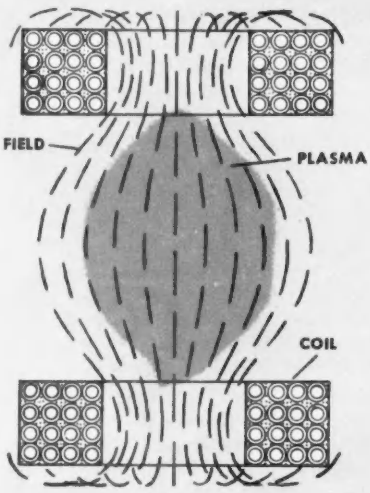
Before discussing the problems associated with magnetic containment, I should like to focus on the specifications that the magnetic "bottle" must satisfy.

If the plasma contains 10^{15} nuclei per cubic centimeter, which is a reasonable figure to consider, the minimum reaction mean-free path is several thousand miles. The magnetic bottles must thus be so perfect that a particle can bounce around inside while traveling a distance comparable to the earth's circumference without finding a hole through which it can escape.

It can be shown that the ratio of the fusion energy generated to the energy invested in heating the plasma is proportional to the product of the pressure times the containment time of the plasma at a given temperature. For example, for the D-D reaction at a pressure of 100 atmospheres and a temperature of 500-million degrees K, the containment time must be about 10 seconds so that the nuclear energy generated equals the energy originally supplied. The corresponding time for the D-T reaction is only about 0.1 second.

The ability of a strong magnetic field to contain a high temperature plasma is based on the fact that a particle moving in a magnetic field must follow a helical path around the magnetic field lines and so is, in effect, partially immobilized by the field. The helical motion, however, tends to reduce the magnetic field so that there is a limit to the containment pressure the field can exert. The arguments used by Clerk Maxwell a century ago to derive the magnetic stress tensor show that this limiting pressure is $B^2/8\pi$. Thus, for example, a 50-kilogauss magnetic field is in a sense equivalent to a wall that can sustain a pressure of 100 atmospheres.

The magnetic wall is, unfortunately, not completely impervious to penetration by the plasma, because collisions between the individual particles cause their orbits to be displaced from their initial magnetic field lines. This process results in a gradual diffusion of the plasma through the magnetic field. The diffusion phenomenon is closely related



pinch effect; similar attempts have also been
ternal coils for their confining fields.

to the fact that the electric conductivity of a plasma is not infinite but limited by the collisions of the plasma particles with each other. Fortunately, the electric conductivity of a plasma at thermal nuclear temperature is extremely high—about 100 times that of copper—so that the diffusion process is expected to take place slowly enough to achieve the required containment times.

Besides strength and leak tightness of the magnetic wall, we must consider the crucial question of stability. On the basis of my foregoing arguments, an engineer could, with perfect equanimity, design a water tank with the water stored at the top and the air space at the bottom. He would see no need of providing a baffle at the air-water interface to prevent the water from splashing down upon whatever happens to be at the bottom. Unfortunately, the thermonuclear engineer has so far not had the practical experience with the new regime of hydromagnetic plasmas that enables him, by common sense alone, to avoid such obvious boners. He must therefore make complex calculations on each magnetic field and plasma configuration one wishes to propose, to demonstrate not only that it is in static equilibrium but also that small displacements away from equilibrium position will tend to decrease rather than to grow with time.

The Stabilized Pinch . . .

The theory of hydromagnetic stability has been extensively developed in recent years so that it is now possible to analyze the stability of a large class of geometries on the basis of approximations having qualitative validity, at least. Many plasma geometries are unstable both theoretically and experimentally. But at least one configuration possesses a region of complete stability according to current theories—namely, the *stabilized* pinch.

For half a century electrical engineers knew of the pinch effect in conducting liquids. This phenomenon occurs when a large current passes through a fluid that tends to contract as a result of the attractive force between parallel current elements. In 1937, Dr. L. Tonks of the Research Laboratory gave a detailed theoretical discussion of its effect as applied to gaseous discharges.

An elementary consideration of the balance of forces in the pinch would lead to the conclusion that the equilibrium temperature is proportional to the square of the current. From this point of view the pinch effect would appear to be ideally suited for producing a controlled thermonuclear reaction, for it would only be necessary to raise the current to a sufficiently high value to obtain the necessary high temperature. Unfortunately, one cannot carry this process very far before running head-on into the problem of stability.

The idealized pinch geometry has uniform rings of magnetic field constricting the plasma through which the discharge is passing (illustration, left). When a small perturbation is produced in the second and third configurations, the magnetic field distorts in such a way that it tends to amplify the perturbations. Theoretically, the imperfections that will always exist in any real situation will grow with a velocity limited only by the sound velocity in the plasma. Because the sound velocity is extremely high (10^8 cm/sec) at thermonuclear temperatures, the unstabilized pinch geometry does not offer promise of providing long-time confinement.

A natural means of attempting to eliminate the instabilities is to use external coils to apply a magnetic field in the direction of the plasma electric current. Another helpful device is to make the walls of the discharge tube out of a conducting material that, on a short-time scale, cannot be penetrated by the magnetic field. Thus, if the plasma moves toward one side of the tube, the magnetic lines of force are compressed and so tend to push the plasma back toward the tube center. Still another improvement in stability would be realized if the longitudinal stabilizing field could be made to exist only in the region where the plasma is located and not external to the plasma. If the current in the plasma were located mainly on the plasma surface, it would create a sharp discontinuity in the magnetic field direction at the plasma surface, which provides a beneficial basket-weave effect.

Fortunately, we don't have to invoke the services of "Maxwell demons" to obtain a well-separated field configuration. For a longitudinal magnetic field initially present in the discharge tube tends to be trapped in the plasma when it becomes ionized, because of the high electric conductivity. Because the walls of the discharge tube are also conducting, the total longitudinal magnetic flux in the tube must remain constant as the plasma is compressed, and therefore the flux outside the plasma must vanish.

The advantages of the trapped field configuration were recognized a few years ago by scientists in the AEC Project Sherwood, and they were pointed out independently in a report by Levine and Combes of Tufts University. Theoretical studies by M. N. Rosenbluth in this country, R. J. Taylor in Great Britain, and V. D. Shrafranov in Russia showed that the configuration is indeed completely stable, provided that separation of the longitudinal and azimuthal magnetic fields is sufficiently sharp and provided that the plasma is not compressed to a radius so small that the stabilizing effect of the conducting walls is lost.

Although the discovery of a fully stabilized pinch configuration constituted an extremely important step toward the ultimate goal, the progress did not come cheaply. For one thing the necessity of providing a stabilizing field that pushes out against the constricting field means that the energy that must be invested in creating a magnetic bottle of the requisite net strength is substantially increased. More important, the fact that we cannot compress the plasma without limit and still retain stability means that attaining sufficiently high temperatures is more difficult. We must now largely rely on such mechanisms as shock heating while the plasma is being pulled away from the tube walls and upon heating by the resistive effects

MECHANICAL SWITCH developed by Dr. W. F. Westendorp is used in large-scale plasma experiments; it can accurately control power in the order of 1000 megawatts.

associated with the various currents flowing through the plasma. The latter effect is a double-edged sword, for it is intimately associated with the diffusing away of the magnetic field that confines the plasma. To what extent we can have our cake and eat it too remains to be seen.

Serious experimental investigations of the pinch effect as a possible means for producing a thermonuclear reaction were initiated several years ago by the groups of P. C. Thonemann and A. A. Ware in England, and the group of J. C. Tuck in the United States. Early Russian pinch studies were reported by I. V. Kurchatov in 1956. The first experiments were conducted in straight or toroidal tubes without provisions for stabilization. These experiments demonstrated that one could produce temperatures of the order of 10^6K (100 volts) for transient periods, but that after a few microseconds the instabilities develop to the point where the plasma touches the tube walls and the high temperature and ionization are lost.

These early experiments dramatically did produce fusion reactions, as evidenced by the appearance of neutrons. But a painstaking series of experiments reported by S. A. Colgate and associates in Project Sherwood gave the discouraging result that these fusion processes did not occur because the plasma was hot, but rather because the plasma was unstable. In other words, the fusion reactions were associated with the violent turbulence that occurs during the breakup of the plasma. The turbulence associated with the instabilities causes such a vast drain of energy, it is little comfort that it also causes a relatively few fusion reactions. At first, the attempts to stabilize the pinch effect reduced the neutron yield; but in the more recent experiments the neutrons are again relatively abundant, and the plasma temperatures may be well above a million degrees.

One of the most interesting pieces of equipment being used in the current crop of stabilized-pinch experiments is the British *Zeta* machine at Harwell. *Zeta*—a large metal-walled toroidal tube —is filled with gas at a pressure of about 10^{-4} mm of mercury. The gas acts as the one-turn secondary of a large transformer. The primary of the transformer is fed by electric current from a capacitor bank, which stores about half a million joules of energy.

Because of the large physical size of this apparatus as compared with that of the machines in other laboratories, the time scale has been spread out from microseconds to milliseconds. This facilitates many of the measurements.

Experiments with this machine have shown a neutron yield consistent with an ion temperature of 500 volts (5-million degrees). Doppler broadening measurements of optical lines from nitrogen and oxygen impurities also are consistent with a temperature of the same magnitude. These facts were originally cited as evidence that the fusion events were probably not associated with instabilities but were indeed bona fide thermonuclear reactions.

Unfortunately, recent experiments on the angular distribution of the neutrons have indicated that the fusions are in fact not produced by deuterons in thermal equilibrium. It is therefore necessary to ascribe the high velocities of some of the plasma particles to instability phenomena akin to those occurring in the earlier unstabilized pinch experiments. The actual situation that prevails in the plasma is somewhat obscure.

The suggestion has been made that certain phenomena discovered by Langmuir many years ago are at work. These phenomena, which relate to a strong interaction of single particles with collective oscillations of the entire plasma, might very well play a significant role in producing the rapid heating observed. However, perhaps these phenomena, welcome as they are for heating, will accelerate the decay of the magnetic field and thereby make the containment time altogether too short.

One hopeful aspect: if the temperature can be successfully increased, the plasma conductivity should also increase so that the containment times should automatically become longer. Also, at the higher temperatures that may soon be obtained, the neutron yield becomes a much more reliable indication of what is actually going on. This means that progress in the immediate future may be rapid indeed.

AEC scientists have recently described two additional magnetic containment configurations differing from the pinch effect in that the confining fields are produced entirely by currents in external coils. The external current approach has the advantage of enabling the magnetic fields to be maintained and controlled more easily. But it sacrifices some of the inherent simplicity of the pinch concept and does not so effectively use the magnetic-field energy.

. . . the Stellarator . . .

The first of these newly disclosed devices, known as the stellarator, is being explored by the Matterhorn Project under the direction of Prof. L. Spitzer of Princeton University. The stellarator concept developed from the idea of holding a plasma in a field configuration having no ends. The simplest configuration of this type—namely, the field produced by a toroidal solenoid current winding—is, however,

toward larger and more powerful experimental machines."

unsuitable because this field is not homogeneous throughout the cross section of the tube. This inhomogeneity can be shown to cause a drift of particles perpendicular to the lines of force that would seriously limit the containment time. Spitzer has pointed out that this difficulty is avoided if the individual lines of force do not close upon themselves after they have gone around the tube.

One means of producing this so-called magnetic field "transform" is to build the tube in the form of a figure eight. A second, possibly more convenient procedure, is to add special helical current windings around the torus, causing the magnetic lines of force to oscillate and gradually rotate as they go around the tube (illustration, right, page 20). Initial heating of the plasma can be accomplished by inducing a current around the tube as in the toroidal pinch experiments. This current is not large enough, however, to cause the plasma to compress. To attain thermonuclear temperatures, it is expected that another heating mechanism will have to be employed in which the magnetic lines of force will be made to move radially inward and outward by alternately increasing and decreasing the magnetic field. We expect that this magnetic pumping will heat the plasma in much the same manner as ordinary gases can be heated by rapid compression and decompression.

Ideally, a thermonuclear reactor based on the stellarator principle would function as a steady-state device and so would be free from the inefficiencies that tend to be introduced by pulsed operation.

. . . and the Mirror Machine

The second recently announced magnetic configuration—the mirror machine—is based on the fact that charged particles spiralling around a magnetic field line tend to be reflected by a region where the magnetic field is stronger so that the magnetic lines come closer together (illustration, page 21). Thus the relatively weak field region between two separated coils will contain charged particles quite effectively, particularly if the energy of the particles is high so that Coulomb scattering collisions are relatively rare. An interesting feature of the mirror geometry is that high energy particles injected into the containment region can be trapped if the magnetic field is made to increase rapidly with time. The increasing magnetic field also serves to add to the kinetic energy of the particles by inductive effects. An extensive program is under way in the AEC Livermore Laboratory, under the leadership of R. F. Post, to explore the applicability of the mirror concept to thermonuclear machines.

A second program using the mirror configuration was recently initiated at Oak Ridge. This program, aimed primarily at the injection and ignition problems, hopes to overcome the serious current limitations of high-energy ion sources by a scheme in which the plasma density can be gradually built up to the desired value. The key discovery that made this approach feasible is that certain arcs developed by John Luce at Oak Ridge have the property of converting deuterium molecular ions to atomic ions with surprisingly high efficiency. Therefore, if the arc is run in a strong magnetic mirror configuration, high-energy deuterium molecular ions, which can be shot through the arc, are converted to atomic ions, which have trajectories of smaller radius of curvature and so are trapped by the magnetic field. Presumably, this injection principle could also be applied to the stellarator configuration.

The Bold Push Ahead

At the present stage of our thermonuclear program—on the threshold of producing thermonuclear events but not yet having achieved the major milestone of a self-sustained reaction above the ignition temperature—it is clearly too early to say which approach will be most fruitful. We are somewhat in the position of a tribe of primitive men attempting to produce fire by such methods as rubbing sticks or striking stones against each other. We observe hopeful signs analogous to traces of smoke and sparks but have not yet seen the crucial first small flame.

To determine whether the ingenious thermonuclear schemes will succeed in their ultimate objective of providing a practical source of power, we must push ahead boldly toward larger and more powerful experimental machines. This requires solving the imposing engineering problems we encounter in learning to handle higher power and higher total energy and to improve our control over the properties of the plasma with which we must work. Typical of the equipment applicable to these relatively large-scale plasma experiments is a mechanical switch (photo) developed by Dr. W. F. Westendorp of the General Electric Research Laboratory. This switch can accurately control power in the order of 1000 megawatts.

