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NASA SP-5015

CONFERENCE ON NEW TECHNOLOGY

LEWIS RESEARCH CENTER

CLEVELAND, OHIO

JUNE 4-5, 1964

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

Welcome to Lewis Research Center and to this Conference on New Technology. We are pleased that you are here, and will endeavor to make your stay interesting and useful.

The vehicles and spacecraft launched from Florida are the visible results of our Nation's space effort. Less evident is the body of technology that makes these and future flights possible. Almost half of NASA's 30,000 employees are among those creating this technology.

Selected topics from this technology are presented in this conference for your review; we believe that you will find much of it adaptable to your use.

Abe Silverstein

ABE SILVERSTEIN,
Director.

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Contents

Introduction

WALTER T. OLSON
Lewis Research Center

IT IS MY INTENTION to give you some of the background and setting for this conference and to tell you briefly what will be presented. Because we are at the Lewis Research Center for this conference, I will speak briefly about the Center and its work. Because the conference fills a part of NASA's objective that new knowledge and know-how related to aerospace be made available to the maximum extent possible, I will relate some information concerning NASA's efforts in this direction.

I am assuming that you have a general familiarity with the national space program, its scientific studies of space phenomena, its manned explorations, its applications programs such as weather and communications, and the extensive research and development both to support present activities and to make future programs possible.

One of 10 major centers of NASA, the Lewis Center is currently the second largest with a staff of approximately 4800 people, 1800 of whom are professional engineers and scientists.

Major tasks of the Lewis Center are research and advanced technology in propulsion and power for flight. Physically, the Center occupies 350 acres with an auxiliary location of 6000 acres at Plum Brook, near Sandusky, Ohio. Lewis comprises extensive laboratories in many buildings for almost every kind of physical, chemical, electrical, and metallurgical research. In addition, unusual tools for propulsion and power technology include such items as space simulation chambers, high-speed wind tunnels of various sizes, engine test facilities that simulate altitude operation, test stands for rockets and components, and radiation sources, including a cyclotron and a 60,000-kilowatt reactor.

The Lewis Center came into being in 1941 as an outgrowth of the powerplants group at the National Advisory Committee for Aeronautics' Langley Research Laboratory, established in 1917 as the first research laboratory for studying flight in the Nation. During World War II, the Lewis Center made major contributions to reciprocating engine cooling and high octane fuels. The period immediately following saw the development to a high degree of the air-breathing turbojet and ramjet engines. Development of these engines relied heavily on basic results from compressor, fuels, combustion, and turbine research here. Every major U.S. engine flying jet aircraft today has been put through its paces here to have some item or other of Lewis research incorporated into it. Early work on liquid-fueled rockets, mostly high-energy propellant rockets, paralleled the air-breathing program and expanded rapidly in 1957.

Today, the current program of the Center is aimed at advancing the technology of chemical, nuclear, and electric rockets, and of space electric power for a wide spectrum of power levels. It includes the background research and technology in metallurgy, basic chemistry, fuels, fluid flow, heat transfer, electronics, control dynamics, nucleonics, and other topics pertinent to these engines and pertinent to new and unusual propulsion and power generation systems.

Additional activities include responsibilities for development, as operational articles of the Centaur launch vehicle, the improved Agena launch vehicle, the SNAP–8 power system, and the 1,500,000-pound-thrust M–1 engine. Centaur and M–1 are based on the hydrogen-oxygen technology that was pioneered at Lewis within the last decade; the technology of flying liquid hydrogen is vital to many of our future missions, notably Apollo, while Centaur itself is a vehicle that is planned to soft-land instruments on the moon.

For the fiscal year just about to end, Lewis will have accounted for about $370 million of NASA's budget. About $80 million will be used for salaries, operations, and general support of in-house projects, including construction; the remaining $290 million represents contracted research and development work—three-fourths of it in four large projects.

In presenting this Conference on New Technology from Lewis, we are contributing to an important NASA program: a deliberate effort to disseminate aerospace-related technology as widely as practicable and appropriate. It is a part of NASA's broad responsibility to ensure maximum value from national space activities. This particular NASA effort is undertaken, in part, to meet a problem: research and development activities and their results are large and growing larger, but these activities and results are isolated from many users by company, by industry, by geography, and by many subtle, but nonetheless powerful, factors, including even psychological ones. For example, we hear cries that the Midwest is not deeply immersed in the stream of new activities based on technology and science.

Consider money as a criterion of size and growth. Research and development expenditures have increased more than an order of magnitude in each of the last two decades and stand now at $17 billion annually. But this growth has been largely for defense and space not for direct and immediate purposes, which now claims only a fourth or less of this effort.

A current national concern is that results from these expenditures may not be used as widely and effectively as possible in the general economy. The tremendous volume of results pouring from laboratories everywhere adds to this concern. I read of enough scientific literature published every 24 hours to fill 7 complete 24-volume Encyclopedia Britannica's. Or, again, that a chemist reading the literature of his field all day, every day, would fall behind 9 years for every year he read. Old-fashioned ways of letting nature take its course in the useful dissemination of this flood of new information are inadequate. Knowledge and need are separated. Consequently, NASA is testing and establishing various new methods of speeding and increasing the dissemination of aerospace-related technology.

One method involves identifying and publicizing innovations. Both in-house and contracted efforts are systematically perused for new products or devices, processes or techniques, ideas or inventions that might have potential usefulness.

Several research organizations—Battelle, Illinois Institute of Technology, A. D. Little, Southern, Stanford—evaluate the commercial or industrial possibilities. Dissemination follows by one or several methods: trade journals, special publications, film clips, letters, conferences, exhibits, etc.

In another method, Midwest Research Institute has obtained information on hundreds of innovations and new technical developments. The task at Midwest has been to translate NASA findings into forms that can be of direct benefit to industry with a view to broadening the range of application of these ideas and reducing the time lag to their practical use. Their work has involved search and study, followed by briefings and visits. In just two years, Midwest has contacted thousands of businessmen and engineers with briefings in approximately 20 midwestern cities. Their experience, briefly, was that a number of firms that were active in aerospace work found profitable applications in the civilian economy:

(1) Methode, in Chicago, a supplier of printed cable to NASA, supplies Buick with printed cable for dashboards.

(2) Thiokol has developed superior printing rolls from the polysulfide rubber developed for cast, solid propellants.

(3) National Research Corporation's ½-thousandth-inch aluminum-coated plastic film, of which the ECHO satellite is made, is also in use as a reflective insulator for very low temperature vessels.

These examples are not surprising.

Midwest further found, however, that, although few nonaerospace firms had any notion of how to put space technology to use, enthusiastic responses to briefings were received from hundreds of companies. Most important, Midwest cites many examples of how nonaerospace companies have put space technology to profitable use after deliberate contact had been established:

(1) A Springfield, Illinois, firm uses magnetic swaging as the best way to fasten terminals onto a low-impedance coaxial cable without damaging the thin insulating sheath.

(2) A midwestern manufacturer of transistors isolates his delicate microbalances from vibrations with air-bearing suspension.

(3) Air bearings eliminated a long-standing bearing contamination problem in a large machine for a Kansas firm.

(4) One of the largest oil-prospecting companies in the nation virtually eliminated soldered-connector troubles in its field equipment by using the NASA-Marshall booklet and training course on Reliable Electrical Connections.

(5) Sintered aluminum oxide ceramic, developed for rocket nozzles, is used for special check valves and special resistor cores.

(6) Refractory, pressure-sensitive tape has been used as a backup to permit continuous single-pass welds on thin-walled rocket tanks. A Tulsa producer of pressure vessels finds that the technique saved both labor and money and produced better welds.

(7) Another company estimates a $2 million capital saving by using explosive forming to make large dished tank heads. Explosive forming is not a new process but was little used in this country until the aerospace industry developed it.

A third method by which NASA diffuses aerospace technology enlists a vital ingredient—"pull" from industry for new technical information, as well as "push" from NASA. At Indiana University about 30 client companies pay an annual fee for a service from a branch of the university. The service consists of selecting and "translating" aerospace literature. Indiana has all this literature on tapes. Two important activities are: First, it supplies a searched and sorted sample from all aerospace literature to the client. They work with the client to establish an interest profile, so that selective dissemination of literature results. And, second, Indiana will try to answer any technical query, first, from the literature, and, that failing, by knowledgeable consulting at a NASA center.

(1) One client says, "this may be a prototype of a future information system. The information explosion is rendering traditional channels of science obsolete."

(2) Indiana University has helped one company learn of certain new testing methods for thin-gage sheet metal.

(3) Another client found one innovation that may lead to a major change in the circuitry of one of their inspection instruments and greatly enhance its value.

(4) A small manufacturer of plumbing and heating specialities will try to introduce a new welding process from aerospace to improve his product and save parts and cost.

(5) Another small manufacturer won a contract with information on high-purity helium produced in 48 hours. He knew of no other way to get an answer so fast.

(6) Efforts similar to those at Indiana are underway in Detroit and just starting in Pittsburgh.

Throughout all of this NASA program, it is very evident that direct transfers of processes, materials, products, and techniques have been and can be effected. An impressively growing list of examples can be cited —so-called spinoff and fallout.

Also apparent is the impetus given to the growth of certain main bodies of technology in the country by aerospace activities. Witness the growth and direction of growth of the electronics industry, with computers and knowledge of systems control and all that they are coming to mean in automation; the use of miniaturized electronics in the medical field; and such new areas of chemical investigation as free radicals at cryogenic temperatures, boron chemistry, and fluorine chemistry—all urged along by the search for better rocket propellants.

The aerospace program involves almost every area of engineering or physical science in some way and many areas in life sciences as well. It both uses and creates knowledge and skill at their frontier. If history conveys a lesson, the biggest rewards that lie in the foreseen and unpredictable at this time. The important first step to the use of new technology is to determine what it is. This conference has just that goal. In a sense, it is still another method by which NASA is trying to fulfill its responsibility to disseminate new technology. In another sense, it is a report on NASA's stewardship of funds and manpower in at least one corner of the aerospace program.

The scope of what will be presented is derived from the particular problems and interests of this Center—a center oriented to propulsion and power research and development. Also, an effort was made to select topics with some relatedness to the kinds of activity in northeastern Ohio: fabrication, metals and materials, power, bearings and lubricants, instruments and controls, and with a few newer topics: liquid metals, superconductivity, and ion and plasma technology.

We hope to describe these few selected areas from the world of aerospace so as to make evident the type and extent of accomplishment in them, important new contributions or trends, and the prospects and limitations for future growth. We invite your further examination of whatever appears important to you.

I. Fabrication

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AUSTIN F. READER, EDWARD F. BAEHR,
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Lewis Research Center

SOME OF THE FABRICATION techniques and equipment utilized by the NASA Lewis Research Center, other NASA centers, the Department of Defense, and the aerospace industry in solving the problems generated by the exact and demanding field of space-age hardware manufacture are described.

The Lewis Research Center was originally the Aircraft Engine Research Laboratory of the former National Advisory Committee for Aeronautics. Since its beginning in 1941, Lewis has been involved with engines and propulsion devices ranging from the gasoline reciprocating engine through the jet era of turbojets, gas turbines, and ramjet engines, the chemical rocket engines, both liquid and solid, to the nuclear rocket and the electric thrustors such as the ion and the plasma jet. The electric thrustors require huge amounts of electric power, and power-generation equipment for space is a major fabrication problem area.

In the reciprocating engine days, the major fabrication problems were fine finishes and close tolerances, and both were within reach by slight extensions of existing techniques and equipment. The jet and turbine era brought with it high rotational speeds and high temperatures. Since high temperatures in the gas stream yielded high specific thrust, heat-resistant materials for combustion chambers, nozzles, and turbines were developed. These materials required new concepts of joining, machining, and forming, and fabrication became more difficult. With the beginning of the space age, however, those in fabrication became sure that previously, men in research and engineering had only been difficult; they then said, "Why be difficult? With just a little more effort we can be impossible."

Saying that the space-age fabrication problems arise because of requests to build things from unmachinable, unweldable, and inflexible materials to impossible shapes, finishes, and tolerances is only a little facetious. Seriously, progressively more difficult fabrication problems have been generated by this transition from Kitty Hawk to the Moon.

The research centers and the aerospace industry are faced with very severe design and fabrication challenges brought about by the requirement of 100 percent reliability of its product in both safety and operation for the time required to complete the mission, which could range from minutes to years.

This finished product may contain such incompatible elements as liquid fluorine, liquid hydrogen, liquid metals, and radiation sources. It must operate perfectly in the hostile environment of space, which includes extremely high and low temperature, vaccum, vibration, radiation, and gravity forces. It must also provide a safe and livable environment for man. The conditions mentioned restrict the selection of materials to those few that can meet the performance requirements with small regard given for fabrication difficulty.

The challenge to inventive engineering,

precision craftsmanship, and versatile tooling is constant. A part must often be made that has never been made before; also, the machine or technique required may be nonexistent. These problems are the ones connected with doing prototype, one-of-a-kind jobs. Once the design is established, a set of specifications, including a suggested fabrication technique, can be written, and the job goes to industry by contract. A large percentage of the Lewis fabrication workload is handled by industry.

Through the years there has been a steady crossflow of information between industry and aircraft research and development in the fabrication field. Since the era of space exploration, this crossflow may have become too much one way. With the huge increase of the requirements of space, aerospace fabricators and manufacturers have had to find, develop, and use many processes that may be unfamiliar to many in more traditional industries.

Because of the heavily industrialized area of northeastern Ohio, we are sad to see so much of the Lewis work going to east- or west-coast aerospace industry for the lack of successful bidders in this area. This happens many times because of a lack of some equipment such as a helium-leak detector or electric-discharge machining equipment or a fear of the unfamiliar materials, processes, tolerances, or finishes required.

Other factors that may enter into this problem are either the lack of interest and initiative by the contractor in a job when any part of the job fails to match his exact capabilities or the lack of a central information center on special skills, materials, or equipment available in this area, which would enable one bidder to act as prime contractor and to subcontract the special work to others. Many jobs leave this area when a contractor well qualified to handle 95 percent of the job refuses to bid because of the 5 percent part of unknown materials or special processes. One requirement, for example, called for a conventional machining and assembly job consisting of materials such as molybdenum, tantalum, stainless steel, microquartz, Magnorite K firebrick, Mycalex, aluminum oxide, zirconium, magnesium oxide, and zirconium oxide. All these materials are available, and sources were listed in the specifications. Out of 30 contractors to whom "Invitation For Bids" were sent, only two responded, one from the East coast and one from the West coast. Both bidders were close to the Lewis estimate.

Forty-three "Invitation For Bids" on service and materials to fabricate, to machine, and to test-assemble two snout assemblies of aluminum for the Plum Brook reactor were issued. Only three contractors responded. Inquiry to several of the nonbidders indicated that the request was turned down because of the difficulty of drilling three blind thermocouple holes at an exact angle and spacing from the inside of a 7½-inch-diameter tube at a point 103 inches from the end. This is not an easy job, but it does not require too much imagination to devise a drilling fixture to accomplish the work.

For several years, practically no vacuum work was done by local contractors because no vacuum testing facilities were available even in the testing laboratories, although the equipment is relatively inexpensive. This situation has changed greatly in recent months. These examples show that management as well as technical problems exist in this space business.

Three basic areas of fabrication familiar to all are discussed: forming, machining, and joining. The discussion of a few new processes and their application, along with the application and extension of many well-established processes will help in an evaluation of some of these techniques for possible application in other fields.

The ideal material, on the basis of performance requirements, always seems to have the characteristic of being difficult in either forming, machining, or joining.

MATERIALS

Research metallurgists are not just turning out impossible-to-fabricate alloys. A great deal of effort is actually going into designing alloys with improved fabrication characteristics. There is a limit to what they can be expected to do in this respect; these improvements in fabricability usually result in a compromise in the properties of the alloy.

In fabrication there is definite progress in new techniques that will give the designer added freedom in both material selection and design. Certainly, a lot of the progress has been with the so-called refractory metals—those seemingly unmachinable, unweldable materials—but as ways of working these refractory metals are developed, these same techniques and methods help in the more efficient use of other alloys like aluminum and steel.

Most commonly, refractory materials are defined as those with a melting point above 3300° F. There are 12 metals in this category, but the principal ones are tungsten, tantalum, molybdenum, and columbium. Some of their properties are shown in the following table:

Material	Melting temperature, °F	Availability, ppm of Earth's crust	Price (powder), dollars/lb	Density, g/cc	Tensile strength at 2000° F, psi	Room-temperature elastic modulus, psi
Tungsten	6170	69.0	3.10	19.3	60,000	50×10^6
Tantalum	5425	2.1	31.50	16.6	15,000	27
Molybdenum	4730	15.0	3.65	10.2	30,000	47
Columbium	4474	24.0	36.00	8.6	15,000	15
Carbon	6740	----------	----------	----------	----------	----------
Lead	----------	----------	----------	11.4	----------	----------
Iron	2790	50,000	.03	7.9	----------	28.5
Copper	1981	70	.31	9.0	----------	16
Aluminum	1220	81,300	.24	2.7	----------	9

With their high melting points, they can be used at temperatures far above the melting points of our common metals. The refractory metals in parts per million of the Earth's crust are not particularly rare; tungsten, for example, compares favorably with copper. Presently they cost from 10 to 100 times as much as iron and copper, but as their application is extended, these prices will be reduced. The pure refractory metals are also dense or heavy. Columbium, however, compares favorably with iron or copper in this respect. All four have usable strength at 2000° F, pure tungsten and molybdenum being much stronger than pure columbium or tantalum.

As is usually the case, the strongest metals and alloys are the most difficult to fabricate, and this is certainly the case with these four metals. Tungsten and molybdenum possess certain characteristics that make them much more troublesome during fabrication. Tungsten and molybdenum can be grouped because they both must be formed at elevated temperatures to prevent them from cracking. They both oxidize rapidly above 800° F. This limitation is serious during both the fabrication and the actual use of these metals.

Most metals start to oxidize in this range, but if the oxides that form on the surface are dense and adherent, they protect the metal from further rapid loss. With these refractory metals, the oxides are not dense and adherent; in fact, they boil off to expose more metal to oxidation until the piece is completely gone.

If there is any ductility at all in the tungsten or molybdenum before it is welded, it is gone after welding. In many cases the solidification stresses are enough to crack the piece before the welding can be completed.

Tantalum and columbium, on the other

hand, can be worked readily at room temperature. This is an advantage during the fabrication, but during actual use at elevated temperatures even small percentages of oxygen, nitrogen, and hydrogen must be kept away from them. Not only do they oxidize, but also these gases diffuse into them very rapidly and seriously embrittle them. For some applications, these gases are not present, for example, in the vacuum of outer space, but in order to extend the applications of these metals, their oxidation resistance must be improved by alloying or by protecting them with reliable coatings.

If columbium or tantalum is welded in carefully controlled atmospheres, the welds are very ductile. No matter how carefully tungsten or molybdenum is welded, the weld is brittle. Working with tantalum and columbium is clearly preferable.

Research with columbium and tantalum is designed to increase their strength and oxidation resistance and, at the same time, to retain these favorable forming and welding characteristics.

METAL FORMING

High-Energy-Rate Forming

The old reliable processes of metal forming are being adapted to handle many of the newer requirements, but the high-energy-rate forming methods that are being developed and refined will probably play an ever-increasing role in the future. Most of these high-energy-rate forming processes are not really new, however, but rather the range of applications has only broadened to make them important. Explosive engraving was used as far back as 1888. Even the heavy steel domes for the pill boxes of the Maginot Line in France were explosively formed.

Four of the high-energy-rate forming methods are as follows:

(1) Pneumatic mechanical
(2) Explosive
(3) Electrospark or electrohydraulic
(4) Magnetic

The pneumatic-mechanical process employs the sudden release of the stored energy of a high-pressure gas, which makes possible forming rates up to about 10 times as fast as a typical press. Early systems employed tension or shear failure of restraining members to provide the sudden release of the work piston. Figure I–1 shows a trigger-gas system that opens an internal valve within the cylinder to provide the rapid application of the stored gas pressure to accelerate the work piston. This type of equipment is frequently used for high-speed forging and extruding operations. This speed is especially useful for working the refractory metals in that the forming process is so rapid that a preheated part is formed before it has a chance to cool.

The next three processes listed are much faster than the pneumatic-mechanical method and make use of explosives or the sudden release of stored electrical energy that occurs with explosivelike speed.

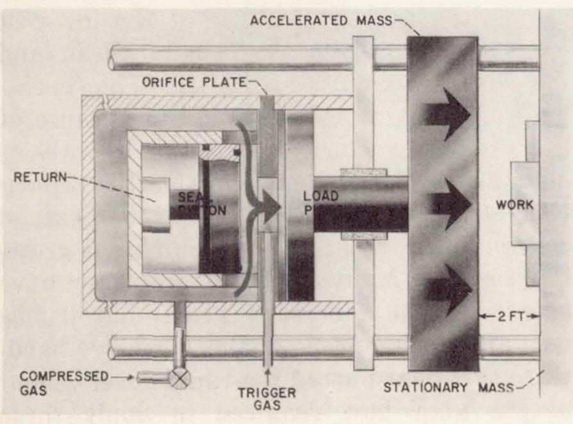

FIGURE I–1.—Pneumatic mechanical forming.

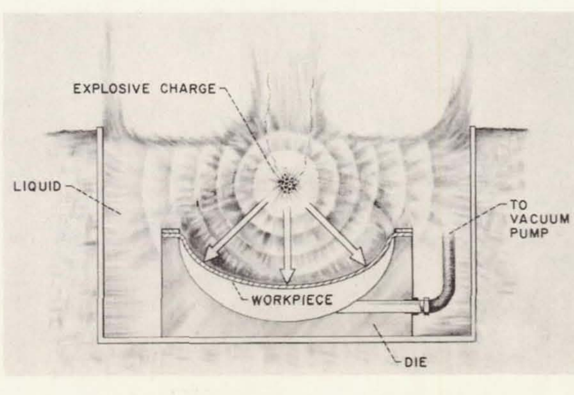

FIGURE I–2.—Explosive forming.

The typical explosive forming setup requires a remote field without close and particular neighbors, a tank of water, an inexpensive die, a vacuum pump, and some explosive. The remote location is required because of the shock and noise that accompany the firing of the explosive charge. In the typical part formed explosively (see fig. I–2), unique differences occur from one formed by conventional press forming. Because no male die is used, no friction restricts the flow of metal, and because the energy of the explosive charge is delivered to the entire face of the work-piece at the detonation velocity of the explosive and water system, the entire part is formed at one time; this reduces to a great extent local thinning that occurs in conventional forming and almost eliminates springback.

The electrospark or vaporizing-wire method uses the same principle as the explosive method, except that the energy is electrically stored in condensors and is released to form a shock wave in the fluid either by discharging a spark or by vaporizing a wire suddenly (fig. I–3). These methods make it possible to move the process into the plant and to reduce the cost to just a few cents per hundred shots. The exploding-wire method costs a little more than the spark-discharge method because of the cost of the wire and the labor required to replace it after each shot, but it does offer the advantage of being able to shape the workpiece into a particular contour to provide a tailoring of energy released in a given area.

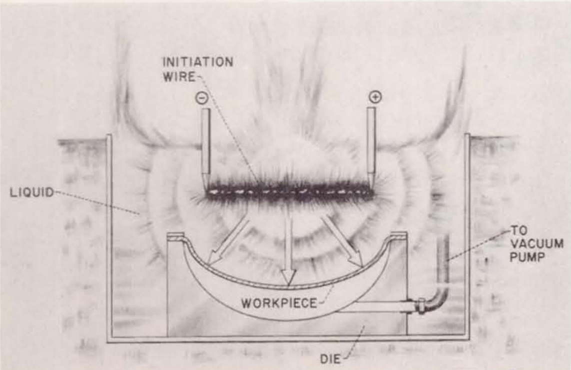

FIGURE I–3.—Electric-spark forming.

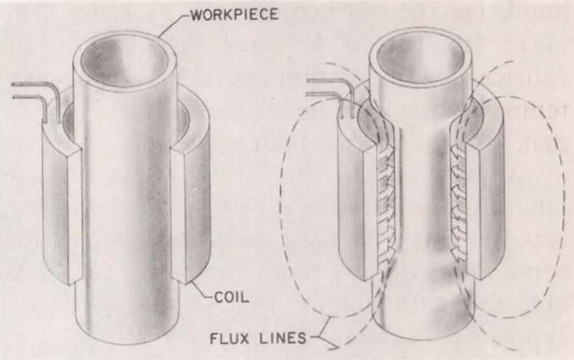

FIGURE I–4.—Magnetic forming.

The electromagnetic process also uses electrical energy stored in large capacitors, but in this case the rush of current is used to generate an intense magnetic field (fig. I–4). This sudden intense magnetic field induces current in the surface of any conductor within its field. If the material is a good conductor, such as copper or aluminum, the induced surface currents create an opposing magnetic field that can result in mechanical forces as high as 50,000 pounds per square inch.

Metals other than good conductors can be copper plated or wrapped with aluminum foil to act as a driver sheet. In figure I–4 the external coil creates a collapsing force, but coils can be designed to be placed within the workpiece to provide expanding forces, or flat coils can be designed to produce a straight push against a surface. Again, operating costs are low because of the low-cost energy source; dies are usually cheap and sometimes are not needed at all. The repeatability of this process is excellent because of the ability to store and release a precise amount of electrical energy from the capacitors. These processes are not used to extend conventional processes, but their use is growing rapidly. Many of these processes have been available for many years, but it has been the unique needs of the space-age hardware that has spurred the rapid development of the know-how required to apply these processes to useful tasks. In addition to the

FIGURE I-5.—Explosively formed aluminum dome. (Courtesy Martin Co., Denver, Colo.)

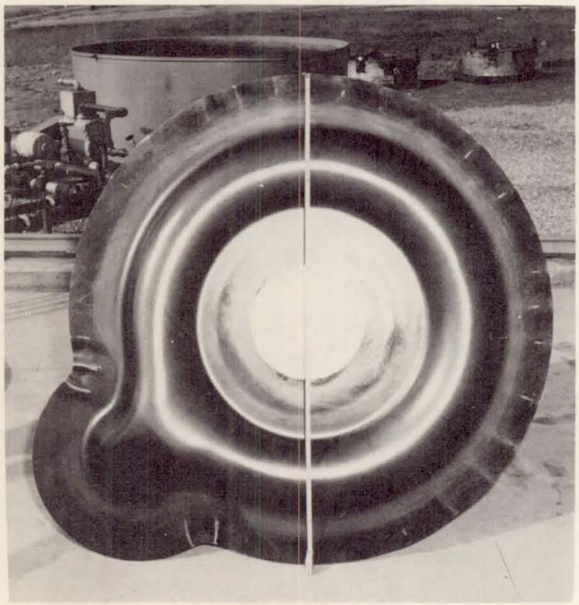

FIGURE I-6.—Explosively formed F-1 exhaust nozzle. (Courtesy Rocketdyne.)

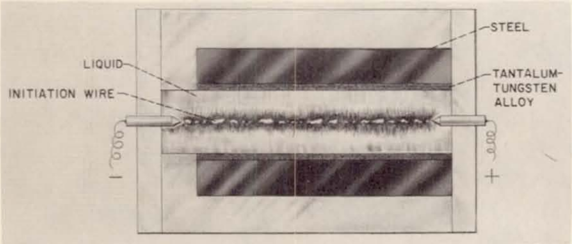

FIGURE I-7.—Electrohydraulic bonding.

unique capabilities that these processes offer, another advantage is the very low capital investment required to form large parts and the low-cost dies that can be used. In many cases the dies can be made of low-melting cast alloys or cast iron; sometimes even epoxy-faced concrete has been used.

A large dome formed by the Martin Company is a good example of this method (fig. I-5). This dome, 10 feet in diameter, was formed from a high-strength aluminum alloy plate by the explosive forming process. In the background is the large pit of water that was used; this material is $3/4$ inch thick and required three blows to form it into the required shape. Because of the low-cost die and explosive charges, it was possible to build it in one piece and to avoid problems of welding it from segments.

In figure I-6 is a turbine-exhaust collector formed by Rocketdyne of North American Aviation by the electrospark process. A water tank is in the background. This collector was made from high-strength nickel-base alloy that springs back excessively when formed by conventional processes; with the electrospark process, however, the springback is reduced to an acceptable level.

Battelle Memorial Institute, Columbus, Ohio, is also working on explosive forming techniques. A refractory metal liner being formed in a steel tube with the electrospark process, for example, is shown in figure I-7; they are not only forming but actually bonding or welding the two surfaces together. Usually the inner surface of the steel tube is roughened in some manner such as blasting or grooving. The electrohydraulic reaction then forces the liner against the roughened surface of the steel tube. In this manner, a bonding or cladding of the surfaces takes place. Battelle is also producing parts from powders compacted by this method.

The electrospark wire wrapped around a green powder compact is shown schematically in figure I-8. The electrohydraulic reaction results in a piece with very high density.

The next process worth discussing further

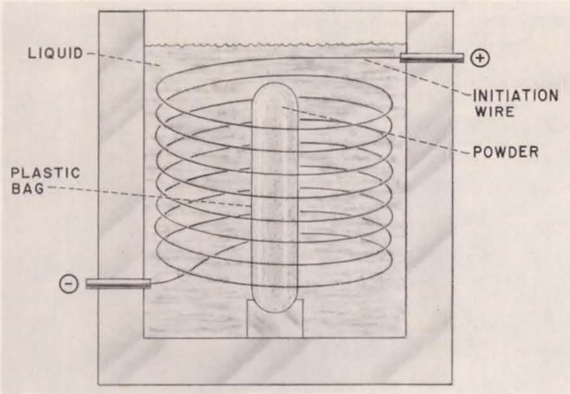

FIGURE I-8.—Electrohydraulic compaction.

is magnetic forming. The NASA Marshall Space Flight Center, Huntsville, Alabama, is working extensively with this process. They are forming stiffener corrugations in a large thin-wall aluminum fuel duct. The part shown in figure I-9 is a Saturn V vehicle component, a portion of the fuel duct with the corrugation already formed. On the right is the magnetic coil that was inserted into the aluminum cylinder. When the coil was energized, its magnetic field moved the aluminum to conform with the forces produced by this field. The extent of metal movement is determined only by the energy input into the coil. This input can be controlled very precisely. In an application such as this, the power of the magnetic coil could actually pull the cylinder apart in the corrugated area. Figure I-10 shows a full-scale field application of the fuel ducts. There are 18 corrugations in the vertical section. The magnetic forming technique is ideal for this part.

An adaptation of the use of magnetic fields to remove welding distortions produced in Saturn V tank segments is shown in figure I-11. This tool, called a magnetic hammer, produces a flat field, which removes irregularities in the weld surface of the tank.

A number of fastening devices formed magnetically are shown in figure I-12. In the two upper left views are hexagonal-head, serrated-shank fasteners, each slipped through a block of metal. A sleeve is slipped over the serrated shank and is magnetically distorted and formed onto the serrations. In the lower right cutout view is a similar application. The sleeve material has actually moved into the thread area of the bolt. The mass-production potential of this technique is considerable. General Motors is using this method for attaching end fittings on hydraulic power steering hoses.

High-Temperature Forming

The processes discussed so far are usually performed at room temperature, but by adding ingenuity and a little heat even the refractory metals such as tungsten and molybdenum can be worked on conventional machines. For example, an order to fabricate a heat exchanger with ½-inch-diameter, 24-inch-long tungsten tubes was received. At the time these items were not available anywhere. After considerable experimentation, a standard roll former was modified (fig. I-13) and successfully used to make the tubes. The tungsten sheet was fed through the rolls hot enough to be ductile; the heat was maintained by the flame jets. After forming, the tubes were pickled to remove oxidation and were welded in an automatic welder under an argon shield.

A standard hydraulic press brake was also altered by installing heating jets in the center of a modified lower die set. This lower die can be air- or water-cooled as required

FIGURE I-9.—Magnetically formed duct. Laboratory made. (Marshall Space Flight Center.)

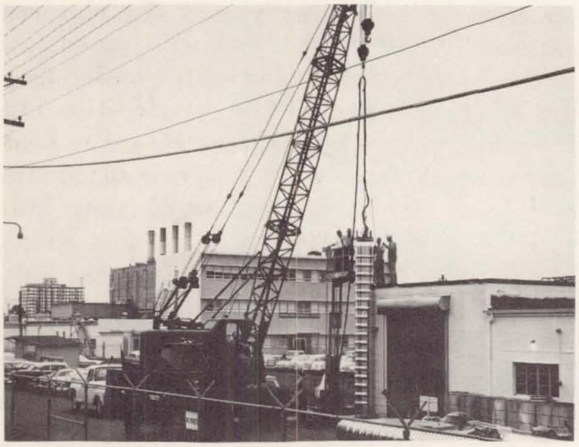

FIGURE I–10.—Magnetically formed duct. Field made. (Marshall Space Flight Center.)

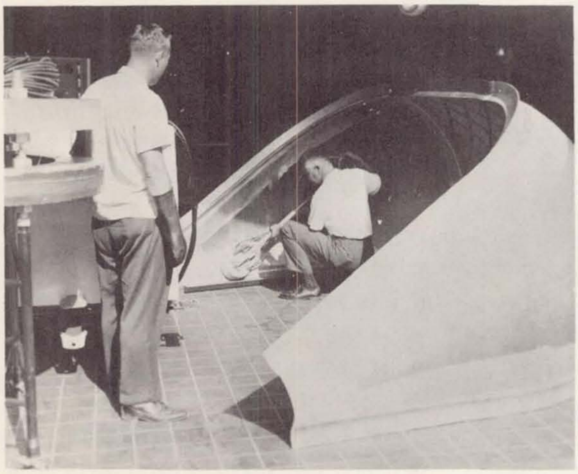

FIGURE I–11.—Magnetic hammer. (Marshall Space Flight Center.)

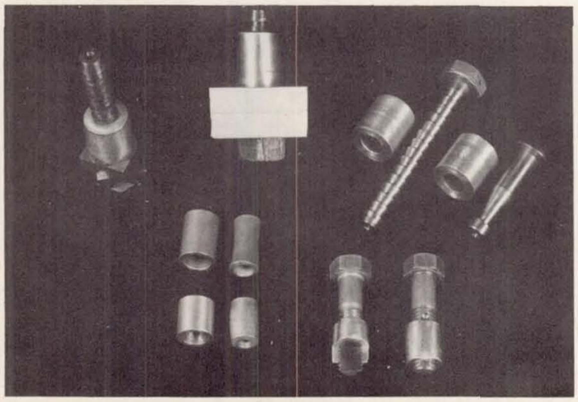

FIGURE I–12.—Magnetically formed fasteners. (Marshall Space Flight Center.)