But in the enthusiasm of our quest for more intense discharges and higher temperatures, we cannot overlook the need for investigations aimed more directly at enhancing our understanding of the basic properties of the high-temperature plasma upon which we center our hopes. It is one of the ironies of thermonuclear research that the production of a fully ionized plasma under well-controlled and well-understood conditions is of commensurate difficulty with the production of a thermonuclear reaction itself. This means that great ingenuity and skill must be directed toward the design and execution of experiments if they are to provide us with interpretable information rather than confusion.

The intensity of the effort being applied to solving the problems of thermonuclear power is increasing rapidly throughout the world. Our group at the General Electric Research Laboratory in Schenectady is one of the latest to join in the investigation. We eagerly look forward to playing an active role in the exciting thermonuclear research that we foresee in the years to come. Our only regret is that Irving Langmuir could not still be here to guide us through the amazing territory, whose landmarks he so clearly perceived many decades ago.Ω

As part of a series of studies to determine radiation effects on chemical compounds and living organisms, Dr. Hans M. Rozendaal examines living human cells being exposed to cobalt-60.

Radiation Works for Man—Biological Studies Use

Modern researchers delving into the effects of radiation are making progress that m beneficial discoveries affecting such important areas as food and drug sterilizatio

Living human cells exposed to radiation from a piece of cobalt-60 represent part of man's continuing effort to come to terms with a changing environment. This work is part of an attempt to learn more about the effects of radiation on chemical compounds and living organisms—a subject that might well have seemed remote a generation ago but that has assumed a disturbing urgency today.

For a number of years, these and similar studies have been conducted in the General Electric Research Laboratory's Biological Studies Section. Dr. Hans M. Rozendaal heads the Section, assisted by Dr. W. Dexter Bellamy. Several years ago, the possibility of sterilizing food and other materials by means of radiation led Bellamy to begin a study of the effect of radiation on bacteria. In the course of this project, he determined the amount of radiation required to kill various types of organisms. After completing this work, he became interested in discovering the factors that could change the sensitivity of these bacteria to radiation from x rays. Recently he has been investigating the effects of such radiation on proteins and amino acids—basic building blocks in living material.

Food Sterilization

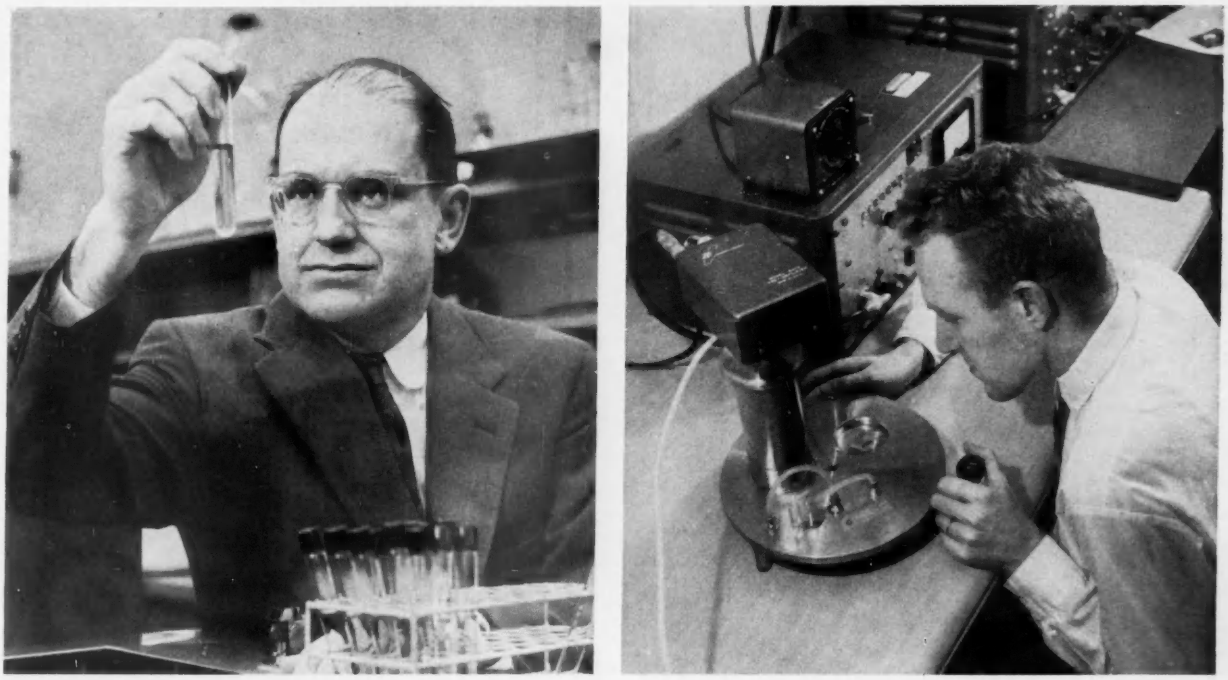
Work in this field by Bellamy and others has brought knowledge of the subject to the point where the U.S. Army Quartermaster Corps has been scheduling large-scale experiments. The Corps plans to sterilize food by irradiation in quantities as high as 1000 tons a month. Sterilization by means of ionizing radiation is expected to be particularly important when applied to certain materials, such as drugs, that cannot readily be sterilized by heat or chemicals.

Cell Growth

Members of the section next turned to the problem of how radiation would affect the growth of isolated cells obtained from animals and humans. For the studies, they use techniques that make it possible to grow many generations of these cells in incubators kept at body temperature. The collection of cells that has been built up includes specimens from normal human skin, liver, and bone marrow as well as cells obtained from cancerous growths in similar organs.

These cells, after having been grown and carefully nourished during their stay in the incubator, are exposed to electron beams, x rays, and ultraviolet and infrared radiation. Study under the microscope then reveals the reaction of both the normal and abnormal cells.

Differences in sensitivity between the various types of cells constitute one important study area. It is possible that a way might be found to protect cells from the undesirable effects of radiation, perhaps this could be achieved by the addition of chemical compounds or by



Radiation Studies Dr. W. Dexter Bellamy (left) conducts studies to determine the effects of radiation on bacteria. Radiation specialist Charles Malone monitors radioactive tracers in irradiated tissue.

a New Tool

ay eventually lead to
and cancer control.

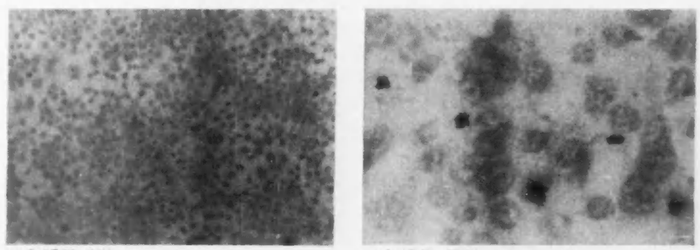
a change in the oxygen content of their environment.

Amino Acid Changes

Tissue cultures are also being used in other projects. For example, exposure to large amounts of ionizing radiation can produce chemical changes in compounds normally present in the human body. In some experiments, the exposure of amino acids to very large doses of high-energy electrons has produced changes that make the compounds act differently toward the growth of bacteria and cells in tissue cultures. Rozendaal and his associates are attempting to learn more about what the newly formed compounds are and why they can inhibit the growth of bacteria and tissues.

Metabolic processes in the treated cells are also being studied by means of radioactive tracers. These substances can be tracked with great accuracy and give valuable information concerning changes in vital functions. Ω

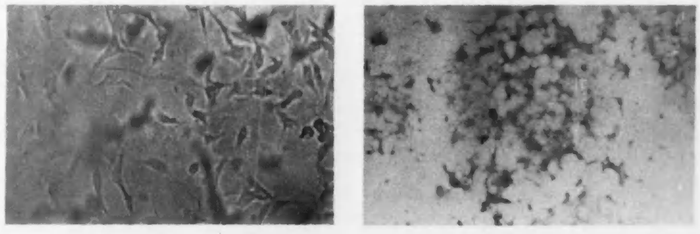
EFFECTS OF IRRADIATION



MAGNIFIED 50X MAGNIFIED 670X

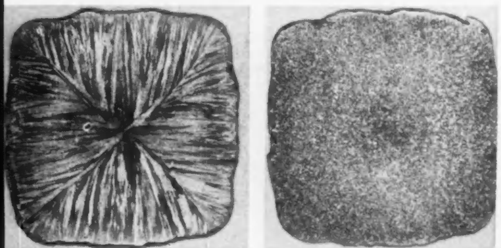
Before Irradiation

Dark areas are chromosomes, grouped together in cancer cells that are about to divide. The large number of cells in the process of division reflects the rapid growth—a characteristic of cancer.



After Irradiation

Irregularities in size and shape of cells exposed to 500 roentgens from cobalt-60 indicate partial destruction (left). Same cells are completely destroyed after exposure to 1000 roentgens (right).



By inoculating a casting with special additives, scientists in the Research Laboratory have produced stainless steel with greatly refined grain structure (above, right) compared with characteristic columnar grain. This technique, although still experimental, resulted from a better basic understanding of how metals freeze from the melt. With E. Van Patten (center) are metallurgists James L. Walker (left) and A. J. Kiesler.

Refining Grain Structure by Inoculation

The Metals and Ceramics Building at General Electric's Research Laboratory is a unique research facility. It resembles a metal-processing factory, with industry-size melting furnaces, extrusion presses, rolling mills, forging hammers, and heat-treating furnaces. But the building is used only for research and has no production schedules to meet. Here scientists, assisted by experienced metalworkers, perform experiments that approach the scale of industrial operations to test many of the principles discovered in the laboratory. New materials and processing methods are developed and evaluated, and significant processes are enlarged before turning them over to operating components of the Company.

Experimental Stage

Near the rear of the high-bay area and to the left of the mezzanine structures, a project is under way that exemplifies an important phase of the work being done in the new building. Two Research Laboratory metallurgists, A. J. Kiesler and J. L. Walker, are performing experiments in an attempt to control the grain structure of stainless-steel castings during the process of solidification from the melt. Molten stainless steel is poured from an induction furnace into a mold, and immediately a finely divided powder is added to the melt. By this inoculating technique, Walker and Kiesler have produced experimental ingots of stainless steel with greatly refined grain structure—a structure expected to improve the properties of the casting, especially its ductility.

Dr. R. L. Fullman, manager of the Laboratory's Materials and Processes Studies Section, illustrates the significance of such work by pointing out the great number of processing steps through which a metal is ordinarily routed to attain the desired grain structure. Fullman states . . .

> It's not uncommon for a metal to be cast, reheated, forged, reheated, rolled, and then heat-treated—all to produce the desired grain structure. The truth is that frequently the only reason for casting an ingot first, rather than casting the metal directly to the final shape, is that much reliance is placed on further processing to achieve the desired structure and, therefore, the desired properties. If we ever find how to control the structure in the freezing process so that these properties are in the casting, further working will frequently become unnecessary, and the final product will be a great deal cheaper.

The properties of a metal are determined by two factors: 1) the composition—in gross terms, so much carbon, so much iron, so much nickel—and 2) the structure, which includes the size and shape of grains (crystals), the nature of the boundaries between the grains, the presence of second phases (that is, smaller crystals dispersed in the grains or along the grain boundaries), and residual stresses in the material.

Because structure depends largely on the processing of metals, a concentrated effort is now being made both here and elsewhere to apply scientific principles to the many phases of metal processing. Walker and Kiesler's objective: prepare fine-grained structures from an ordinarily coarse-grained material. In other instances, notably alnico magnets, the reverse is true: coarse columnar-grained materials (which maximize the magnetic properties) are derived from ordinarily fine-grained materials.

Producing Grain Refinement

The method of producing grain refinement in stainless steel, developed by Walker and Kiesler, is accomplished by adding to the melt a material that produces two effects: 1) provides nuclei around which crystals can form from the melt and 2) changes the freezing temperature in a localized region of the melt so that the nucleation particles will be able to effectively produce grain refinement.

The study of nucleation is concerned with how the first solid material forms from the liquid in the freezing process. In a crystalline solid the atoms form an orderly geometric array; however, in a liquid they are disposed essentially at random. Thus the problem of nucleation is to bring order from chaos—thermodynamically possible only under certain conditions.

When the free energy associated with the solid is lower than the free energy of the liquid, freezing can occur. When the energy balance is tipped the other way, freezing cannot occur. These energy terms are related to the temperature and the size of the particle trying to grow. A particle must be larger than a certain critical size before it can grow from the melt at a given temperature—the smaller the particle, the colder the liquid phase must be.

It has been known for some time that phase changes are nucleated by bits of foreign matter larger than critical size and sufficiently like the freezing crystals to act as seeds for their growth. When such particles are absent, a liquid requires a large amount of supercooling before it begins to freeze. A spectacular demonstration of nucleation was afforded by the famous weather experiments of Langmuir, Schaefer, and Vonnegut, when silver iodide crystals were used as nucleating agents in producing snow from the supercooled vapors in clouds.

Vonnegut later turned his interest to the study of nucleation in metals. He joined Dr. David Turnbull, and together they worked out a theory correlating the effectiveness of certain nucleating crystals with the degree of similarity between their crystal structure and that of the freezing crystal.

Applying the Theory

Then Turnbull and Walker got together and planned a research project that would apply the theoretical work of nucleation to practical foundry work. The grain-refinement program arose from this planning. Later Kiesler—a metallurgical engineer with wide experience in foundry practice—joined Walker.

Solidification of tiny droplets of metal in a laboratory experiment and solidification of a foundry-size casting, of course, pose many different problems—a major one being that of heat transfer. Consider what happens when molten metal is poured into a mold (illustration). Because the melt cools more rapidly near the mold walls, solidification begins there. Grains start to form around impurities at the walls, then gradually extend toward the center of the melt. For solidification to proceed, heat must be conducted from the liquid through the liquid-solid interface and into the mold wall. Because the heat flows in that direction, the liquid ahead of the interface must be hotter than the interface, which is at the freezing temperature, and nucleation cannot occur except at the interface. The grains that form near the mold walls ordinarily continue to grow; no new grains are permitted to form ahead of them in the melt, even though the proper type of nucleating centers may be available. This type of growth accounts for the characteristically large columnar-grain structure of stainless steel.

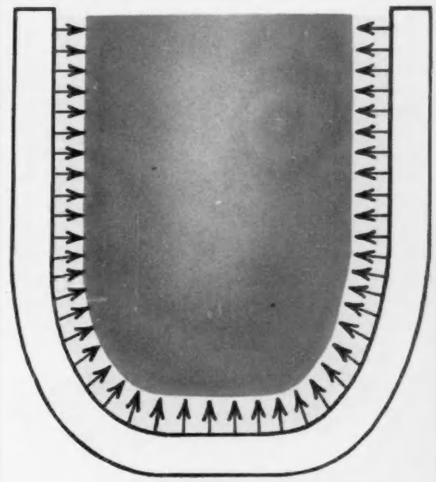
Fortunately the principle of constitutional supercooling can be utilized to prevent columnar growth. Walker and Kiesler did this by adding certain materials to the melt that alloy with the metal being cast but have greater affinity for the liquid state than for the solid. As the crystal freezes from the melt, it rejects part of this material and enriches the solution near the interface. Therefore, the liquid immediately ahead of the interface has a composition different from that of the rest of the melt; if the impurity is the proper type, it also has a lower freezing temperature.

Now solidification proceeds in this manner: As before, crystals first begin to form at the mold wall; as they grow, the liquid just ahead of the freezing zone changes to a composition with a lower freezing temperature than the rest of the melt. The temperature profile remains the same: the liquid is hottest at the center of the casting and coolest at the mold walls.

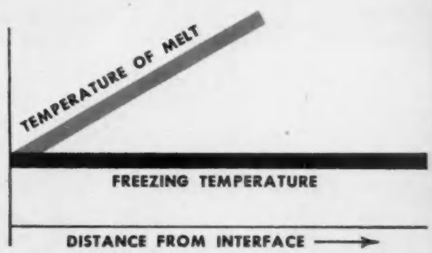
But now this zone of changed composition acts as a buffer to keep the metal immediately adjacent to the frozen part in the liquid state until the liquid elsewhere has cooled below the freezing temperature of the main composition. Thus crystals will form in the interior of the melt rather than at the interface, even though the temperature of the interior is higher. As a result the columnar grains are choked off, and the desired fine-grained structure is achieved.

Nucleating centers of the proper type are still necessary for solidification. Thus two types of impurities must be added for grain refinement: a soluble impurity to produce constitutional supercooling and an insoluble impurity to form the nuclei for freezing. Ω

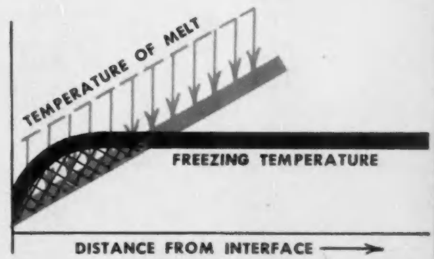
EFFECT OF SUPERCOOLING



COLUMNAR GRAINS form at mold wall, grow inward. Additive rejected from growing crystals accumulates near interface and depresses the freezing temperature there.



PRIOR TO INOCULATION, or in the usual situation, metal is at freezing temperature only at liquid-solid interface; so columnar grains grow inward from mold walls.



AFTER INOCULATION a supercooled region—represented by the crosshatched area—is formed, and new grains begin to freeze out ahead of the advancing interface.

AUTOIGNITION

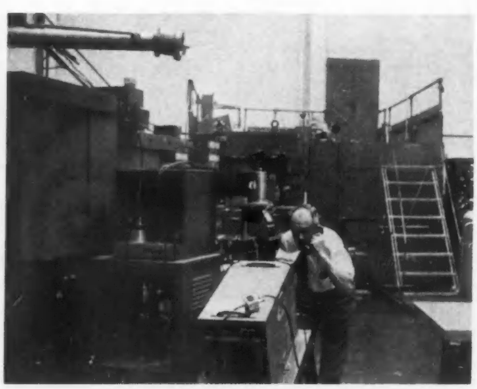
A shock tube in the Combustion and Gas Dynamics Building is being used to study how liquid-fuel sprays burn when injected into air at high temperatures and pressures. In a 50-foot-long tube, air at 500 psi bursts an acetate diaphragm, sending a shock wave down the tube at velocities up to 1.5 times the speed of sound. C. W. Moon (photo, left) is shown installing this diaphragm. After the shock wave has been reflected from the end of the tube, fuel is injected into the air, which is at predetermined temperatures ranging between 600 and 1300 F.

George Mullaney photographs the reaction that takes place at speeds up to 8000 frames per second, with the aid of the Fastax camera.

From these films and other instrumentation, new information that may prove important in engine design is gathered on the vaporization of the fuel, the time lag between injection and ignition, and the "fast reaction" in which the fuel burns.

Probing into Chemical and Physical

Synchrotron helps nuclear physicists investigate structure discharge phenomena in original gases with shock tubes



STRUCTURE OF MATTER

High-energy research revolves about the 300-million electron-volt (Mev) synchrotron. In its design and construction, as well as in its continued application to research problems in nuclear physics, it stands as the latest in a series of noteworthy Research Laboratory advances in the investigation of the structure of matter. The big machine, operated by the Electron Physics Department, has been used for research since

DISCHARGE IN GASES

The use of a shock tube facilitates the studies of discharge phenomena in gases. In a 10-foot-long tube, a low-molecular-weight gas at high pressure is allowed to expand suddenly into a high-molecular-weight gas at low pressure. The resultant shock wave travels down the tube at supersonic speed. The high temperatures associated with the shock wave excite and ionize the high-molecular-weight gas, producing light. Spectra of the light produced are photographed through the quartz sections at the end of the tube. In one trial, helium at four atmospheres and xenon at one millimeter produced temperatures of about 10,000 K.

Dr. Walter Roth (left)—physical chemist—and George Brengelmann—physicist—photograph the shock-excited spectrum in the laboratory.

Phenomena with Shock Tube and Synchrotron

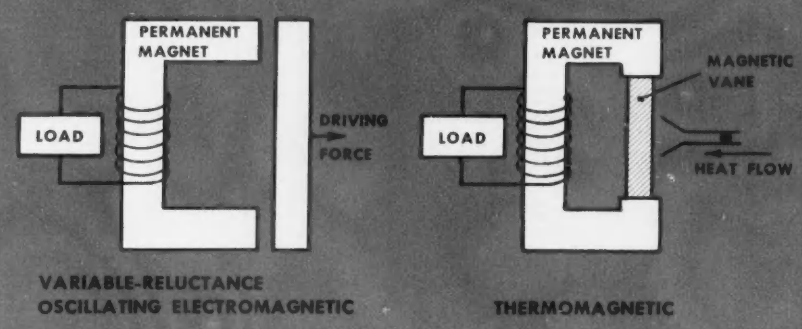
of matter: chemists study autoignition of liquid-fuel sprays and gas producing supersonic velocities.

1953. Its predecessor, a 70-Mev machine, was the first working synchrotron in the United States.

Dr. William Jones, Jr., (photo, left) phones control room while checking a Cerenkov counter—which measures the energies of x-rays produced when the synchrotron's beam interacts with matter. Jones, Dr. James Rouvina, and Dr. Howard Kratz (photo, right) are participants in the project.

Unconventional generating methods produce electricity without the use of rotating machinery or commonly used batteries. They involve phenomena that convert different forms of energy—mechanical, thermal, chemical, and radioactive—to electric energy.

CONVERTER SYSTEMS—POSSIBLE



Small-Scale Unconventional Power Sources Now

Arising from the demands of an increasingly complex technology, the search into tricity has uncovered definite possibilities. Some might overcome and even take

By DR. JOHN F. FLAGG

Methods for generating electricity have always aroused great scientific and technological interest. Electric power in amounts that range from microwatts to megawatts can be generated in many ways—utilizing fossil fuels, the tides, nuclear phenomena, geothermal energy, or solar energy, either directly or indirectly. As these energy sources generally require large installations for their utilization, they are best suited for producing power on a substantial scale.

In recent years a great variety of special needs—powering satellites, for instance—have demanded sources for producing power on a smaller scale. Certain phenomena, and they are numerous, have received attention as possible "unconventional" power sources. By unconventional generating methods, we mean those ways of generating electricity other than by the use of rotating machinery or commonly used batteries. Instead, they involve phenomena that provide various means of converting different forms of energy—mechanical, thermal, chemical, and radioactive (including radiant)—to electric energy. (For the story of solar energy, excluded here, refer to the article in the September 1957 REVIEW, page 26.)

Dr. John F. Flagg is a member of the Project Analysis Section of the Research Laboratory. Joining GE in 1946 as a research scientist at the Laboratory, he became Manager of Chemistry and Chemical Engineering at the Knolls Atomic Power Laboratory and later Manager of Industrial Atomic Products for the Atomic Power Equipment Department. The Project Analysis Section helps to establish the priority and scope of research effort in different scientific areas and to evaluate the results of research to speed application and development by the Company's operating components.

Converting Mechanical Energy

The following are some methods that can be used to convert mechanical energy to electricity . . .

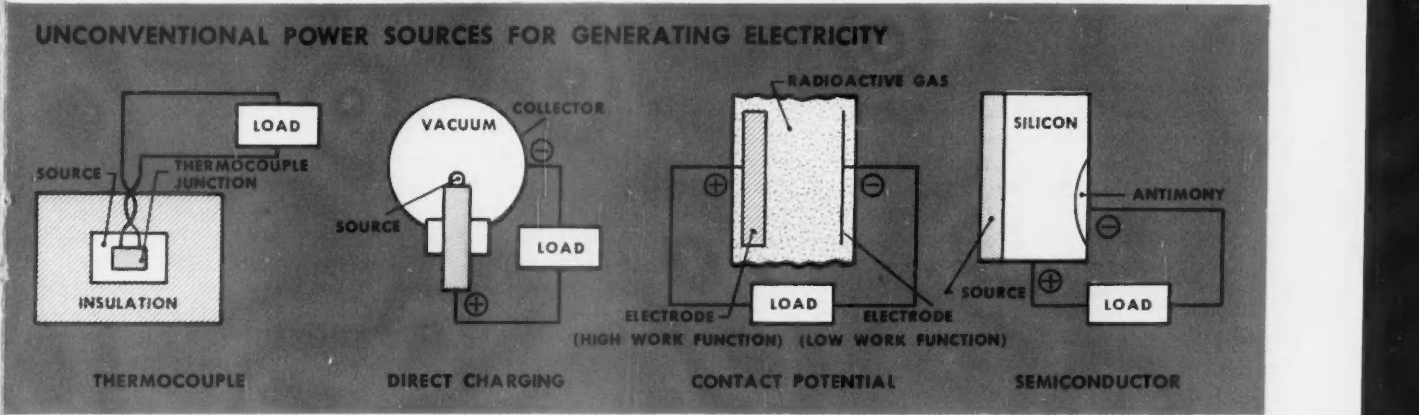
. . . *Piezoelectric effect.* When a crystal such as quartz or sodium potassium tartrate (Rochelle salt) is compressed or otherwise deformed by stretching, twisting, or bending, opposite faces become oppositely charged. The charging is reciprocal with the mechanical motion; that is, the charges reverse with reversal of the impulse. Under optimum conditions of operation the conversion efficiency of mechanical to electric energy can be substantially in excess of 50 percent, and power can be produced in the range of a few watts per square centimeter of crystal surface. Numerous opportunities exist for the study and application of such devices for small-scale power production in environments where mechanical energy, such as vibration, is available.

. . . *Electromagnetic induction.* The principle of electromagnetic induction is the classical basis for generating electric power through the agency of rotating machinery. Vibratory, or oscillatory, motion is converted in the variable reluctance phonograph pick-up to electricity, and this device thus is an elementary sort of power source (illustration).

Recently there has been broader interest in oscillating generators as small power sources. Under the sponsorship of the Wright Air Development Center, experimental oscillating generators have been built at Oklahoma A&M College with the objective of producing power. These units have delivered about ½ watt at 0.3 amp and 3 volts, employing frequencies up to 100 cps.

These generators reportedly produce no electrical noise, and it has been suggested that high voltages might be achieved by use of appropriate snap action in the oscillating mechanism. Mechanical problems would be the consequence of vibration rather than rotation, as in conventional generators. Output may be increased by the utilization of a higher oscillation frequency, or greater flux density in the air gap of the magnet.

. . . *Magnetostrictive effect.* In another form of induction the magnetic flux variation attendant upon dimensional changes in a magnetized material can be used to induce an electromotive force (emf). Compression may be achieved by



UNCONVENTIONAL POWER SOURCES FOR GENERATING ELECTRICITY

Assume New Significance

unconventional methods of generating elec-
advantage of environmental limitations.

subjecting a core within a coil to pressure waves, as from an acoustic source. When used in the conversion of electric to mechanical energy, the magnetostrictive conversion efficiency will be as high as 90 percent. The corresponding figures for the reverse phenomenon have not been published.

. . . *Electrostatic generation.* Many laboratory devices have been made for generating static electricity by mechanical action. A well-known modern version of these is the Van de Graaf generator, which operates on the principle that a charged conductor will transfer its charge to a hollow second conductor upon contact, regardless of the charge on the latter. Maximum voltages as high as 10 Mev are attainable in these machines. In general, they are characterized by a very low power conversion efficiency and a maximum current output in the range of a few hundred microamperes. Such devices are of importance in nuclear research but have received no serious consideration for electric power generation on any scale.

. . . *Streaming potential.* A potential is generated when a fluid flows past a solid surface; this is known as the streaming, or electrokinetic, potential. This principle is used in the electrokinetic transducer, in which fluid moves through a porous solid, such as sintered glass, under sonic impulses. An alternating current is produced having the same frequency as the sonic impulse. The device has been used to measure pressure fluctuations in oil pipelines, but in view of the low power conversion efficiency, the device is probably the least promising of the mechanical converters as a power source. Some characteristics of the mechanical converters are shown in Table I.

Conversion of Thermal Energy

. . . *Thermoelectric generation.* The production of an emf upon heating a junction of two dissimilar materials has long been recognized—and in recent years intensively studied—as a possible source of electric power. The materials may be either elements or compounds. In general, thermoelectric generators have shown conversion efficiencies of up to 10 percent. The actual value is usually a function of materials and design. They have small power and relatively large weight and volume per watt of output (Table II). Though they contain no moving parts, mechanical complexities can arise in fabrication.