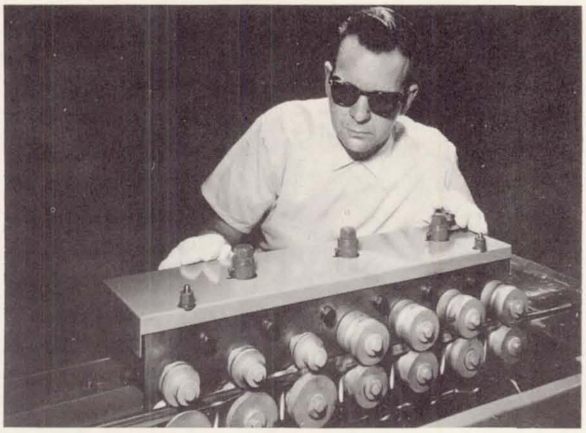

FIGURE I–13.—Hot forming of tungsten tube.

FIGURE I–14.—Hot cylinder forming of tungsten on heated brake.

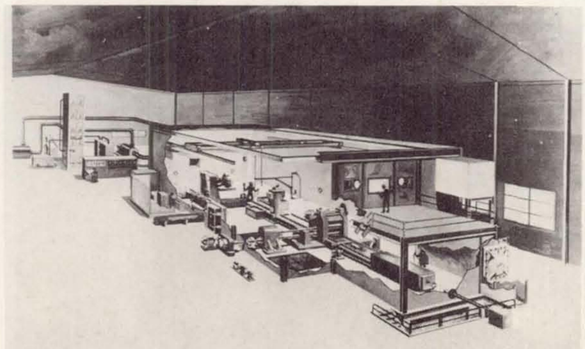

FIGURE I–15.—Argon atmosphere room. (Courtesy Universal Cyclops Corp.)

to maintain its strength while the jets heat the refractory metal to sufficient temperature to obtain the necessary ductility. The metal shown in figure I–14 is in the process of being formed into a cylinder.

These examples illustrate how conventional equipment can be modified to do refractory metal work, but a facility that Universal Cyclops has for refractory metal work, which they operate for the Navy, is a complete room in which they maintain an inert atmosphere (fig. I–15). All the air with its harmful oxygen, nitrogen, and other gases is replaced with argon. This inert gas will not affect any metal at any temperature in any way. They have a high-temperature electric furnace, a rolling mill, and forming equipment completely within the room. Technicians and welders working in this room must carry their own oxygen supply, and they even carry equipment to store their exhaled air (fig. I–16).

Metal Deposition

Two problems associated with making refractory metal shapes have been emphasized: the hot-forming problem and the welding problem. Tungsten and molybdenum are extremely brittle after welding. There are some processes that can build up these metals directly into the required shapes.

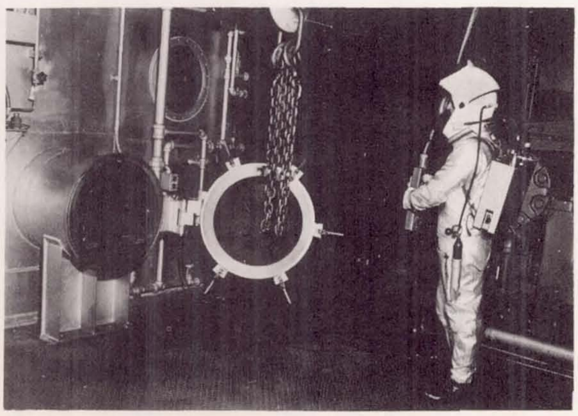

FIGURE I–16.—Technician in suit in argon atmosphere room. (Courtesy Universal Cyclops Corp.)

Plasma spraying is one such process (see fig. I–17). Plasma torches developed during the past 5 years utilize an electric arc to heat a stream of inert gas. The electric arc is contained within a water-cooled tube into which the gas is injected. The gas gains energy from the arc and issues from the unit much like a welding flame. By continually adding electrical energy, gas temperatures as high as 50,000° F can be achieved. These temperatures are in contrast to the oxygen-acetylene flame temperature of 6200° F. Metal powders such as tungsten and molybdenum can be injected into the nozzle by a carrier gas, melted, and spray-deposited on the prepared form. Removing the form later leaves the desired refractory metal shape. The very high temperature of this plasma torch also makes it useful for machining and cutting jobs. In these applications, the extreme temperature makes it possible to melt and blast away any material with much less heat effect on the remaining part than is possible with conventional torches.

Another so-called buildup process that is finding considerable application is the vapor-phase plating process (see fig. I–18). Almost any metal, including tungsten and molybdenum, can be converted into a metal compound, such as a fluoride. At relatively low temperatures, usually less than 500° F, this compound is vaporized and introduced into the deposition chamber. It is mixed with

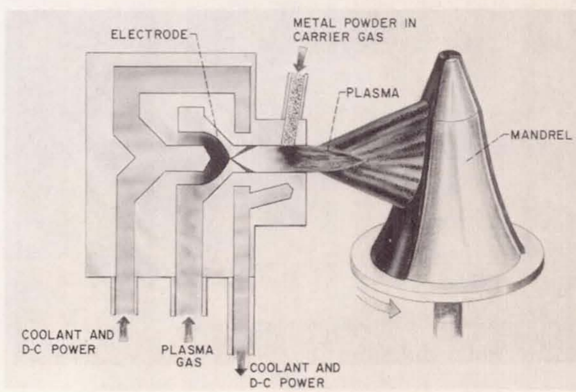

FIGURE I–17.—Plasma spraying.

hydrogen, which reduces the metal vapor to the pure metal. The reduced metal deposits and builds up in thickness on the heated form, which is later removed from the formed metal piece.

Both of these buildup processes that have been discussed have numerous applications. The purpose for their continued development, though, is to produce deposits of higher density, that is, the absence of any small voids, and also to obtain better strength properties in the deposits.

Still another process for building up shapes is electroforming. This is really an electroplating process that is used for building up the surfaces of parts that have complicated internal surfaces and cavities. Very fine tolerances and high finishes can be obtained with this method. Figure I–19 shows how heavy layers can be deposited over a machined mandrel. The mandrel material may be chosen to facilitate its later removal. The only requirements are that the mandrel surface be conductive and be compatible with the plating solution.

A wind-tunnel nozzle formed in this manner is shown in figure I–20. This drawing shows the normal segmented construction in the top portion of the figure and the one-piece electroformed construction in the lower portion. The nozzle is about 16 feet long. It could not be machined to close tolerances and finishes in one piece. One-piece construction of these nozzles adds to their operating efficiency through increased heat-transfer capability. The electroforming process provided this advantage.

The material properties that might be obtained with this type of process are shown, to a certain extent, in the following table (data from Electroforms, Inc.):

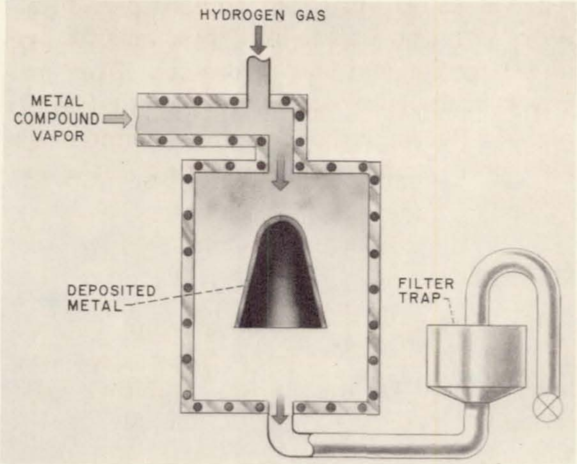

FIGURE I–18.—Vapor-phase forming.

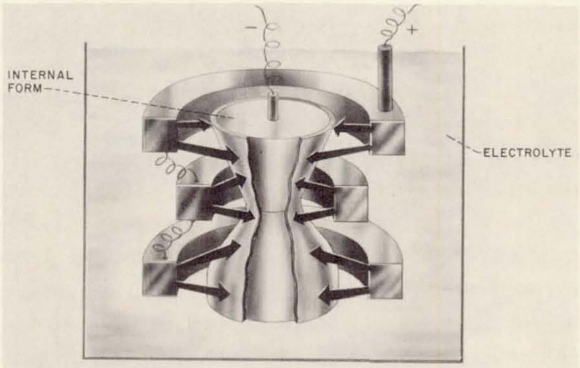

FIGURE I–19.—Electroforming.

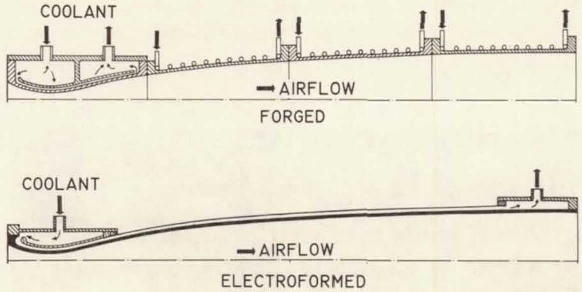

FIGURE I–20.—Electroformed nozzle. (Courtesy Douglas Aircraft Co.)

Property	Nickel	Silver	Iron	Copper
Minimum tensile strength, psi	160,000	30,000	60,000	30,000
Minimum yield strength, psi	100,000	------	------	15,000
Minimum elongation, percent in 2 in.	4	15	15	15
Average Vickers hardness	300	55	135	50

The values are quite high and compare favorably with the values for these metals produced by conventional processes. This process is limited only to those metals that can be plated. Recently this forming technique has also been improved by inducing ultrasonic vibration in the plating bath.

Cold Working

Even though there is no attempt to cover all the forming methods being used, one more should be mentioned. Building high-strength pressure vessels usually means working with hard-to-form and difficult-to-weld materials. One way to overcome this difficulty is to make the vessel from a soft material, such as annealed 301 stainless steel, which is relatively easy to form and to weld, and then to expand it or cold work the material to strengthen it (see fig. I–21). In this case, it is really cold worked because the material is stretched at a temperature of −320° F. This process is known by the trade name of Arde-Form. In this process the preformed vessel is filled with and surrounded by liquid nitrogen. The vessel is then pressurized to expand it to some predetermined diameter within a die. A cold reduction of only a few percent at this temperature has the same strengthening effect that a 30- to 40-percent reduction would have at room temperature.

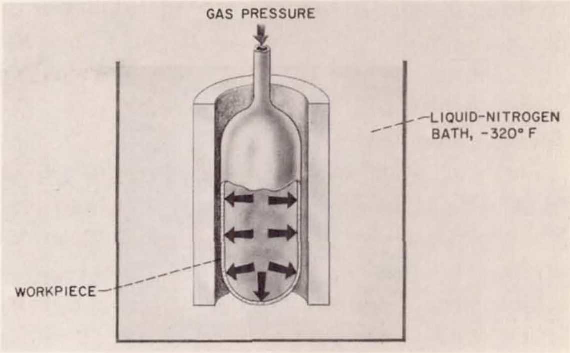

FIGURE I–21.—Cryogenic stretch forming.

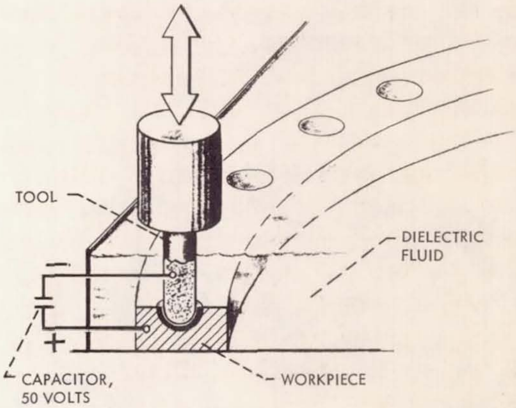

FIGURE I–22.—Electric-discharge machining.

MACHINING

Electric-Discharge Machining

One of these machining or metal-removing processes is electric-discharge machining or EDM (see fig. I–22). This process is not new, but it has been growing rapidly in application since its introduction by the Russians in 1943. The direct effect of an electric arc is used to remove material. The EDM tooling is machined in the desired shape and placed within 0.001 to 0.002 inch of the workpiece. Both the tool and the workpiece are immersed in a dielectric oil. A current control charges a capacitor to approximately 50 volts, which causes the dielectric fluid to break down and establish an arc between the tool and the workpiece during which time small volumes of both work and tool material are heated and melted. The molten metal is then expelled into the dielectric fluid, which leaves minute craters in the work. Each discharge occurs at the point closest to the tool, and as a result the location of each discharge differs from the previous one. The frequency of this arcing process ranges up to 250,000 cps. As machining progresses, a servomechanism advances the tool into the work to maintain a constant gap.

In figure I–23 is a shaped electrode in position after cutting a blade shape into a molybdenum alloy disk. This alloy is brittle

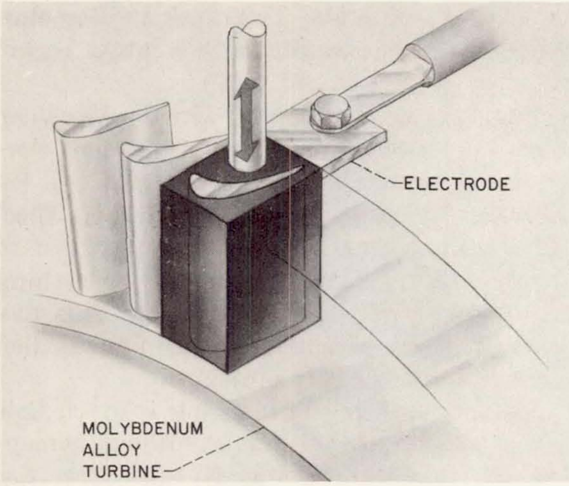

FIGURE I-23.—Phantom view of molybdenum turbine. Electric-discharge machining

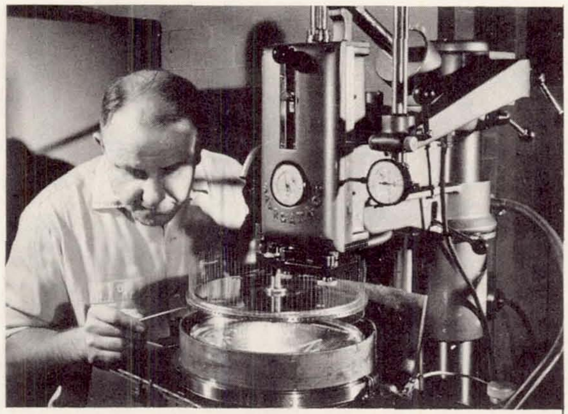

FIGURE I-26.—Multiple drilling machine. Electric-discharge machining.

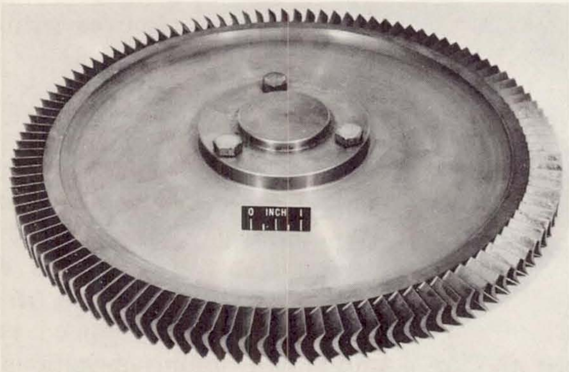

FIGURE I-24.—Molybdenum turbine wheel. Electric-discharge machining.

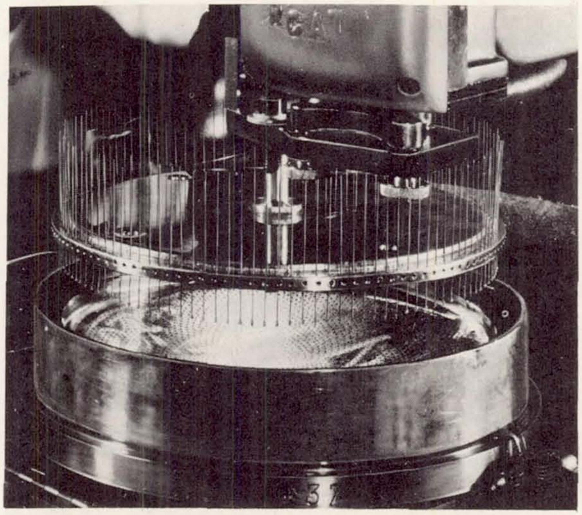

FIGURE I-27.—Closeup view of multiple drilling. Electric-discharge machining.

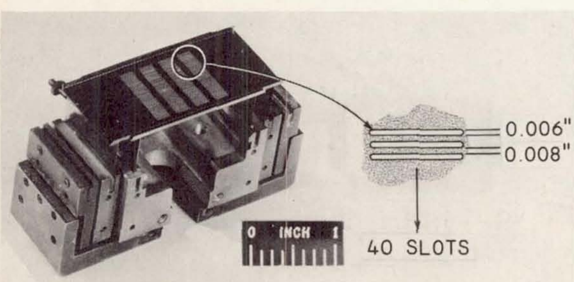

FIGURE I-25.—Tungsten grid. Electric-discharge machining.

near room temperature, and the complete absence of tool pressure is an essential feature of this process. The completed refractory alloy turbine (fig. I-24) will be driven at high speeds by sodium vapors at 2000° F.

Extremely fine detail is possible with relatively simple and inexpensive tools. The tungsten grids in figure I-25 were produced by electric-discharge machining 40 slots at a time.

Multiple drilling of fine holes is another example of the versatility of this machine.

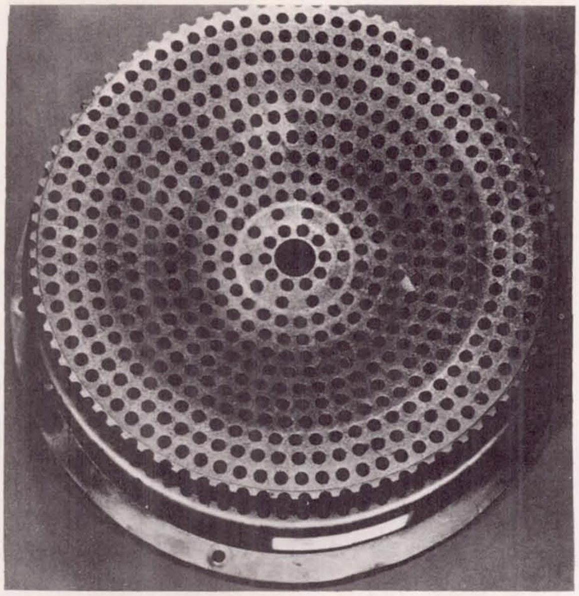

FIGURE I-28.—18-Inch injector. Electric-discharge machining. (Courtesy Rocketdyne.)

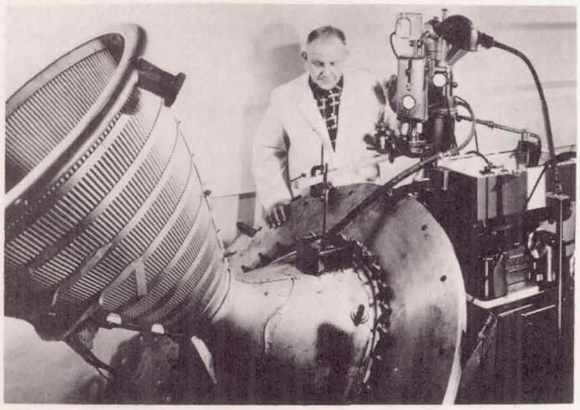

FIGURE I-29.—General view of rocket nozzle. Electric-discharge machining.

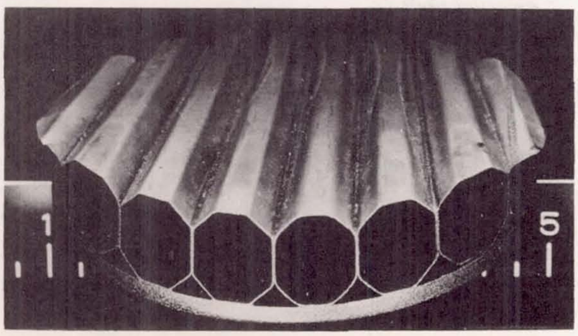

FIGURE I-30.—Cutout of rocket nozzle. Electric-discharge machining.

A total of 180 holes, 0.020 inch in diameter, were machined simultaneously into a rocket injector (figs. I-2 and I-27).

Rocketdyne Division of North American Aviation, Inc. uses a one-piece carbon electrode to electric-discharge machine an 18-inch-diameter injector body (fig. I-28). Electric-discharge machining is frequently used for drilling holes, but in this case everything but the hole material is removed. This tool leaves a group of posts that are later drilled to form the tubes of the injector.

It was necessary to machine a 4-inch hole into a tubular rocket nozzle without damaging the thin-wall Inconel X tubes (see fig. I-29). Extending the electrode servomechanism and building a temporary dielectric reservoir made possible the use of a standard machine to do the job. This thin-wall-tube section, attached to the ⅛-inch-thick Inconel X jacket material, was removed without distortion of the tubes (see fig. I-30).

Electrochemical Machining

Although EDM certainly has many fine applications, many of these jobs can also be done by electrochemical machining (ECM). Although ECM development started as a low-cost grinding method for carbides, the process has been more recently applied to die sinking, turning, and milling operations.

A point-by-point comparison of these two processes can be seen in figures I-22 and I-31. In ECM, an electrolyte is used rather than a dielectric fluid. The power supply for

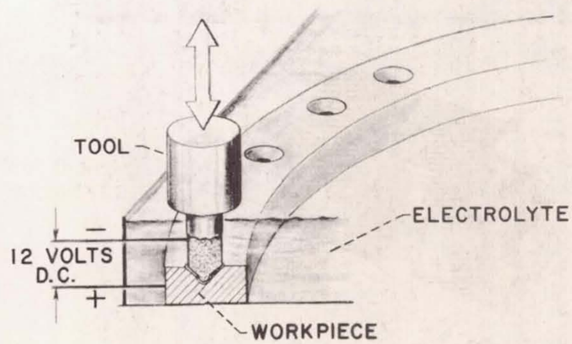

FIGURE I-31.—Electrochemical machining.

ECM is a steady high-amperage direct current rather than the pulsing type used in EDM. In ECM the metal removal is accomplished by rapidly converting the surface of the metal into metal hydroxides and plating out hydrogen gas on the tool. This deplating in ECM is contrasted to spark erosion for EDM. The important detail that is not adequately shown in figure I–31 is the need for very careful tailoring of the flow of electrolyte between the tool and the workpiece to produce a laminar flow at high velocity. It is this tailoring of the electrolyte flow that normally limits ECM to moderate to large quantities to amortize the tool-development costs; however, once the tool is developed, the metal-removal rates are much faster than in EDM and tool wear is nonexistent.

A particular application of ECM that is especially intriguing is the deburring operation shown in figure I–32. In this case the velocity of the flow of the saline solution is used to do natural rounding of the corners. The part shown is a rocket injector, but this same principle is being used by the automotive companies for deburring oil holes in connecting rods and similar parts. This method represents a real breakthrough because no really satisfactory mechanical deburring method existed to do this job.

In figure I–33 is an ECM die sinking machine produced by Steel Improvement & Forge Co., Cleveland, Ohio, which has done considerable developmental work in this process. Before and after views of a turbine-blade forging are shown in figure I–34. At the left is the as-forged part, and on the right, the electrochemically machined blade. Doing this job requires that two very carefully tailored opposing tools simultaneously

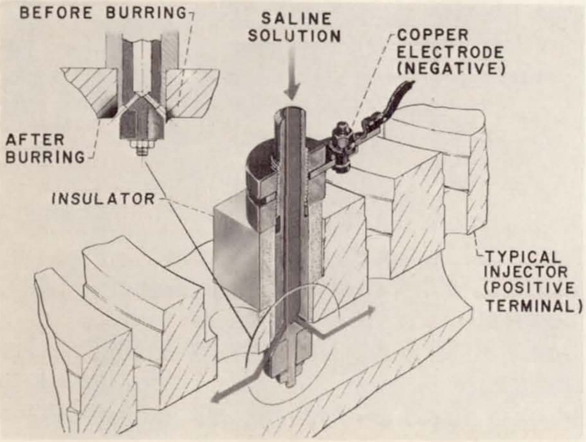

FIGURE I–32.—Test setup of burr-removal devices. Electrochemical machining.

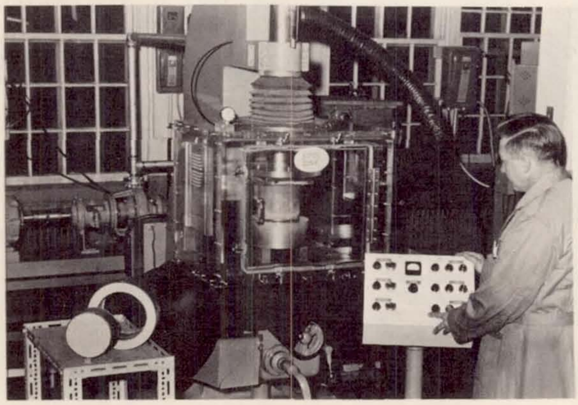

FIGURE I–33.—Sifko sink machine. Electrochemical machining. (Courtesy Steel Improvement & Forge Co.)

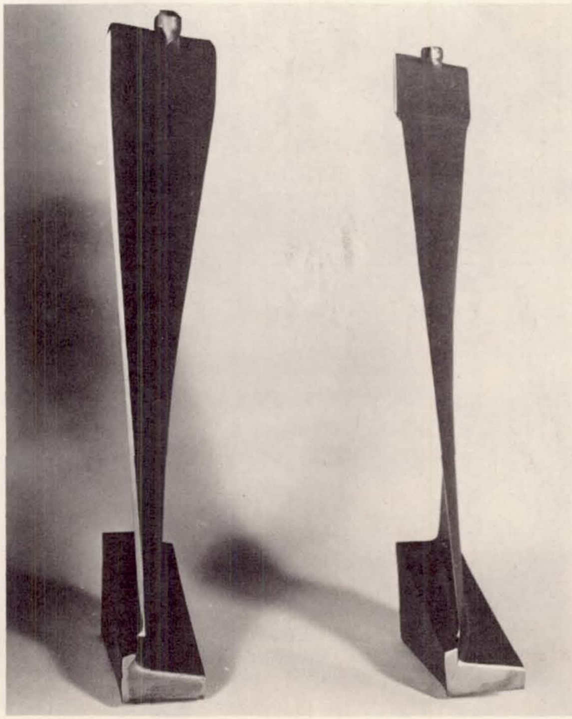

FIGURE I–34.—Turbine blades. Electrochemical machining. (Courtesy Steel Improvement & Forge Co.)

contour both surfaces of the blade to the final shape. Incidentally, although there is no tool contact with the workpiece during the machining operation, the high pressures used to make the electrolyte rapidly flow make opposing tools ideal for this rather flexible part. This process is being used extensively to produce parts of this type by all the large turbine-engine manufacturers in this country because of its high production capabilities.

Chemical Milling

Another metal-removal process that is finding considerable application is chemical milling. The simplest chemical milling operation is the one in which removing an equal amount of material from the entire surface is required. The part to be milled is simply immersed in a circulating bath of a selected chemical etchant (fig. I–35). The entire surface is uniformly dissolved by the etchant. If it is desired that certain areas be unaffected, these areas must be masked off or protected with a maskant material that will not be affected by the etchant. Plastic tapes of various widths are often desirable if simple areas are to be protected, but the most popular maskants are the elastomers (such as butyl rubber and neoprene) and plastics (such as polyvinyl chloride) that can be applied by spraying, dipping, brushing, or rolling. The usual procedure is to cover the entire area with maskant and then to scribe and remove the maskant from the areas requiring milling.

An important feature to remember is that the etchant undercuts the maskant an amount equal to the depth; that is, as the etchant dissolves downward, it also dissolves metal under the exposed edge of the maskant (fig. I–36). It is therefore necessary to consider this when the scribe pattern is laid out on the piece.

At Lewis, many rocket injector faceplates have been chemically milled to create cooling passages to prevent overheating and burning of the surface. This pattern was produced by covering the entire convex surace with a 4-inch-wide plastic tape, scribing, and removing the appropriate areas (see fig. I–37). The depth of mill was approxi-

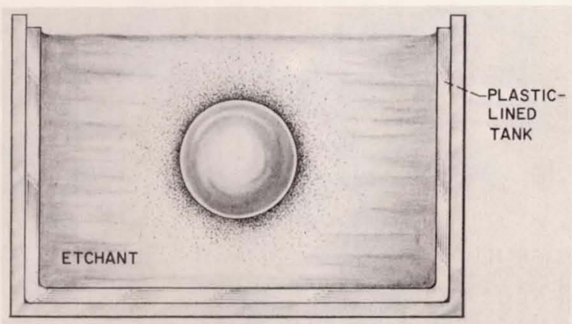

FIGURE I–35.—Chemical milling.

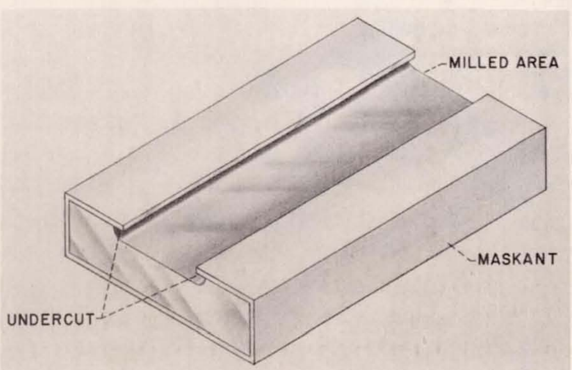

FIGURE I–36.—Undercutting in chemical milling.

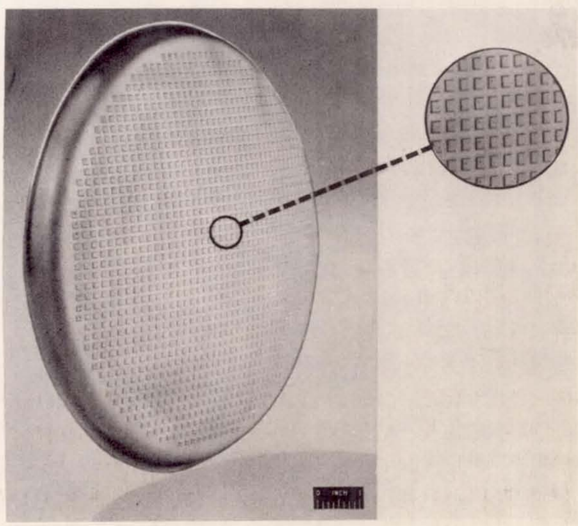

FIGURE I–37.—Nickel injector face. Chemical milling.

mately 0.030 inch. It was necessary then to have the maskant of each little square 0.060 inch larger in each direction than the final desired dimensions.

Chemical milling is being used by Straza Industries in California to produce tapered-wall stainless-steel tubes for the large M–1 rocket engine. Twenty of these tubes 6 feet long are tapered simultaneously in a fixture by slowly withdrawing the tubes from the etchant (fig. I–38). The depth of removal is proportional to the time the surface is exposed to the etchant. In this case the tube walls were tapered from 0.030 to 0.014 inch in the 6-foot length. Today, many large, difficult-to-machine contours are being chemically milled.

A large Saturn tank segment being chemically milled by the Chemical Contour Corporation, Los Angeles, California, is shown in figure I–39. The weight of the tanks can be reduced by reducing the thickness of the center area of these segments. The edges

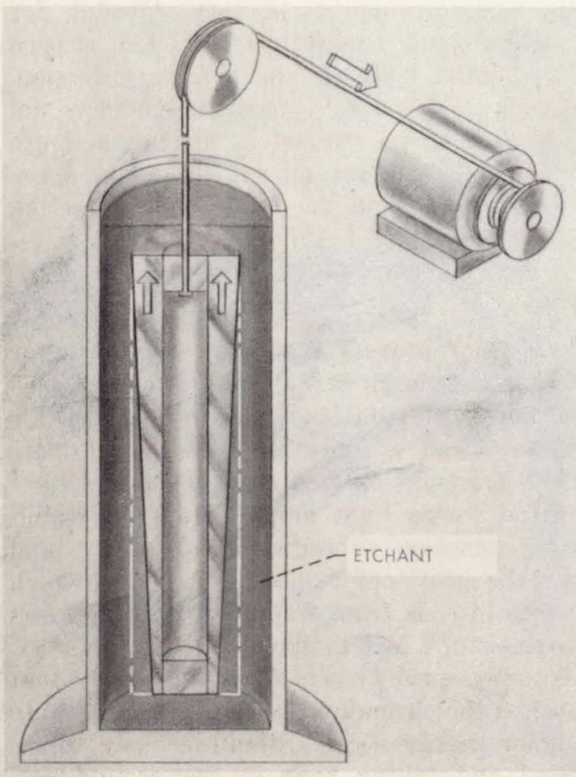

FIGURE I–38.—Tube-wall tapering. Chemical milling.

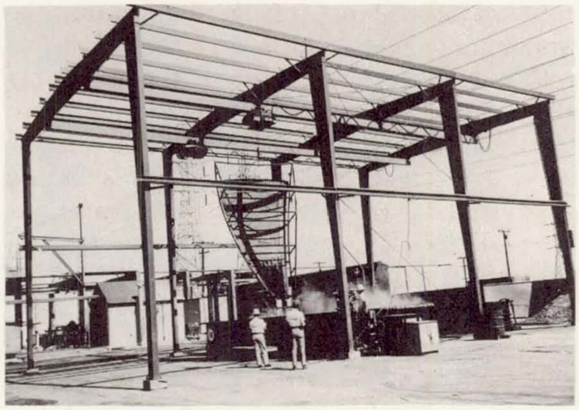

FIGURE I–39.—Large bulkheads. Chemical milling. (Courtesy Chemical Contour Corp.)

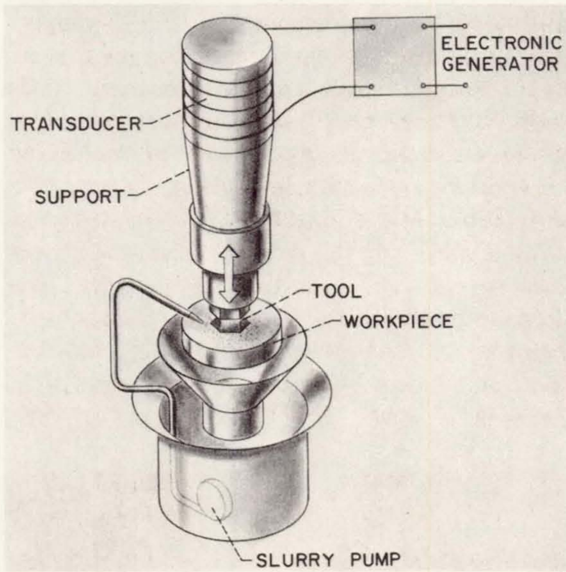

FIGURE I–40.—Ultrasonic machining.