At present, there is much interest in using semiconductors for thermoelectric generators in place of metal couples. The semiconductors offer the prospect of operating at high temperatures and high temperature gradients; in addition, they must possess low thermal conductivity, low resistivity, and large junction potentials, compared with materials hitherto available.

Thermoelectric emf's may also be produced in electrolytic cells in which the electrodes are of the same metal but are held at different temperatures. A salt of the metal is used as the cell electrolyte. The thermogalvanic potentials thus obtained may be considerably higher than from thermocouples.

. . . *Thermionic emission.* Thermionic emission is the liberation of electrons from a surface through the kinetic energy imparted to the electrons by the application of heat. The emission current density (amp/cm^2) is a function of the absolute temperature and the work function of the emitter. For many years the process received little attention as a source of electric power, owing primarily to the very low conversion efficiency.

However, interest in the thermionic generation of electricity has recently been stimulated by the Research Laboratory's announcement of a contact potential thermionic emission cell. In this device, current flows between the surfaces of two materials having different work functions. These materials are held at different temperatures, and the gap between the electrode surfaces is filled with gas at low pressure. In this respect, there is an important distinction between it and the thermocouple: the electrodes are at different temperatures, thereby increasing the efficiency.

Experimental converters already have changed more than 8 percent of the applied heat energy into electric power, and conversion efficiencies of as much as 30 percent are anticipated. The thermionic converter is a low-voltage high-current device, with a power output near 3 watts/cm^2 of electrode surface, at a current density of 4 amp/cm². Individual elements could be cascaded for desired voltage and current characteristics.

. . . *Thermomagnetic generation.* A thermomagnetic generator that was patented in 1935 depended for its action on the alternate heating and cooling of a magnetic material, which produced changes in the relative magnetic permeability of the material. These changes altered the flux in a magnetic circuit, which in turn induced an emf in a coil. The heat was supplied as a heated gas, controlled by a suitable valving mechanism. The output frequency of such a device would be determined by the time constants in the heating and cooling cycle of the magnetic material (illustration, page 30).

. . . *Pyroelectric phenomena.* When heat or infrared radiation falls on a properly oriented crystal, such as tourmaline or tartaric acid, a potential is generated between two faces of the crystal. After they cool, the signs of the charges are reversed. This phenomenon has been used to measure small temperature variations by observing changes in the pyroelectric current. The current produced in such devices is generally in the range of millimicroamperes; the very low power developed in these systems limits their possibilities as power converters. Some characteristics of the devices for converting heat to electricity are given in Table II.

. . . *Phase-transition potentials.* The production of an electric potential during the freezing of water has been observed. Voltages in excess of 200 volts may be produced between ice and the solution from which it forms, when the solution contains small amounts of inorganic solutes, such as ammonium salts. Solute concentrations determine the magnitude of the voltage, and the current is determined by the freezing rate. The effect appears to involve the adsorption of ions from the solution by the crystal lattice.

Converting Chemical Energy

. . . *The fuel cell.* In the fuel cell (Article, page 40), the energy released during a chemical reaction between two elements is converted directly into electricity, without the use of intermediate thermal or chemical stages.

. . . *Ion-permeable membrane batteries.* Synthetic ion exchange resins are available in sheet form that have good electric conductivity, resulting from a high internal concentration of ions, such as potassium or chloride. Current is transferred through these membranes almost exclusively through the migration of the anion or cation in the resin. This feature is sometimes referred to as "perm-selectivity." These membranes may be used to construct concentration cells consisting of alternate dilute and concentrated electrolyte solutions, compartmented by alternate anion and cation membranes. A tenfold concentration difference in a uni-univalent electrolyte between individual membranes produces a maximum potential of 59 millivolts. In principle, desired voltages could be obtained by combining the appropriate number of individual concentration cells. Such cells are necessarily limited to relatively low temperature operation, as they contain organic materials that are thermally unstable.

Converting Nuclear Energy

Nuclear energy appears in two forms: as the energy released in the *fission* of uranium or plutonium, or as the energy released in the *decay* of a radioactive element when it emits an alpha, beta, or gamma ray.

While a nuclear reactor is indeed an unconventional power source, it presently serves as a source of heat rather than as a direct source of electricity. The reactor heat may, of course, be used to produce electricity by methods previously discussed or others. The radiation from the reactor fuel or coolant might be used to produce chemical substances suitable for generating electricity from chemical reactions.

Electricity may also be generated directly from radioactive decay energy as follows. . .

. . . *Thermocouple junction.* Radiation from a radioactive source can be used to heat a thermocouple junction (illustration, page 31). An alpha emitter would most probably be used for this purpose, as the range of the alpha particle approaches a few microns in solids, and the

TABLE I—MECHANICAL-ELECTRIC CONVERTERS

Phenomena	Efficiency Percent Theory	Efficiency Percent Measured	Pounds/Kw	Volts	Amp
Em Induction	—	70	35	3	0.4 (1)
Electrostatics	90	—	high	10^7	10^{-4}
Streaming potential	—	10^{-4}	high (10^8)	300	0.01 (1)

(1) ASTIA Report AD 63967

TABLE II—HEAT-ELECTRICITY CONVERTERS

Phenomena	Efficiency Percent Theory	Efficiency Percent Measured	Pounds/Kw	Volts	Amp
Thermoelectric	—	8	4000	Variable	Variable
Thermionic contact potential	—	8	—	2-3	4/cm²
Thermomagnetism	—	—	8000	—	—(1)
Phase transition	14	0.004	90,000	230	10^{-6} (1)

(1) ASTIA Report AD 63967

or plutonium, or . . . in the decay of a radioactive element. . . ."

energy liberated per particle is large. The half-life of the radioactive source will determine the life of the device and its total power output. Isotopes for possible use in such sources include polonium 210 ($t_{1/2}=133$ days) and americium 241 ($t_{1/2}=470$ years).

. . . *Collection on a plate.* The beta particles (electrons) emitted by a radioisotope may be collected on a conducting plate (illustration, page 31), insulated from the isotope source. The potential attainable in such a converter can be as high as the energy of the beta particle, which may in some cases approach a million volts. The instantaneous current available will increase with the amount of radioisotope used and with its decay rate, which ultimately limits the useful life of the device. The load determines the operating voltage.

. . . *Contact potential converter.* In this device the field produced by two electrochemically dissimilar electrodes collects charged particles produced in a gas by nuclear radiation (illustration, page 31). Electrodes may consist of materials such as lead oxide anodized on stainless steel or magnesium, and the radiation source can be tritium, with argon as the gas separating the electrodes. The potential difference between the electrodes determines the cell potential. Voltages of the order of 1 to 2 volts have been obtained, and multiple cells have produced 100 volts. The beta current is multiplied about 100 times, as contrasted with the direct-charging converter already mentioned, which achieves no current multiplication.

. . . *Semiconductor junction battery.* A battery can be made utilizing the junction field to collect charges produced when the junction is exposed to beta or gamma radiation (illustration, page 31). In the case of beta particles, a current multiplication of several hundred thousand is realized. Germanium and silicon p-n junctions have been proposed for this application. With 50 millicuries of strontium-90 a voltage of about 30 mv has been produced in germanium and 250 mv in silicon. In each case, maximum power was a fraction of a microwatt. Unfortunately, one of the principal limitations inherent in this type of power source is the ultimate damage to the junction.

. . . *And others.* Other devices for converting nuclear energy to electricity can be envisioned. Thus, it is possible to produce scintillations in a phosphor by means of alpha, beta, or gamma radiation. The light thus produced could be converted to electricity by means of a photoelectric device but at very low efficiency.

It is also possible that radiation could be used to produce electron emission from a sensitive surface, to be collected in the manner described under "Collection on a plate."

Let's summarize the information on nuclear power sources (Table III). The power obtained from nuclear converters is generally in the range of microwatts to milliwatts. Costs are determined principally by radioisotope costs, and as these elements must be carefully separated and purified, it is unlikely that substantial reductions in cost will be achieved. Thus, assuming that the power is delivered to a matched load for one half-life at a conversion efficiency of 2 percent, the cost using Sr-90 is \$30/watt-hr; Kr-85 and H^3, \$40/watt-hr; as compared with 4 cents/watt-hr from dry cells.

The advantage of the nuclear battery is its long life and possible wide-temperature range of operation. Disadvantages are the low power output, cost, and possible hazards arising from breakage.

A comparison of some of these possible power sources with conventional power sources is shown in Table IV. The unconventional sources might overcome and often take advantage of environmental limitations, such as high temperature, radiation, and shock. Obviously, it is not possible to assess the value of any of these in general terms. Of the less well developed devices, those employing the piezoelectric and thermomagnetic phenomena seem to offer opportunity for exploitation of new materials, and for more detailed analysis. But in view of reasonably anticipated performance characteristics and the state of the technology, it appears that the thermoelectric generators and the contact potential thermionic emission cell are among the more promising power sources discussed here.Ω

TABLE III—PERFORMANCE OF NUCLEAR CONVERTERS

Type	Efficiency Percent: Theory	Efficiency Percent: Observed	Volts/Cell	Current (Amp)	
Direct charge	—	—	365	0.6×10^{-9}	(1)
				40×10^{-12}	(2)
Contact potential	3 A	—	1.7	7×10^{-10}	T_2-A-PbO_2-Mg (3)
	8 Kr	—	—		
P-n junction	2-8	0.23 Ge	0.031	1×10^{-5}	50 mc Sr-90 (1)
		2 Si	0.250	9×10^{-6}	

(1) Linder, Rappaport, Loferski, Geneva Conference Paper P-169
(2) Coleman, Nucleonics *11*, 42 (1953)
(3) Thomas and Petrocchi, ASTIA Report AD 47430

TABLE IV—APPROXIMATE POWER DENSITY, VARIOUS SOURCES

Source	Kw/ft³
Oscillating em inductor	0.01
Thermopile	0.04
Fuel Cell	1
Lead acid battery	1.3 kwh/ft³
Steam boiler	5
Electric generator	50
Airplane engine (piston)	75
Steam turbine	100
Jet engine	750
Power reactor	1200 (core)

The magnetron principle, proposed in 1920 by Dr. A. W. Hull (left), affords new versatility through voltage tuning, developed by Dr. D. A. Wilbur (center) and P. H. Peters.

New Voltage-Tunable Magnetrons—How They

The tube's unique voltage-tuning characteristic assures its application in frequency-tronic countermeasures, newest types of precision altimeters, and other important

Since the beginning of World War II, magnetrons have become famous for their extensive use in all types of radar equipment. These electron tubes were of inestimable value in wartime radar because of their ability to efficiently generate very high levels of pulsed microwave power. As continuous-wave generators, they were further utilized in countermeasures successfully employed in jamming enemy radar.

The war story of the magnetron is, in fact, a fabulous one; many lives were saved, and the success of more than one military campaign has been ascribed to its use. Since the war, magnetrons have assumed a central and important role in a new peacetime industry—microwave dielectric heating. In this field, one phase of which is the important new area of electronic cooking, magnetrons have great potential for an active industrial future.

New Applications

The Research Laboratory has been active in developing magnetrons for all these applications, which largely utilize the power capabilities of these tubes. Now, a new method of magnetron operation, called *voltage tuning*, is opening up different areas of application for magnetrons—applications that call for automatic high-speed frequency control over very wide frequency ranges.

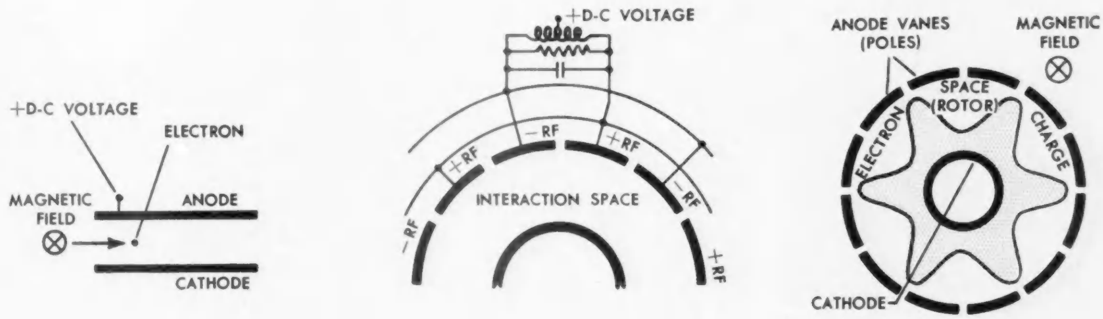
Voltage tuning was discovered in 1949 by Dr. D. A. Wilbur and P. H. Peters (photo) of the Laboratory's High-Frequency Electronics Research Section while they were working under a broad magnetron contract sponsored by the Army Signal Corps.

Tuning ranges of about two percent of the center frequency were typical before 1949, but new microwave systems can now utilize tuning ranges as wide as two to one. Wilbur and Peters discovered that, with the proper design and mode of operation, magnetrons can be tuned over wide bands merely by varying the d-c anode voltage. With voltage tuning, the frequency is set by the value of the d-c anode voltage and, therefore, can be varied electrically, remotely, and almost instantaneously (illustration, left, page 36). The frequency of the more conventional magnetron is set by the anode circuit, and tuning is mechanical.

Applications for the voltage-tunable magnetron (VTM) are found in wide-frequency-range spectrum analyzers, new types of precision altimeters, frequency agile radar, electronic countermeasures, sequential pulse communications, swept signal generators covering very wide frequency ranges, and in the very broad new field of telemetering—an electronic means for monitoring a number of far-flung metering stations from a central point. In many of these applications, the capability of the VTM to be frequency modulated over extremely wide frequency ranges is essential.

Ten years ago, there were no microwave tubes that could be voltage tuned over a wide frequency range. The reflex klystron was employed where only very narrow band tuning at low power levels was required. Since that time, the development of the VTM has been paralleled by development of *M* and *O* type backward-wave oscillators, which have frequency tuning ranges comparable to the VTM. The voltage-tunable magnetron is comparable in efficiency to these microwave generators. Its straight-line voltage-frequency response is unique,

PRINCIPLE OF VOLTAGE TUNABLE MAGNETRON OPERATION



Electrons interact simultaneously with electric and magnetic fields oriented at right angles to each other (left). With the two forces effectively counteracting each other, the electrons move along the interaction space parallel to anode and cathode, speeding up if the electric field is increased and slowing down if it is decreased (center). The induced r-f field, interacting with the d-c field, causes electron bunching, making the electron space charge take on the shape of a spoked wheel.