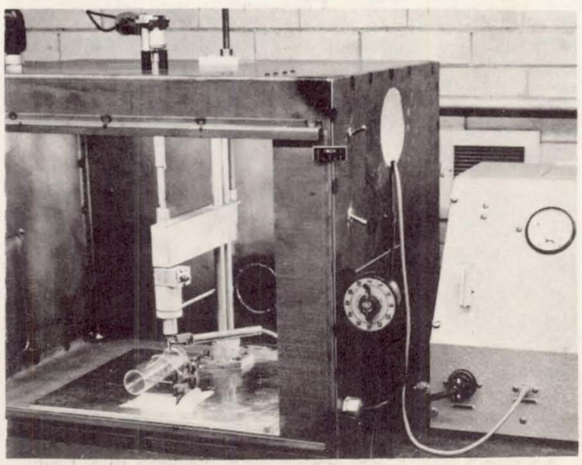

FIGURE I–41.—Abrasive dental drilling tool.

must be masked and left thicker because the welding process to join these segments together reduces the strength of the aluminum alloy adjacent to the weld.

Although some metals are more difficult to control than others, this process is finding application with many types of materials. For example, it is a very satisfactory and productive way of blanking out refractory sheet-metal pieces. In this case, in which only the edge is milled, surface finish is not important.

Abrasion

Most of the removal processes mentioned previously require either a conductive surface, or as was the case with chemical milling, a surface that can be dissolved quite readily. There are, however, processes that can be used on other surfaces or materials. Some processes base their operation on ultrasonic vibration. Figure I–40 shows a schematic drawing of the process. The transducer is energized by the electronic generator. The ultrasonic vibration in the transducer is then transmitted mechanically to the tool bit. The tool bit and the workpiece do not touch; there is a small gap between them. The slurry pump supplies an abrasive in this gap. While vibrating ultrasonically, the tool bit transmits its energy into the abrasive, which in turn loses its energy by impacting the workpiece. This rapid contact causes the material to be cut away. These techniques are used in grinding, cutting, drilling, or shaping operations.

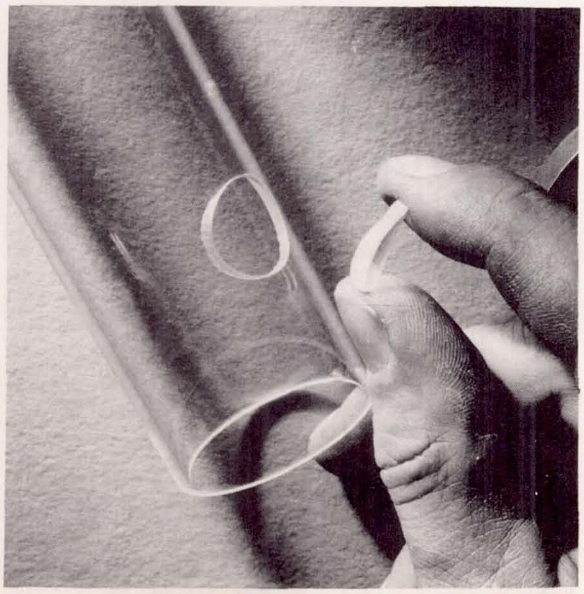

FIGURE I–42.—Glass drilled with abrasive dental tool.

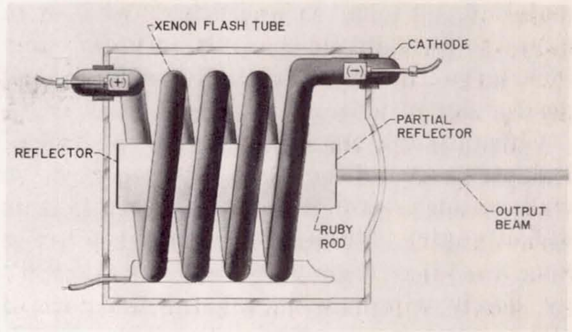

FIGURE I–43.—Ruby laser head. Light amplification by stimulated emission of radiation.

Another tool used at Lewis, based on abrasion techniques, is very efficient for machining hard materials. This tool is used for drilling teeth by the dental profession. We devised a circle generator holder and installed it in a cabinet as shown in figure I–41 to drill holes and cut shapes in glass, in ceramics, and in other nonconducting material (see fig. I–42).

Laser

Another process that shows promise for this type of work is the laser. It can be used to bore holes in any known material by melting and evaporating. The word laser is an acronym derived from the first letters of the words *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. The first and still the most popular laser is the ruby, which comes in rods from 2 to 15 inches long and up to about 1 inch in diameter (see fig. I–43). Around the ruby rod is a xenon flashtube that excites the chromium atoms in the ruby into higher energy states. Simultaneously stimulated and falling back to the ground-level energy state, these atoms produce an intense beam of light that bounces back and forth against the reflective ends of the rod and then bursts through the partly reflective end of the rod as an amplified light beam. The output is in the form of bursts of energy of extremely short duration. The interest in this device is indicated by the fact that in 1960 about 1 million dollars was invested in laser research, and this amount has grown to about 27 million dollars for the year of 1964. The rate of advance is rapid, but this device is just in its infancy as far as a metal-working tool is concerned. Lasers have been used to drill, to mill, and to weld, but they are not much beyond the laboratory curiosity state. As the efficiency is advanced from the present 1 to 4 percent, more applications can be expected from these devices.

JOINING

In aerospace fabrication, there is a need for many exotic materials and difficult-to-assemble designs that require the application of the newer processes such as electron-beam welding, but the more conventional processes will still play a vital role in fabrication. There are many research and development projects that are designed to modify and improve welding techniques; these projects range from arc to electron-beam to laser-beam welding.

Regardless of what is being welded, or how it is being welded, the problems are usually very similar. The weld must be deposited so that the weld area is free of cracks, porosity, and other defects. The weld procedure must not reduce excessively the strength or ductility of the metal adjacent to the weld. In some cases, it is possible to restore the strength or ductility by heat treatment, but when it is not, a better welding process must be sought—a different material or perhaps a different joining process. Many times there is a process for making satisfactory joints, but the distortion or residual stresses caused by the welding cannot be controlled. Again, a different technique or process must be found.

Inert-Gas Welding

Very often cracks, porosity, and loss of ductility are caused by contamination of the weld metal by gases in the air that surround the weld puddle. All welding procedures are designed to protect the weld metal, but for many materials such as tantalum and columbium, additional precautions must be taken. One such method is to place the parts to be welded within a so-called welding chamber. The welding chamber in use at Lewis is somewhat typical of the many welding chamber designs used throughout the country (see fig. I–44). These chambers can be evacuated with a vacuum pump to very low pressures and backfilled with very pure argon gas after the workpiece is installed in the weld fixture. The heliarc torch is within the chamber, but the welder must work through rubber gloves that are sealed in the chamber wall. With this process, the welder can be certain that the weld is not being contaminated by the surrounding atmosphere.

Another technique that can be used on pieces too large for available welding chambers is the plastic-bag technique. In figure I–4 is shown a large columbium component sealed and welded in a plastic bag. The bag is filled with argon and also equipped with sealed rubber gloves. Actually, the ideal way to prevent contamination is to weld in a

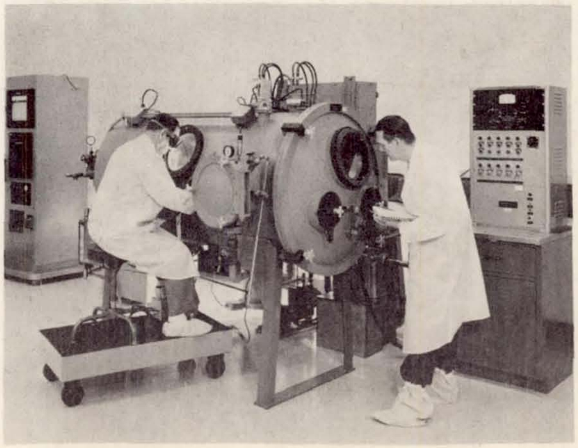

FIGURE I–44.—Inert-gas welding chamber.

high-quality vacuum; however, it is impossible to do arc welding in a vacuum.

Electron-Beam Welding

When requirements for joining necessitate ultrahigh cleanliness and also a minimum amount of heat-affected area, electron-beam welding techniques are employed. The best way to describe an electron beam is to consider heating a wire white hot. When heated, electrons in the wire tend to swirl around the surface of the wire. If a voltage is impressed between the white-hot wire and ground potential, the swirling electrons are pulled from the wire to ground. This is the electron beam (see fig. I–46). When the beam is focused by a magnetic coil, the highly concentrated electrons impinge on the grounded workpiece and give up heat. The heat produced is capable of melting any known material.

Electron-beam welding is conducted in vacuum chambers to give the most efficient and concentrated beam. Vacuum welding is the cleanest method known. Stainless steel is welded completely free of discoloration in vacuum, while it is extremely difficult to weld stainless steel stainfree by heliarc methods. Also, electron-beam welding gives the smallest weld and smallest heat-affected area. A comparison is given in figure I–47 for the same depth penetration. The central tooth is the electron-beam weld, while the cup-shaped area is the heliarc weld. Electron-

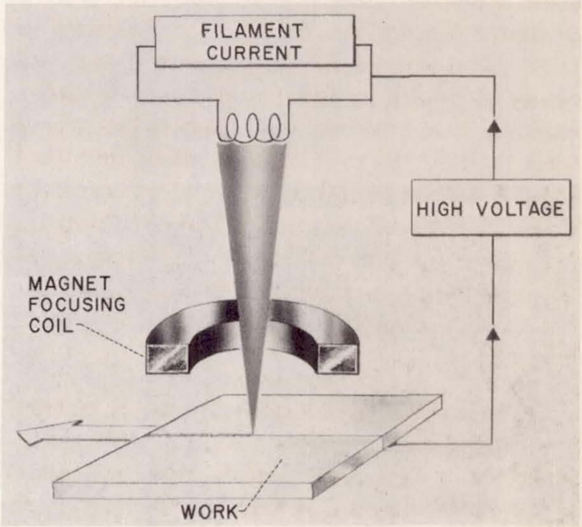

FIGURE I–46.—Electron-beam heat source.

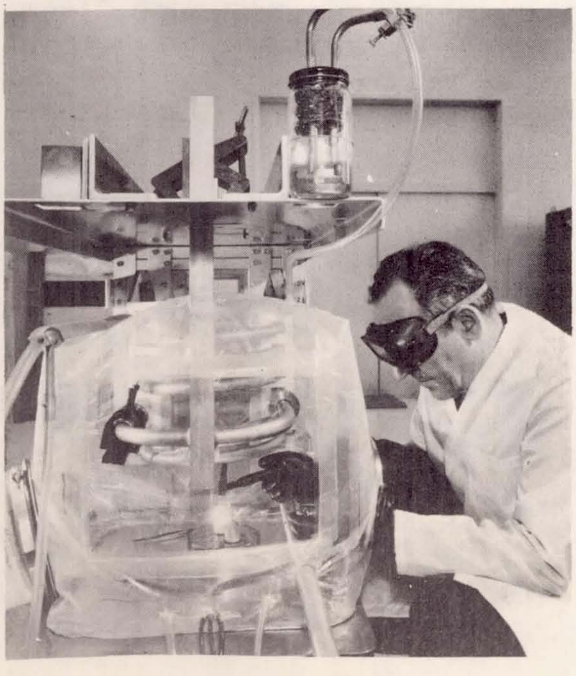

FIGURE I–45.—Plastic-bag technique in inert-gas welding.

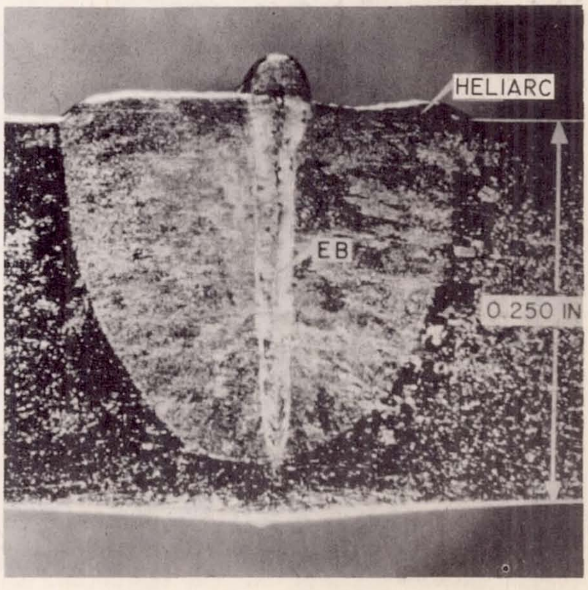

FIGURE I–47.—Comparison of weld zones. Electron beam and heliarc techniques. (Courtesy Hamilton Standard Div., United Aircraft Corp.)

beam welding will thus cause less distortion because of this minimum weld area. The penetrating power of the beam is illustrated in figure I–48. With one pass, the beam penetrates and welds three 0.050-inch-wall tubes simultaneously. This highly concentrated beam capability allows welding through one plate or ring into a central or base component, with a very limited amount of distortion.

Since the welding is done in a vacuum chamber, motions must be provided within the chamber for maneuvering the welding operation. Figure I–49 shows the possible movements. The work can be moved for seams in the x and the y planes; it can be tilted, revolved, or moved up and down automatically by controls outside the chamber. In addition to work movements, the electron gun has vertical movements and automatic y-direction movements; also, the gun can be preplaced on mounting supports at almost any desired angle. The beam itself can also be rotated electronically to form circles.

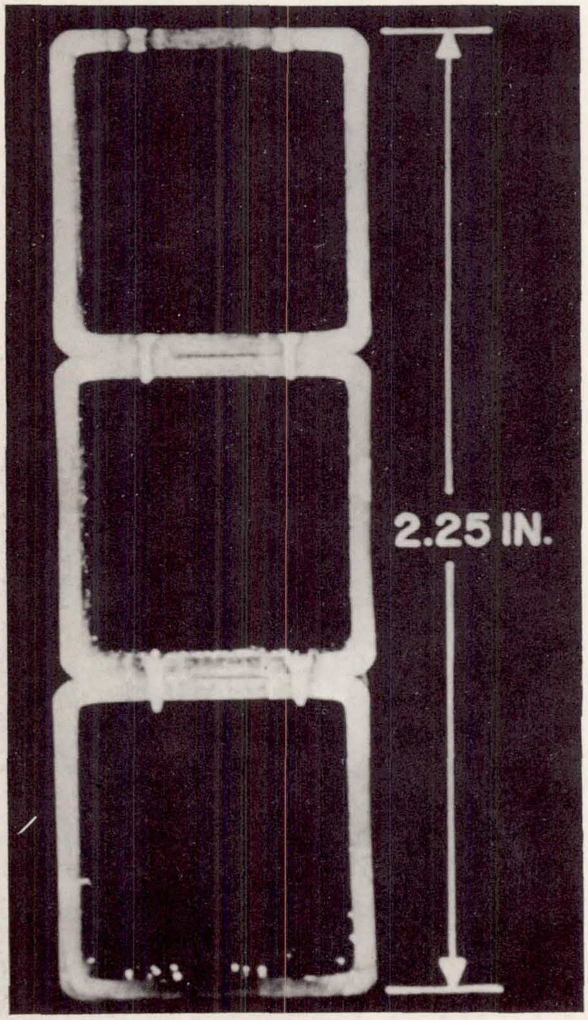

FIGURE I–48.—Multiple tier weld in 18–8 stainless steel. (Courtesy Hamilton Standard Div., United Aircraft Corp.)

One of the first problems solved with the electron beam at Lewis was the manufacture of ion-engine emitters. Ion engines are one means of propulsion in space. The emitters in these engines must be enclosed in a tungsten housing. Figure I–50 is a sketch

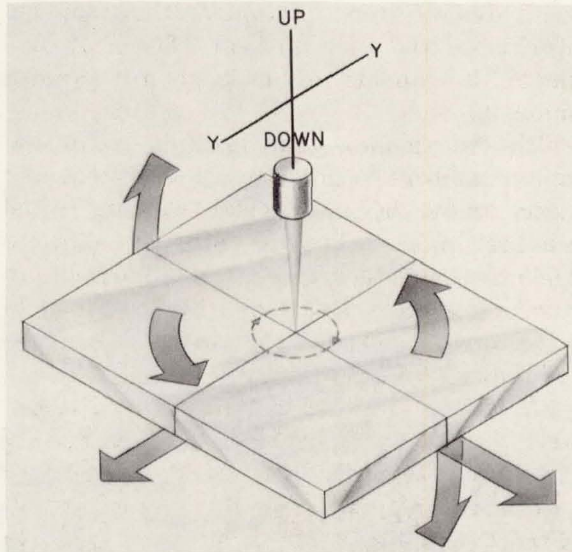

FIGURE I–49.—Degrees of freedom in electron-beam welding.

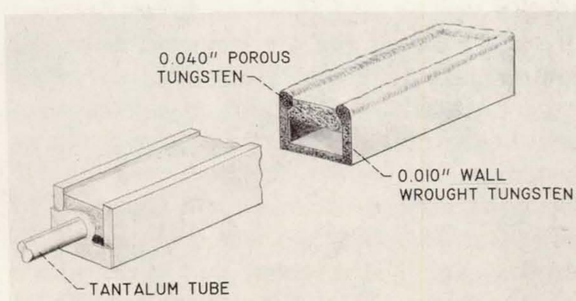

FIGURE I–50.—Ion-emitter assembly.

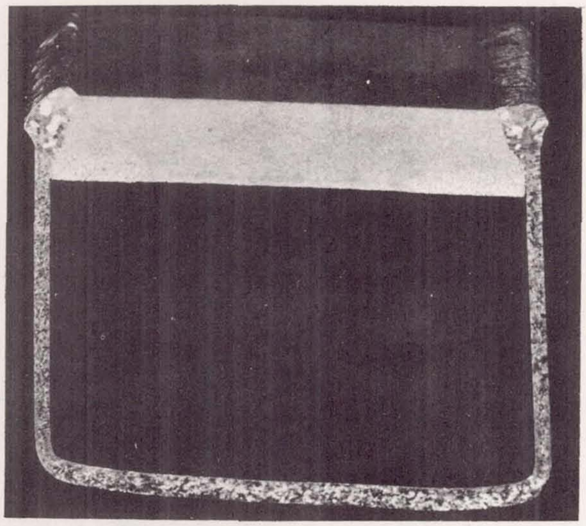

FIGURE I-51.—Tungsten ion emitter. Electron-beam welding.

and figure I-51 is a cross-sectional view of an ion emitter. The porous tungsten through which vapors must pass and ionize is shown in figure I-50. It is joined to a channel made from tungsten sheet material. The relative size should be noted. The channel is 0.010-inch tungsten sheet. The porous tungsten is 0.040 to 0.060 inch thick. This part is impossible to join with heliarc methods but is completed with ease by electron-beam methods. A cross section of an ion-engine emitter is shown in figure I-51. Once again, the thin walls of the housing in comparison with the heavy-wall porous tungsten should be noted.

Some parts are joined by the electron-beam method primarily for the cleanliness of the operations. Many research efforts require metals and powders to be enclosed in cans with all the air removed from the can. Figure I-52 shows how this operation is performed. On the right, an electric solenoid holds the lid off the can. The pumping system of the welder then removes the air from the vacuum chamber and the can. At this point, the electric solenoid places the lid on the can. The electron gun right above the can then welds the seam between the lid and the can while the can is rotating. Variations of this technique, of course, can be used and are used for many industrial applications where the absence of air in a part is a necessity.

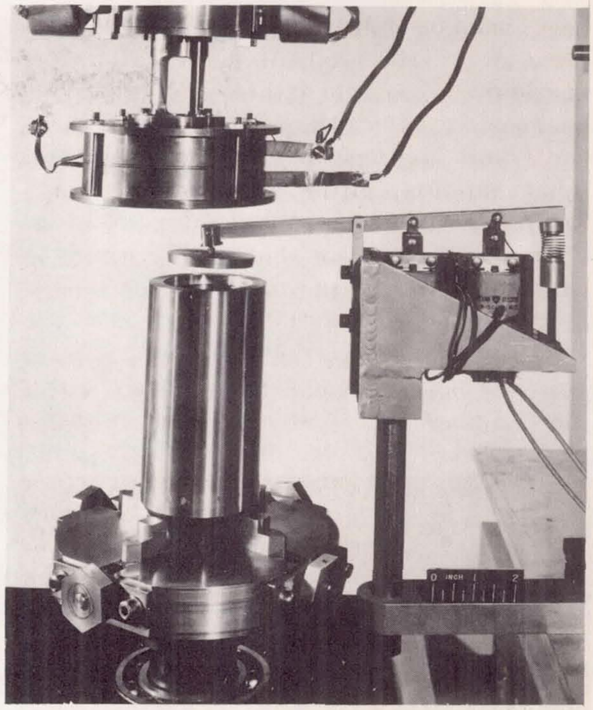

FIGURE I-52.—Sealing procedure in vacuum. Electron-beam welding.

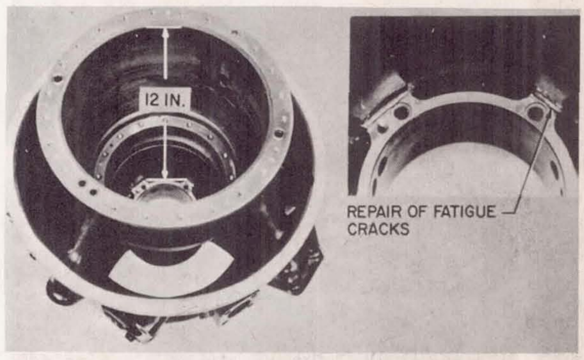

FIGURE I-53.—Magnesium turbine shaft seal. Electron-beam welding. (Courtesy Hamilton Standard Div., United Aircraft Corp.)

Now there are also other reasons for this type of welding. Sometimes, components are machined and joined by conventional techniques but subsequently must be repaired. Conventional joining methods at times are not conducive to repairing these parts because of physical dimension limitations. A magnesium housing with a crack that has been repaired with the beam is shown in figure I–53. The contour of this part adapted itself quite readily to electron-beam techniques. A machining error repair in an aluminum housing is shown in figure I–54. This type of repair work, not adaptable to normal heliarc methods, is accomplished successfully by the electron-beam method. The bore was slightly large as machined. A ring insert was placed in the hole, and with the deep focal length of the beam, the insert was welded to the housing.

Sometimes, a part requires only a spot-welding technique. Figure I–55 shows a 0.005-inch-wall tungsten cylinder rolled from sheet material and spot welded by the beam. The electron-beam apparatus is capable of automatically pulsing the beam to form these spot welds.

Frequently, parts are too large to fit into a vacuum chamber. In figures I–56 and I–57 are shown a 250-foot liquid-metals heater being made from 20-foot lengths of

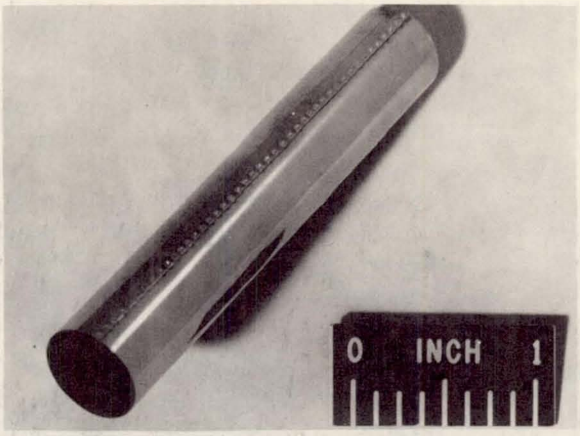

FIGURE I–55.—0.005-Inch-wall tungsten cylinder. Electron-beam spot welding.

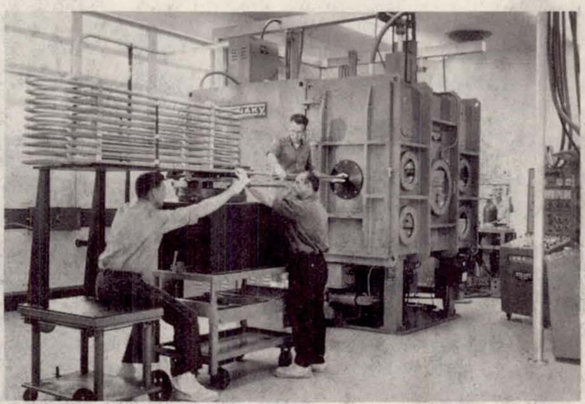

FIGURE I–56.—Columbium—1-percent-zirconium liquid-metals heater fabrication. Electron-beam welding.

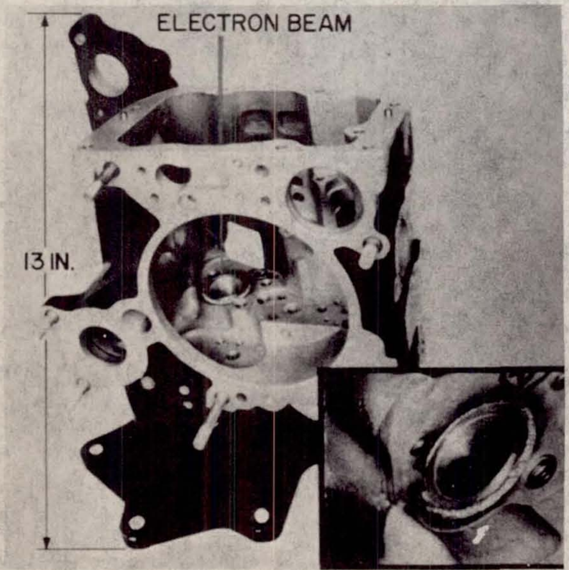

FIGURE I–54.—Repair of machining error in aluminum housing. Electron-beam welding. (Courtesy Hamilton Standard Div., United Aircraft Corp.)

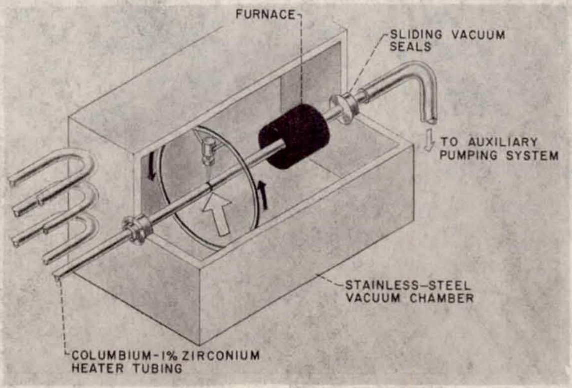

FIGURE I–57.—Columbium—1-percent-zirconium tube heater. Electron-beam welding.

columbium tubing. It is welded and the welds are heat treated in the electron-beam welder. The coil is shown partly complete, fitting through seals in the chamber and then through the welding fixture where the tubes are butted and welded by the rotating electron gun. The tube then passes through a furnace coil that heat treats the weld. At this point, the vacuum is released and the seals are removed. A tube bender then forms the tubing into a coil 18 inches wide and 6 feet long. The fixture on which the gun rotates is shown in figure I–58. The power supply to the electron gun is delivered by stationary copper rails on the outer periphery of the fixture. Through the center of the fixture the tube passes horizontally. The gun rotates around the stationary tubing and makes the weld.

Another adaptation of electron-beam welding to large structures is the 33-foot-diameter aluminum ring for the Saturn booster (fig. I–59). This ring is fabricated in three 120° segments that when welded form a ring 33 feet in diameter. The wall thickness is about 4 inches. A split vacuum chamber that clamps onto the ring is shown in figure I–60. Two electron guns follow the seam on each leg of the Y to form the complete weld (fig. I–61). The narrow electron-beam weld limits the distortion and provides a very fine seam weld.

An example of electron-beam drilling is shown in figure I–62, which is a view of 0.002- to 0.003-inch-diameter holes drilled in 0.010-inch molybenum sheet. The beam is closely focused at high intensity to enable the material in the hole area to be vaporized.

The beam can be used as a means for evaporating metallic films onto nonmetals

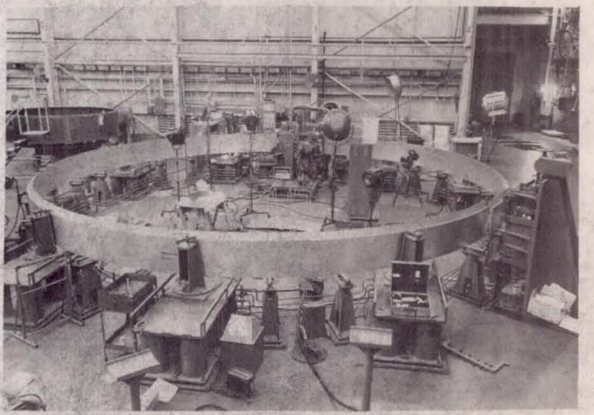

Figure I–59.—Saturn booster aluminum ring. Electron-beam welding. (Marshall Space Flight Center.)

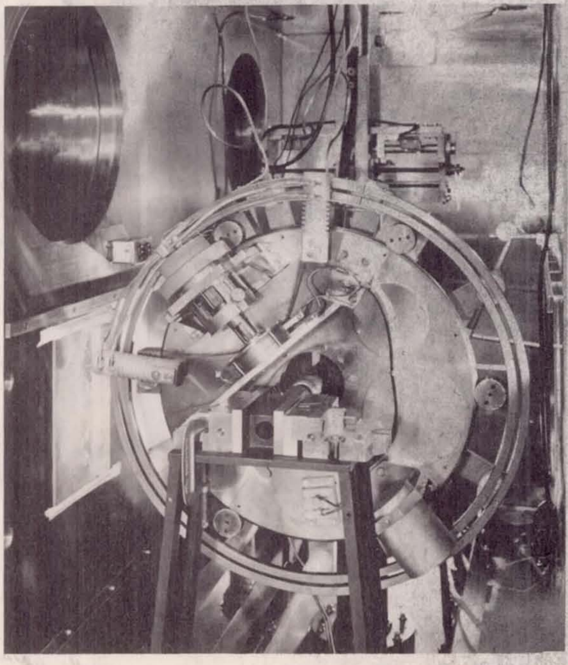

FIGURE I–58.—Welding fixture for columbium—1-percent-zirconium liquid-metals heater. Electron-beam welding.

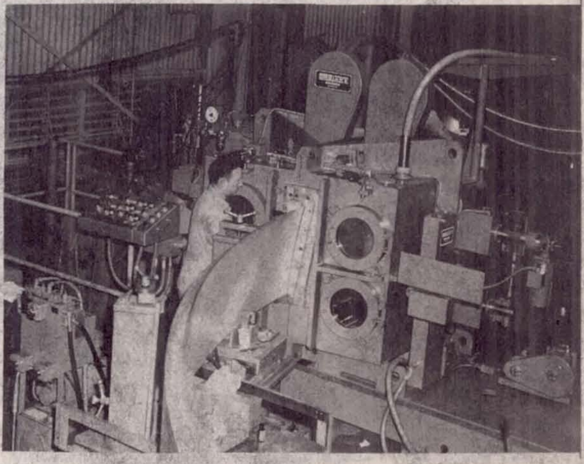

FIGURE I–60.—Split-chamber electron-beam welding of Saturn ring. (Marshall Space Flight Center.)

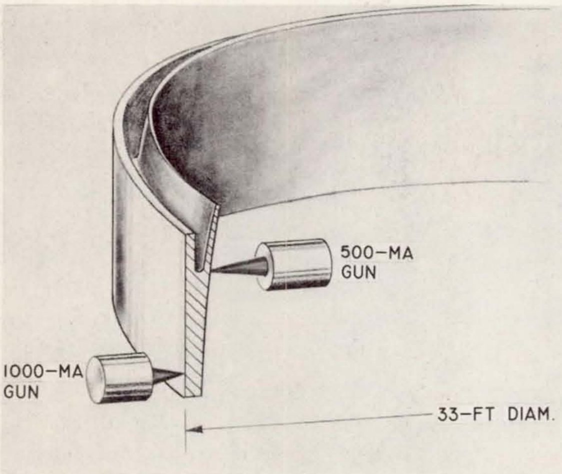

FIGURE I-61.—Dual penetration by two electron guns on Saturn ring.

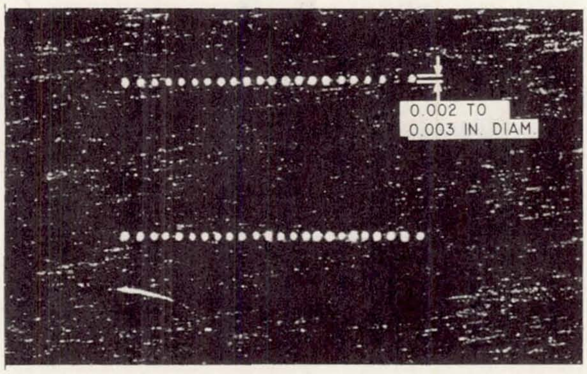

FIGURE I-62.—Electron-beam-drilled holes in 0.010-inch molybdenum. (Courtesy Hamilton Standard Div., United Aircraft Corp.)

such as heat-treated glass (fig. I-63). This technique requires the beam to be focused on the material to be vaporized; the vapor is then deposited on the part to be coated. Figure I-64 shows a square heat-treated glass tube with a thin film of aluminum vaporized selectively on two opposite sides. A primary application of the beam is the vaporization of high-melting-point materials such as tungsten and molybdenum. Although these materials melt at temperatures above 4000° F, they are readily evaporated by electron-beam methods.

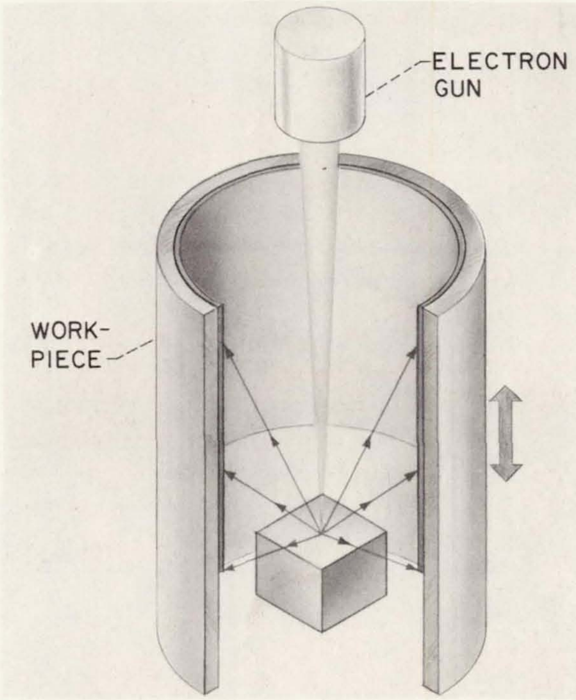

FIGURE I-63.—Evaporative coating by electron beam.

Furnace Brazing

A process that is being used on many complex designs is furnace brazing. Like many other fabrication processes, it has peculiar requirements and limitations, but for many designs it is a valuable process. The progress that is being made in welding, particularly in electron-beam welding, is impressive. Many of the jobs that used to be done by furnace brazing are now being done by electron-beam welding. There is, however, a great deal of work that can best be done by furnace brazing.

The basic difference between brazing and welding is that in welding the temperature is high enough to melt the pieces being

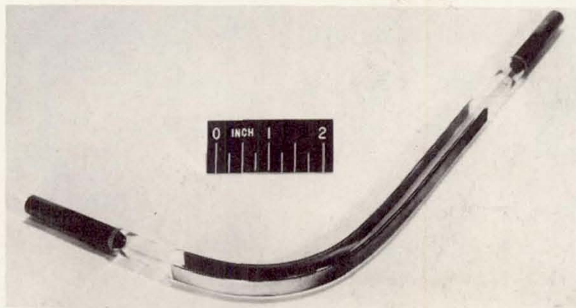

FIGURE I-64.—Electron-beam evaporative coating of aluminum on heat-treated glass.

joined. In brazing, either with a torch or in a furnace, the braze metal melts below the melting point of the pieces being joined. This is very often a big advantage in brazing, particularly when dissimilar metals are being joined or when the metal being joined has a tendency to crack when it is actually melted.

Furnace brazing certainly is not a new process, but in the aerospace field, it is being applied to some complex assemblies. The furnace-brazing process can be illustrated by the use of a rocket-injector assembly (fig. I–65). In welding, one of the problems is the distortion produced by the local heating of the weld area. Even with the minimum effect with electron-beam welding, it is not feasible to weld an assembly like this one. Incidentally, the chemically milled injector face that was discussed earlier can be seen at the bottom of this cutaway section.

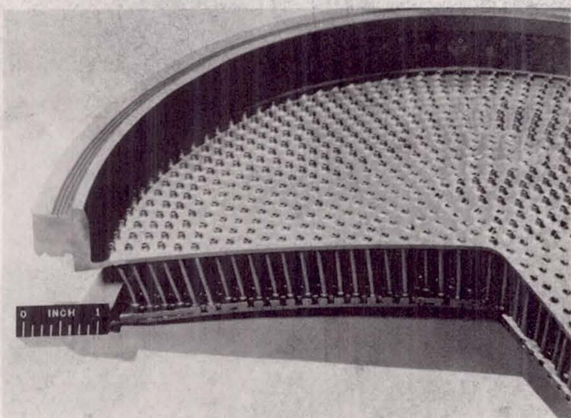

FIGURE I–65.—Rocket injector. Furnace brazing.

Each of those 1400 stainless-steel tubes must be brazed to the injector face and sealed into the top plate. One leak that develops in those top joints would allow the rocket propellants to mix inside the injector. For furnace brazing of this assembly, all components are carefully cleaned and assembled with a closely controlled fit of all joints. A little ring of pure copper braze metal is placed over each tube at the bottom joint and also at the top. The complete injector, in its brazing fixture, is positioned in the furnace, ready for brazing. No flux is necessary because the entire heating and cooling cycle is in a high-quality vacuum. The metal surfaces and the braze metal stay bright and shiny throughout the cycle. There is no need for fluxes to dissolve away oxide that would prevent the braze from wetting and flowing into the joints. The entire assembly is uniformly heated and cooled, so that distortion is essentially nonexistent.

The top plate is a heat-treatable alloy, and it was selected because the brazing temperature in this case, 2000° F, was just right to provide the heat treatment at the same time it was being brazed.

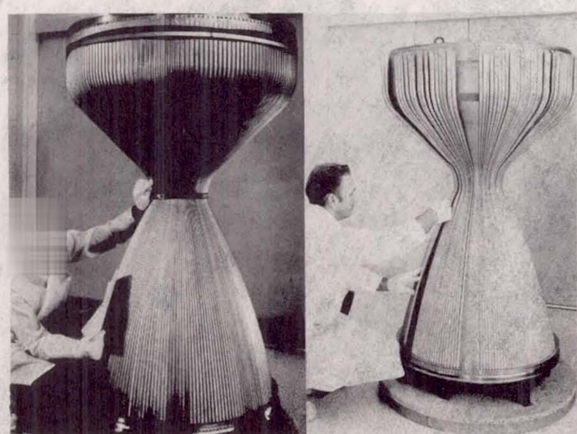

FIGURE I–66.—Tube assembly for KIWI engine. Furnace brazing.

Most of the large rocket thrust chambers in use today are furnace-brazed tubular designs. In figure I–66 is one of the smaller thrust chambers being assembled for brazing at Lewis. During the actual firing of these regeneratively cooled rockets, the fuel is circulated through these tubes to the injector. This flow of fuel keeps the wall of the chamber, which consists completely of these thin-walled tubes, from melting under the intense heat of the combustion.

Cleanliness and a close fit of these tubes are essential for successful brazing. The molten braze will not bridge a gap larger than 0.004 or 0.005 inch. Following the fit and inspection, the tube bundle is placed

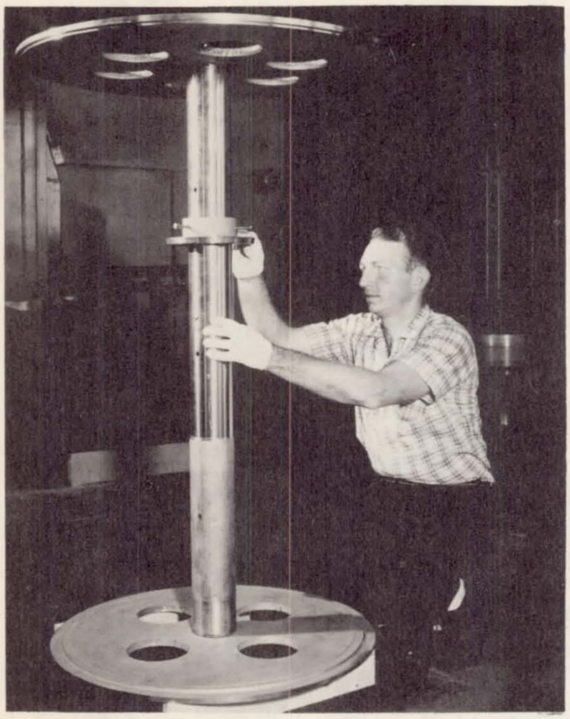

FIGURE I-67.—Shaft fixture for KIWI engine. Furnace brazing.

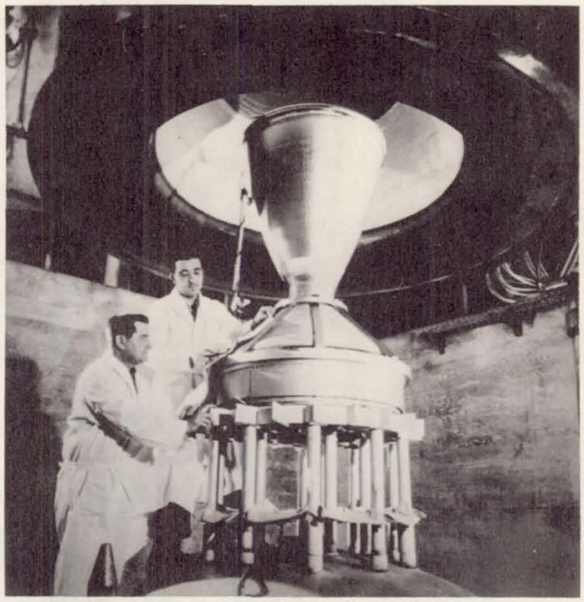

FIGURE I-69.—Completed KIWI chamber under vacuum retort. Furnace brazing.

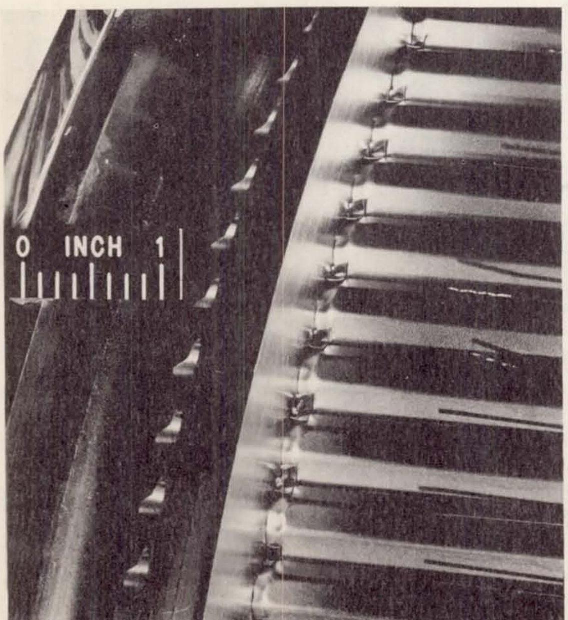

FIGURE I-68.—Placement of braze alloy on KIWI engine. Furnace brazing.

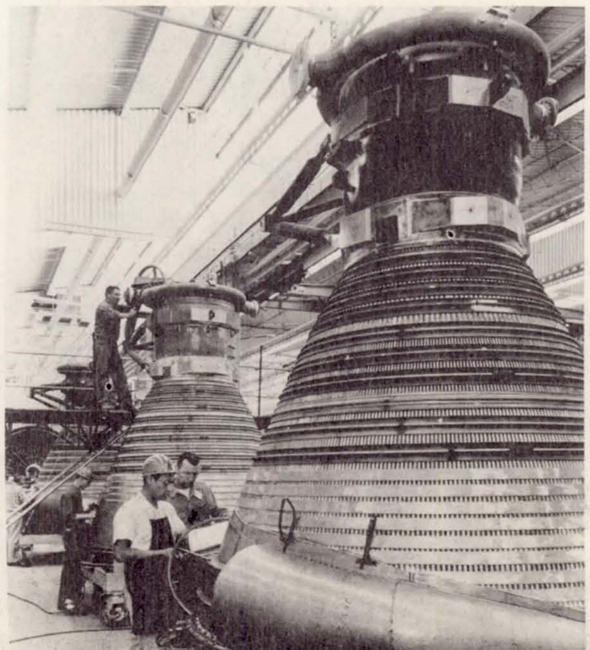

FIGURE I-70.—F-1 thrust chamber. (Courtesy Rocketdyne.)

over the brazing fixture (fig. I–67), and the braze alloy is applied. Various forms of braze are used, depending on the type of braze alloy and the type of joint to be made. Small pieces of braze in foil form and wire form applied close to the joints to be made are shown in figure I–68. Powdered braze can also be used on many complex assemblies.

The brazed tube bundle is shown in figure I–69 on the furnace support ready for brazing. The retort being held just above the tube bundle is lowered, and it completely encloses the work during the brazing cycle and contains a high-quality vacuum. The large heating bell in the background is lowered into position over the retort to heat the work by radiation through the retort wall. Furnace brazing temperatures vary from approximately 1800° to 2200° F, depending on the melting point of the braze being used.

At Lewis all brazing is done in vacuum furnaces, but some excellent work is being done in protective-gas atmospheres. Some large rocket-engine chambers being brazed in an argon atmosphere at Rocketdyne in California are shown in figure I–70. Incidentally, this engine, the F–1, produces a thrust of 1,500,000 pounds. These chambers are brazed at Rocketdyne in the clam-shell-type gas-fired furnace shown in figure I–71. The rocket chamber with the braze applied is sealed in the retort that contains the pure argon gas. The two halves of the heating bell are moved in to heat the entire retort and workpiece to the brazing temperature. After the brazing is completed, the furnace is moved back to this position and two water-cooled half sections are moved in to shorten the cooling cycle.

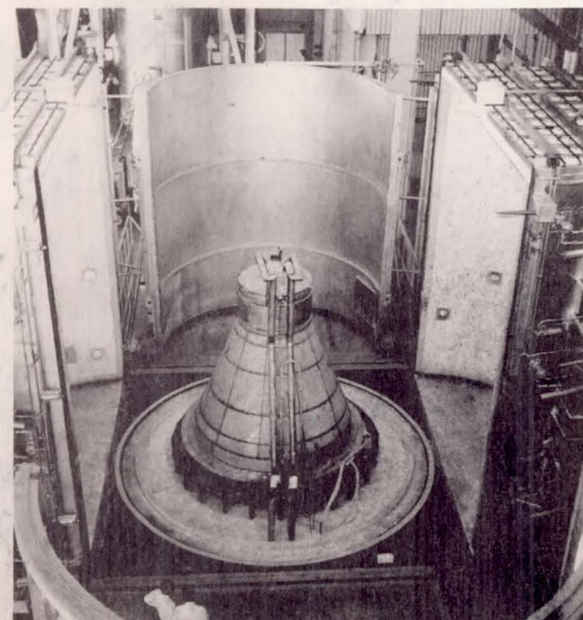

FIGURE I–71.—F—1 clamshell furnace. (Courtesy Rocketdyne.)

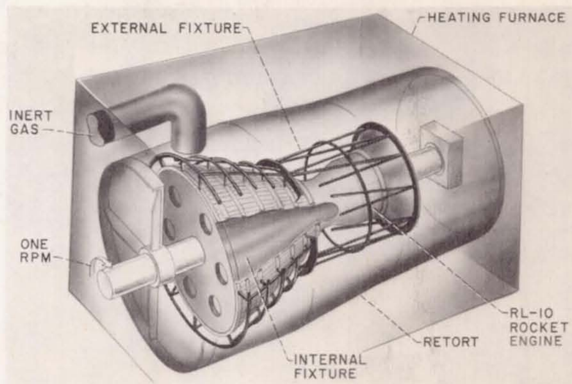

FIGURE I–72.—Pratt & Whitney brazing furnace.

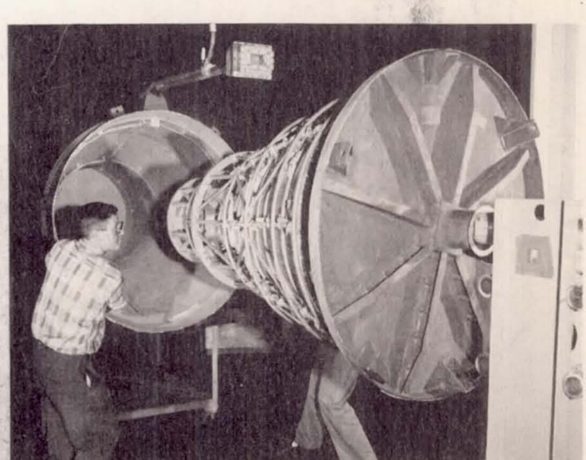

FIGURE I–73.—RL–10 thrust chamber retort loading. (Courtesy Pratt & Whitney Aircraft.)

One problem in furnace brazing is that the braze alloy has a tendency to run to the bottom of the assembly being brazed. Various techniques are used to prevent this on long joints that are in the vertical position, but Pratt & Whitney Aircraft uses an unusual furnace design (fig. I–72). They position the thrust chamber horizontally in the furnace and actually rotate it to provide a more uniform distribution of braze. This method requires more fixtures during this "rotisserie" operation, but this technique has been highly successful. Figure I–73 shows the chamber and fixtures being fitted into the retort that is sealed by welding and purged with pure argon protective gas prior to the heating cycle.

A drawing of a 1,500,000-pound-thrust engine under development at Aerojet General Corporation, Sacramento, California, is shown in figure I–74. The tubular chamber for this engine will be brazed in the world's largest vacuum brazing furnace, now nearing completion at Aerojet.

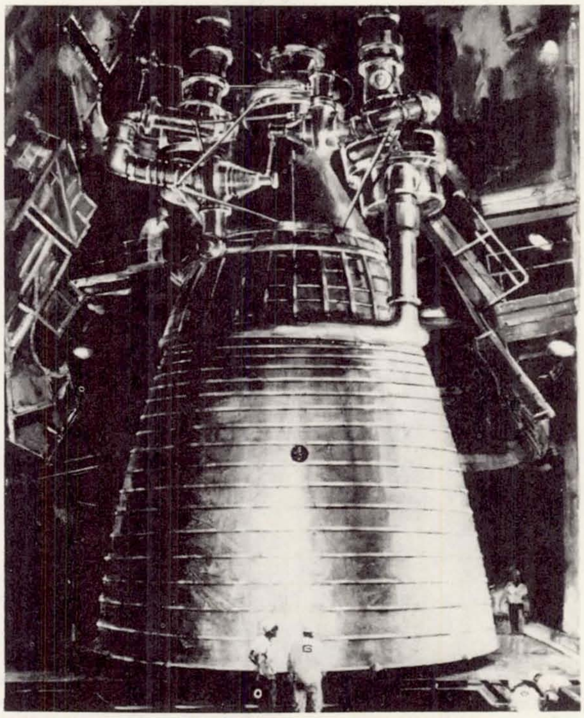

FIGURE I–74.—M–1 engine. (Courtesy Aerojet General Corp.)

II. Materials

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FROM VERY EARLIEST HISTORY, man has always used as one of his criteria for determining the state of progress of his civilization the most advanced materials available to him. We have had the Stone Age, the Iron Age, and the Bronze Age, and in all of these periods, man has always used naturally occurring materials or materials that he could readily put together from those that occur in nature. From these he has made tools and other mechanisms. Using these tools and mechanisms, he has gone on to discover and exploit new materials. Finally, we are at a point today where we know all of the basic elements that we can incorporate into our materials. The periodic table is quite complete, and now the problem is how to put these materials together in such a way as to achieve the optimum combination of elements for the various purposes we need to satisfy. Ours might be called an "age of tailored materials" because no single material can serve all the purposes. We must find a different material for each of the many applications we have.

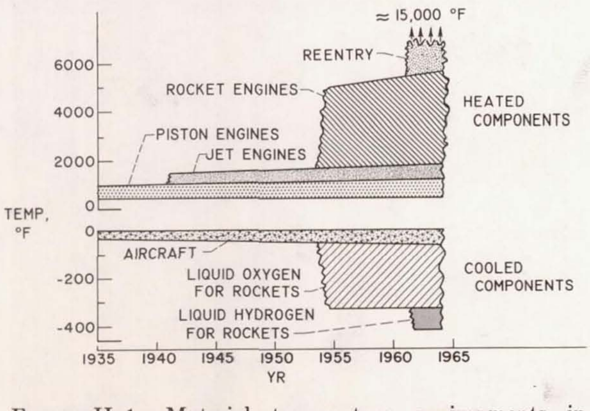


FIGURE II-1.—Material temperature environments in transportation vehicles.

As an indication of the great extent to which the need for different materials has increased in recent years, reference may be made to figure II-1. Here the problem of transportation is illustrated. We have chosen one variable, temperature, and shown how the range of this variable has expanded during the past few years. If we go back to the 1930's, when the piston engine was the main source of propulsion, the range of interest in temperature was bounded by about 1000° F on the upper end, and on the low side our interest was limited to about −40° F, primarily for an occasional encounter in a low-temperature atmosphere. In the early 1940's, when the jet engine was introduced and turbine buckets and combustors became of interest, the upper limit of the temperature range was extended to about 1500° F. On the low side, values near −40° F still remained extreme. In the middle 1950's, when the rocket engine was introduced, we became interested in temperatures up to about 5000° F for the rocket nozzle. At the lower extreme, the need to store liquid oxygen extended the range of interest to −300° F. More recently, when reentry vehicles became important, for example, in the Mercury Program, the upper temperature of interest was extended to approximately 15,000° F. This is the temperature in the air ahead of the reentry vehicle. Obviously, no material is able to withstand these temperatures for any extended length of time, because the melting point of the most refractory material known is a little over 7000° F. A new concept of materials application had to be introduced, namely, that of ablation, which is a process in which the surface gradually vaporizes away to protect the main body. The material never really achieves the temperature in the air ahead of it. At the lower extreme, we became interested in the storage of hydrogen at a temperature of −423° F, which is only 37° above absolute zero.

To meet all these requirements, a great many different materials must be considered. It is extremely important how these materials are put together, because very small changes in the material's content can have drastic effects on its properties. As is discussed later when applications of tungsten are described, concentrations of oxygen and carbon of the order of several parts per million introduce changes in properties that can spell the difference between successful use and failure in service. Electronic materials, especially, gain their properties from very small concentrations of impurities. These concentrations are of the order of parts per billion, and, in fact, are so small that they can hardly be measured. Composition is thus an important variable in materials.

Another important technology is the testing of materials so that we may be sure they will satisfactorily serve the purpose for which they are intended. Laboratory tests are sometimes a little misleading, and we must know how to run the proper tests and how to interpret the results properly to ensure that the conclusions drawn will be valid. As an illustration of improperly interpreting results, consider the Liberty ships used during and right after World War II. The particular ship shown in figure II–2 was not out on the ocean in a storm; it was standing in a Boston harbor when it broke in half. The material used in the ship's construction had been evaluated in the laboratory and was deemed to be satisfactory, but it did not serve the purpose intended. This was a case of "brittle fracture," which is discussed later.

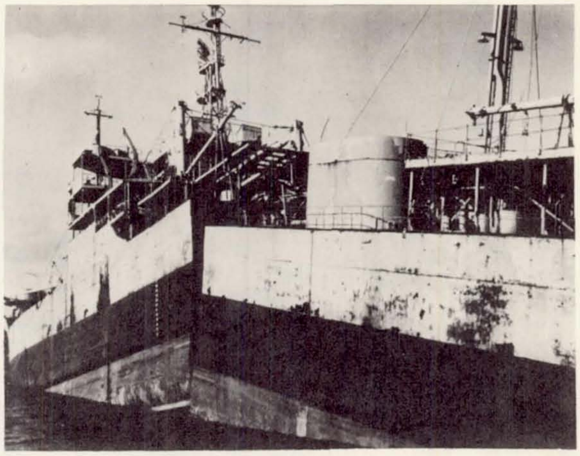


FIGURE II–2.—Brittle failure of Liberty ship.

Figure II–3, a photograph that appeared in the Plain Dealer about 20 years ago, shows what happened on the east side of Cleveland when a tank storing liquid gas at about −250° F developed a leak as a result of brittle fracture. A large area was devastated from the resulting fire and explosion, and many lives were lost. Here again it was a question

FIGURE II–3.—Devastation from gas storage tank failure and explosion. (Courtesy of Cleveland Plain Dealer.)

of improperly interpreting material for its intended purpose.

Considerable materials research is conducted here at Lewis, and in numerous other places in this country. The purpose of this conference is to present some of the results of this research. Naturally, those areas with which we are most familiar, namely, the aerospace applications, will be featured; however, we believe this information is of interest in technological applications other than aerospace.

BRITTLE FRACTURE PROBLEMS

The spectacular failures of Liberty ships and the gas storage tank occurred in materials that appeared to have adequate strength and ductility based on tensile test data. Ductility means that the material has the capability of taking on a permanent deformation without fracture, such as a mild steel at room temperature. Under some conditions, however, materials thought to be ductile can fail in a brittle manner just as if they were glass. Our problem is to determine the conditions under which failure of normally ductile materials will occur in this brittle manner. Perhaps the failure of truly brittle materials should be discussed first. Such materials have no capacity to deform.

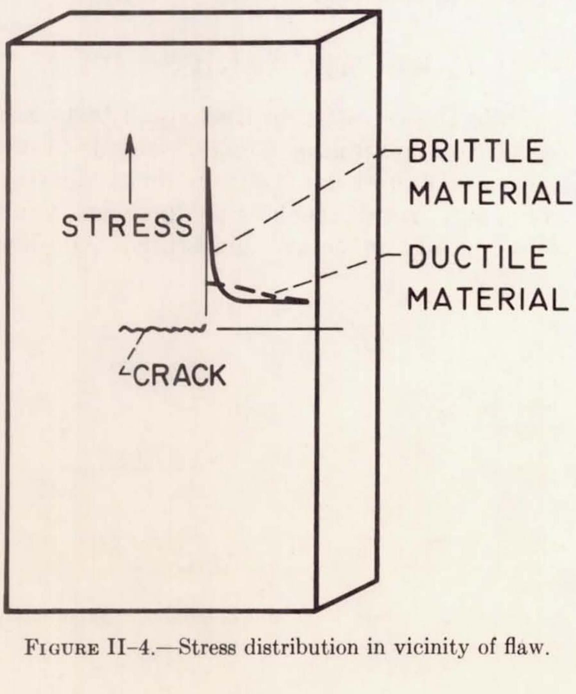


FIGURE II-4.—Stress distribution in vicinity of flaw.

If a structure is made from a brittle material and contains no flaws whatsoever, the structure might be very strong indeed, because brittle materials are often inherently very strong. The problem develops when the structure contains a flaw. Consider, for example, the plot shown in figure II–4, in which a crack is assumed to be present at the center of a specimen. A rigorous analysis of the stresses reveals that a very high localized stress develops in the vicinity of the edge of the crack. Thus, although the load applied is sufficient to produce only a rather low average stress across the specimen, the localized stress may be so high as to exceed the strength of the material and it fails. An observer, not knowing perhaps that the flaw existed, notes that failure has occurred at a low average stress and with a brittle appearance, and hence may conclude that brittle materials are weak.

Now what happens if the material is ductile instead of brittle? Its ability to deform plastically alters the stress distribution, as shown by the dashed line in figure II–4. If the material can indeed deform, the stress concentration is relieved. This material in the presence of the small crack may then not be much weaker than it is without flaws. The important criterion is whether the material is able to adjust properly in the presence of a flaw. Whether it can or not is, however, a subtle property, which depends on many factors inherent in the characteristics of the material itself, the structure in which it is incorporated, and the test conditions under which the structure is evaluated.

Because brittle behavior is so dependent on the existence of flaws, it is natural to expect that evaluation of the material for application in the presence of flaws will be best accomplished by testing materials in which such flaws are present. Simple as this concept is, it is surprising that significant recognition of this fact has really only occurred within the past 10 to 15 years.

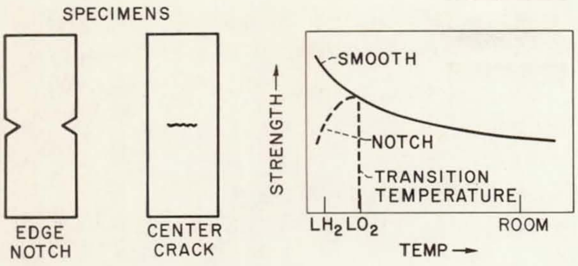


FIGURE II–5.—Smooth and notched strengths at various temperatures.

Figure II–5 shows two specimens that have been developed to measure toughness, that is, the strength of material in the presence of cracklike flaws. In these specimens, the action of cracklike flaws is simulated by the introduction of either edge notches or a central crack. The sensitivity of a material to cracks is determined by comparing the strength of these specimens with that of specimens which contain no notches or cracks. The latter specimens are called smooth specimens. A schematic representation of the behavior of notched and smooth specimens is also shown in the figure. The strength of either specimen is plotted as a function of temperature. There is a particular temperature above which the notched and smooth strengths are identical; the material is thus insensitive to cracklike flaws in this temperature region. Below this temperature, however, the strength of the notched specimen decreases rapidly, indicating the development of crack sensitivity. Thus, the notched specimen has defined a temperature region wherein dangerous strength losses result from the presence of cracks. Notice that this embrittlement goes undetected in the conventional smooth-specimen tests.

The particular temperature at which a transition from ductile to brittle behavior occurs varies with material. Thus, transition temperatures are known to occur anywhere frmo −400° F to above room temperature, depending on the material. Recalling the liquid gas explosion, the temperature of the tank was about −250° F, while the transition temperature of the tank material was around −200° F or higher. Thus, the tank was operating in a brittle range and could have been predicted to fail in a brittle manner in the presence of cracks. The same holds true for the Liberty ship failures; the operating temperature was below the ductile to brittle transition temperature of the material.

Two materials may differ considerably in their ability to withstand cracks, though they may be similar in the absence of cracks. This crack resistance is illustrated in figure II–6, which shows the behavior of two stainless steels, AISI 301 and PH 15–7Mo. Both materials have identical smooth strengths over a wide range of test temperature, but the AISI 301 stainless is far superior in the presence of cracks at low temperatures.

FRACTURE MECHANICS

While the recognition that notch tests are useful for toughness comparisons is obviously a valuable advance in materials testing technology, results such as we have described serve mainly to screen materials. Another

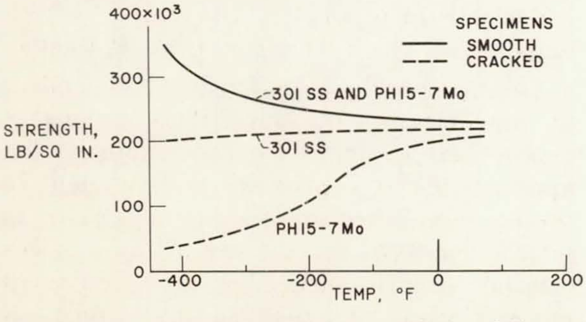


FIGURE II–6.—Comparison of two steels in ability to withstand cracks at low temperatures.

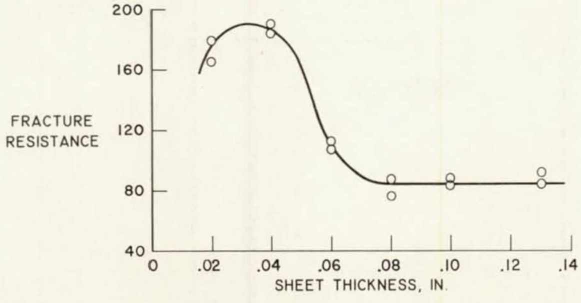


FIGURE II–7.—Effect of thickness on fracture toughness of a high-strength tool steel.

factor of concern with high-strength thick-walled structures is material that may exhibit completely ductile behavior in small specimens and can behave in a brittle manner in thick walls such as in the Liberty ships or the gas storage tank.

Figure II–7 shows the effect of thickness on the ability of a material which contains flaws to resist crack propagation. There is a very significant effect of thickness. From data such as those shown, it would therefore be reasonable to test specimens of the same thickness as that required for the material in a specific structural application. Such an approach certainly has merit, but it is difficult to test very thick sections of high-strength materials because of limitations in test equipment capacity. Therefore, scientific procedures are needed that will permit use of data from small, thin tensile specimens to predict the behavior of thicker materials and also to predict the occurrence of brittle fracture in structures. In recent years a science has been established called

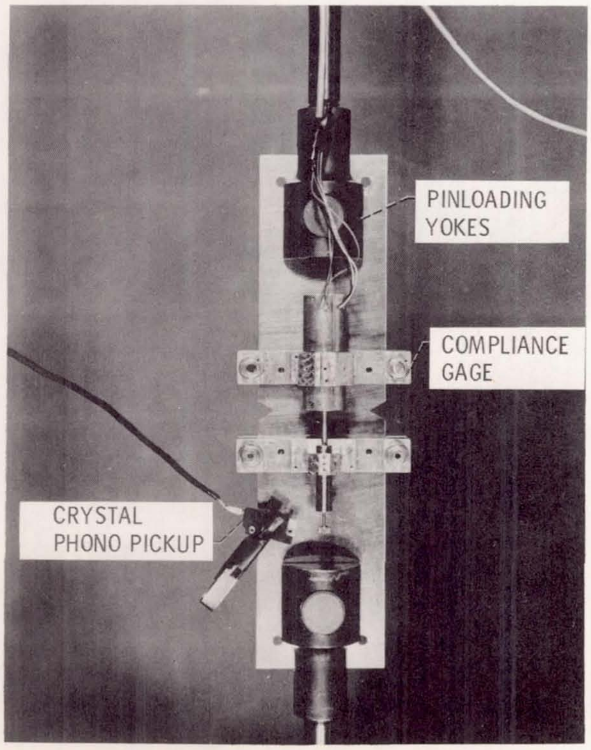


FIGURE II–8.—Acoustic pickup and compliance gage on edge-notch specimen.

Fracture Mechanics that has as its goal predicting brittle failure in structures.

The fracture mechanics problem is quite complicated, and many novel techniques have recently been introduced in both testing methods and the required mathematical procedures for predicting fracture occurrence. One test technique depends on determining the time crack propagation is initiated by using sound pickups attached to the specimen, as shown in figure II–8. Another technique utilizes compliance gages, also shown in the figure, where crack propagation is indicated by separation of the gages by an amount greater than that which occurs due to normal elastic strain. Research in fracture mechanics is being directed toward use of techniques such as these to predict brittle fracture occurrence in thick materials based on testing of thinner materials.

Fracture mechanics research has been used for determining materials, heat treatments, and welding procedures that provide greater reliability in high-strength-pressure vessels. It has also been determined that the lightest pressure vessel is not necessarily the one made of the highest strength material. High-strength materials have a greater tendency toward brittle fracture resulting from the presence of small flaws and therefore cannot be stressed to the levels indicated by their tensile strengths. By use of fracture mechanics methods, we are able, at least, to approach the optimum material and material heat treatment for a specific application.

The environment of a material can also significantly affect the brittle fracture characteristics of some materials. In the early Polaris rocket motor cases, made of a high carbon steel, there was an embrittling effect of water on the steel when it was under stress. Figure II–9 shows a Polaris case that failed at a load much lower than that expected while it was being pressurized with water. The presence of water was believed to be a contributing factor to the premature failure. Research at Lewis has shown that, if water is placed in the notches of notched tensile specimens of high carbon

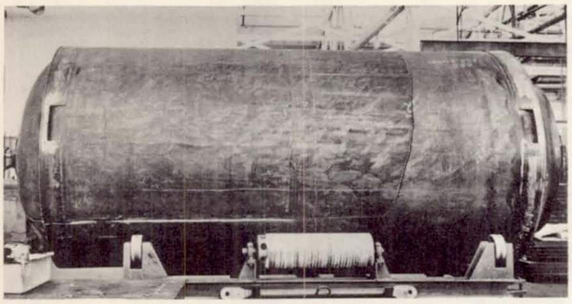


FIGURE II–9.—Brittle facture of large rocket motor case.

steel, the specimens can fail at a load less than three-fourths of the load that would be required if the specimens were dry.

Such performance of a material would suggest the desirability of a material change in a structure. Polaris motor cases are now built of glass-fiber reinforced plastic.

The value of fracture mechanics is illustrated in figure II–10, which shows the success achieved in taking tensile specimen data and predicting failure occurrence in small pressure vessels. The solid lines show two methods of predicting this failure stress based on the results of data from tensile tests of a notched specimen and a smooth specimen. To check these predicted failure stresses, we tested a series of tanks containing cracks of various lengths, pressurizing the tanks until they failed. The data points are the actual measured failure stresses in the tanks as a function of crack length. These particular tanks were filled with liquid nitrogen, which resulted in a material temperature of −321° F. We were quite successful in predicting the conditions at which the tank would fail. Note how low these failure stresses can become. A crack length of 2 inches is only 15 percent of the length of the tank, but the strength is reduced 90 percent compared with that for a tank which does not contain a crack. If the failure behavior were ductile, rather than brittle, the strength would have been reduced only 15 percent.