Work and Where

agile radar, telemetering, elec- defense and industrial areas.

and its power output is relatively flat over the tuning range. It is small in size and weight, mechanically rugged, and is easily adapted to high production manufacture.

How the VTM Works

A fundamental, yet simple, relation between anode voltage and frequency can be shown to exist in the VTM. Magnetron action occurs when electrons interact simultaneously with electric and magnetic fields oriented at right angles to each other (illustration, left). As the electrons traverse the interaction space, the electric field exerts a force on them that tends to direct them toward the anode. At the same time, the magnetic field causes them to be diverted with a force proportional to the velocity of the electrons so that on the average they move parallel to the anode and cathode. This action automatically adjusts the average velocity of the electrons along the interaction space so that the two forces effectively counteract each other; the electrons speed up if the electric field is increased, slow down if it is decreased.

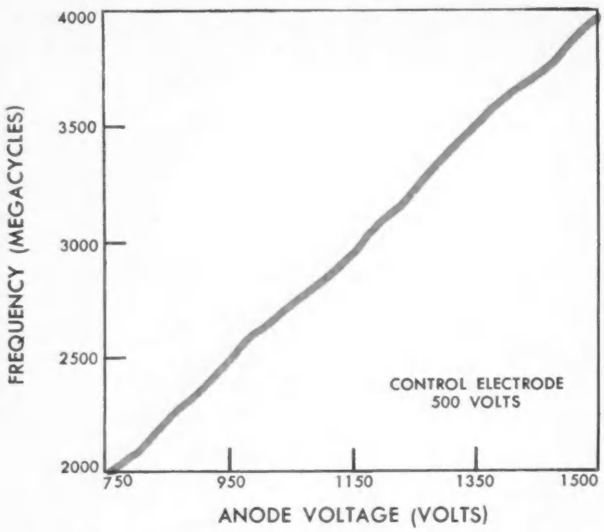
In a practical magnetron the electrodes are arranged in the form of concentric cylinders, with the anode segmented and the alternate segments, or *vanes*, tied together (illustration, center). When anode voltage is applied, the electrons encircle the cathode as a rotating cloud. Perturbations in the electron cloud induce a radio-frequency field in the external circuit as the cloud passes the breaks in the anode. As a result, the radio-frequency polarity of successive vanes is opposite and alternates once during each r-f cycle. Now, as the electrons travel around the interaction space, they are subjected to this r-f field as well as the d-c field. As they pass under an r-f plus vane, they speed up, and when they pass under an r-f minus vane, they slow down. These interactions cause the electrons to bunch; and the space charge, or electron cloud, takes on the shape of a spoked wheel (illustration). The speed of rotation of the spoked wheel depends on the value of the d-c voltage.

The magnetron may be compared to an a-c generator (alternator) with a very fluid rotor. To sustain oscillation, the spokes of space charge must rotate synchronously with the r-f voltage induced on the vane structure of the anode circuit. Each time a spoke passes a pair of vanes, it generates a full cycle of r-f power. The frequency generated is a function of the number of vanes (analogous to the poles in an alternator) and the speed at which the spokes (analogous to the rotor) revolve. For example, the rotor of a 12-vane magnetron oscillating at 4000 megacycles rotates at 40-billion rpm.

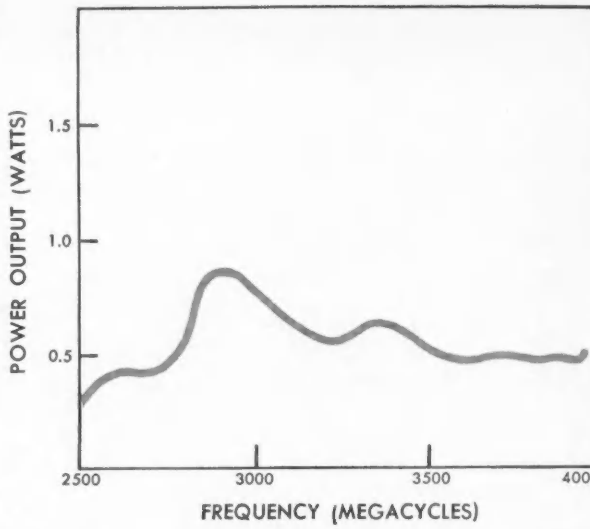
Stabilizing Influence a Problem

Wilbur and Peters, in examining the fundamentals of magnetron action, came to believe that all magnetrons were intrinsically voltage tunable. In tubes designed to produce large amounts of power, however, the effect was inherently very small because of the stabilizing influence of the anode circuit. They decided that two things must be done to make magnetrons voltage tunable. First, they had to employ an anode circuit having a low effective parallel resistance, that is, a heavily loaded circuit. In the construction of one type of tube, they used an interdigital arrangement of vanes to insure that this heavy loading was applied uniformly. Second, they had to control the number of electrons in the interaction space.

At first, these two scientists regulated the amount of space charge in the interaction space by controlling the cathode temperature and later by moving most of the emitting part of the cathode outside the interaction space and leaving a nonemitting portion inside. However, these methods of control were sensitive to variations in the power supplied to the cathode and tended to produce instability in operation of the first voltage-tunable magnetrons. They then introduced a new type of grid control that



FREQUENCY set by the d-c anode voltage varies almost instantly.



POWER up to 10 watts is possible through narrower tuning ranges.

made the operation of the newer tubes insensitive to variations in cathode power and emission.

Wilbur and Peters applied their new approach to a family of tubes covering different frequency bands. In doing so, they made use of a ceramic-to-metal sealing technique, developed at the Research Laboratory and now employed commercially in the microminiature ceramic tubes in production at General Electric's Owensboro, Ky., and Scranton, Pa., plants.

Laboratory models were supplied to engineers of General Electric's Power Tube Department, who undertook the job of developing a line of marketable tubes.

Commercial Designs

Dr. Myron Weinstein, Gerald J. Griffin, Jr., and their associates have been developing VTM's for several frequency ranges and output powers and are studying some of the problems involved in the manufacturing of VTM's. An S-band VTM has been in pilot production since mid-1957. A series of low-power wide-frequency-range types that also are suitable in narrow-band applications are now being developed. These will be marketed in the package form. (The word "package" refers to the assembly of the tube with the circuit and magnet.) Work has also been done toward developing special VTM's with power levels as high as 150 watts.

Important Future

Kenneth E. Anspach, product planning specialist in the Power Tube Department, sees an important future for the voltage-tunable magnetron in a wide variety of military and industrial applications.

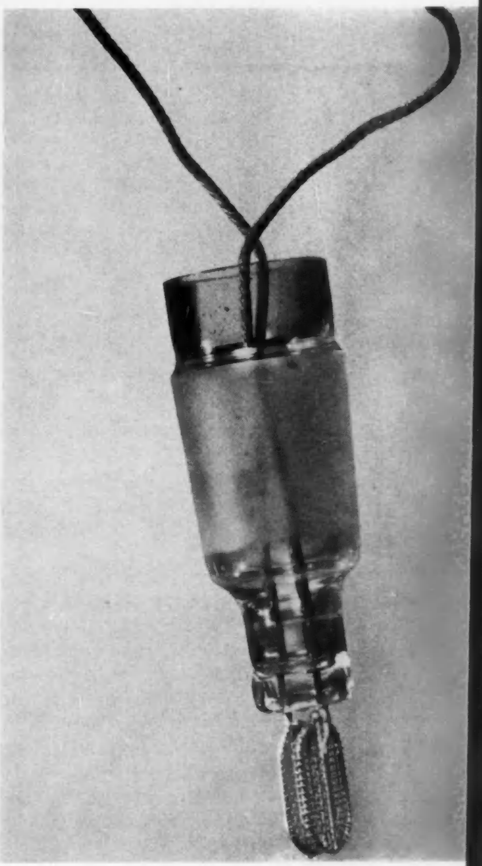
"Customer interest in the VTM has been quite intense," comments Mr. Anspach "and the demand for tubes has been very encouraging. So far, we have concentrated on frequencies between 2500 and 4400 megacycles and have several developmental VTM's that operate within this range. Future plans include going above—and below—these frequencies.

"The power output of the VTM's scheduled for pilot production in 1958 range from milliwatts to as high as 10 watts, obtainable from the same tubes when they employ much narrower tuning ranges (illustration, right).

"The VTM looms large in the future plans of the Power Tube Department. We already have government contracts for tubes to meet particular specifications and have a number of VTM's in the hands of many customers for evaluation tests.

"We believe that the VTM will perform many electronic functions better than any other device and will do it at lower cost." Ω

WIDE-BAND SPECTRUM TESTS from 2500–4000 megacycles are run on production voltage-tunable magnetrons by G. J. Griffin, Jr. (standing) and Frank Yatsko.



When reports of the development of a dielectric pump (right) reached authors Auer (left) and Sharbaugh, they were puzzled. If the information was correct, a novel pumping method had been discovered. But not being able to think of any reason why such a pump should work, they began . . .

Investigating the Dielectric Pump

By Dr. P. L. AUER and Dr. A. H. SHARBAUGH

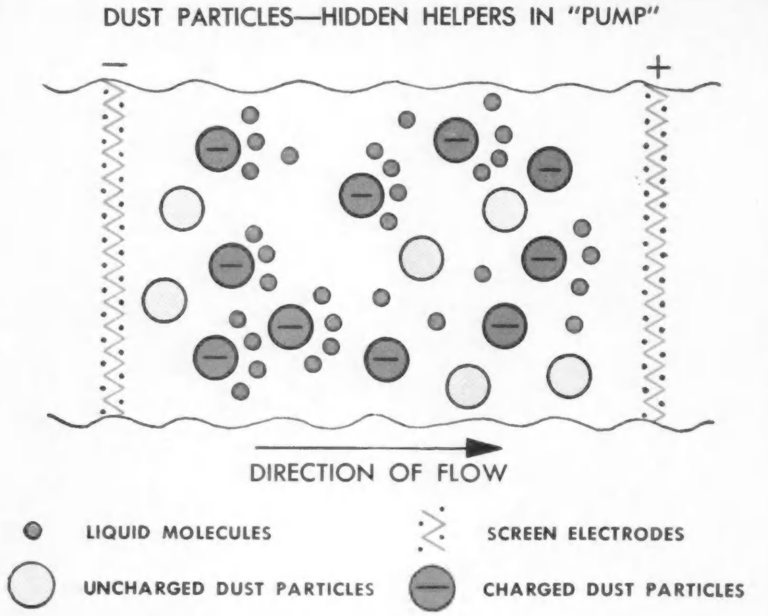
On a summer day two years ago a puzzling bit of information came to our attention. An article in *Chemical and Engineering News* reported some strange discoveries by a group of research workers at the University of Cincinnati. While investigating the behavior of insulating liquids in the presence of strong electric fields, this group had developed a dielectric pump that operated on direct-current high voltage. The pump construction, simplicity itself, consisted merely of two pieces of metallic screen material supported in a parallel-plate arrangement. When such an assembly was completely immersed in an insulating liquid and a d-c voltage applied across the electrodes, it was reported that the liquid moved in a direction perpendicular to the screen's face.

This was the extent of our information, and it puzzled us. If the observations of the Cincinnati people were correct, it would appear that they had discovered a novel pumping method, involving no moving parts. The method sounded reminiscent of the electromagnetic pumps used with liquid metals in the Atomic Energy Commission reactor program.

At first, we couldn't think of any reason why such a pump should work. When an electric field is imposed upon a dielectric, it gives rise to what are usually termed electrostrictive forces. In the case of a fluid these forces become balanced out by pressure gradients and cannot contribute to pumping. In addition to these forces, another force arises from the mutual attraction of the two screens that act as capacitor plates once the d-c voltage is applied. This force tends to squeeze the liquid and cannot contribute to pumping. According to electrostatic theory, all things considered, there was no rational explanation for any pumping action in an ideal dielectric fluid.

As mentioned in the beginning, we learned about this discovery on a summer day. It was a very pleasant day, the sort that drives even the most devoted research man to thoughts of fishing or some other bucolic pastime. And, we decided to go fishing—in a sense. We constructed a pump out of two pieces of common garden-variety screening material, spaced by a piece of glass tubing, and tied together with a nylon string. Placing our "pump" in a glass beaker

Dr. Auer, a member of the Research Laboratory's Physical Chemistry section, joined General Electric in 1954. His fields are theoretical physical chemistry, applied mathematics, and electrical discharge phenomena. Dr. Sharbaugh, also with the Physical Chemistry Section, came with the Company in 1943. He is the author of several papers on electric breakdown, dielectric properties, microwave spectroscopy, and radiofrequency heating.



CHARGED DUST PARTICLES move toward anode. As dust collects out, pumping diminishes.

filled with nitrobenzene, we applied a constant d-c field of roughly 10 kv per centimeter across the screens. We then injected a dye solution on the far side of one screen to see if any liquid motion was present. With mixed feelings, we watched the dye swoosh through the screens with great ease. The pump, so it would appear, was pumping!

The next step was to establish whether the dye motion truly represented liquid motion. Improving slightly on the original experiment, we placed the pump assembly in the annulus formed by a beaker set inside a large cylindrical dish. To detect liquid flow, we observed the movement of thin palladium foils and the dust suspended in the liquid: the dust could be viewed as a Tyndall beam. Upon moving to the larger apparatus, we found our limited supply of nitrobenzene inadequate and had to switch to chlorobenzene. The pump still appeared to operate just as a pump should. According to our observations, the motion of the liquid was in the direction that a negative charge carrier would take in the presence of the applied field. Upon reversing the electrode's polarity, the liquid motion appeared to reverse.

To obtain some quantitative data, we upgraded our summer day's venture into a small-scale research project. A toroidal glass loop was constructed with a segment of the loop containing a Venturi tube that we used as a flow indicator. The liquid levels in the manometer tubes on either side of the Venturi were monitored visually with a cathetometer, and the difference in liquid levels provided a measure of linear flow velocities. The electrode assembly became slightly more sophisticated (illustration), but the basic design remained the same. A large number of observations were made with this apparatus under varying conditions. Both chlorobenzene and benzene were used as test liquids.

On the basis of our observations, we were led to the following explanation: the dielectric pump as described is actually a dust pump. We stick by our original thesis that the pump will not operate in an ideal dielectric fluid.

However, ideal substances are difficult to obtain. Liquids designated as chemically pure usually contain large amounts of suspended dust. Many of these dust particles are charged electrically; and, for some reason, in the liquids we studied they are more often charged negative than positive. The application of an electric field between the screen electrodes causes the inherently negative dust particles to move toward the anode, where they become collected and discharged. In the course of their motion, they drag along liquid molecules, thus giving rise to pumping. As soon as an appreciable portion of the charged dust particles collects out, pumping will diminish and eventually stop; this is actually observed in practice.

The magnitude of pumping depends, of course, on the previous history of the liquid. Using fresh reagent-grade liquid chlorobenzene, we obtain linear flow velocities of the order of one-tenth centimeter per second when voltages of 5 to 10 kv are applied across screens separated 2 to 4 mm in distance. In the limited range of the above variations, the flow velocities appear to be linearly proportional to applied voltage and to increase somewhat with electrode spacing for given field strengths. Chlorobenzene is easier to pump than benzene; the difference may be ascribed to the difference in dielectric constants.

If, we concluded, the dielectric pump is a dust pump, it should be possible to increase pumping action by increasing the concentration of charged dust particles. We found striking an arc between the screen electrodes a convenient way to effect this increase. The arc partially disintegrates the electrodes and introduces colloidal metallic particles that become charged. In such a manner we find the magnitude of pumping can be increased ten to twentyfold at a given field value.

Next we set our sights on the development of a dielectric pump that would operate on 60-cycle alternating voltage. The dust principle certainly cannot be used to operate an a-c pump. However, investigations on electrical conduction processes in liquid dielectrics at the Research Laboratory lead us to believe that electrons injected in liquids such as chlorobenzene are effectively trapped most of the time and move as if they were massive liquid molecules. We reason that such trapped charge carriers might be able to produce pumping. Field emission from cold electrodes could be used to inject electrons into a clean dust-free liquid at high field strengths. Thus it should be possible to construct an a-c pump operating on a rectification principle.

We constructed a pump using two dissimilar metals—aluminum and stainless steel. Aluminum is a fair emitter in hydrocarbons, while stainless steel is a poor one. Observations on the pumping action of this device show that, unless the liquid is quite pure, a-c losses produce heating and obscure the pumping. Under ideal conditions, we have repeatedly observed slight pumping at applied fields of 50 to 150 kv rms per centimeter. And as predicted, the direction of the flow moves from aluminum to steel. Ω

With a mechanical analog of an electron tube—the latest of a variety of mechanical models that make electrons appear larger—Dr. Andrews studies the electron's journey from cathode to anode.

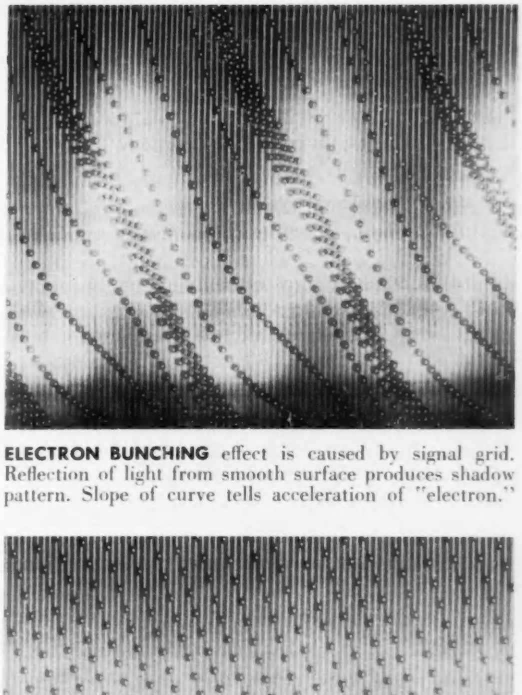
Tracing Electron Paths

The physicist's understandable desire to see, if possible, what he is investigating has led to the creation of various mechanical models in which electrons appear several times larger than life. One of the latest and most ingenious is a mechanical analog of an electron tube (photo, above), in which the tube has assumed the dimensions of a packing case and the electrons have grown to the size of ball bearings. With it, Dr. C. Luther Andrews, who does work for the Laboratory on a part-time basis, is studying the electron's classic trek from cathode to anode.

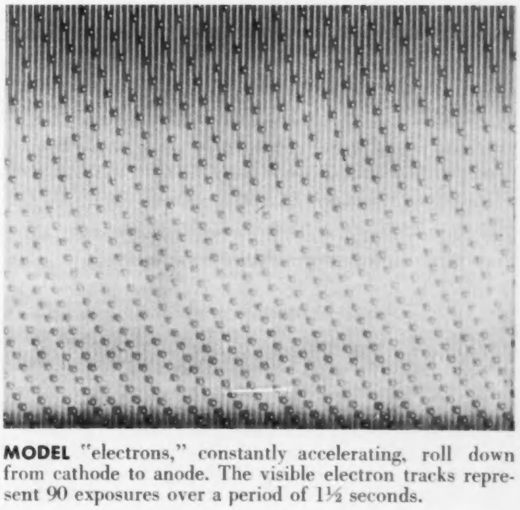
The oversize "electrons" are poured into a funnel-topped glass tube, from which they drop, one by one, into small depressions in the surface of a revolving cylinder. As the cylinder brings each ball bearing to the bottom of its circle, the latter drops out onto the end of an inclined board, down which it begins to roll. The end of the board beneath the cylinder is hinged, while the other end is free to move up and down. This it proceeds to do, raised and lowered by a motor-driven arm. When the ball bearing reaches the end of the board, it drops off into a glass beaker. The rotating cylinder corresponds to the cathode, the up-and-down motion of the board is the "signal," and the end of the board is the "anode." A stroboscopic light flashes at intervals of 1/60 of a second so that the electron's progress down the pitching runway can be recorded by a camera mounted directly above.

From this film record (photos, right) Andrews can determine the total time required for an electron to make the trip (indicated by the number of times a given ball appears in a photograph) and the speed of the electron at any time and at any point (indicated by the slope of the curve). Previous analogs have not simulated the effect of the signal and thus have not been able to reveal the effect of electron "bunching."

Andrews, who is chairman of the physics department at New York State College for Teachers, began construction of the analog early last year, devoting one afternoon each week plus vacation time to the project. He has followed a similar schedule at the Laboratory for the past 13 years, during which he has investigated such subjects as the diffraction of microwaves and testing of triode oscillators. Ω

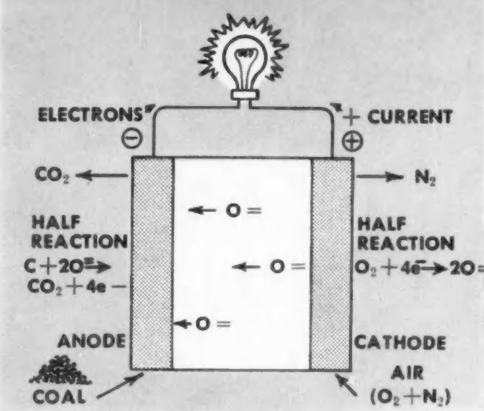


ELECTRON BUNCHING effect is caused by signal grid. Reflection of light from smooth surface produces shadow pattern. Slope of curve tells acceleration of "electron."



MODEL "electrons," constantly accelerating, roll down from cathode to anode. The visible electron tracks represent 90 exposures over a period of 1½ seconds.

CARBON-OXYGEN FUEL CELL



Fuel Cells May Provide an Important Source of Power

Until the sun and fusion can be efficiently harnessed, science must discover a way to retard the depletion of our fossil-fuel reserves. The fuel cell looks promising.

By Dr. D. L. DOUGLAS and Dr. H. A. LIEBHAFSKY

A good bank husbands resources to be drawn upon as needed. The accessible portions of the earth's crust form an energy bank where nature has stored fossil and nuclear fuels for our use. The energy balance in this bank is more important to our future than all the monetary balances in the world. As with money, the size of the energy balance isn't everything—availability and convertibility must also be considered.

Each year we use more and more energy, and this energy must be readily convertible to serve our complex modern civilization. The sun, falling water, and perhaps the tides are energy sources outside our bank. Since we have not yet learned how these sources can supply all our increasing needs, we ask our bank to honor larger and larger energy drafts. This leads to bankruptcy. To prevent this, we must find a means of extending our fossil fuel resources until we can make the sun serve us better and we can learn to generate useful energy by fusion. The fuel cell may provide an answer.

To appreciate what the fuel cell might do for us, let's first see how we get electric energy from fossil fuels today. In appraising this admirable but necessarily roundabout process, let's remember that it exists only to force electrons through various devices that serve us.

A coal-burning power station (illustration, next page) converts chemical energy into heat (Step 1) by burning coal under a boiler to generate steam. In Step 2, the heat is changed to mechanical energy by expanding the steam in a turbine. In a generator driven by the turbine (Step 3), this energy is converted to electric energy, which then lights the lamp. A great deal of complex, costly equipment is needed for the chemical energy of the reaction between coal and oxygen to force electrons from copper conductors in the generator to flow through the lamp.

Why does this process look roundabout to the electrochemist? He knows that the reaction between carbon and oxygen involves a flow of electrons from the carbon to the oxygen atoms. What is more natural than to have these electrons flow through the lamp after they are given up by the carbon but before they are captured by the oxygen? The electrochemist suggests, in effect, that we use these valence electrons to do the work instead of getting it done by the conduction electrons from the copper coils of the rotor in the generator.

The Fuel Cell

The simplest way the electrochemist might do this (illustration) is to feed carbon and air into a battery consisting of an anode, a cathode, and an electrolyte. At the anode, oxide ions are consumed as the carbon undergoes electrochemical oxidation to carbon dioxide, releasing electrons to the external circuit. The electrons flow through the external circuit to light the lamp, and return to the cell at the cathode. There they are captured by oxygen molecules to form oxide ions. The flow of these oxide ions through the electrolyte from the cathode to the anode completes the electric circuit. This battery is a fuel cell. The illustration, though incomplete, shows the inherent simplicity of the fuel cell as a method of generating electric power.

Simplicity is not the only advantage of the fuel cell. It has a further outstanding advantage—its efficiency is not limited inherently as is that of a heat engine. Before we consider this important point, let's be sure to distinguish between unavoidable limitation and avoidable losses in the generation of power. Progress in research, engineering, and manufacturing has reduced avoidable losses to where they are much less serious than the unavoidable limitation imposed by thermodynamics.

Carnot-Cycle Limitation

The unavoidable limitation on the conversion of heat into work derives from the nature of heat itself. All forms of energy except heat are freely interconvertible. This is a truth learned from experience, and we explain it as resulting from the randomness of the molecular motion that is heat. To convert heat into other forms of energy, we must pay a price to overcome this randomness. This price is given by the Carnot-cycle limitation discovered by Sadi Carnot in 1824: When heat is converted into another form of energy, it must fall from absolute temperature T_1 to absolute temperature T_2, and the maximum fraction that can be converted under ideal conditions is $(T_1-T_2)/T_1$. A banker would say that he must discount heat by 100 (T_2/T_1) percent before we can withdraw it as useful work from the energy bank.

Let's see what this means in modern practice. Under good operating conditions, T_1 and T_2 will be near 1510 R (1050 F) and 540 R (80 F) respectively. The Carnot efficiency for these temperatures is 64 percent. The over-all efficiency of the power plant might be 40 percent. That this efficiency approaches the Carnot is an eloquent tribute to modern industry. It is likely that further appreciable improvement will entail raising T_1, thus making

Dr. Liebhafsky—Manager, Physical Chemistry Section at the Research Laboratory—began his career with the Company in 1934. Associated with the mercury boiler, chemistry of oxide-coated cathodes, various corrosion problems, and rocket propellants, he has published more than 90 scientific papers. Dr. Douglas came to General Electric in 1951 and went directly to the Knolls Atomic Power Laboratory. Joining the Research Laboratory in 1955 as a physical chemist, he specializes in the fields of physical and inorganic chemistry.

greater demands upon construction materials. There is every reason to expect such improvement, but it will not come easily.

Energy Conversion

We come now to the most important part of our story. The fuel cell escapes the Carnot-cycle limitation because it never converts heat directly into work. It converts chemical energy directly into electric energy. The valence electrons that light the lamp are forced to do so before the chemical reaction is completed—the electrons are compelled to work between half-reactions as it were. Consequently, all the electric energy delivered by the cell is converted chemical energy, and here the Carnot-cycle limitation does not apply.

Actually, heat changes do occur when a fuel cell, or any other battery, operates. For the present, we'll think of them as adding to or subtracting from the chemical energy converted in the cell reaction and later discuss the changes themselves. But remember that a fuel cell, or any other battery, can operate isothermally: devices subject to the Carnot-cycle limitation cannot.

Let's sketch the thermodynamics of a fuel cell in which carbon is oxidized to carbon dioxide (illustration, opposite). The treatment can be extended to other, more practical fuels.

When 1 mole (12 grams) of carbon reacts with 1 mole (32 grams) of oxygen at a given temperature in a closed container, the reaction is accompanied by a definite decrease $\triangle E$ in internal energy. Think of the energy change in this way: the difference in internal energy between carbon and oxygen as elements on the one hand, and the compound, carbon dioxide, on the other. It is not exactly identical with the looser term, chemical energy, we used earlier.

Let's carry out this oxidation of carbon at constant pressure—that is, with the cell open to the atmosphere. In this arrangement the atmosphere will do a small amount of work on the cell because the carbon dioxide occupies less volume at the same temperature than the elements from which it was made. Customary procedure in physical chemistry combines this work term with the internal energy change $\triangle E$ to give a more convenient function, the heat of reaction $\triangle H$. Here $\triangle H$ is larger than $\triangle E$, but $\triangle E$ will be the larger when the reaction entails a volume increase. Like $\triangle E$, $\triangle H$ is fixed by the amount of chemical change and does not depend on how the reaction is carried out.

Of greater importance than the work term just discussed are the thermal changes that accompany this reaction. Suppose again that we carry out the reaction in a fuel cell open to the atmosphere. We shall find that the reaction then liberates or absorbs a quantity of heat q, and we might detect this by observing whether the cell tends to heat or cool.

Electric Work

We shall now apply the Law of Conservation of Energy to our fuel cell. Most of the electric work w_e will have to come from the heat of reaction $\triangle H$. The Law tells us that any heat absorbed by the cell as reaction proceeds will be added to $\triangle H$ so that the electric work becomes the sum of $\triangle H$ and q. Similar reasoning leads to the conclusion that w_e will be less than $\triangle H$ by the quantity q if heat is liberated by the cell as electricity is generated. With work by or against the atmosphere included in $\triangle H$, w_e and q remain the only energy changes to be considered in applying the Law of Conservation of Energy to our system.