The significant point to make from this figure is that it is possible to predict the stress that a tank can withstand for a given crack length by using data from only two relatively simple tensile specimens. Crack-like defects cannot be completely eliminated from large pressure vessels. With information of this type being generated and knowing the size of cracks that can be found by routine inspection techniques, it is reasonable that pressure vessels can be designed so that they will approach minimum weight and still be safe on the basis of catastrophic failure.

FATIGUE

Another type of failure that frequently manifests itself in appearance as brittle fracture is that known as fatigue. Fatigue is a process in which the material gradually disintegrates over the application of more than one cycle. Although sometimes we are interested in as few as two or three cycles, at

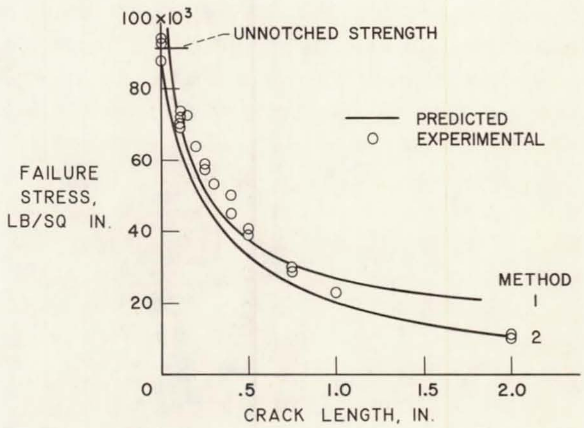


Figure II–10.—Crack length effect for tanks at −321° F.

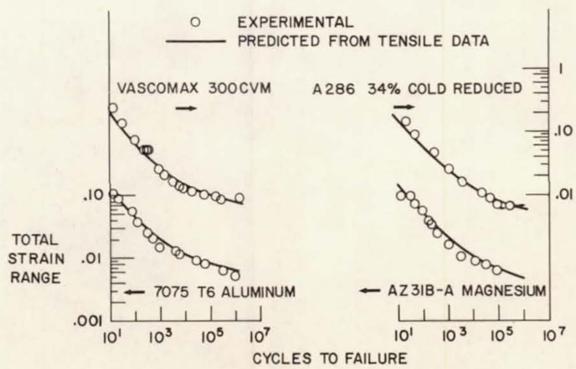


Figure II–11.—Axial fatigue characteristics of several materials.

other times our interest lies in the order of millions of cycles.

Because long-time testing in fatigue can sometimes be rather expensive, interest at Lewis has been directed toward the development of a method whereby the fatigue characteristics of a material can be estimated from properties measured in simple static tensile tests. From tests for tensile strength, ductility, fracture stress, and elastic modulus, fatigue properties can be estimated. The mathematics of the approach involved is somewhat too complicated for the present discussion, and we shall concentrate only on the type of results that have been obtained.

Figure II–11 shows typical results for four different classes of materials, high-strength steel, a high-temperature alloy, an aluminum alloy, and a magnesium alloy. The cyclic life is plotted as a function of the strain range imposed on the specimen. This form of presentation is slightly different from conventional fatigue plots in that it is more usual to represent cyclic life in terms of stress rather than strain range. One of the contributions that we have made at Lewis is the observation that fatigue can be related more fundamentally to strain than to stress. In most cases, however, the stress analyst will be able to convert strain to stress, even in the plastic range. The solid lines in figure II–11 represent predictions based on tensile tests on these materials. The data points represent experimental results that were obtained after the predictions were made. Obviously, the correlation is extremely good.

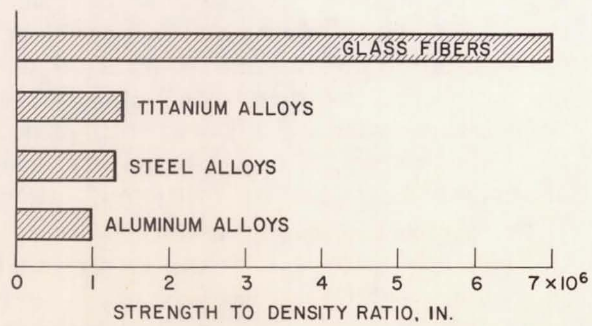


FIGURE II–12.—Materials comparison on basis of strength to density ratio.

Not all the materials tested are quite as good as those shown in the figure. But nearly 30 materials have been tested and the agreement between specimen and prediction is sufficiently good to give us confidence that the fatigue characteristics can be predicted on the basis of a simple tensile property for most metallic materials of technological interest.

HIGH-STRENGTH MATERIALS

In applications ranging from space vehicles to automobiles and step ladders, there is a continuing effort to save weight. The most direct approach, from a materials standpoint, is to increase material strength. As a result, there is a continuing research effort directed toward higher strength materials.

Figure II–12 shows the strength potentials of a variety of materials. By comparing these materials on the basis of ratio of tensile strength to density, we obtain a measure of the weight of the material required for application where the stress to be carried is in tension, as it is in pressure vessels. The commonly used metal alloys, such as titanium, steel, and aluminum have strength to density ratios less than 1.5 million inches. Improvements can surely be expected with further development, but it is unlikely that the strengths can be doubled or tripled. You will observe that the glass fibers do have strength to density ratios that are five to seven times those of the more common metal alloys. Therefore, we have a very great interest in trying to utilize this high-strength potential.

There is a general familiarity with one example of a material utilizing glass fibers, namely, glass-fiber reinforced plastics. Some early applications include fishing rods and poles for pole vaulters, but pressure vessels, as shown in figure II–13, are now being built in a similar manner. In the upper right is an inset that illustrates a cross section of the pressure vessel. The glass fibers that carry the load are embedded in a plastic binder

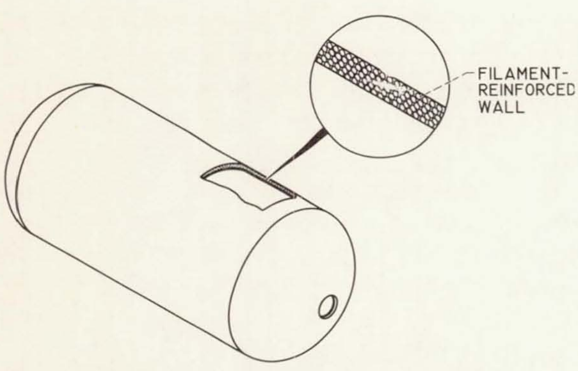


FIGURE II-13.—Filament-wound pressure vessel.

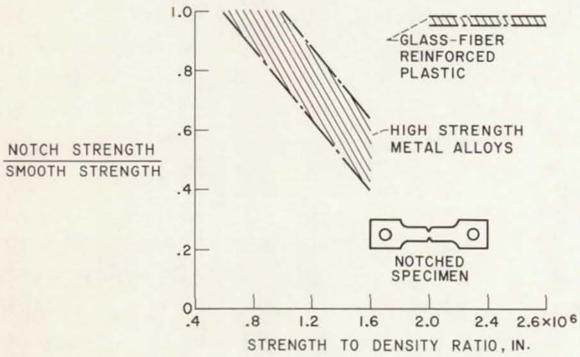


FIGURE II-14.—Material strength at −423° F.

that holds the fibers in place. It might be expected that such a material would be less subject to catastrophic failure since each fiber is an independent load-carrying element, and crack propagation through the material is less likely than that for the more homogeneous metal alloys.

The notch sensitivity of glass-fiber reinforced plastics is compared with metals in figure II–14. The ratio of notched specimen strength to smooth specimen strength shown as the ordinate is a measure of the notch toughness of a material.

The band shown for metal alloys includes aluminum, titanium, and stainless-steel alloys used for high-strength pressure vessels. There is a general trend of reduced notch toughness as the strength of these metal alloys is increased. As a result, efforts to reduce pressure-vessel weight by using stronger materials result in a greater probability of catastrophic failure by brittle fracture.

The glass-reinforced plastic does not have this characteristic of metal alloys. The strength-density ratios of the glass-plastic composite can be two to four times that of metal alloys, and the glass-reinforced material is very insensitive to crack propagation.

Pressure vessels are being built of glass-reinforced plastic at the present time for use at temperatures of the order of 50° to 200° F. The most notable example is the rocket motor case for Polaris. Research is now under way at NASA to use this approach for pressure vessels at cryogenic temperatures.

LINERS FOR GLASS-FIBER-REINFORCED PRESSURE VESSELS

A rather significant problem that occurs with the use of glass-reinforced plastic for pressure vessels results from their fibered construction. The wall of filament-wound structures is not pressure tight. Therefore, it is necessary to provide some sort of an impermeable liner to keep the structure from leaking. For application near room temperature, providing a liner is relatively simple. An elastomeric material, such as rubber, provides an inner tube, so to speak, that provides an adequate seal. So far, it has not been possible to develop a "tubeless" filament-wound pressure vessel.

Although glass fibers have very high strength, their modulus of elasticity is low. As a result, the elastic strain during operation of glass-filament-wound pressure vessels can be as much as 2.5 percent. A rubber inner tube at room temperature can take this strain very easily, and no problems develop, but if an attempt is made to use filament-wound pressure vessels at very low temperatures, such as for storage of liquefied gases like helium, nitrogen, or natural gas, elastomeric liners become brittle and crack.

The problem of finding a suitable liner is illustrated in table II–I. It can be seen that glass fibers exhibit a relatively large maximum elastic strain, about 2.67 percent. What is needed in a liner is a material that shows a similar large maximum elastic strain. Unfortunately, no other material known exhibits a value of this quantity that even

TABLE II-1—Stretch Capability of Materials at −423° F

Material	Maximum elastic strain, percent
S994 Fibers	2.67
Aluminum	.50
Stainless steel	.62
Alpha titanium	.89
Mylar	1.27
FEP Teflon	1.56

approaches that of glass fibers. Values for some other materials are shown in the table. All exhibit a maximum elastic strain well below that of the glass fibers. Thus, it is obvious that finding a nonelastomeric liner material can be a serious problem.

From table II–I, it would seem that metal alloys would not be suitable for liners because they do not have enough elastic stretch capability. This is unfortunate because metal liners have other characteristics that would make them extremely desirable, such as essentially zero permeability to flow of gas or liquid and chemical compatibility with nearly all fluids. The problem, therefore, is how to increase their strain capability.

A possible solution to the problem is illustrated in figure II–15. One way of making a metal tube stretch in a longitudinal direction is to form it into a bellows. In this manner the metal itself does not stretch much but it bends in the hinge points formed by the convolutions of the bellows. The bending stresses are kept below the elastic limit, but it is still possible to make bellows that will stretch more than 50 percent of their original length. An ordinary metal tube cannot stretch more than 1 percent of its original length without exceeding the yield point.

The liner for a tank is a little more complicated than a bellows. When a bellows stretches in the longitudinal direction, it

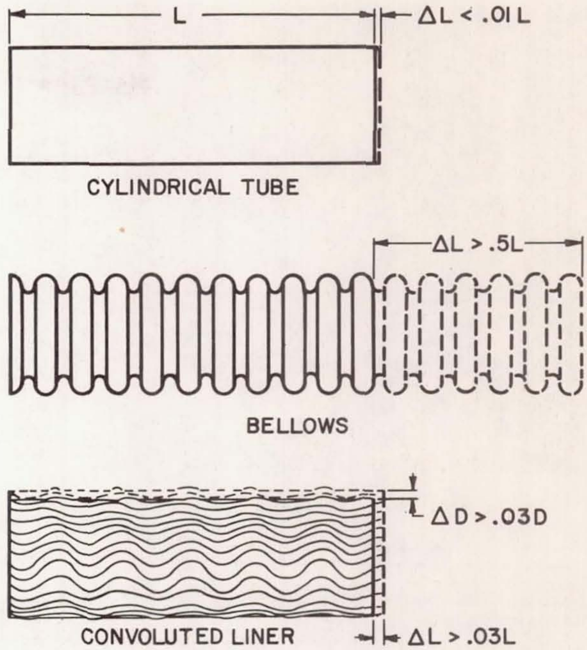


FIGURE II–15.—Extensibility in liners.

shrinks in the circumferential direction. A tank liner must be able to stretch in both directions at the same time. This means that we must be able to provide bellowslike hinge points in all directions, rather than in just a single direction as in an ordinary bellows. Fortunately, the liner will not have to stretch nearly as much as bellows have to.

An approach that we have developed at NASA is illustrated schematically in the bottom sketch in figure II–15, which shows a series of wavelike convolutions in the liner. In this manner the liner can stretch a few percent in any direction.

In preliminary tests conducted on a very crudely constructed liner of this type made of soft aluminum, the liner withstood 18 pressure cycles installed in a glass-reinforced tank filled with liquid nitrogen. These pressure cycles strained the tank and liner 2 percent on each cycle. Without building in these special convolutions, liners of all materials investigated failed during the first cycle or at the beginning of the second cycle.

These results are very encouraging. Research is now getting under way on more refined embossed-type patterns for liners that permit extension in all directions with-

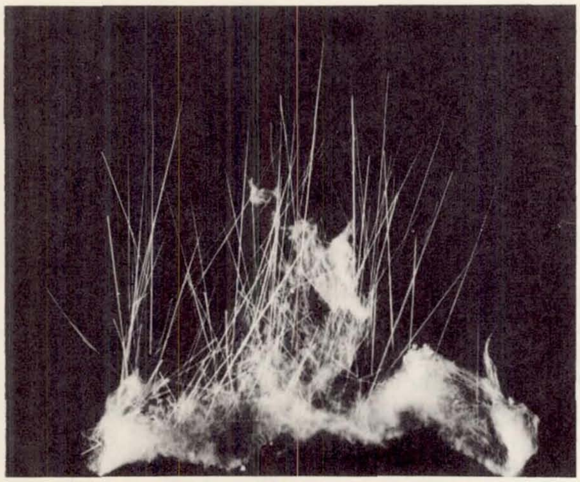


FIGURE II-16.—Sapphire (Al_2O_3) whiskers.

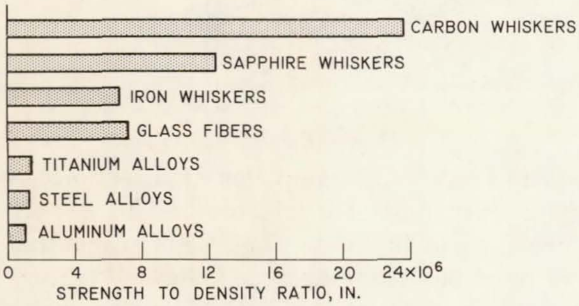


FIGURE II-17.—Material strength to density ratios.

out exceeding the elastic strain capabilities of the liner material.

To summarize the status of nonmetallic material research for application in pressure vessels, it has been shown that there are very substantial advantages to using fiber-reinforced plastics to reduce the weight of pressure vessels as a result of their very high strength to density ratios. At the present time, it is not apparent that any metal alloys will be competitive on the basis of weight. The potentials are very great, and fiber-reinforced plastics are being used in Polaris missiles, but there are still some problems involved for low-temperature application, particularly with finding suitable liner materials and configurations. We are confident that the solutions to these problems are not far away.

The technology in reinforced-plastic materials is quite new and it is growing rapidly. Metallurgical improvements have been made in alloys for many years, but it is really only in the last decade that reinforced plastics have been exploited for high-strength structures. Active research is being conducted all over the country as well as here at Lewis on improved materials and new applications of these materials. We have really only scratched the surface in exploring the potentialities of fiber-reinforced plastics. In the future, these materials will find more and more use in applications presently reserved for metal alloys.

FIBER METALLURGY

The physicist has maintained for many years that the measured strength of engineering materials is far below the theoretical strength; in fact, measured strengths of pure metals are usually only 5 percent of the theoretical strength. The theory of dislocations has been developed to explain the low strength of engineering materials. Nevertheless, researchers have always been alert to the possibilities for finding materials that approach more nearly their theoretical strength. It is well known by now that such materials have been found in the form of small fibers called whiskers. Generally, whiskers have a diameter from about one-millionth of an inch to a few thousandths of an inch. Figure II–16 shows aluminum oxide (or sapphire) whiskers that have measured strengths of 1,800,000 psi. If these whiskers could in some way be incorporated to form a bulk material analogous to glass-fiber-reinforced plastics, perhaps phenomenally strong materials might be realized.

Figure II–17 compares the strength to density ratio of a variety of materials including iron, sapphire, and carbon whiskers. These values of about 7, 12, and 24 million inches are far greater than the values of about 1.5 million inches for metal alloys and represent the ultimate in what might be achieved in material strength. At Lewis and at other research installations in the country, the possibilities of producing composite materials from whiskers is being studied. Unfortunately, large quantities of whiskers have not been available, so our studies have been conducted by using alternative materials, namely, fine wires.

Figure II–18 shows some information about the strength of tungsten wires. On the right is a bar that indicates the strength of tungsten in normal bulk form, for instance, in a ¼-inch-diameter rod at room temperature. The strength is about 80,000 psi. As tungsten is drawn into finer and finer wire, strength increases until fibers about 0.0005 inch in diameter are formed and the strength is of the order of 600,000 to 700,000 psi. Examples of the previously mentioned whiskers are also shown for comparison. Lewis fundamental research has used fine wires of tungsten in the range shown. These fibers have strengths of 250,000 to 600,000 psi. We have been making bundles of these wires into solid rods, called composite materials, by bonding the tungsten wires together with soft copper. A greatly enlarged view of one of these composite specimens is shown in figure II–19. The tungsten wires are actually about 0.007 inch in diameter, the largest size that has been used.

Figure II–20 shows the strength of the composites. On the left is shown the strength of bulk copper that bonds the wires together, and on the right is the strength of the tungsten wire used to produce the composites. The two central bars indicate the strength of the composites for various volume percents of fibers in the specimen. The strength is in almost direct proportion to the amount of fiber present.

An important point is that these test specimens were made with long wires that were continuous from one end of the test specimen to the other. It is not too surprising then that good strengths have been achieved. The whiskers that have the truly phenomenal strengths are not now available in such lengths, however, and may never be available in quantity in lengths beyond a few tenths of an inch. Thus, the question is raised as to whether good strengths could be achieved if specimens were made having

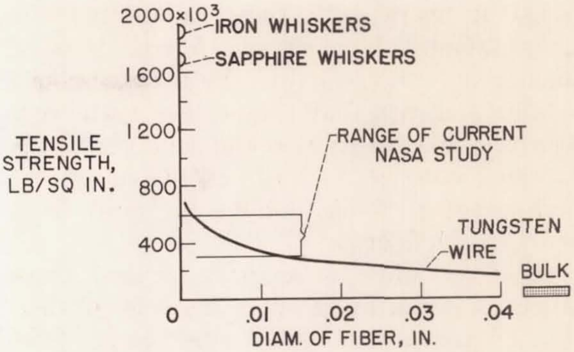


FIGURE II–18.—Strength of whiskers and fibers at room temperature.

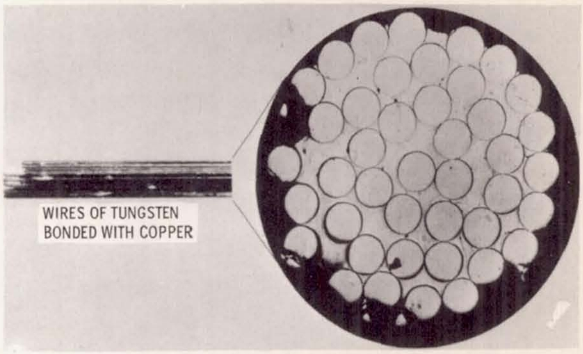


FIGURE II–19.—Composite materials from metal fibers.

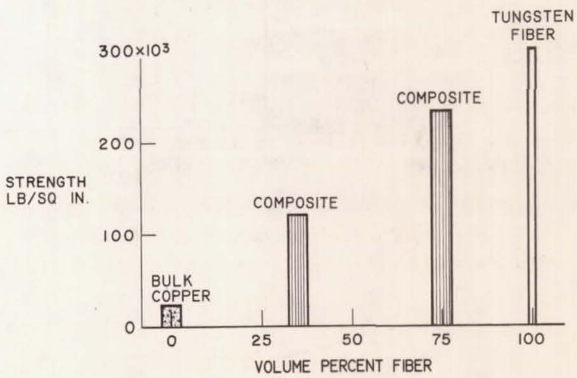


FIGURE II–20.—Tensile strength of composites of various volume percent continuous tungsten fibers in copper.

noncontinuous fibers, that is, if all wires were of short lengths, none running from one end of the test specimen to the other.

Studies have been made to investigate this point. Figure II–21 compares the strengths of specimens of copper containing 35 volume percent of discontinuous or short length tungsten fibers with those containing the same amount of continuous fibers. It is of considerable interest that the data available to date indicate that composites containing discontinuous fibers have the same strengths as composites containing continuous fibers; high-strength bodies can be achieved from short-length fibers.

Another point to be made is that these laboratory specimens are a clear demonstration of the advantage of fiber composites. On the left the strength of copper bonding material is shown. The addition of 35 percent by volume of short tungsten fibers increases the strength of bulk copper by a factor of 4 to about 120,000 psi. On the far right the strength of bulk tungsten is shown. The composites of fibers of tungsten in copper have nearly twice this strength.

A final point concerning whiskers can be made with the aid of figure II–22, resulting from studies at the General Electric Company. Here the tensile strength of whiskers of aluminum oxide and bars of aluminum oxide ceramic are compared as temperature is increased. The conventional ceramic bars lose strength rapidly as temperature is increased, whereas whiskers hold their strength without sudden dropoff almost to the melting point of aluminum oxide. Composites made from whiskers may also retain strength to very high temperatures and may be a basis for excellent very high-temperature materials.

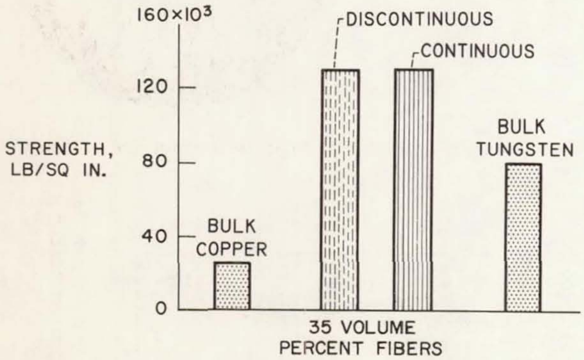


FIGURE II–21.—Tensile strength of composites containing 35 volume percent continuous and discontinuous tungsten fibers in copper.

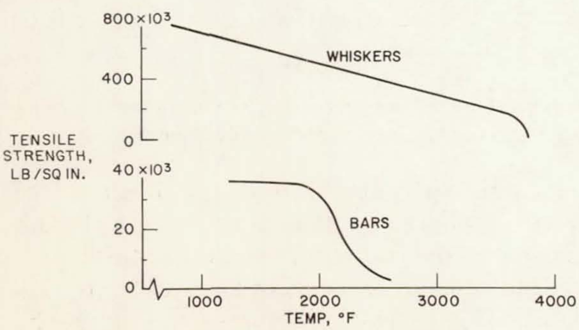


FIGURE II–22.—Sapphire (Al_2O_3) whiskers strength retention at high temperature.

Research on fiber metallurgy is of a fundamental nature designed to examine the concepts and mechanisms of fiber strengthening; thus, the combinations being studied are not yet of particular value as engineering materials. The observations do serve to indicate the opportunity of achieving unusually strong and high-temperature materials through research on composites utilizing fibers and whiskers.

The purpose of this research is to develop new materials. There are other materials that are relatively new, at least as far as application is concerned. For certain applications, materials such as beryllium and titanium are unsurpassed.

BERYLLIUM

Beryllium is one of the newer materials that has come into prominence in recent years, particularly in the aerospace field. Approximately 200 tons of beryllium were produced in the U.S. in 1962 with about 10 percent going into structural applications, and it is finding increasing acceptance in structural applications in space vehicles as heat shields and guidance and optical parts, and is under consideration for jet engine compressor parts.

Beryllium has several important physical characteristics that give it major advantages over other materials. For example, it has a higher heat capacity than any other metal. In other words, it is able to absorb great quantities of heat without melting. This characteristic makes beryllium a useful material as a heat shield in space vehicles to absorb the heat created by air friction upon reentry into the Earth's atmosphere.

Perhaps the most outstanding property of beryllium is its light weight. Figure II–23 illustrates the comparative weight of several of the lighter structural metals expressed in terms of weight percent of iron. Beryllium is approximately one-fourth the weight of iron, and it is considerably lighter than either titanium or aluminum, which have approximately 55 and 35 percent, respectively, the weight of iron.

The importance of light weight in any engineering application, particularly aerospace applications, is obvious; however, light weight alone is not enough. A metal must also be strong to be a useful engineering material. At the present state of development, beryllium alloys have strength to density ratios comparable with or slightly superior to titanium alloys up to temperatures of about 1000° F.

Beryllium has another characteristic that is important when heavy loads are applied to a part. This is its stiffness, or resistance to elastic deformation. In other words, how much force must be applied to stretch the material? Figure II–24 illustrates the stiffness of beryllium relative to other lightweight metals at several temperatures. Data for a stainless steel have also been included to provide a further frame of reference. Beryllium has more than twice the stiffness of titanium and more than four times that of aluminum. It is even approximately one-fourth greater than that of stainless steel up to about 1000° F.

Unfortunately, beryllium has two major drawbacks associated with its use. The first of these is the problem of toxicity. The major hazard is due to inhalation of beryllium and beryllium compounds, which can cause irritation of the respiratory tract and lungs. By compliance with safe breathing concentrations established by the Atomic Energy Commission as the result of extensive industrial experience, beryllium can now be machined and handled safely.

The second and now the primary problem associated with the use of beryllium is its brittleness. Because the metal is brittle, it cannot be formed readily into complex shapes or into tubing and it has low fracture toughness in structures. Extensive research is under way in various organizations to establish the causes and provide a solution for the brittleness problem. This research includes attempts to make ultrapure beryllium in the hope that the removal of impurities will reduce brittleness. Alloying with other metals and advanced and carefully controlled forming techniques have been applied in fabrication of this metal. Alloying studies have resulted in some notable improvements in ductility. Figure II–25 illustrates the dramatic improvements in formability over unalloyed beryllium obtained with some beryllium-aluminum "alloys" recently developed by Lockheed. (These are

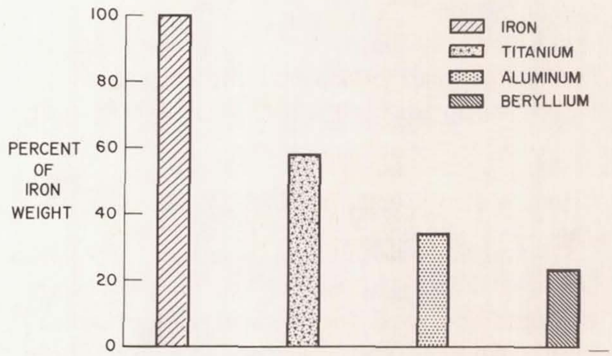


FIGURE II–23.—Relative density of various structural materials.

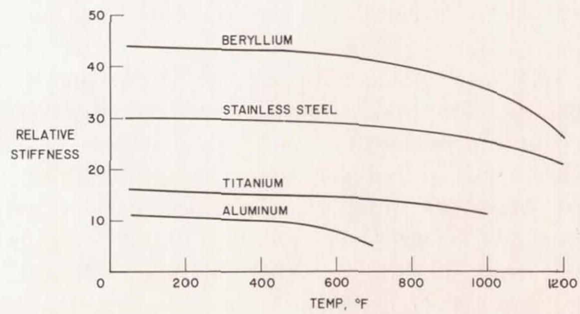


FIGURE II–24.—Resistance to deformation of various metals.

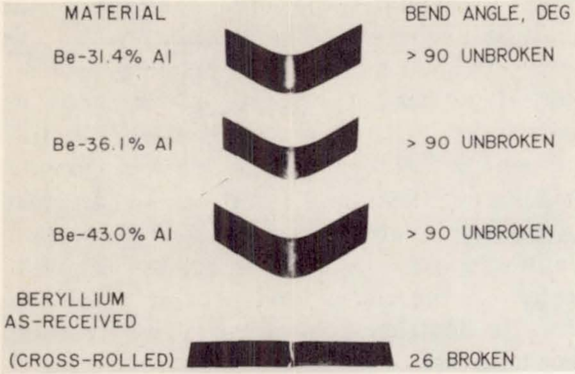


FIGURE II–25.—Bend angle comparison between beryllium-aluminum alloys and unalloyed beryllium.

not strictly alloys but rather composite materials with beryllium particles embedded in aluminum.) All of the beryllium-aluminum alloy strips shown were bent through angles greater than 90° without breaking. The unalloyed metal broke after bending to only 26°.

Notable advances are being made in beryllium technology which show promise that beryllium will come into its own as a structural material, and that the advantages of low weight, stiffness, and high strength to weight ratio that beryllium affords may soon be utilized.

TITANIUM ALLOYS

Although beryllium has a great potential because of its light weight and high strength, it cannot be used for a very wide range of applications. Titanium has the advantage over beryllium because it is ductile over an extremely wide temperature range, it can be frabricated relatively easily, and it is not toxic.

As a result, titanium alloys exhibit a unique combination of light weight and outstanding mechanical properties, which make them well suited for wide ranges of service in aerospace industry. Titanium production has increased from about 100,000 pounds per year in 1950 to about 15,000,000 pounds per year at the present time. Approximately 93 percent of this output is presently used in aerospace applications.

As can be said for any structural material, specific titanium alloys are tailored to specific applications. To indicate the versatility of titanium alloys, its use for storing cryogenic propellants such as liquid hydrogen, which has a temperature −423° F, will be discussed briefly, and later a higher temperature application will be discussed.

For propellant storage tanks, the highest strength possible is desired to reduce weight, but at very low temperatures brittle fracture, as discussed previously, can become the limiting design factor. A large number of candidate materials were surveyed in an extensive research effort at Lewis, and a titanium alloy containing 5 percent aluminum and 2.5 percent tin proved to be superior to others at liquid hydrogen temperature. A simplified comparison of candidate materials is shown in figure II–26. The maximum stresses are shown that could be used in pressure vessels containing small flaws or cracks for aluminum, stainless steel, and a titanium alloy. Some materials, such as cold-worked stainless steels, have strength properties that differ in longitudinal and transverse directions of the sheet. By proper orientation, these materials can be used efficiently in cylindrical pressure vessels, but less efficiently in spherical pressure vessels, where the pressure-induced stresses are the same in all directions. The titanium alloy is shown to be dramatically superior to both stainless steel and aluminum for spherical pressure vessels and somewhat better than stainless steel for cylindrical pressure vessels.

This is not the complete story, however; the stainless steel suffers a serious joining problem. Because it derives its strength from heavy amounts of cold-rolling, fusion-welding results in soft, weak joints that require weighty reinforcements. These reinforcements, themselves, present a serious crack-starting hazard. The titanium alloy, on the other hand, may be used in the annealed condition, so that the welds have essentially the same strength as the parent metal and do not need reinforcement as is required for the stainless steel. This gives the titanium alloy a substantial advantage over the stainless steel that is not reflected in the representation of figure II–26. Because of its decided superiority, a great deal of research has been conducted at this laboratory on the titanium alloy. Two findings are of great interest.

The strength of titanium alloys is greatly influenced by the composition of certain alloying elements such as the gases hydrogen, oxygen, and nitrogen and the elements carbon and iron. It has been shown at Lewis that increases in these elements, while increasing the strength, reduce the crack resistance of titanium alloys substantially.

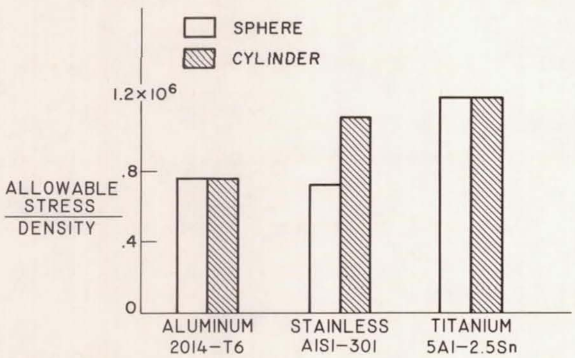


FIGURE II–26.—Comparison of tank materials with cracks at liquid-hydrogen temperature. Sheet thickness, 0.050 inch.

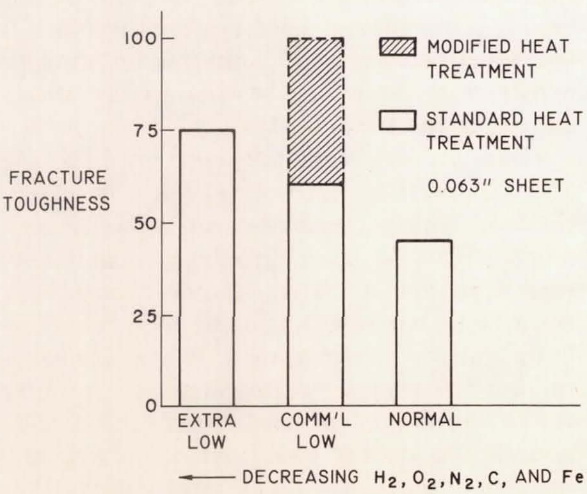


FIGURE II–27.—Fracture toughness of 5Al–2.5Sn titanium alloy at liquid-hydrogen temperature.

Such results are shown for the 5Al–2.5Sn titanium alloy in figure II–27. The solid bars represent the crack resistance of the titanium alloy as it is produced at the mill. Three compositions are shown: a normal mill composition, a commercial low composition, and a special laboratory composition that is extra low in the aforementioned elements. The crack resistance is seen to increase as the composition of these elements decreases.

An additional finding in our research is that the crack resistance of this alloy is substantially improved by a modification to the commercial heat-treatment practice. This modification raises the crack resistance of the 5Al–2.5Sn titanium alloy beyond that of the extra low composition, suggesting that a change in heat-treatment practice may be used in a trade-off for composition control.

Based on weight considerations, it would be desirable to make liquid oxygen tanks from titanium, but for this application extreme caution must be exercised because titanium is one of the most reactive metals known. Some time ago, there was some concern about whether a reaction might occur when liquid oxygen was in intimate contact with titanium. Under static conditions, no reactions occurred, but impact sensitivity still causes concern. A reasonably safe way of checking impact sensitivity is to fire a small projectile into a small tank containing the fluid to check compatibility.

Impact sensitivity tests of this type were conducted on a variety of materials in contact with liquid oxygen. Of aluminum, steel, and titanium alloys investigated, only the titanium alloys were impact sensitive. For impacts in which there was sufficient energy to fracture the wall of tanks containing liquid oxygen, a reaction was started that continued until either the titanium face was consumed by burning or the liquid oxygen was exhausted. These reactions were quite violent with multiple explosions and gave a Fourth of July fireworks type of appearance.

From investigations of this type it was concluded that titanium pressure vessels should not be used in contact with liquid oxygen if there is a possibility of an impact occurring.

One of the most promising applications of titanium at a higher temperature is in the structure of supersonic transports. Nearly all conventional aircraft are made of aluminum, which is an excellent material for ordinary temperatures, but it loses strength very rapidly at temperatures above about 350° F. Figure II–28 shows the temperatures that will be encountered on a supersonic transport flying at three times the speed of sound (Mach 3). With temperatures like these, it will be necessary to build aircraft of titanium alloys, stainless steel, or what are called superalloys, which will be discussed later.

The recently announced A–11 reconnaissance aircraft, which flies at Mach 3, is fabricated of titanium. This is the first time titanium has been used for the entire fuselage in any aircraft, and a great deal of confidence in its continuing use has been expressed by aircraft manufacturers. This experience combined with our research on evaluating materials most suitable for supersonic transports flying at Mach 3 indicates that the United States' supersonic transports will be built of titanium alloys.

At Lewis alone, over 3000 tests have been conducted to evaluate suitable supersonic transport materials. Some results from our screening program are shown in figure II–29. Here strength to density ratios are compared for two types of materials for a range of temperatures. Also shown are the operating temperature ranges for several types of supersonic aircraft.

Within the operating temperature range of the British-French Concorde Mach 2.2 aircraft, the aluminum alloy 2014–T6 maintains a high value of strength to density ratio. Because of our long experience in using aluminum alloys in aircraft, it was hoped that its use could be continued in the Mach 3 transport. Note, however, that the

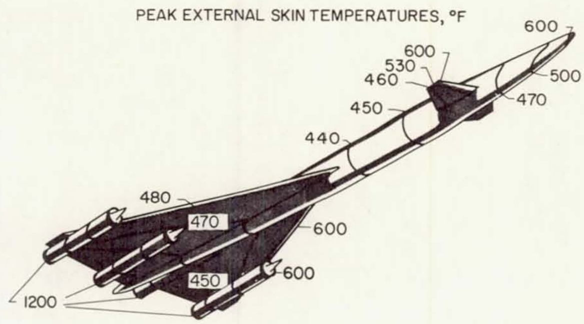


FIGURE II–28.—Temperatures encountered on Mach 3 supersonic transport.

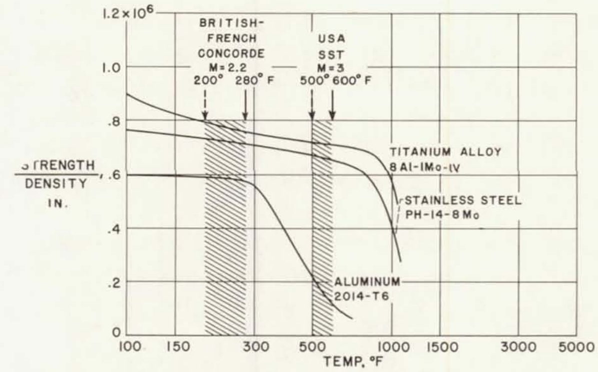


FIGURE II–29.—Materials for exposed surfaces of supersonic airplanes.

strength to density ratio of the aluminum alloy is reduced to extremely low values within the operating temperature range of the Mach 3 transport. At present, it appears that the titanium alloy 8Al–1Mo–IV would be a better material selection for the Mach 3 transport because of its superior strength to density ratio and because it is a more stable alloy than the PH–14–8Mo.

There are still some problems with the use of titanum that have not been completely resolved, and further research is being conducted. One of these problems is salt corrosion that can be encountered near sea coasts and when salt is used to clear snow from runways. Another problem is determining the very long-time strength stability for a minimum operating life of 30,000 hours. We do not feel that there are any insurmountable problems and think that titanium has a very bright future in supersonic aircraft.

CREEP

Up to now, failure that occurs either in a single cycle of loading or, as in the case of fatigue, in many cycles has been discussed, but no mention has been made of the dependence of the strength of the material on the time to which it is subjected to loading. When high temperatures are considered, however, a new variable must be introduced, namely creep and stress rupture.

When a material is loaded at elevated temperatures, it may not immediately fracture. Upon continued application of the load, however, the material may continue to deform or "creep," and the time required to achieve a given amount of deformation is of considerable importance in design. After a sufficient time of loading the material may, in fact, rupture, with the time involved being known as the stress-rupture time. In representing the data, this time factor must thus be included, as illustrated in figure II–30.

In the figure, the rupture time for a typical alloy at two temperatures is plotted on the horizontal axis and the stress on the vertical axis; thus to obtain the combination of stress and time to produce failure at 1200° F the upper curve is used, and for failure at 1300° F the lower curve is used. It will be noticed that the times of interest extend out in this curve to 100,000 hours. For other applications the time of interest may be even longer. Obviously, therefore, it is not practical in many applications to conduct tests to determine the stress-rupture properties of a material prior to the selection of the material when the application involves very long times.

Consider, for example, the supersonic transport just discussed. Here the interest is in lives of the order of 30,000 to 40,000 hours. Since there are many possible materials and many methods of testing involved, and since 30,000 to 40,000 hours represent almost 5 years of continuous testing, it would appear impractical to laboratory test each of the materials of interest for the full rupture time involved. A more extreme case is that illustrated by nuclear equipment for generating electric power. Such powerplants have recently been introduced both in this country and in England. To be economically competitive with steam power generation, such equipment should operate for 20 to 30 years before being replaced. Again it is impractical to laboratory test materials in this time range prior to selection as an operating component.

What we need, therefore, is a method of estimating the long rupture times involved without actually running the long-time tests. One method that has been developed at Lewis is known as the time-temperature parameter method, in which temperature is essentially substituted for time. The basis for this method is illustrated in figure II–31, which is the same as figure II–30 except that some dashed lines have been added. Suppose

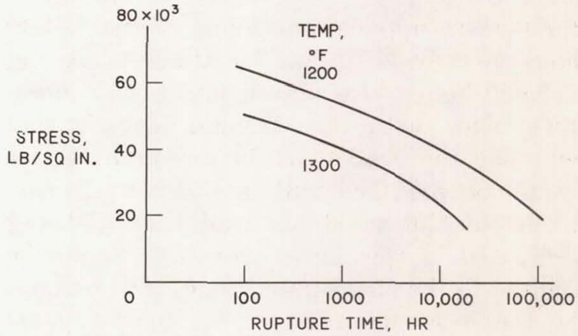


FIGURE II–30.—Stress to rupture of typical alloy.

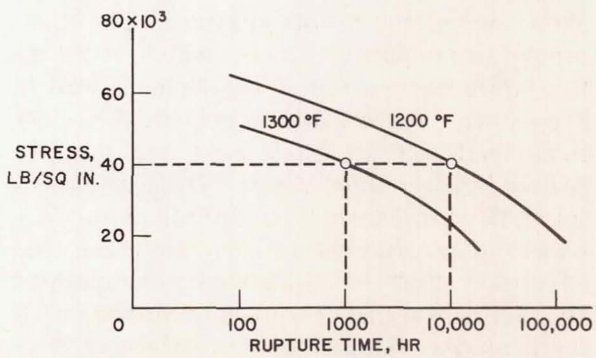


FIGURE II–31.—Reduction of test time by increasing temperature.

we are interested in the stress-rupture time for 40,000 psi and 1200°F. The figure shows that the rupture time is 10,000 hours. But suppose we did not wish to devote 10,000 hours to the test and chose instead to test at 40,000 psi and 1300° F. The rupture time would now be only 1000 hours. A method has thus been developed whereby the rupture conditions at one level of stress and temperature can be extrapolated to predict longer rupture times at the same stress and lower temperatures. The method for accomplishing this is quite mathematical and beyond the scope of the discussion herein; however, it is outlined in our literature. Only one of the results obtained with this method is illustrated.

To evaluate the validity of predictions made from tests conducted in the moderate time range, it was necessary to obtain check data in the extremely long-time range. A program has been underway in Germany since World War II to evaluate several steels for turbine application. Some of these tests have already been run for times exceeding 100,000 hours. An arrangement was therefore made with the German investigators whereby the NASA Lewis Research Center would be provided with a number of specimens of the same material that is being evaluated in Germany. Our tests would be limited to the short-time range, for instance, of the order of 1000 to, at most, 10,000 hours, and the results would be extrapolated in the long time range for comparison with the experimental German data. Figure II–32 shows one of the results obtained. The time-temperature parameter P, which contains the rupture time t and the temperature T are shown. The solid lines represent predictions made on the basis of Lewis data in the moderately short range. The experimental data points are those obtained in Germany. The triangle on the right on the curve for 1202° F is at a time very close to 100,000 hours, and it agrees quite well with the predicted line for this temperature. Several such materials have been tested at Lewis with approximately equally good results.

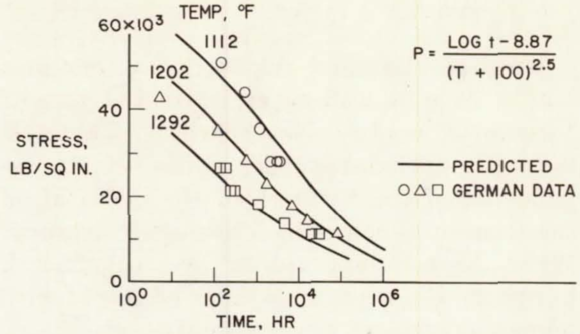


FIGURE II–32.—Parameter extrapolations for German steel based on short-time NASA data.

Our work is continuing in this field and we are verifying long-time data obtained at various laboratories by applying this method to predict such long-time data for various materials on the basis of short-time tests.

NICKEL-BASE ALLOYS

Many superalloys have been developed for use in the temperature range between approximately 1500° and 2200° F by using conventional alloying techniques. Among these, nickel-base superalloys have become the workhorse materials for a variety of applications such as turbojet engine components and structures of reentry vehicles in which high-temperature strength coupled with generally good oxidation resistance is required. Figure II–33 categorizes several generations of superalloys since World War II. The two major variables affecting the life of a metal are the load or stress imposed upon

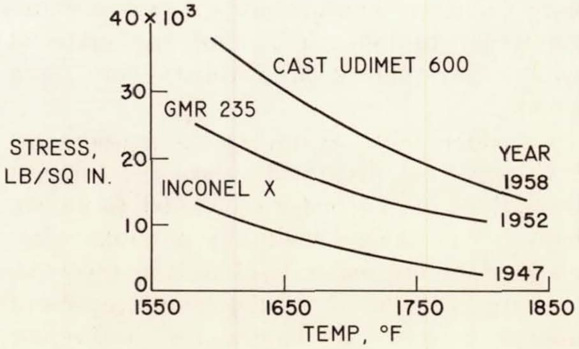


FIGURE II–33.—100-Hour stress-rupture life of various alloys.

it, plotted along the vertical axis, and the temperature at which such load is applied, plotted along the horizontal axis. Various combinations of stress and temperature can give a desired life. One-hundred-hour life is a commonly used criterion in evaluating high-temperature materials, and this value has been chosen as the basis of comparison in the figure. The curve for Inconel X is representative of the strength level of both nickel- and cobalt-base superalloys shortly after World War II. Several generations of nickel-base alloys have been developed since then, with the general level of their capability defined by GMR 235 and cast Udimet 600.

Research at Lewis is directed toward extending the high-temperature capability of nickel-base alloys, and we are now working in the region beyond that defined by the curve for Udimet 600. When our program was initiated about 6 years ago, the development of nickel-base alloys had reached the level represented by the cast Udimet 600 curve. This alloy gave approximately 100-hour life at 1820° F and 15,000-psi stress. Substantial improvements in stress-rupture life as well as use temperature have since been realized with nickel-base alloys in industry as well as at NASA. Illustrative of this improvement are the as-cast stress-rupture properties of the NASA TaZ–8 alloy shown in figure II–34. Temperature is plotted against life for a constant stress of 15,000

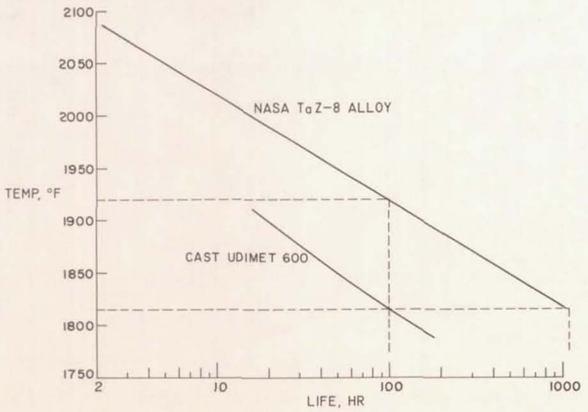


FIGURE II–34.—Improvement in stress-rupture life of nickel-base alloys at 15,000 psi.

psi. Average rupture life at about 1800° F was extended from approximately 100 to 1200 hours. For an average life of 100 hours, use temperature was extended from about 1800° to over 1900° F.

It is interesting to note that, for reentry space vehicles, the constructional material experiences only short-time service: for 1-hour life, temperatures near 2100° F can be endured by the NASA TaZ–8 alloy.

COBALT-BASE ALLOYS

In addition to the nickel-base alloys, cobalt-base alloys have potential for applications where high-strength materials are required in the intermediate temperature range between approximately 1500° and 2200° F. Although emphasis was placed on nickel-base alloy development during the war years because of a shortage of cobalt, alloys of cobalt base are now being studied with increasing interest, and for good reason. Cobalt has a melting point of 2720° F, almost 100° higher than that of nickel. This suggests a somewhat higher use temperature potential than that for nickel-base alloys.

Our main interest has been for applications in space, where cobalt-base alloys have a few additional potential advantages, but the conventional cobalt-base alloys also have a disadvantage. On the credit side, consider the compatibility with mercury used as a heat-transfer fluid in space power systems. The compatibility of cobalt is better than that of nickel-base alloys. Also, both cobalt and nickel are magnetic at room temperature, but cobalt retains magnetic properties to a higher temperature than nickel, higher in fact than any other metal. Cobalt-base alloys thus afford the best potential for application to high-temperature generator components of turboelectric power systems.

On the debit side is the evaporation problem in the vacuum of space. All conventional cobalt alloys contain 20 to 25 percent of chromium to achieve suitable oxidation resistance and strength. Space, however, is an excellent vacuum, and oxidation resistance is not required. On the other hand, at high temperatures in this vacuum, solid metals tend to vaporize or sublime in a fashion analogous to dry ice at room temperature. Chromium is one metal that vaporizes most rapidly. Figure II–35 illustrates what can happen to an alloy containing a high percentage of chromium (in this case 20 percent) on exposure for a relatively short time (250 hr) at 1500° F in a vacuum of 10^{-5} millimeter of mercury. This is the metal as seen in a metallurgical microscope at a magnification of 250. The metal matrix shows considerable porosity near the exposed surface due to the selective evaporation of the chromium. Obviously, the structural integrity of such an alloy will be adversely affected as this evaporation process continues.

It is thus obvious that, for use in vacuum environments, we should emphasize alloying additions that have the least tendency to evaporate. Figure II–36 shows the rate of evaporation of several metals. They are compared on the basis of the temperature at which 0.010 inch would be lost from the surface in 1 year in service. Shown is the use temperature for cobalt on this basis, about 2000° F. To the right of cobalt are metals that evaporate more rapidly and thus should not be alloyed with cobalt. On the left of cobalt are many metals that evaporate more slowly. Of most interest are the refractory metals, tungsten, tantalum, columbium, and molybdenum.

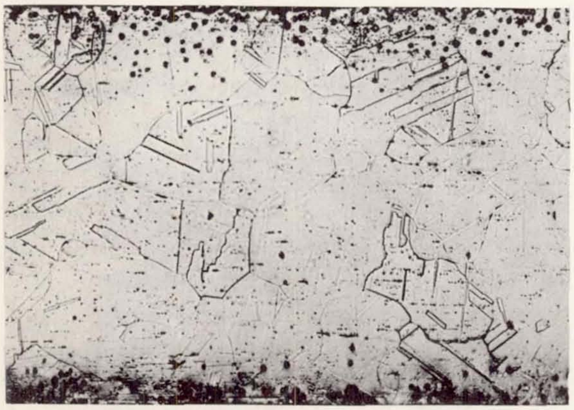


FIGURE II–35.—Selective evaporation of chromium from Nichrome heater wire. Temperature, 1500° F; time, 250 hours; pressure, 10^{-5} millimeter of mercury; ×145. (Reduced 42 percent in printing.)

Some recent data by Russian investigators have come to light which suggest that there may be a point of controversy as to the vapor pressures and thus the evaporative loss rates of metals such as cobalt and nickel. Until these new data that predict very high evaporation rates in space can be checked, the data described herein are believed to represent the most accepted data on this subject.

Lewis is engaged in a program to provide high-strength cobalt-base alloys that are strengthened primarily by low volatility alloying constituents such as the refractory metals. Chromium is either not used or used only in small quantities not exceeding 3 percent. Figure II–37 compares the stress-rupture properties of the strongest cobalt—refractory-metal alloy developed in this

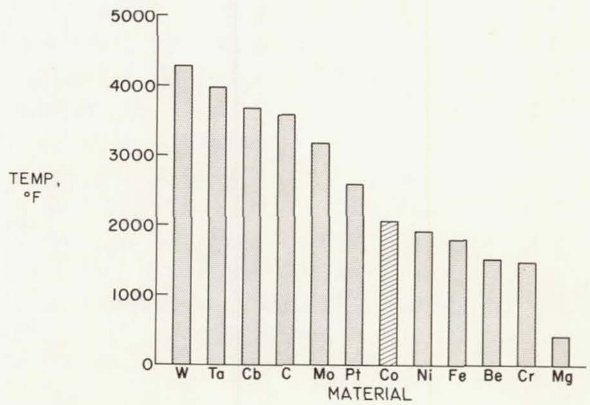


FIGURE II–36.—Use temperature of metals in space based on rate of evaporation.

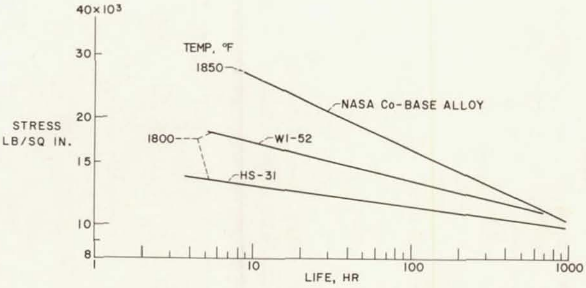


FIGURE II–37.—Comparison of stress-rupture properties of several cobalt-base alloys.

program to date with the stress-rupture properties of two conventional (i.e., high chromium) cast cobalt-base alloys, WI–52 and HS–31. The data for the conventional alloys are for a temperature of 1800° F and the data for the NASA alloy are at 1850° F. All data were obtained in air with no protective coating on the experimental alloy. Even at a 50° higher temperature the NASA alloy is stronger than the commercial alloys.

It should not be inferred that the oxidation resistance of these experimental cobalt—refractory-metal alloys is as good as that of high-chromium-bearing superalloys; however, the cobalt—refractory-metal alloys do not oxidize catastrophically and have at least limited applicability in the uncoated condition in an air environment. The provision of suitable coatings would, of course, further enhance their usefulness in oxidizing environments.

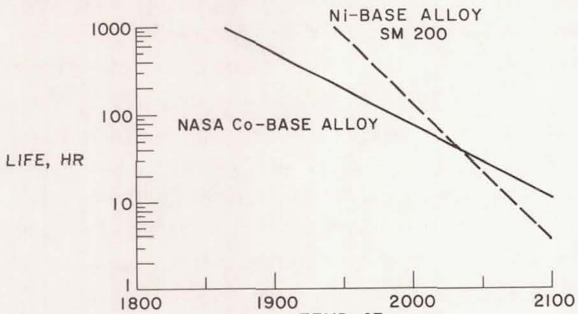


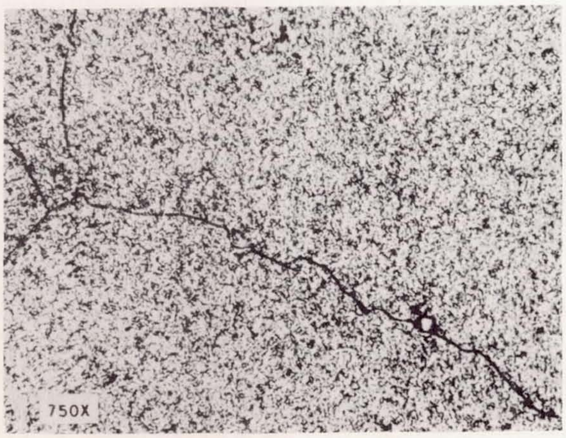
FIGURE II–38.—Comparison of cobalt- and nickel-base alloys. Stress, 10,000 psi.

A comparison of the general status of cobalt- and nickel-base alloys is provided in figure II–38 for a NASA cobalt—refractory-metal alloy and a strong nickel-base alloy, SM–200. The stress was held constant at 10,000 psi. The interesting feature illustrated here is the crossover in the strength curves. At temperatures below approximately 2000° F, the nickel-base alloys are generally stronger. Above this temperature, cobalt-base alloys tend to have a strength advantage.

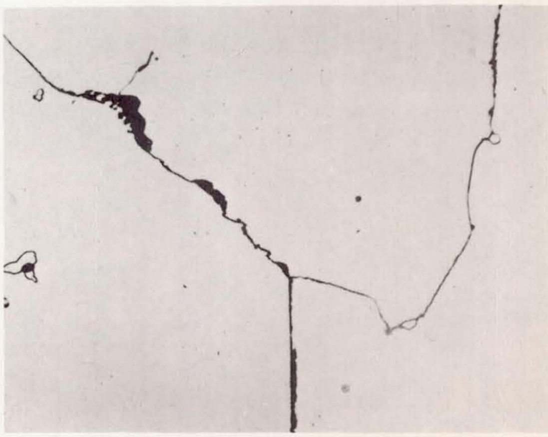
Research with cobalt—refractory-metal alloys is continuing at Lewis to extend their high-temperature capability and hopefully to develop improved high-temperature magnetic materials.

DISPERSION-STRENGTHENED MATERIALS

For cobalt- and nickel-base alloys, pure metals were alloyed to improve their strength. The alloys that are best at high temperatures usually contain second phases or precipitates in their structure as shown in figure II–39 for the structure of a high-temperature alloy as seen in the metallur-



STRONGEST CONDITION



AFTER HEATING TO 2175° F

FIGURE II–39.—Microstructure of typical high-temperature alloy. ×645.

gical microscope at a magnification of 750. The small particles shown tend to key the structure—to make it resist flowing or deforming under load and thus to make it strong. For highest strengths, it is important that these particles be very small and very close together. Generally, the closer the particles are to each other, the greater the strength. Particles about ½-millionth inch in diameter and 10-millionths inch apart are desired. The metallurgist can alter this structure by heat treatment. At very high temperatures, the particles will dissolve into the solid matrix, and at lower temperatures the particles will reprecipitate or reform. Unfortunately, as an effort is made to use the alloys at higher and higher temperatures, the temperature at which the alloy is to be used is the temperature at which the particles dissolve into the matrix, and thus the strength is lost. As a rule of thumb, alloys rapidly lose their strength at about 70 percent of their melting point.

To raise the use temperature of alloys, metallurgists are trying to apply the methods of powder metallurgy to produce "dispersion-strengthened" alloys. The idea is to distribute small particles that will strengthen but will not dissolve into the metal. Recently available commercial materials are aluminum oxide distributed in aluminum and thorium oxide in nickel. The strength of the dispersion-strengthened nickel is shown in figure II–40, which is a plot of stress for rupture in 100 hours against temperature in °F. Shown as dashed lines are the strengths

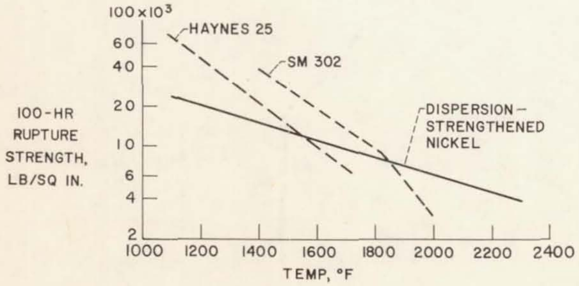


FIGURE II–40.—High-temperature strength comparison of dispersion-strengthened nickel and conventional superalloys.

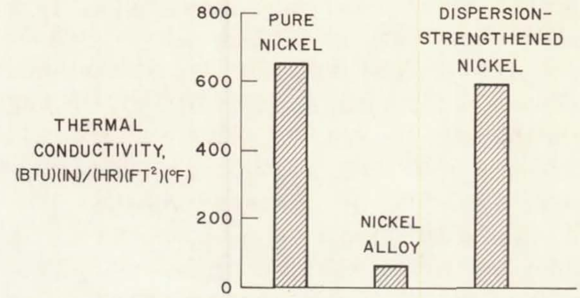


FIGURE II–41.—Conductivity of dispersion-strengthened metal compared with unstrengthened metal.

of two conventional superalloys of the type discussed previously. The solid line is dispersion-strengthened nickel. Most impressive is the flat slope of the strength curve for the dispersion-strengthened nickel: it does not lose strength rapidly as temperature is increased. Although the conventional alloys are stronger at low temperatures, they rapidly lose strength as temperature is increased, because the particles that are largely responsible for strengthening are dissolving into the metal. The thorium oxide particle in the dispersion-strengthened nickel is stable and strength is retained.

Another advantage of dispersion-strengthened materials is retention of physical properties not possible in alloys. Alloying severely reduces thermal conductivity and electrical conductivity. For example, just 2 percent of aluminum added to copper reduces the thermal conductivity of copper by 75 percent. This fact can be shown also for the nickel-base materials just discussed. Figure II–41 shows the thermal conductivity of nickel and the conductivity of a high-strength nickel alloy. The alloy has only 10 percent of the conductivity of pure nickel. The previously described dispersion-strengthened nickel strengthened by the addition of 2 volume percent of discrete particles of thorium oxide has 90 percent of the conductivity of nickel. Thus, composite materials offer opportunities to develop materials with unique combinations of properties.

As mentioned previously, dispersion-strengthened materials generally achieve greater strength as the distance between the hard particles is reduced. Spacings between the particles of as little as 10-millionths inch are sought. One way of achieving such fine spacing is to make the material by blending ultrafine powders of metal and the hard particles. This process requires the availability of extremely fine powders. Fine powders of the hard component were readily available. One method of producing these is by ball-milling, a process illustrated in figure II–42. A container partly filled with balls of a hard material such as tungsten carbide is shown. Coarse powders of the material are placed in the container along with a fluid such as alcohol. The containers are rotated causing the balls to impact the powders thus fracturing them and reducing their particle size. As stated, this works well for hard, brittle ceramics, but when soft metal powders were ball-milled, the process was unsuccessful.

Figure II–43 illustrates the problem of ball-milling soft metal powders. The particle size is plotted against the milling time in hours. As shown, the particle size of soft metal powders is reduced for a period of time, but then the soft particles began to stick together or agglomerate and become larger rather than smaller. Our metallurgists have learned that, when certain chemicals are added to the grinding fluids, the metal powders no longer stick together but continue to diminish in particle size. This phenomenon is shown in figure II–44. The dashed curve is from figure II–43. The solid line shows how the particle size continues to diminish when the additive is used. After milling for 15 days by using a chemical additive in ethyl alcohol, the particle size of all powders averaged less than 4-millionths inch and probably as small as 1-millionth inch. This powder has about the same particle size as cigarette smoke.

Another way to illustrate the extremely small particle size of these powders is to demonstrate a problem encountered working with them in our laboratory. When metal powders are extremely fine, the surface area per unit weight increases dramat-

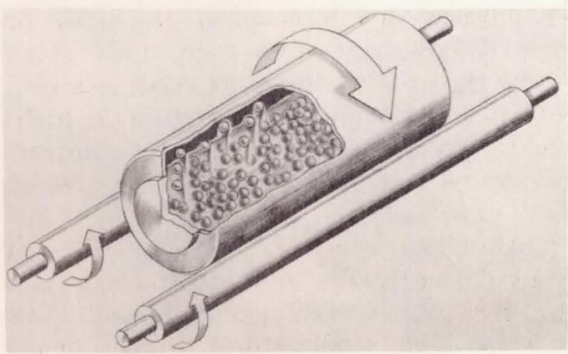


FIGURE II–42.—Ball milling of powders.

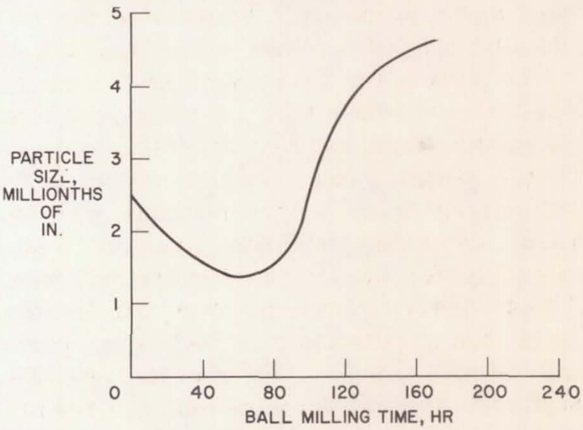


FIGURE II–43.—Variation of particle size during ball milling of soft metal powders.

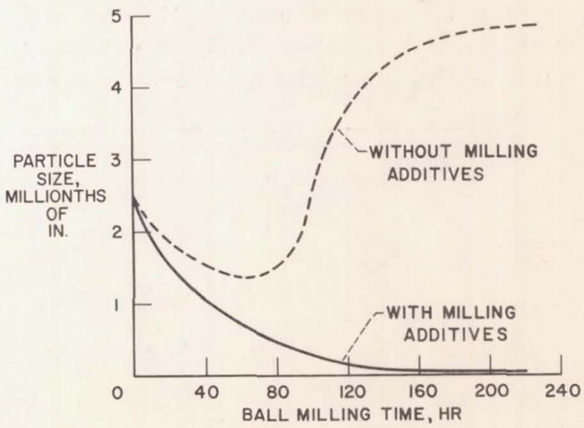


FIGURE II–44.—Variation of particle size during ball milling of soft metal powders with and without milling additives.

ically. For example, if a 1-inch cube of material were cut in half, more surface area would be added. If the cube is subdivided further until the particle size of 1-millionth inch is reached, the surface area of the metal in the cube will be increased by a factor of 1 million. Chemical reactions are highly dependent upon surface area. An ordinary piece of tungsten could be heated to its melting point, 6170° F, in air. It would oxidize, of course, but if the source of heat were removed, it would rapidly cool to room temperature without further significant reaction. Ultrafine powders, however, are extremely reactive. If poured out into a dish, they will oxidize rapidly and may ignite and burn spontaneously. If blown into the air like dust, they can explode.

The process for producing ultrafine metal powders developed here at Lewis involves an improvement in the ball-milling process by the use of special chemical additives to ball-milling fluids. Other methods such as vapor deposition are now available commercially for producing ultrafine powders. These other processes, however, are limited in their application to pure metals or to certain simple alloys. The process just described is the only process that can readily be applied to any complex alloy of any metal.

REFRACTORY MATERIALS

Using the dispersion-strengthening technique discussed earlier makes it possible to retain useful strengths in nickel- or cobalt-

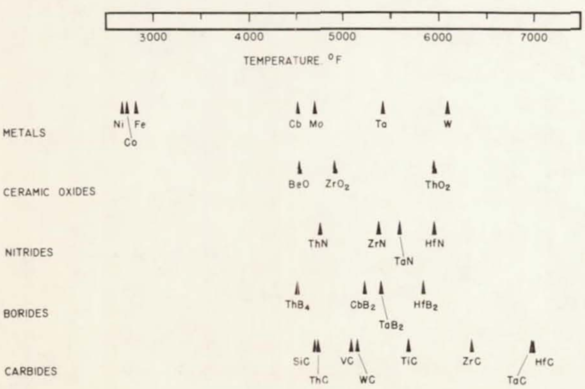


FIGURE II–45.—Melting points of materials.

base materials to temperatures of about 2000° to 2200° F; however, the relatively low melting points of these materials, about 2650° F for nickel and 2720° F for cobalt, impose a firm upper limit on their use. There are many applications where materials that can be used at very much higher temperatures are needed. For example, in solid-propellant rocket nozzles, material temperatures may reach 5000° to 6000° F. To meet such needs, we have to go to a different class of materials with melting points thousands of degrees higher than those of the nickel- and cobalt-base superalloys. These high melting materials are commonly referred to as refractory materials. Figure II–45 compares the melting points of some of these materials. There are only four readily available metals with melting points above 4000° F, columbium, molybdenum, tantalum, and tungsten. The highest melting of these, tungsten, has a melting point of about 6170° F. In addition to these metals, there are quite a few refractory compounds with high melting points. These include the ceramic oxides, nitrides, borides, and carbides. Of these materials, the carbides of tantalum and hafnium have the highest melting points, about 7000° F.

There are a fairly large number of materials that are potentially useful at very high temperatures. Our problem is to learn how to use these materials, how to take advantage of their desirable properties, and how to minimize or design around their limitations. Actually, very little is known about the physical and mechanical properties of most of these refractory compounds. Much of our research on these materials has concentrated on simply making them in high-purity high-density form so that their properties can be studied and they can be used as the need arises.

Fortunately, considerably more is known about the properties of the refractory metals. Because of their potential usefulness at very high temperatures, these metals have been studied extensively by many organizations in recent years.

It is convenient to group the refractory metals into two classes based on their strength and ductility. Tungsten and molybdenum have the best high-temperature strength but tend to be brittle at low temperature. Tantalum and columbium have excellent low-temperature ductility but comparatively poor high-temperature strength. Figure II–46 compares the strengths of these metals at temperatures above 2000° F. The strength of tungsten is much higher than that of the other refractory metals. None of them, however, has particularly good strength at high temperatures, and alloying is required to provide sufficient strength for many high-temperature applications.

There is also a large difference in the low-temperature ductility of these metals. This difference is shown schematically in figure II–47, where ductility is plotted against temperature in °F. At sufficiently high temperatures, all the refractory metals have high ductility. As the temperature is lowered all except tantalum undergo a relatively sharp transition from ductile to brittle behavior, as indicated by these curves. It is common to refer to the temperature corresponding to the midpoint of these curves as the ductile-brittle transition temperature. Thus tungsten has the highest transition temperature, usually about 300° to 400° F. The transition temperature of unalloyed molybdenum usually lies very close to room temperature. Columbium undergoes this transition from ductile to brittle behavior at temperatures near −300° F, while tantalum apparently exhibits no sharp transition but retains good ductility even below −400° F. The differences in ductility of these metals is reflected in their ability to be joined by welding. Both tantalum and columbium can be readily welded to produce joints with good strength and ductility at room temperature; on the other hand, welds in molybdenum and tungsten tend to be very weak and brittle at room temperature. For this reason, joints in tungsten and molybdenum are usually made by mechanical techniques such as riveting rather than by welding.