It seems a little surprising that we might ever recover electric work in excess of the heat of reaction. Why not choose a fuel cell reaction that absorbs heat from the surroundings as it generates electricity? We could then get electric work in excess of $\triangle H$, with $\triangle H$ the maximum energy recoverable as electric work if a conventional power plant could escape the Carnot-cycle limitation. Unfortunately, the matter is academic. Suitable fuel cell reactions are hard to find. Even if we found a suitable fuel cell reaction that could absorb enough heat to make the scheme appealing on paper, we would discover that a practical fuel cell absorbs heat very slowly indeed from surroundings at ordinary temperatures.

So much for the sign of q. Now, let's look at its magnitude. Unlike $\triangle H$, q is not fixed by the amount of chemical reaction alone. Its magnitude depends also on *how* the reaction is carried out, which explains why we write it as a small letter. To begin with, q includes the heat generated by the passage of current through the electrolyte. This heat, I_2R, depends more strongly upon the current I than it does upon the electrolyte resistance R. Because I measures the rate at which energy is withdrawn from the cell, this is an important point. Other contributions to q are the irreversible heat changes that occur at the electrodes (illustration, opposite); these also may be expected to increase for a given cell with increasing current.

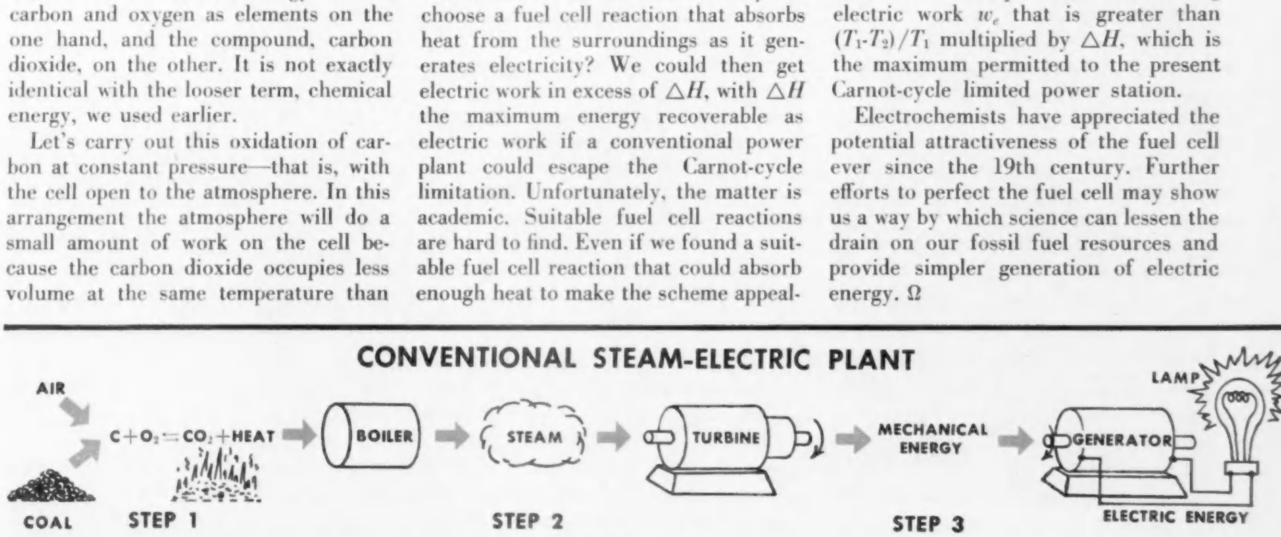
The electric work w_e will thus depend on the sign and magnitude of q, and q is an unpredictable quantity because its value depends on a good many characteristics of both the reaction and the cell. The maximum electric work w_e is predictable, and this occurs only under ideal conditions, when the cell operates reversibly. The current I then approaches zero, and the electromotive force $\mathbf{E}$ of the cell has its maximum value $\mathbf{E}_r$—a valuable reference point. The more nearly $\mathbf{E}$ for an operating cell approaches $\mathbf{E}_r$, the smaller become the irreversible contributions to q described earlier.

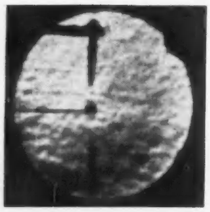
Attractive Application

The fuel cell is attractive because it holds forth the promise of delivering electric work w_e that is greater than $(T_1-T_2)/T_1$ multiplied by $\triangle H$, which is the maximum permitted to the present Carnot-cycle limited power station.

Electrochemists have appreciated the potential attractiveness of the fuel cell ever since the 19th century. Further efforts to perfect the fuel cell may show us a way by which science can lessen the drain on our fossil fuel resources and provide simpler generation of electric energy. Ω

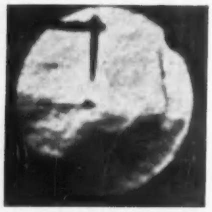
CONVENTIONAL STEAM-ELECTRIC PLANT



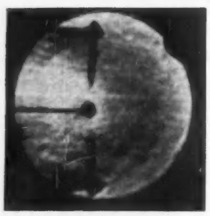


Frames from movie show fuel drop before ignition . . .

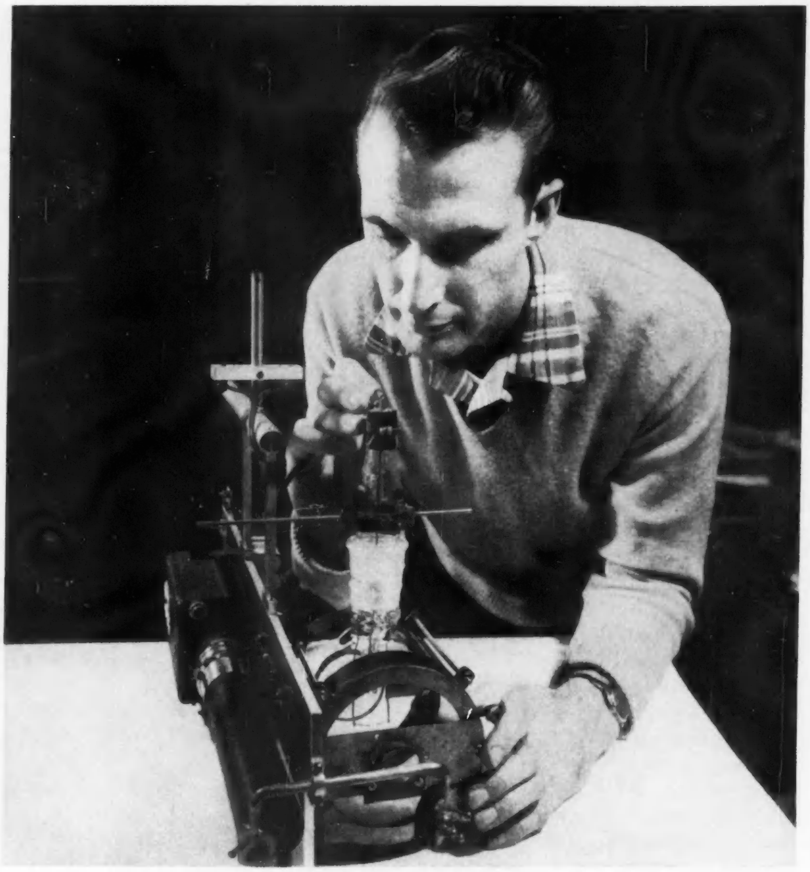
. . . during early turbulence created by a spark . . .



. . . and the growth of the flame during the fall . . .



. . . with drop of fuel as dark spot in the center.



MOVIE CAMERA, light source, and glass cylinder attached to an aluminum supporting plate are used in a project to find out how fire burns in the absence of gravity.

HISTORY of burning fuel drop as it plunges down stairwell is recorded by movie camera.

Flame Drop

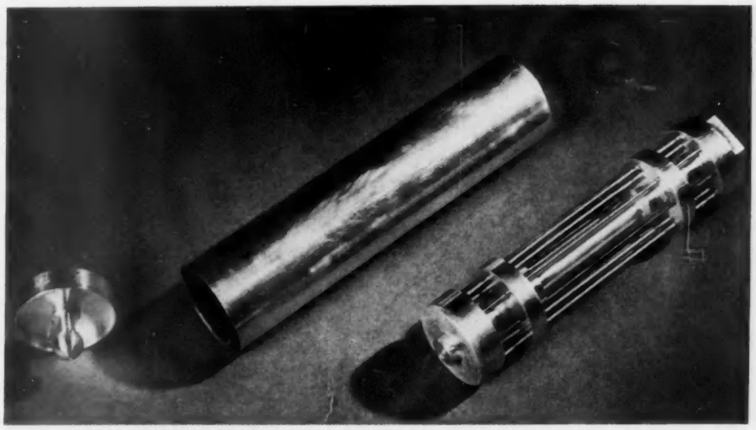
Scientists strive to discover another answer that would bring them closer to the conquest of outer space.

How fire would burn in the absence of gravity is a question that has intrigued scientists for many years. Today, as man's technology moves toward flight in outer space, where weightlessness is the rule, the problem assumes more than academic significance. The first step toward an answer is illustrated by a drop of fuel, burning as it plunges down a stairwell (photo, lower left). During its fall, a movie camera records its brief history.

The apparatus that makes such studies possible was developed in the Combustion Research Unit of the Research Laboratory's Chemistry Department, under the direction of Dr. George E. Moore. It consists essentially of an aluminum supporting plate to which are attached the movie camera, a light source, and a glass cylinder (photo, top right). The droplet of fuel burns inside the glass cylinder, protected from the rush of air, after having been expelled from a small reservoir by an electric heater and ignited by a pair of electrodes before the fall began.

The built-in light source consists of a flashlight bulb and two batteries. An optical system directs the light through the glass cell in parallel rays, making possible schlieren photographs. Conventional motion-picture records can also be made by the light of the flame itself.

Four frames selected from a schlieren film consisting of 93 frames show significant stages during the burning process that is undergoing test (photo sequence, top left). Ω



Studies of properties of irradiated materials being investigated in the Research Laboratory provide keys to new nuclear fuels and structural materials. One method of pile irradiation uses an aluminum jig, wire alloy samples, and a 4½-inch helium-filled aluminum can.

Research Findings Speed Nuclear Progress

By DAVID W. LILLIE

Because nuclear energy is so important to both national defense and to future civilian activities, responsible companies with sufficiently broad competence are serving simultaneously in both areas. At General Electric we sometimes think we live in two worlds of nuclear activity.

In the world of participation in our country's defense readiness, for example, we develop naval propulsion reactors and make plutonium, operating government-owned or leased facilities, with government funds, receiving a small fixed fee in return for our services. In the world of work toward satisfying people's wants in tomorrow's civilian market place, we are proceeding on schedule with construction of the country's largest privately financed all-nuclear power plant—the Dresden Nuclear Power Station, being built near Chicago for the Commonwealth Edison Company and the Nuclear Power Group, Inc. This is but one activity in our continuing effort to harness nuclear energy for peaceful development of the national economy. One of the most important of our research programs is devoted to nuclear materials and is aimed at improving our understanding of radiation damage, developing new alloys, and generally enhancing General Electric's skill in this vital field.

Nuclear materials can be conveniently divided into six classes: fuels, moderators, structural materials, shielding, controls, and coolants. We are primarily interested in two of them: structural materials and fuels.

Structural Materials . . .

One vital problem the designer must face in planning a pressurized water reactor is the selection of cladding materials for the fuel elements and for the associated coolant channels. The corrosive environment is water at about 300 C, and the most promising materials are stainless steel, zirconium, and aluminum.

. . . *Stainless steel* has a relatively high thermal neutron-absorption cross section of 2.85 barns. (A "barn" is a measure of the probability of a given nuclear reaction.) The Dresden Power Station will be completely nuclear-powered for generation of 180,000 kw. In its reactor, use of such high-cross-section material as stainless steel would require a uranium fuel highly enriched with the U-235 isotope. Because increased isotopic enrichment rapidly boosts the cost per gram of U-235 (illustration, left, page 45), the use of stainless steel would result in high fuel cost.

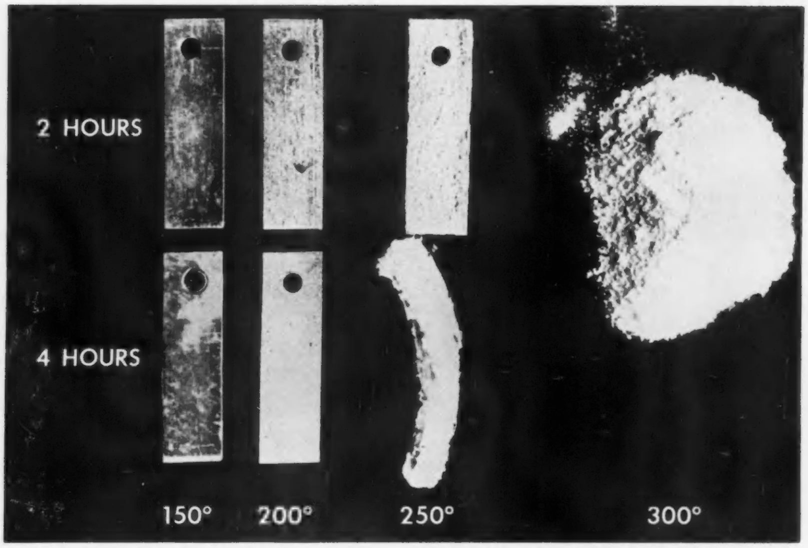
. . . *Zirconium*, although permitting use of low-enrichment fuel, is itself very expensive. In one reactor, for example, estimates of the material cost (including fabrication) are $6,300,000 for zirconium and only $3,300,000 for stainless steel.

. . . *Aluminum*, on the other hand, has a low neutron-absorption cross section (0.22 barns, compared to 2.85 for stainless steel and 0.18 for zirconium). It is also far less expensive than zirconium. Aluminum's chief drawback: catastrophic corrosion in 300 C water (photo, page 44). Information from the Argonne National Laboratory indicates, however, that the corrosion resistance of aluminum can be substantially improved by adding minor amounts of alloying elements such as nickel.