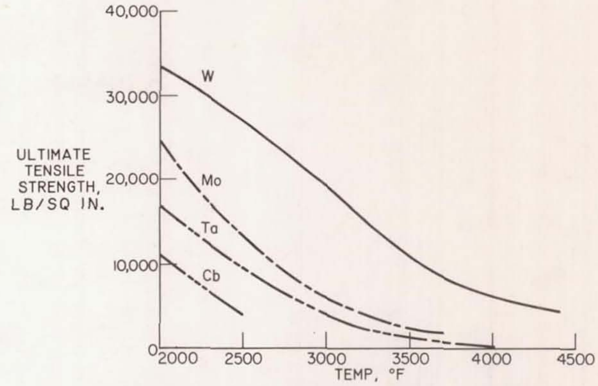


FIGURE II–46.—High-temperature tensile strength of unalloyed refractory metals.

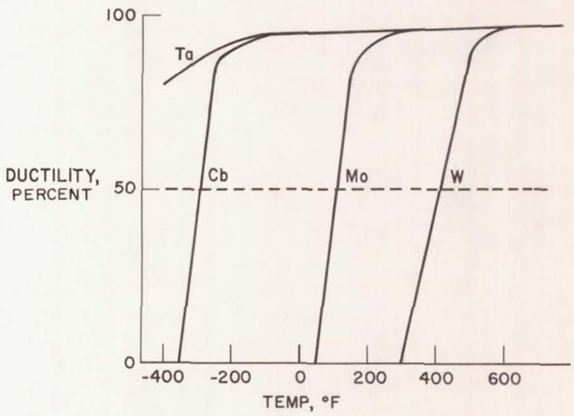


FIGURE II–47.—Ductile-brittle transition for unalloyed refractory metals.

Over the last decade, considerable effort has been devoted to improving the properties of the refractory metals by alloying. For the most part, alloying of tantalum and columbium has had the goal of improving the high-temperature strength while retaining the excellent low-temperature ductility of these base metals. The progress that has been made in this direction is shown in figure II–48, where tensile strength is plotted as a function of temperature from 2000° to 3000° F for two commercially available columbium and tantalum alloys along with similar data for the unalloyed metals. It is apparent that alloying has been very effective in increasing high-temperature strength.

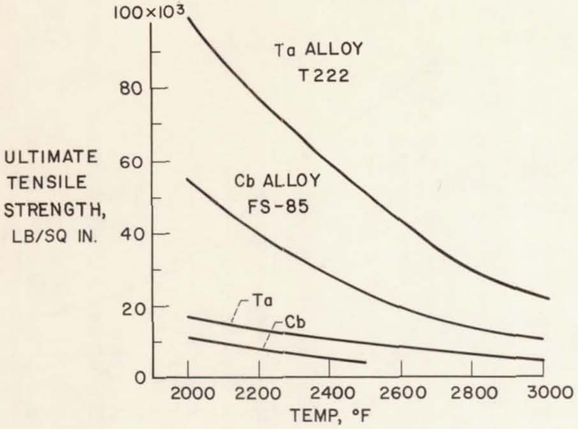


FIGURE II–48.—High-temperature strength of fabricable columbium and tantalum alloys.

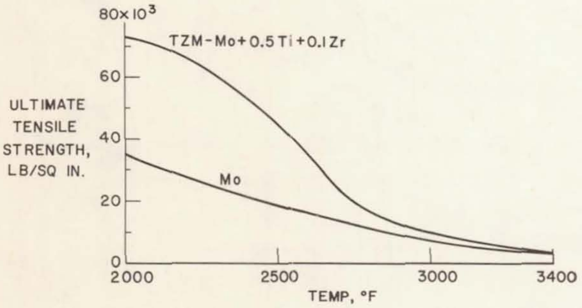


FIGURE II–49.—High-temperature strength of molybdenum and commercial molybdenum alloy.

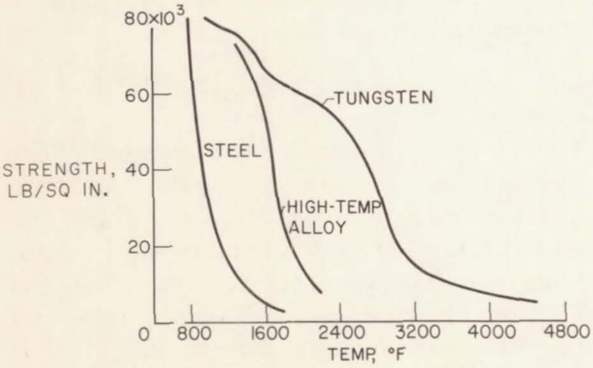


FIGURE II–50.—Comparative strengths of several materials.

Both these commercial alloys also have excellent low-temperature ductility, even at liquid nitrogen temperature (−321° F).

Alloying of molybdenum has been conducted in an effort to improve both high-temperature strength and low-temperature ductility. The high-temperature tensile strengths of molybdenum and a molybdenum alloy are shown in figure II–49. The commercial alloy TZM, which contains about 0.5Ti–0.1Zr and a small amount of carbon, has the best combination of strength and ductility of the available molybdenum alloys. In addition to its good high-temperature strength, as shown here, this alloy in sheet form has a transition temperature near −100° F.

Until recently, tungsten alloys have received comparatively little study. Here at Lewis, however, we have been studying tungsten alloys because of our interest in tungsten for possible use in advanced nuclear rocket engines.

TUNGSTEN ALLOYS PROGRAM

Our work on tungsten alloys is aimed at improving both high-temperature strength and low-temperature ductility. The reason for wanting to improve the high-temperature strength of tungsten is shown in figure II–50, where tensile strengths of steel, high-temperature superalloys, and tungsten are compared as a function of temperature. Although tungsten has good strength at temperatures where these materials are very weak, its strength decreases rapidly with increasing temperatures. At 3000° F, the tensile strength of unalloyed tungsten is only about 20,000 psi; at 4000° F, it is less than 5000 psi. Remembering that tungsten is a very heavy metal, with a density of about two and one-half times that of steel, we can appreciate that use of tungsten at such low strength levels would result in a severe weight penalty. Thus, there is a real incentive to develop tungsten alloys with better high-temperature strength. Some of the progress that has been made at this Center in alloying tungsten is shown in figure II–51, which shows the ultimate tensile strength of unalloyed tungsten and several experimental tungsten alloys as a function of temperature. Very small alloying additions are very effective in increasing high-

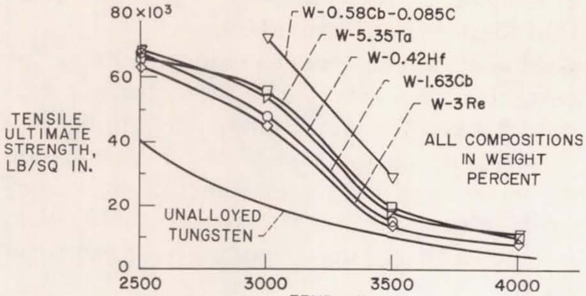


FIGURE II-51.—Effect of temperature on strength of wrought arc-melted tungsten alloys.

temperature strength. For example, an addition of only 0.4 percent hafnium more than doubles the tensile strength at 3000° F.

The strongest alloy produced to date is the ternary alloy containing small amounts of columbium and carbon. At 3000° F, this alloy had an ultimate tensile strength of 73,000 psi; to the best of our knowledge, this is the highest strength yet reported for any material at this temperature. The strength of this alloy decreases rapidly with increasing temperature, but at 3500° F, it is still almost three times as strong as unalloyed tungsten.

Significant progress has been made in improving the high-temperature strength of tungsten by alloying. If tungsten is to be a really useful metal, however, its poor room-temperature ductility will have to be improved. Although parts utilizing this metal are always intended for use at very high temperatures, room-temperature ductility is desirable to permit the parts to be handled and shipped without danger of fracture. In addition, most parts return to room temperature at some time during their service history. If they are very brittle, they would be fragile and subject to fracture by residual stresses. Some recent developments hold considerable promise in providing a tungsten material that is not brittle at room temperature.

For some time, we have been trying to improve the room-temperature ductility of tungsten by increasing its purity. This approach seemed logical since there is considerable evidence that the brittleness of tungsten is associated with the presence of very small quantities of impurities, such as carbon or oxygen, which concentrate at grain boundaries and embrittle them. The method used to purify tungsten is to melt it repeatedly in high vacuum, thus boiling off the embrittling impurities. Although improvements in ductility were achieved, it became apparent that the purification attained in this way would not by itself produce tungsten with good room-temperature ductility.

Alloying is another way to improve ductility. For example, alloying elements may react with embrittling impurities and tie them up in a form that is less harmful to ductility. Of all the metals studied, only one metal, rhenium, greatly improves the ductility of tungsten. The magnitude of the improvements achieved by alloying with rhenium is shown in figure II–52, which indicates the ductile-brittle transition temperature in bending for unalloyed tungsten and two tungsten rhenium alloys. This transition temperature should be below room temperature. The bar indicates the transition temperature for unalloyed tungsten, ranging from about 200° to about 500° F. Several years ago, transition temperatures of tungsten sheet were frequently as high as 500° F. In the last 2 or 3 years, improvements in purity and process control have lowered the transition temperature to about 200° F for the best available unalloyed material.

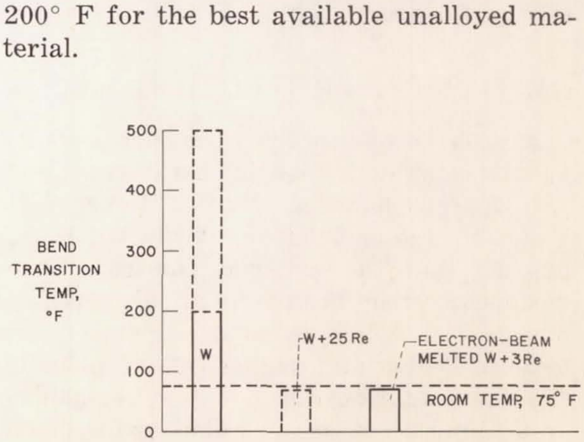


FIGURE II-52.—Bend transition temperatures of tungsten and tungsten-rhenium alloys.

It has been known for several years that the addition of 25 percent rhenium to tungsten by powder-metallurgy techniques lowers the transition temperature of tungsten slightly below room temperature, generally in the range from 0° to 70° F as shown here. The main trouble with this alloy is that it is very expensive. Rhenium is a comparatively rare metal that is more expensive than gold. Although this alloy has found use in highly specialized applications, such as thermocouple wires and sheaths, its high cost is prohibitive for most structural applications.

Recently the properties of tungsten were investigated with much lower rhenium contents—about 3 to 7 percent. These alloys were made by melting in high vacuum in an electron-bombardment furnace, with the assumption that the higher purity of alloys made in this way would favor improved ductility. This study indicated that a vacuum-melted alloy containing only 3 percent rhenium has significantly better ductility than unalloyed tungsten. In fact, as indicated here, a sheet 0.04-inch thick of the vacuum-melted tungsten 3-percent rhenium alloy showed good bend ductility at room temperature. Although this is a preliminary observation that needs confirmation, it suggests that a combination of purification by vacuum melting and alloying with small amounts of rhenium may yield a reasonably inexpensive tungsten alloy with good room-temperature ductility.

OXIDATION PROTECTION

A problem of concern with all refractory metals is oxidation at temperatures above just a few hundred degrees Fahrenheit. Tungsten and molybdenum form vapor oxides so that the material can completely disappear when heated in an air environment. The other refractory metals form loose scales but still oxidize catastrophically. Considerable research has been conducted on alloying programs to reduce oxidation in the manner similar to that for iron and nickel in which chromium and aluminum are added to form an adherent oxide scale that inhibits further oxidation.

This approach reduces oxidation rates for refractory materials, but the rates are still exhorbitant for very long-time application in air. For application in the high vacuum of space, the refractory metals are very satisfactory for high-temperature application since there is no oxygen present to form an oxide.

Extensive research has been conducted on oxidation protection of columbium and molybdenum by alloying. The results indicate that the required oxidation resistance cannot be obtained without severely decreasing high-temperature strength and low-temperature ductility. Consequently, emphasis has shifted to providing oxidation protection by the application of coatings.

Over the last decade, many organizations have been working to provide suitable oxidation-resistant coatings for the refractory metals. Figure II–53 shows the current capability of some of these coatings. The temperature to which each refractory metal can be protected with currently available coatings for 1-hour operation in air is represented by the height of the vertical bars. Within each bar is shown the composition of the coatings as applied. At the top of each bar the compounds are shown that form during heating and provide oxidation resistance.

Coatings for columbium and molybdenum

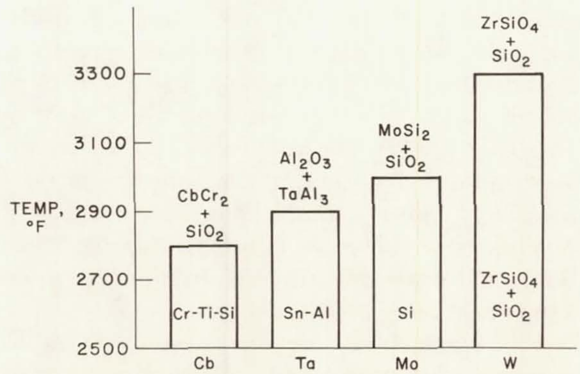


FIGURE II–53.—Current protective coatings for refractory metals for 1-hour operation in air.

have been extensively studied for use in reentry gliders and represent a relatively advanced state of development. Their capability for 1-hour service is limited to temperatures of 2800° to 3000° F. Coatings for tantalum and particularly for tungsten have received very little study, and the coatings shown here have not yet been extensively evaluated. Thus, the temperature capability indicated should be considered only tentatively.

Although the constituents of the coatings applied are substantially different, the oxidation resistance at high temperatures is generally provided by an oxide that forms on heating in air. For columbium, molybdenum, and tungsten, the oxide is usually silica (SiO_2), a glass, or a silica-containing compound. The presence of a viscous glass coating on the surface provides some degree of self-healing of defects that may develop in the coating.

Figure II–53 gives a general representation of our current status. These data are for the relatively short time of 1 hour in static air. Continued efforts are necessary to improve the reliability of coatings and to extend their useful life and temperature capability.

Although coatings can provide excellent protection, oxidation may occur at a catastrophic rate if the coating develops a defect. One common type of coating failure is "spalling" or cracking away of the coating from the metal being protected. This type of failure can often be traced to inadequate bonding of the coating to the base metal. Bonding is illustrated schematically in figure II–54.

On the left is the type of bond frequently associated with coating failures. Here the interface between the coating and substrate is easily distinguishable by the discontinuity in the grain structure. Such a bond is purely mechanical in nature and usually is very weak.

On the right is the type of bond that is desired. The original interface is not distinguishable. There has been interdif-

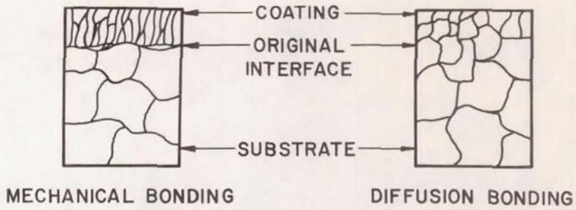


FIGURE II–54.—Bonding of coatings.

fusion of the components of the coating and substrate, resulting in continuity of grain structure across the interface. Such a bond can be very strong.

The quality of the bond depends strongly on the coating conditions. To obtain a good bond, the interface between coating and substrate must be clean, and there must be an opportunity for diffusion, or atomic interaction, between the components of the coating and the substrate.

One coating process that is of particular interest to us is plasma spraying. In this process, the coating material in powder form is carried in a gas stream through an electric arc. The particles are heated to very high temperatures and sprayed at high velocity onto the piece to be coated. Figure II–55 shows a plasma torch in operation. The operator is seen spraying a coating onto the workpiece from this plasma torch.

As this process is usually conducted, the heated particles strike a relatively cool

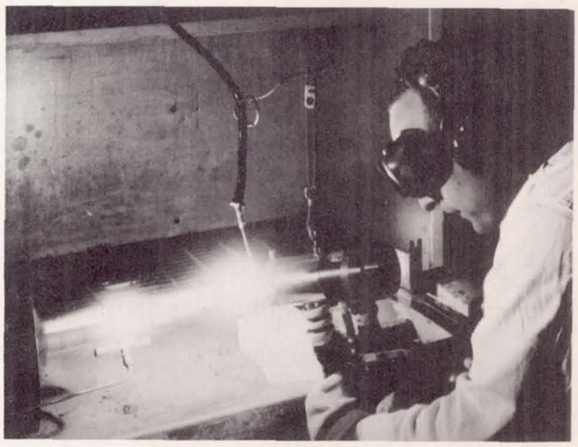


FIGURE II–55.—Application of sprayed-on coatings with plasma torch.

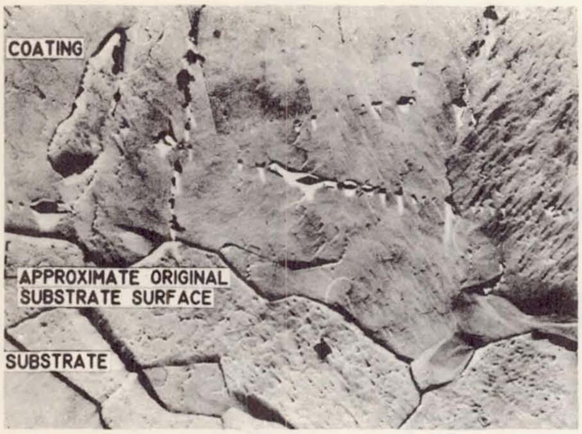


FIGURE II–56.—Cross section of coating and substrate. ×4,100.

surface to be coated and are immediately chilled. Thus, there is little opportunity for diffusion to occur, and the bond is usually only a mechanical one. To improve plasma-sprayed coating, a systematic study of many of the variables in the coating process was made including the influence of substrate temperature. Significantly, by preheating the substrate to a temperature less than one-half of its melting point, true diffusion bonds were achieved between a metallic coating and the substrate. Preheating was accomplished simply by directing the hot gas from the torch onto the workpiece prior to starting the flow of the coating material. An example of an actual bond achieved in this way is shown in figure II–56, where a polished section through the coating and the substrate is shown as seen through a microscope of a magnification of about 10,000. Grain growth has taken place right across the region of the original interface in the fashion that provides good bond strength.

Our work to date has been conducted with metallic rather than ceramic coatings, but we believe that the principle demonstrated is a valid one that should find wide practical application.

PYROLYTIC GRAPHITE

Pyrolytic graphite is a relatively new form of graphite that exhibits desirable properties for space systems as well as industrial applications. The usual forms of graphite are made by reacting mixtures of coke and coal tar. Pyrolytic graphite, on the other hand, is made by a vapor-deposition process. While usual forms of graphite have their crystallites arranged in a random manner, the crystals of pyrolytic graphite grow from the vapor in a highly oriented manner, giving a structure quite analogous to a deck of cards. It is this high degree of orientation of pyrolytic graphite plus its unusual purity that impart its unique properties. If measurements are made perpendicular to the material surface or parallel to the surface, the properties show great variation.

An outstanding illustration of this directional variation is indicated in the thermal conductivity of pyrolytic graphite. Figure II–57 shows two pieces of graphite being heated by a torch. The conventional graphite on the left shows a general glowing in the

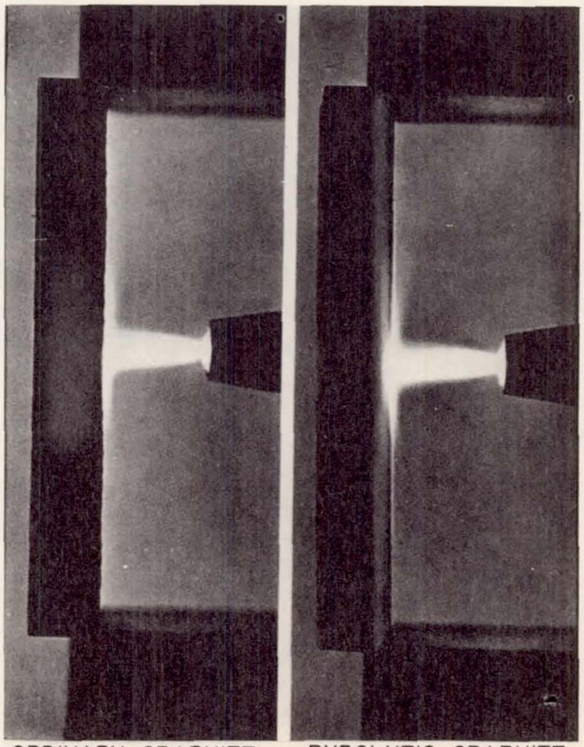


FIGURE II–57.—Heat conduction in ordinary and pyrolytic graphite.

area of the torch. The pyrolytic graphite on the right is seen to conduct heat along its surface rather than through the sample. In fact, in such a test the rear of the sample remains cool to the touch. The conductivity along the surface is 100 times the conductivity in the thickness direction. Along the surface the conductivity is as good as copper, one of the best conductors. Through the thickness, pyrolytic graphite is one of the best high-temperature insulators with a conductivity less than that of zirconium oxide ceramic.

This ability to conduct heat primarily in one direction makes pyrolytic graphite of interest for space applications such as nose cones and leading edges of reentry vehicles. The use of pyrolytic graphite would allow heat conduction along the surface rather than through the piece and thus would prevent excessive heating of underlying structural members. Pyrolytic graphite also shows improved strength and oxidation resistance over conventional grades of graphite.

As promising as this material appears, there still is much to learn about the material and the process by which it is formed. The thermal expansion of this material also varies in different directions, so that severe stresses can result from this varying expansion rate. To circumvent such a problem, design criteria must be established for the successful application of pyrolytic graphite.

CONCLUDING REMARKS

An effort has been made to present a brief sketch of recent progress in the materials field. While the illustrations have been drawn from results of programs intended largely for contributions to aerospace applications, it is evident that in materials, perhaps more so than in any other field, developments are directly translatable to other technological applications. Because high strength, light weight, resistance to temperature, to fatigue, and to oxidation are important in so many everyday structural applications, some of the contributions discussed carry over directly. Others may take some time to become useful, or the usefulness may be indirect.

Better materials for space application may find their use in industrial vacuum technological applications—a field of ever growing importance. Likewise, materials for low-temperature use are becoming of increasing interest in many industrial applications.

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III. Electric Power Generation

NEWELL D. SANDERS, JAMES F. MORRIS, LESTER D. NICHOLS, ANDREW E. POTTER, JR., HARVEY J. SCHWARTZ, AND WARNER L. STEWART

Lewis Research Center

NEW DEVELOPMENTS in electric power generation that have their origins in the space program or allied programs are discussed. The discussion is slanted toward the possible future application of these developments to Earth-bound applications.

The need for electric power in space vehicles is obvious. It is not surprising that a large effort is directed into research and development of power systems suitable for use on spacecraft. The space power program has generated some new ideas, and it has taken old ideas and developed them in new directions. An example of the latter is the simple battery, such as a flashlight or automobile battery. Batteries were developed and put into widespread use long before the coming of the space age. Space applications, however, placed stringent new demands on batteries. New battery developments have been directed toward meeting these requirements. The results are batteries with new characteristics which, in all probability, will be useful in more common applications.

Although the NASA space program has been a major stimulant to the development of new power systems, other programs of government and industry have played a large part in power generation. In fact, the cross-feed of ideas among these programs is so extensive that a clear separation is impractical. This discussion is not limited solely to NASA or Lewis Research Center contributions; developments are discussed without regard to their origin.

The topics discussed are batteries, solar photovoltaic cells, thermoelectric converters, fuel cells, turbine conversion systems, magnetohydrodynamic converters, and thermionic converters. In each case, the fundamental principles are explained briefly, the state of the art with respect to space application is discussed, and some guesses are made concerning applications to everyday living.

There is some uneasiness about the guesses concerning possible future applications. It is realized that many economic, managerial, and even political considerations are important in such applications; therefore, the suggestions should be treated as guesses, not as recommendations.

BATTERIES

Batteries were a logical choice for the power systems for early spacecraft and will continue to play an important part in the space power program. At the same time, batteries represent a sizeable commercial industry for which the Federal Government is a major customer. Although batteries are items with which we have contact every day, the principle behind their operation is not generally known. We are all familiar with a general type of chemical reaction process called combustion (fig. III–1). The burning of natural gas with air in your home furnace and the burning of gasoline in an automobile cylinder are typical examples. In each case, one substance acting as a fuel mixes and reacts with a second called an oxidizer to form one or more new compounds or products. This reaction process is accomplished through a transfer of electrons from the fuel through the oxidizer. It is also accompanied by the evolution of heat. If handled properly, certain reactions can be made to produce electricity.

In an electrochemical process, the substances are made to react "from a distance," so that the electron transfer is forced to occur through an external circuit. By controlling the process in this manner, electrical energy, instead of heat, is the main reaction byproduct. In many common batteries, zinc metal acts as the fuel (fig. III–2). Since it is physically separated from the oxidizer, the only path for electron transfer is through the external circuit, and electron flow cannot occur until the circuit is completed. When power is required, the switch is closed and a controlled reaction proceeds. The zinc releases electrons and forms positively charged zinc ions. The electrons must flow through the external circuit to reach the oxidizer and in so doing, perform useful work. The electrons combine with the oxidizer and zinc ions to produce the reaction product; the same product would have been obtained if the reaction had been conducted by straight chemical means. Some reactions can be driven in reverse by putting electric energy into the battery. Current is made to flow in the opposite direction, decomposing the product and reforming the zinc metal and oxidizer. This gives rise to the cyclic mode of operation, which is characteristic of the rechargeable or secondary battery as opposed to the one-shot or primary type. Both types have their place in the space program just as they do on the ground.

Nonrechargeable or primary batteries supplied all the power for the Mercury capsule (fig. III–3) and for certain short-life satellites. These batteries supplied power for guidance and communication and operated the components of the life-support system which made it possible to maintain a man in orbit for 24 hours.

Long-life Earth satellites (fig. III–4) used solar cells for power in the daytime and battery power during the time spent in the Earth's shadow. Here batteries provide an

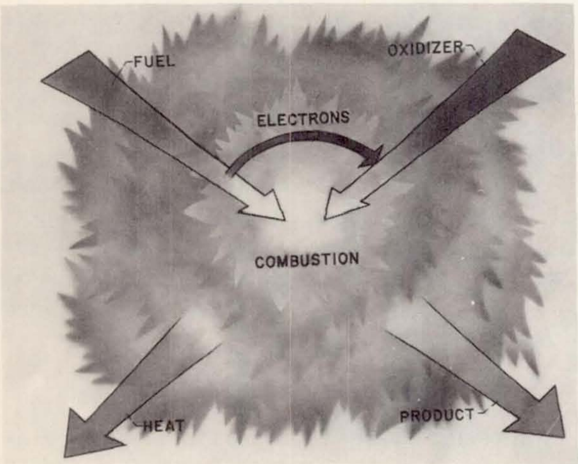


FIGURE III–1.—Combustion.

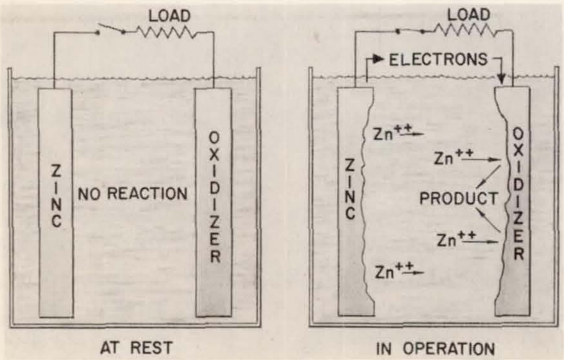


FIGURE III–2.—Zinc batteries.

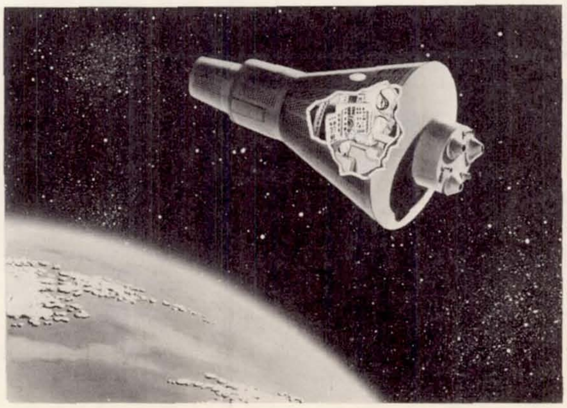


FIGURE III–3.—Mercury capsule.

energy storage function. Solar panels power the satellite during the Sun part of the orbit and supply enough extra power to charge the battery pack as well. During the shade portion of the orbit, the solar panels are inoperative and the batteries are the sole source of power.

As might be expected, there are several noticeable differences between space-oriented batteries and those for ground use. The weight and volume of any component of a spacecraft are important, and a parameter called the energy density, or the watt-hours contained in a pound or cubic inch of battery, is an important criterion for battery selection. A premium price is paid for batteries which are made of higher energy content materials. NASA vehicles operate in the vacuum of outer space, which means that the battery must be tightly sealed. This requirement also restricts the choice to those systems which do not release gases during operation. The lead-acid automobile battery is not used for this reason. Then too, the space program requires a more reliable battery than ever produced before, since it is impossible to replace a defective battery once it has been launched into orbit.

A comparison of the commercial and space-oriented primary or nonrechargeable cells is given in the following table:

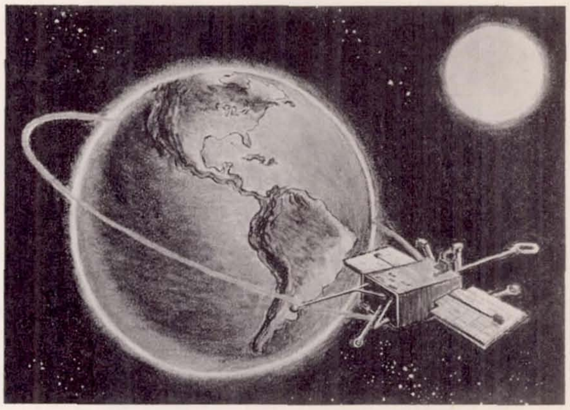


FIGURE III-4.—Typical Earth satellite.

required. In actual practice, the Leclanche battery can theoretically deliver 67 watt-hours per pound for the complete battery. As the cells are used, they normally deliver about 30 watt-hours per pound at a cost of about 3 cents per watt-hour. Another commercial battery is a mercury cell, which, although it has a theoretical energy density of only 115 watt-hours per pound, delivers as high as 44 watt-hours per pound for a complete cell. The cost of this power is approximately $2.00 per watt-hour. However, because of its higher energy density, better discharge characteristics, and, particularly, its higher energy content per unit volume as compared with the Leclanche cell, the mer-

System	Energy density, W-hr/lb		
	Theory		Actual
	Reactants only	Complete battery	
Leclanche	166	67	30
Mercury	115	60	44
Silver	215	115	100
Advanced system	766	350	200

The Leclanche system, used in the common flashlight or dry-cell battery, is capable of delivering 166 watt-hours per pound if only the reactants are considered. A number of other components, however, such as case, seals, separators, and current collectors, are cury battery finds commercial applications in such specialized uses as hearing-aid batteries. For space use, the so-called silver battery, which has a theoretical energy density of 215 watt-hours per pound, and which has delivered as much as 100 watt-hours per pound in service, is the one that is presently used for flight applications. Like the mercury battery, this energy costs approximately $2.00 per watt-hour. The direction of NASA's interest is shown in the advanced system category. Research is presently being supported on a number of exotic battery couples which are capable of producing extremely high energy densities. A typical system is shown in the preceding table. It has a theoretical output of 766 watt-hours per pound, and it is expected that a complete battery can be built which could theoretically deliver 350 watt-hours per pound. Of this, it is felt in actual practice that as high as 200 watt-hours per pound may be obtained, twice the energy that can be obtained from conventional batteries.

The problem of obtaining better batteries is being explored in another way too. The dry tape battery concept is illustrated in figure III–5. Instead of putting the reactive chemicals into a can, they are coated on opposite sides of a continuous tape. The center part of the tape contains the battery fluid in encapsulated form. The complete tape constitutes a self-contained battery, which can be activated by pressure as it is needed. This results in highly efficient material utilization and favorable dry-storage characteristics that will allow using more highly reactive or otherwise difficult to handle materials. Some technical personnel who are familiar with the commercial market feel that someday batteries for children's toys may be purchased by the yard rather than by the battery through adoption of this concept.

Consider next the rechargeable cells, the capabilities of which are shown in the following table:

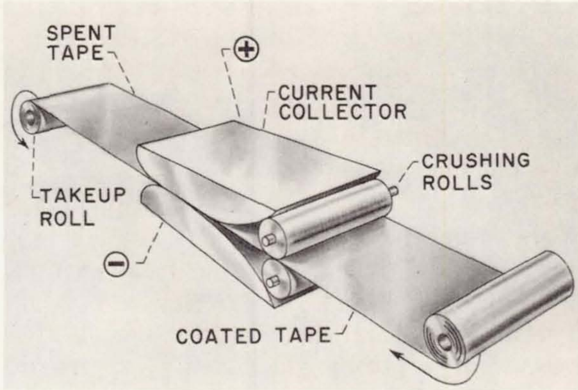


FIGURE III–5.—Dry tape battery concept.

Cycle life is an important parameter in this case. A cycle is defined as the complete discharge of a cell followed by recharge to its original state. Cycle life is the number of cycles a battery can undergo prior to failure. It determines when a satellite stops transmitting data or when a car battery will not start an automobile. With respect to energy, the commercial lead-acid battery appears attractive. It has a theoretical energy density of 53 watt-hours per pound and in normal service can deliver as high as 20 watt-hours per pound for a complete battery. At best, however, it is capable of delivering from 50 to 500 cycles. These cycles are not the shallow discharges that the battery normally undergoes in starting an automobile, but rather the complete or nearly complete discharge of the battery.