In 1955, Dr. William E. Tragert of the Research Laboratory began studying aluminum corrosion in high pressure water. He found that the nickel addition was effective through protective modification of the oxide film, particularly through the formation of complex Al-Ni oxides. Work on this alloy continues.

A second effort in the field of structural materials was a brief study of the possible development of iron-base alloys with usable mechanical properties and with neutron cross sections substantially lower than that of stainless steel. Alloys maximizing the carbon, beryllium, magnesium, silicon, aluminum, and zirconium—all elements with thermal-neutron cross sections of less than 1 barn—appear most promising. Phase diagrams and the published literature on the subject also show that of these, silicon and aluminum are the most promising—their cross sections and cost are low and their solubilities in iron extensive.

A member of the Research Laboratory staff since 1954, David W. Lillie is a metallurgist in the Materials and Processes Studies Section of the Metallurgy and Ceramics Research Department. Before joining the Laboratory staff, he served for six years as Chief—Metallurgy Branch, division of Research, U.S. Atomic Energy Commission.



CATASTROPHIC CORROSION of aluminum in 300°C water is impeded by minor amounts of alloying nickel, which aids resistance by oxide-film modification.

. . . *Iron-silicon alloys* have this disadvantage: The addition of silicon in amounts greater than about four percent by weight is accompanied by drastic reduction in ductility. One purpose of our experimental program, therefore, was to attempt to understand and overcome this difficulty. Reference to the iron-silicon phase diagram (illustration) shows solid solubility of silicon in alpha iron up to 14 percent at 400 C. In spite of this wide solubility, brittle behavior begins as low as 4 percent Si.

One explanation appeared to be the formation of an ordered structure above 4 percent Si. We therefore attempted to obtain a disordered structure by quenching and tried to determine the disordering temperature (if one existed) in the range 8 to 14 percent Si. High-temperature tensile and bend tests were also made to determine the range of ductility at temperatures up to 1000 C.

From this study we concluded that no disordering occurs up to 1200 C in Fe-Si alloys of 8 to 14 percent Si content, and that brittle behavior persists up to 800–1000 C. Alloying with copper, molybdenum, nickel, zirconium, and aluminum is not effective in improving ductility of Fe-6 percent Si alloys. Addition of cerium up to 2 percent imparts a slight but insufficiently beneficial effect.

. . . *Iron-aluminum alloys* appear more promising as nuclear structural materials, because about eight percent by weight (14 atom percent) aluminum can be added without seriously impairing room-temperature ductility. It is believed that an Fe-8 percent Al base with small amounts of other additives for corrosion resistance in specific environments may prove useful in nuclear engineering.

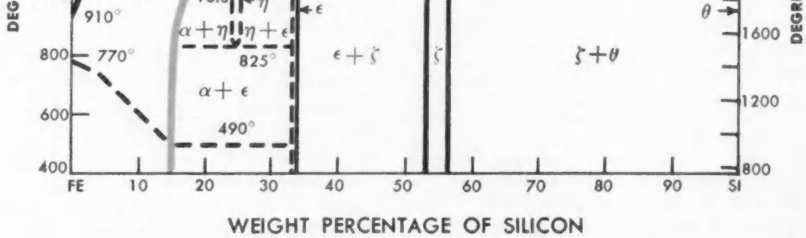
. . . and Fuels

Probably the most critical problem in metallic fuels is the dimensional and mechanical integrity of uranium. Fissioning of uranium atoms creates two product particles for each fission event. These product particles, or fission fragments, are largely metallic elements that can be accommodated fairly readily in the metal lattice. However, 12.5 percent of the fission fragments are isotopes of the rare gases xenon and krypton. The effects of these gaseous elements within the lattice are not precisely understood, but presumably they are a major factor in the deterioration of properties that occurs during irradiation.

When unalloyed uranium is irradiated at low temperature, a density decrease occurs that is linear with exposure (illustration, right, next page). This is accompanied by serious embrittlement at relatively low exposures. When long-time exposure takes place at high temperatures (above 500 C), gross swelling results, accompanied by considerable internal porosity.

Such changes may be the limiting factor in fuel lifetime and hence in operating cost. The use of refractory uranium compounds, such as uranium oxide, UO_2, appears to solve the problem of radiation stability. The economics of UO_2-fueled systems, however, leave something to be desired, because UO_2 has a lower density of uranium atoms per cubic centimeter of fuel than does uranium metal. It is, therefore, essential to understand the changes occurring in irradiation of fissionable materials. In particular, it is important to understand the behavior of any internally generated gases, in order to devise fuels that optimize both cost and radiation stability.

Working with irradiated uranium requires extensive, shielded "hot-laboratory" facilities to permit examination and measurement. Because these were not available at the Research Laboratory, it seemed desirable to examine systems in which radiation produces gas atoms uniformly within a metallic lattice



SOLID SOLUBILITY of silicon reaches 14 percent in alpha iron at 400 C (color curve). In spite of this, brittle behavior begins as low as 4 percent Si and persists up to 800–1000 C.

but without excessive accompanying radioactivity. An alloy containing boron is satisfactory, for capture of a neutron creates helium (an α particle) and Li^7. Another satisfactory series of alloys contains lithium, for the Li^6 isotope in naturally occurring lithium reacts with a neutron to form tritium, H^3, and helium. Both reactions have high cross sections, and neither is accompanied by serious radioactivity.

Boron, unfortunately, is not soluble to any appreciable extent in metallic systems. Attention has therefore been centered on lithium-bearing systems, even though the presence of both a rare gas (He) and an active gas (H^3) somewhat complicates the analysis. The system Mg-Li is particularly attractive because lithium is soluble in hexagonal magnesium to four percent by weight (about 10 atom percent) and a single-phase body-centered cubic alloy exists from 10 weight percent Li (28 atom percent) to pure lithium. With such systems the effect of gases in two different crystal structures can be simply examined. The use of an Al-0.4 percent Li^6 alloy provides information on a third crystal structure, called a face-centered cubic.

In this phase of the investigation, an experimental program was carried out on 0.040-inch diameter wire specimens, emphasizing mechanical property measurements at room temperature, 150 C, and 250 C. Wires were irradiated in a research reactor at Argonne National Laboratory in a thermal neutron flux of 2×10^{13} neutrons per square centimeter per second. For the pile irradiation, the wire samples were placed in an aluminum jig and sealed within a helium-filled aluminum can or capsule (photo, page 43). Burnup of greater than 0.1 percent of all atoms was obtained in a few months of irradiation. This is equivalent, in terms of gas generation, to fuel operation for about 1½ years in a Dresden-type reactor.

In addition to mechanical properties, physical dimensions and electric resistivity were also measured. X-ray powder patterns were taken prior to irradiation and compared with similar patterns after irradiation.

The results indicated that the Mg-Li alloys decrease in density because of the formation of internal pores. These are believed to be produced by agglomeration of the helium and tritium gas atoms formed by the irradiation. The pressure of this internally produced gas is sufficient to expand the solid metal, which is relatively soft at the irradiation temperature of 250 C. Surprisingly, the Al-Li alloy does not follow suit, but seems to tolerate relatively large amounts of gas without swelling. We hope that further understanding of this difference in behavior may provide clues for minimizing swelling effects in nuclear fuel alloys.

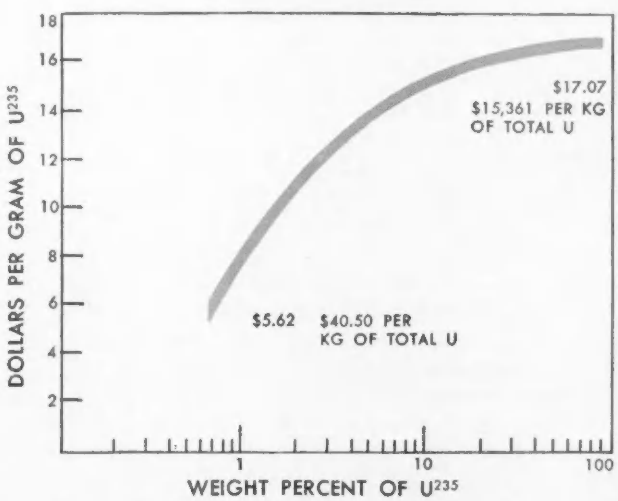
Radiation Damage

Although radiation damage in structural metals has not been of major engineering concern, it is of great fundamental interest. It provides insight into the mechanisms of radiation damage of all kinds and into the nature of the solid state. We are particularly ignorant of the precise nature of the defects produced by a bombarding neutron or other particle and the resulting secondary recoil atoms. Clearly both vacant lattice sites and extra atoms, probably jammed into interstitial sites, must be produced. Depending on temperature and the nature of the defect, these may or may not anneal out (return to equilibrium sites) during or after the irradiation.

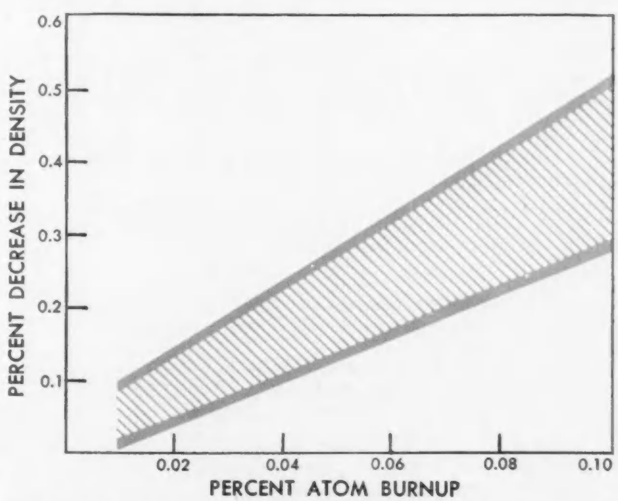
Dr. J. W. Corbett and Dr. R. M. Walker have been studying this problem by carrying out electron irradiations at extremely low temperatures (4 degrees K) and then measuring property changes as the specimen is warmed up. The major portion of their work to date has been on pure copper. They find that several simple types of defects must exist, because several different stages of annealing are observed even below 70 K. The clarification of these various stages is leading to a more exact picture of the defects radiation produces, the ways in which these may be removed, and their effects on the important properties of matter.

Research Contributions

These selected examples of Research Laboratory efforts in the realm of nuclear materials range from relatively applied to highly fundamental. They do not represent the entire effort in the nuclear materials field, but they may at least suggest some of the ways in which application of fundamental understanding or development of new understanding can help solve critical engineering problems.Ω



HIGH-CROSS-SECTION material requires a uranium fuel highly enriched with U-235; cost per gram varies with enrichment.



UNALLOYED URANIUM that is irradiated at low temperatures undergoes a decrease in density linear with exposure.

Abstracts

For your convenience to clip and file for ready reference: brief summaries of articles appearing in this issue.

Plasticity of Solids Explored by New Technique *Classification:*

Gilman, John J.

After describing basic mechanical properties of engineering materials, the author explains dislocations and tells how etch pits in a crystal's surface locate dislocation lines.

GENERAL ELECTRIC REVIEW July 1958 pp 9–12

The Future of Science and the Liberal Arts *Classification:*

Giddings, Glenn W.

In our ever-widening technology, the author recognizes the necessity for integrating science into our culture and suggests more dynamic liberal-arts curricula.

GENERAL ELECTRIC REVIEW July 1958 pp 13–15

Helium Tunnel Tests High-Speed Models *Classification:*

Operating what is believed the world's largest and fastest helium wind tunnel, the Research Laboratory probes for a greater understanding of air flow above Mach 20.

GENERAL ELECTRIC REVIEW July 1958 pp 16–17

The Problems of Mastering Thermonuclear Power *Classification:*

Hurwitz, Henry, Jr.

Tremendous problems of control will accompany fusion power as attested by the intricacies of magnetic configurations—the stabilized pinch, the stellarator, and the mirror machine.

GENERAL ELECTRIC REVIEW July 1958 pp 18–23

Radiation Works for Man *Classification:*

Learning more about the effects of radiation on chemical compounds and living organisms, scientists are making progress in turning radiation into a beneficial tool for mankind.

GENERAL ELECTRIC REVIEW July 1958 pp 24–25

Refining Grain Structure by Inoculation *Classification:*

Metallurgists performing experiments on stainless-steel castings attempt to control the grain structure as it solidifies from the melt by applying the inoculation technique.

GENERAL ELECTRIC REVIEW July 1958 pp 26–27

Probing into Chemical and Physical Phenomena with Shock Tube and Synchrotron *Classification:*

Nuclear physicists and chemists are aided in their studies by the synchrotron and shock tube—important tools of research.

GENERAL ELECTRIC REVIEW July 1958 pp 28–29

Small-Scale Unconventional Power Sources Now Assume New Significance *Classification:*

Flagg, John F.

The article affords a close look at several unconventional power sources, with a detailed description of how each works. Some offer possible small-scale applications.

GENERAL ELECTRIC REVIEW July 1958 pp 30–33

New Voltage-Tunable Magnetrons: How They Work and Where *Classification:*

In the new voltage-tunable magnetron, frequency is set by the value of the d-c anode voltage, which facilitates electric, remote, and almost instantaneous variations.

GENERAL ELECTRIC REVIEW July 1958 pp 34–36

Investigating the Dielectric Pump *Classification:*

Auer, P. L.
Sharbaugh, A. H.

Hearing of the discovery of a dielectric pump, the authors investigated into the particulars of why such a pump should work.

GENERAL ELECTRIC REVIEW July 1958 pp 37–38

Tracing Electron Paths *Classification:*

Mechanical analog of an electron tube represents the newest and most ingenious device to aid in the study of electrons.

GENERAL ELECTRIC REVIEW July 1958 p 39

Fuel Cells May Provide an Important Source of Power *Classification:*

Douglas, D. L.
Liebhafsky, H. A.

The inherent simplicity of the fuel cell's operation is analyzed. Because it escapes the Carnot-cycle limitation, the fuel cell may promise more efficient electric power.

GENERAL ELECTRIC REVIEW July 1958 pp 40–41

Flame Drop *Classification:*

Research Laboratory's Chemistry Unit tackles the question of how fire would burn in the absence of gravity.

GENERAL ELECTRIC REVIEW July 1958 p 42

Research Findings Speed Nuclear Progress *Classification:*

Lillie, David W.

Some of the results of General Electric's research in nuclear structural materials and fuels are discussed and appraised.

GENERAL ELECTRIC REVIEW July 1958 pp 43–45