The nickel-cadmium battery is presently the workhorse of the space effort. Though its theoretical energy density is 96 watt-hours per pound, batteries in actual satellite applications deliver only from 3 to 7 watt-hours per pound. The difference is attributable to two factors. First, there is a relatively

System	Energy density, W-hr/lb		Life, cycles
	Theory (Reactants only)	Actual (Complete battery)	
Lead-acid	53	20	50–500
Nickel-cadmium	96	3–7	1000–11,000
Silver-cadmium	150	30	2000–3000
Silver-zinc	215	40	80–100

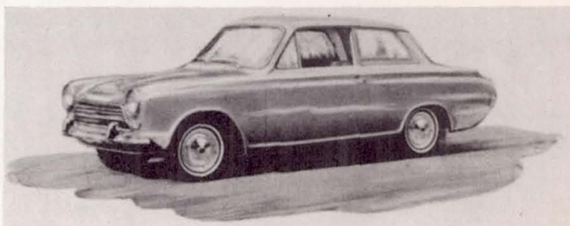
large amount of inert materials contained within the case as the battery is actually built. A second important factor is that in order to obtain long cycle life under satellite operating conditions, it is necessary to use only a small percentage of the energy contained within the battery on each cycle. However, despite the drawback of relatively low energy density, the nickel-cadmium cell is used because it is capable of delivering from 1000 to 11,000 cycles depending upon the conditions of operation.

The silver-cadmium battery is now coming into use for flight applications. It may eventually deliver as high as 30 watt-hours per pound for the complete battery, and laboratory cells deliver an appreciable fraction of this amount for from 2000 to 3000 cycles. Unfortunately, cycle life and energy density appear to follow an inverse relation and the nickel-cadmium cell, which has the lowest energy density, is the one capable of delivering the highest cycle life. Conversely, the silver-zinc battery which, as a rechargeable cell, might deliver as high as 40 watt-hours per pound, is presently capable of operating only from 80 to 100 cycles. An effort is being made to solve the problems which limit cycle life in the silver-zinc battery.

Not all the batteries mentioned so far are entirely new in a commercial sense. One of them, the nickel-cadmium cell, is already in commercial use. It is selling well in electric toothbrushes, rechargeable flashlights, cordless shavers, and hand-power tools. This type of market is expected to become a sizable one over the next few years. The rechargeable nickel-cadmium cell could be the answer for the frustrated parents who are going bankrupt keeping their children's toys supplied with batteries.

Government research on increasing energy density and reliability will lead to better products for the civilian market. The Lewis Research Center is interested in the development of an improved separator for silver-zinc cells that will make repeated recharge possible. This could mean a compact hearing-aid battery that could be recharged on house power at 2.4 mils per watt-hour instead of the present $2.00 per watt-hour charged for mercury cells for this purpose. A so-called "third electrode" is under development that will make it virtually impossible to overcharge destructively a sealed battery.

One might even consider that classic transportation concept, the electric car. Electric delivery vans, lift trucks, and golf carts are already in service. The electric car lost its competitive position because of limited range and performance compared with automobiles powered by internal combustion engines. With the trend toward suburban living and two-car families, several companies have explored the possibility of a compact electric town car. A composite view of this type of auto is shown in figure III–6. It is generally pictured as a two- to four-passenger automobile selling in the $1800 to $2500 price range. The car is expected to weigh from 1500 to 2500 pounds and to be capable of top speeds from 40 to 50 miles per hour. The speed is adequate for city driving. These cars are generally powered by two direct-current motors independently driving the rear wheels. The range and performance characteristics are presently still governed by the size and the weight of the lead-acid batteries necessary to power the 1- to 3-horsepower-drive motors. These batteries are expected to weigh from 500 to 700 pounds and deliver a range of 50 to 100 miles. If



WEIGHT	1500 - 2000 LB
CAPACITY	2 TO 4 PASSENGERS
MAXIMUM SPEED	40 - 50 MPH
DRIVE POWER	2 TO 6 HP
BATTERY WEIGHT	500 TO 700 LB
RANGE	50 TO 100 MILES
COST	$1800 - $2500

FIGURE III–6.—Hypothetical battery-powered town car.

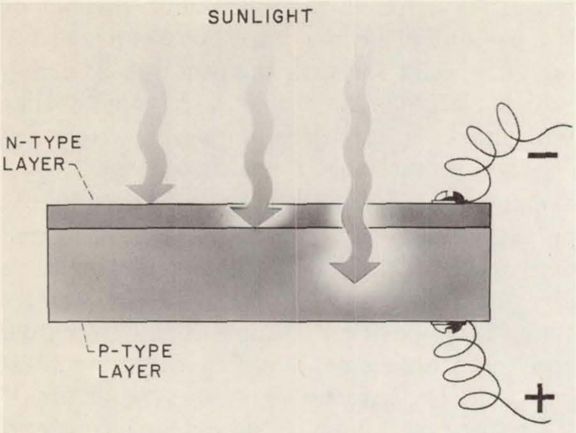


FIGURE III–7.—Solar cell.

specially designed nickel-cadmium cells were used, the range apparently could be extended to 200 miles while the same volume is still maintained for the battery. As the more advanced batteries become available, both higher performance and longer range are foreseen for the same battery weight and volume. Several companies, including at least one automobile manufacturer, have begun exploring the possibility of such a car during the past few years. The idea of an almost silent automobile with no differential, transmission, clutch, radiator, or crankcase oil certainly sounds appealing, especially when you consider that the cost of the electric fuel will be equivalent to a gasoline engine delivering 100 to 150 miles per gallon. As a fringe benefit, it would move the corner filling station to a wall plug in your garage.

The battery is not an exotic means of energy conversion compared with others under development. It has earned its place in the space program through a combination of availability and favorable characteristics. As a silent, static, compact, reliable energy source, it offers an almost ideal power supply for spacecraft requiring moderate amounts of energy and will continue to make significant contributions to the space effort.

SOLAR CELLS

Almost all our unmanned satellites and space probes obtain electric power from the Sun by means of silicon solar cells. Consequently, it is desirable to begin a discussion of solar cells by examining in detail the inner workings of silicon solar cells. A solar cell in cross section (fig. III–7) consists of two layers of silicon, one n-type, the other p-type. The n-type and p-type silicons are produced by deliberately adding impurities such as phosphorous or boron to the silicon. One type of impurity (phosphorous) causes the electric potential, or voltage, of the silicon to decrease when exposed to sunlight. This is n-type silicon. Another type of impurity (boron) causes the voltage to increase when exposed to sunlight. This is p-type silicon. To get the largest possible voltage difference in the solar battery, we use layers of both n- and p-type material. When sunlight is absorbed by the two layers, the n-layer becomes negatively charged, the p-layer becomes positively charged. The resulting voltage difference is about 0.5 volt in sunlight.

Three kinds of solar cells are illustrated in figure III–8. They all work on basically the principles just described. The selenium cell is the first kind of solar cell ever made and has been known for about 80 years. Little improvement has been made during this time. Efficiencies are low, a few tenths of a percent. The cell remains useful because it responds to light in exactly the same way as

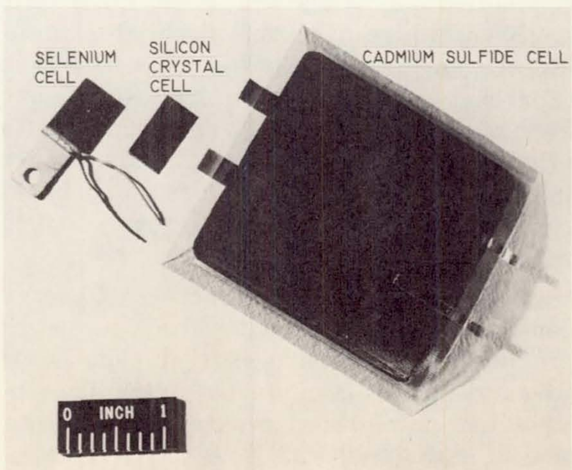


FIGURE III–8.—Three solar cells.

does the human eye and photographic film. As a result, it can be used in photographic lightmeters, the principle application of the selenium cell. The other two cells shown in the figure also respond to infrared light invisible to the eye making them undesirable for use in lightmeters.

The silicon crystal cell is perhaps the best known of the solar cells. It is the most efficient device ever made for converting sunlight into electricity. On occasion, cell efficiencies as high as 14 percent have been observed. More commonly, the efficiency is around 10 percent. The silicon solar cell is important to the space effort because nearly all satellites and space probes obtain power to operate radio transmitters and to perform scientific experiments from these cells.

The experimental cadmium sulfide cell has yet to find a practical application. It is not as efficient as the silicon cell, but it is much more efficient than the selenium cell. Its principle advantages are flexibility, light weight, and expected low cost. Possibly it might be useful in making large solar power systems that can be folded into small volumes for launch because the cell is flexible.

In considering uses for solar cells, it is helpful to look at the area of cells required to generate 1 watt of electric power and the cost of power generated in this way:

Kind of cell	Area needed to give 1 watt, sq ft	Price of 1 watt, dollars
Selenium	3.0	700
Cadmium sulfide	.6	250
Silicon crystal	.1	200

Selenium cells, being very inefficient, require large areas, and 3 square feet are required to give 1 watt of electric power. At current market prices, selenium cells required to do this would cost $700. The cadmium sulfide film cells require less area, only 0.6 square foot, to generate 1 watt, but the cost based on current prices of the cells is still high, about $250. Silicon cells are the most efficient and only about 0.1 square foot is required to generate 1 watt. The price is still high, about $200 for the cells. Only the price of the cells is given here. If an array of cells is desired, the price rises to about $1000 per watt, because the cells are very small and much labor is required to assemble the cells into an array.

These efficiencies and prices are the present ones. Future efficiencies and prices are shown in the following table:

Kind of cell	Area needed to give 1 watt, sq ft	Price of 1 watt, dollars
Cadmium sulfide	0.4	10–50
Silicon crystal	.1	100

It is unlikely that the future will bring any improvement in the selenium cell, and therefore it is not listed. The cadmium sulfide cell can probably be made about 3½ percent efficient, which will make about 0.4 square foot yield 1 watt. The price of this cell should drop considerably, to $10 to $50 per watt. The silicon cell will probably not become much more efficient; therefore 0.1 square foot is still needed to generate 1 watt. With Government sponsorship, a new technique has been devised for making silicon crystals which should reduce the cost of the cells by half—down to about $100 per watt for the cells.

It is clear that solar cells are not going to affect the central electric power generation industry mainly because of price, not efficiency of the cells. For example, if the roof of a 1000-square-foot house in Arizona were covered with solar cells, about 30 kilowatt-hours per day would result—sufficient to operate air conditioners and other appliances. However, the price of the cells for such an installation would be astronomical—about $2,000,000.

The best applications of solar cells are in situations where small amounts of power are needed in remote, sunny places. Small amounts, because of the cost of the cells; remote places, because if small amounts of power are needed in nearby places, wires can be connected from a central power generator; sunny places, because these are solar power devices and need sunshine to operate.

The perfect example of a small power requirement in a remote sunny place is the space satellite. It is here that the solar power system has reached its greatest development. The satellite power system consists of two parts, the solar paddles, which are covered with silicon solar cells, and a bank of storage batteries inside the satellite. The storage batteries are an important part of every solar power system, since sunlight is not constant. As the satellite spins around the Earth, it is occasionally in the shadow of the Earth, and the solar paddles are not always pointed at the Sun.

An example of an application on Earth of solar power systems being used to give small amounts of power in a remote sunny area is the emergency radiotelephone system shown in figure III–9. This system is in use along one of the Los Angeles freeways to provide emergency calls for stranded motorists. It is used because it is the most economical way of doing the job. The cost of all other methods considered was higher.

In summary, solar cells are practical devices for getting small amounts of electricity from sunlight. In special applications, where a small amount of power is needed at a distant or isolated place, solar cells may be the most economical way of doing the job, even though the cells are expensive.

FIGURE III–9.—Emergency radio telephone system.

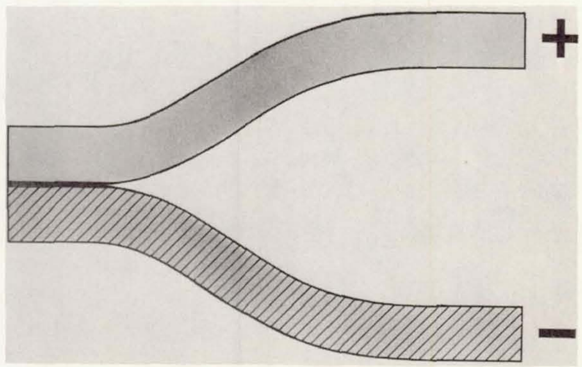


FIGURE III–10.—Thermoelectric power generator.

THERMOELECTRIC CONVERTERS

One of the very old ways of converting heat to electricity that modern technology has revived is the thermoelectric effect. This effect has been known for more than 100 years, but only recently has it been used as a practical means for generating electricity. The essential parts of a thermoelectric power generator are shown in figure III–10. The two materials involved are indicated in the figure by two kinds of shading. These are put into electric contact at one end. Heat is applied to the contact and the other ends are kept cold. Heat flows through the generator, and voltage appears at the cold ends. This is the thermoelectric voltage. It is worth pointing out that the thermoelectric effect is completely reversible. Instead of the flow of heat generating electricity, an electric current can be forced backwards through the generator to produce a flow of heat from the cold to the hot junction. In other words, operating the power generator in reverse turns it into a refrigerator.

The amount of electric power produced by a thermoelectric generator depends on the amount of heat flowing through the generator, as might be expected. However, it also depends on the kinds of material used to make the generator. The best materials are semiconductors, that is, materials that conduct electricity poorly. When semiconductors are used, the two legs of the generator can be made out of the same basic material but with different impurities in the two legs.

Until about 7 years ago, the only good thermoelectric material known was the semiconductor lead telluride (PbTe), and its only use was in home gas furnaces as a safety device. About that time, intensive research was sponsored by government agencies on finding new materials suitable for thermoelectric power generators. Many thousands of materials were tested. From all these, two new materials have emerged. The new thermoelectric materials are shown in the following table, along with lead telluride.

Material	Temperature range, °F
Bismuth telluride	−75 to room temperature
Lead telluride	+75 to 600
Silicon-germanium alloy	+75 to 1500

The best thermoelectric materials now available are bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon-germanium (Si-Ge) alloys. Bismuth telluride is particularly useful for refrigeration. Thermoelectric refrigeration units using it are now commercially available.

Lead telluride is useful for power generation since it is most efficient at converting heat to electricity at temperatures near 600° to 700° F. The material, silicon-germanium alloy, is efficient at even higher temperatures, 1500° to 1600° F.

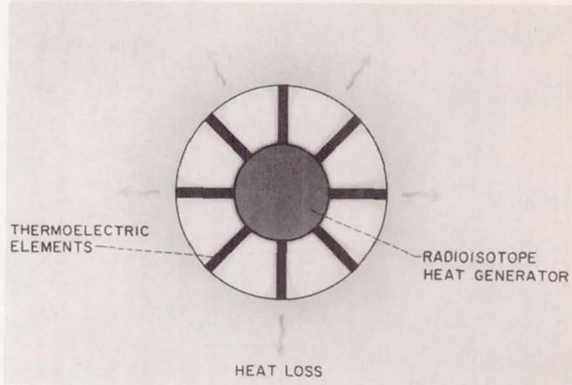


FIGURE III–11.—Radioisotope thermoelectric generator.

Generally, efficiencies of approximately 5 percent can be expected with thermoelectric generators and refrigerators, which is poor compared with efficiencies usually obtained with rotating machinery. Efficiency, however, is not the sole criterion by which an electric generator or refrigerator should be judged. Thermoelectric devices are absolutely quiet, since they contain no moving parts. They require no attention. They last a long time—a year's service life before replacement is reasonable for a power generator, and service life for refrigerators is much longer.

One of their most important advantages is that the efficiency is independent of size. This is not true of rotating machinery such as generators and refrigerators, which tend to become inefficient in small sizes. Consequently, for small generators and refrigerators, thermoelectric devices become competitive with rotating machinery devices.

The small size and long life of thermoelectric power generators naturally makes them attractive for use in space. For power generation in space, we have a problem with the heat source, since it must be very compact and long-lived. An attractive heat source for space power generation is a radioisotope, an element which spontaneously generates heat by radioactive decay. A power generator using a radioisotope heat source is shown schematically in figure III–11. The

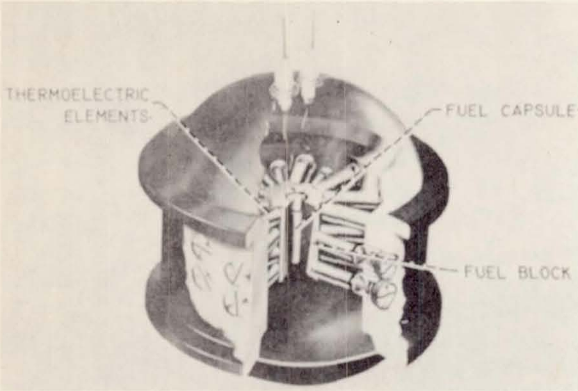


FIGURE III–12.—SNAP-3 thermoelectric generator. (Courtesy Martin Co.)

following figure (III–12) shows a cutaway drawing of the SNAP-3 thermoelectric generator. Generators such as these have been used in a few spacecraft. They have also been used in powering automatic weather stations in Greenland and the Antarctic.

The heat producing radioisotope used in these generators are byproducts of nuclear pile operation. Through control of the nuclear processes, it is possible to emphasize production of radioisotopes suitable for power generation. Space power systems using isotopes may eventually require production of these isotopes in quantities large enough to make them available for other uses.

Just one application of thermoelectric power generation has been described, the radioisotope power generator. There are many others. Propane-gas flames, for example, have been coupled with thermoelectric generators to produce compact portable generators that are used for powering radio equipment in railroad cabooses, powering radio relay stations on remote mountain tops, and for cathodic protection against corrosion of pipelines and well casings. Similarly, there are many applications of thermoelectric refrigeration. Camping refrigerators and hotel room refrigerators are only a few such applications.

All these applications have two outstanding features in common: (1) small size, and consequently portability, and (2) reliability. In any application where either or both of these two factors are needed, thermoelectric devices can probably be used and may actually be the best way of doing the job.

FUEL CELLS

An electrochemical device closely allied to batteries is the fuel cell. This is a glamour device that has attracted considerable interest in recent years and in which the Federal Government is investing heavily for a variety of Earth-bound and space applications.

As shown in figure III–13, the fuel cell is closely allied to the battery, the same parts appearing in both. The main difference is that, in the battery, both the fuel and the oxident are contained within the case, while in the fuel cell the reactants are stored outside the case. As a result, the composition within the battery changes during use, and when the active materials are used, it simply stops operating. In the fuel cell, the reactants are fed in as required and the reaction product is removed at the same rate at which it is formed, with the result that no net change in composition occurs within the case. This invariance is, perhaps, the distinguishing feature of the fuel cell. In principle, therefore, the operating life of the fuel cell is limited only by the size of the reactant storage facilities.

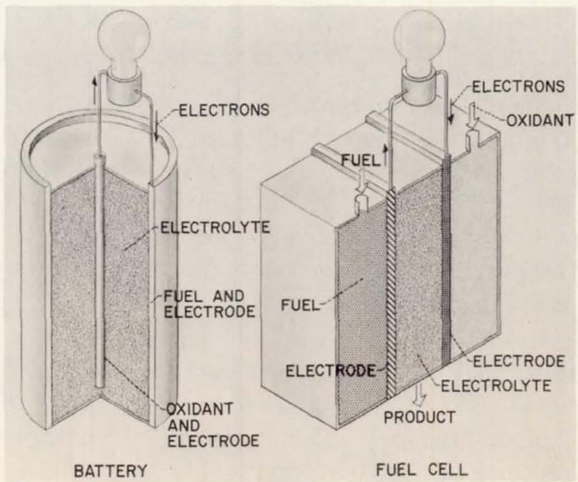


FIGURE III–13.—Comparison of battery and fuel cell.

Two types of fuel cells are receiving major attention today. One operates on hydrogen and oxygen, while the other operates on petroleum-type fuels and air.

The fuel cell like so many novel ideas, is really an old device, first discovered by Sir William R. Grove over a century ago. The prospect of converting coal directly to electricity caused a flurry of interest around the turn of the century, but the successful development of the steam turbine power cycle led to a decline in activity until after World War II. Today, the steam turbine cycle has been refined to the point where further major improvements are not expected. As can be seen from figure III–14, a typical steam powerplant has inherent thermodynamic losses that amount to about 45 percent of the total energy put into the system. Mechanical losses of various types add up to another 21 percent for the particular case shown. As a result, such a plant may recover only 34 percent of the input energy. Even the newer, more highly refined steam powerplatns have efficiences in the range of 40 to 42 percent. Since electrochemical reactions are direct conversion processes, they avoid the heat production step and are inherently more efficient. As a result, as shown in figure III–15, thermodynamic and other losses may total from 35 to 55 percent, and the net power obtainable is 45 to 65 percent of the theoretical energy available. This is exceptionally high compared with other methods of energy conversion, as shown by figure III–16. Photovoltaic and thermoelectric systems are potentially able to produce efficiencies of about 10 to 15 percent; the internal combustion engine runs at about 25 percent efficiency; a gas turbine can produce values of around 30 percent. As mentioned earlier, steam power cycles are typified by central power stations having efficiencies of 35 to 42 percent. A fuel cell with its ability to convert fuel to electricity without first degrading it to heat offers efficiencies of 45 to 65 percent—as much as 50

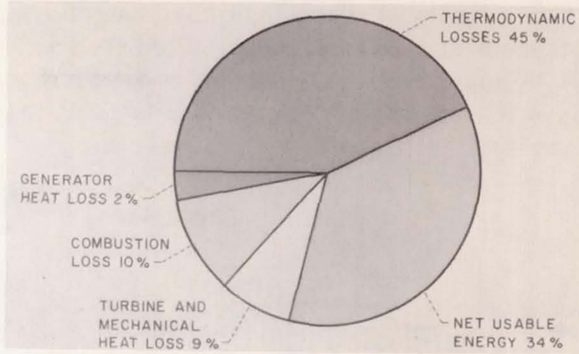


FIGURE III–14.—Typical steam powerplant energy balance.

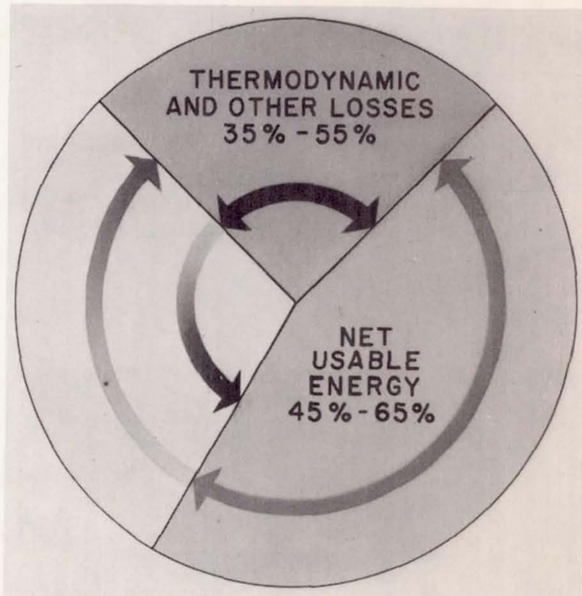


FIGURE III–15.—Energy balance for electrochemical processes.

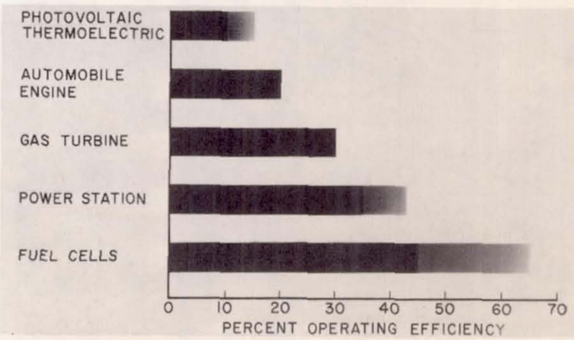


FIGURE III–16.—Typical efficiencies for energy conversion systems.

percent more efficient than the best of the other methods of energy conversion shown.

As might be expected, a device that offers such a marked advantage over its competition has aroused interest on a variety of fronts. Potential government usage for fuel cells is as follows:

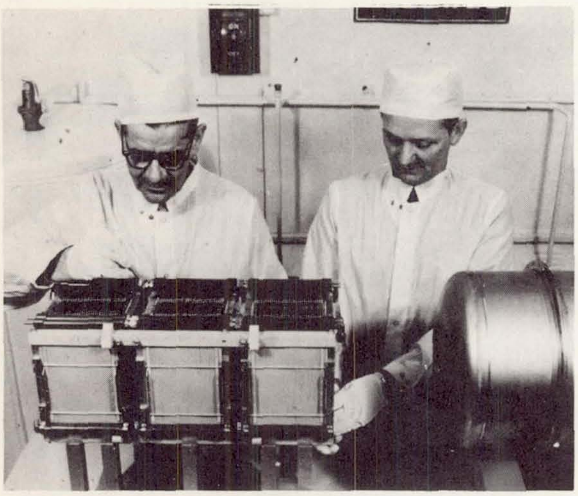


FIGURE III-17.—Gemini fuel cell. (Courtesy General Electric Co.)

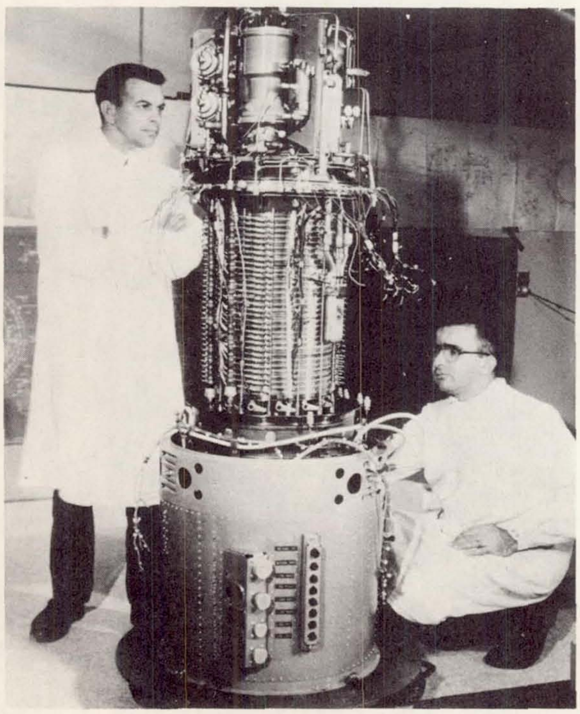


FIGURE III-18.—Apollo fuel cell. (Courtesy Pratt & Whitney Aircraft Co.)

Army:
- (a) Small power units—high energy density
- (b) Large power systems—efficiency, logistics, economy
- (c) Vehicle propulsion—efficiency, quick start, high torque, low maintenance

Navy: submarine power—silence, reliability, safety

Air Force and NASA: space vehicles—reliability, light-weight

The Army wishes to take advantage of the high energy density available in fuel cells for small portable power units of the back-pack type for outputs up to 200 watts and for larger power systems where the efficiency results in logistics advantages and greater economy of operation. Vehicle propulsion is another military application for the fuel cell, since the high efficiency of the fuel cell can be mated to the favorable operating characteristics of electric power systems, resulting in high performance vehicles with low maintenance and operating costs. The fuel cell is also an ideal powerplant for Navy submarine applications. It offers a silent power system, high reliability, and safety. Quite naturally, the Air Force and NASA are looking to the fuel cell for power systems for space vehicles. We are interested in taking advantage of the inherent reliability and light weight of fuel cell power systems.

NASA will begin using fuel cells in manned vehicles in the near future. Both the Gemini and Apollo programs rely on fuel cells for vehicle power. In each case, the chemicals used are hydrogen and oxygen. In addition to electricity, the fuel cells produce potable water for the astronauts. The fuel cell being built for the two-man Gemini spacecraft is shown in figure III-17. It will supply all of the power required to sustain a Gemini vehicle in Earth orbit for periods of up to 2 weeks. Figure III-18 is a photograph of a different type of fuel cell that is being built to power the Apollo craft that will carry three Americans to the moon and back.

If we are willing to entrust the lives of astronauts to spacecraft that are powered by fuel cells, it is obvious that the fuel cell is more than just a laboratory curiosity. At the same time, it is appreciated that no one can get too excited about consumer devices that require pure hydrogen and oxygen for operation. While the hydrogen-oxygen fuel cell is being refined to a high degree at present, the real plum will be the development of a cheap fuel cell running on air and a petroleum-base fuel. As as example of how important this could be, consider the fact that during World War II, 55 percent of military shipments to theaters of action consisted of petroleum fuel, oil, and lubricants, the so-called military POL. This amounted to 400 million pounds per day. In order to demonstrate the significance the fuel cell may hold, one need only study the effect fuel cells could have on such a logistics problem. From present day utilization figures, it might be expected that 10 percent of this material would be used in motor-generator sets for electric power production. A fuel efficiency of 8 to 12 percent would be typical for such equipment, therefore, an arbitrary figure of 10 percent has been applied for the total POL diverted to power generation. An additional 20 percent is used for heating and cooking purposes, and no credit is applied for the presence of fuel cells. The remaining 70 percent, or 280 million pounds per day for this example, might be used for transportation. An efficiency of 25 percent is assigned, which is acknowledged to be somewhat high but sufficiently accurate for this analysis. If a fuel cell with an overall efficiency of 50 percent had been available, a saving of 172 million pounds per day or 43 percent might have been effected (see following table). Even in peacetime, military POL amounts of 250 million barrels per year. In fact, the joint military and civilian expenditures from petroleum products amount to 45 to 47 billion dollars per year. Thus, a general fuel-cell technology appears to carry with it an implication of a potential savings of the order of 20 billion dollars per year.

Obviously, we are not going to stop generating power and propelling vehicles by established methods and make an immediate transfer to the fuel cell for a variety of reasons. It does seem, however, that the high efficiency offered by the fuel cell can make an important contribution toward conserving our fossil fuel resources, reducing the cost of vehicle operation, and improving the logistics burden of our military establishments.

As shown in figure III–19, a variety of civilian applications immediately come to mind. Transportation has already been discussed. Emergency use is self-evident. Materials handling looks especially attractive. As far back as 1959, a tractor was operated by fuel cells. Presently fork-lift trucks are considered a promising potential use. The feasibility of home or central station power depends on an extremely complicated economical evaluation including, of course, such things as fuel costs, availability, installed cost of the fuel cell and power conditioning equipment, and operating life. The gas

Field use	Total POL, percent	Consumption, lb/day	Conversion efficiency, percent	POL required for 50 percent fuel cell, lb/day
Electric power generation	10	40×10^6	10	8×10^6
Heating and cooking	20	80	------------	80
Transportation	70	280	25	140
Total	------------	400×10^6	------------	228×10^6

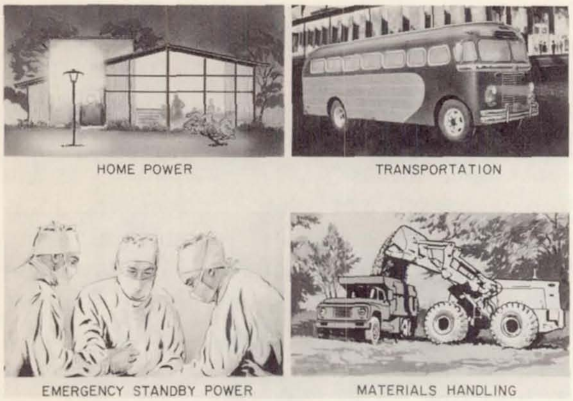


FIGURE III-19.—Potential commercial fuel cell uses.

companies have expressed interest, looking to the possibility of a truly all-gas home. They point out that extensive gas distribution systems already exist, and that distribution costs are less than those for electricity. On paper, even central station power looks possible. It has been estimated that the installed cost of a 40 percent efficient powerplant is of the order of $125 per kilowatt. A 60 percent efficient fuel cell may be able to tolerate a first cost $25 per kilowatt higher and still be competitive. In fact, if the plant serviced an industrial complex with a high demand for direct-current power, a $200 per kilowatt cost for the fuel cell might be tolerable just because of the savings on equipment for converting alternating to direct current. Getting costs down to these levels will be a major task, however.

After such a glowing picture is painted for the future of the fuel cell, an obvious question arises as to why the conversion to fuel cells has not already begun. The reason is that though hydrogen-oxygen fuel cells are fairly well developed, a good fuel cell operating on hydrocarbon fuels is not as yet available. Scientists in both the government and industry have been working on the problems associated with hydrocarbon fuel cells for some 10 to 15 years. Unfortunately, the electrochemical combustion of petroleum is not nearly as simple as the combustion of hydrogen in a fuel cell. At present, we are capable of building fuel cells that last for a few hundred hours of operation at efficiencies of the order of 40 percent. One solution to the problem is to react the fuel with water to obtain an impure hydrogen first, and then to use the hydrogen in a hydrogen-air fuel cell with a sacrifice in efficiency (25 to 30 percent). There are other factors to consider too.

Ultimately, cost and service life will determine the extent to which fuel cells will be adapted. Ideally, to extend life, the engineer tries to keep the operating temperature as low as possible. If a fuel cell operating at near-ambient temperatures is desired, however, a reaction-promoting catalyst like platinum or palladium is required. This requirement increases the cost of the fuel cell and will preclude a major conversion to fuel cell power generation because of the limited supply of this and other catalytic precious metals. Fortunately, fuel cells can be made by using nickel as their major active catalytic material if temperatures of the order of 400° to 500° F are acceptable. The problems to be solved are formidable, but the potential gains to be made are so outstanding as to make a concentrated research effort worthwhile. Much of the fundamental research conducted to develop the Apollo and Gemini fuel cells is being applied to the solution of these problems. To date, progress has been slow, but steady progress is being made.

TURBINE POWER SYSTEMS

Satellites launched to date had internal power requirements that usually fell in the range of a few watts to a few hundred watts. In the near future, power requirements will be several kilowatts and will grow to several thousand kilowatts. The demand for thousands of kilowatts will come from electric propulsion systems. For example, a manned expedition to Mars with electric propulsion will need a 20,000-kilowatt power system.

Turbines are widely used, of course, to produce large amounts of power. Steam turbine systems have been the backbone of our electric power production industry for nearly a century. Gas turbine systems are comparative newcomers, having emerged during the second World War as prime power systems for military aircraft. Since then, gas turbines have been widely used in airplanes and are starting to appear in ships and automobiles.

The gas turbine system is also finding application in the electric power field. A system currently being built is shown in figure III–20. Ten jet engines are mounted circumferentially and the exhaust gases from all these engines power a single 18-foot-diameter turbine, which produces 150,000 horsepower. Systems such as this, because of the capability of rapid starts and stops, are finding increasing use as a means for augumenting normal power systems during periods of peak demand.

The features that make turbines attractive are simplicity, compactness, and fuel flexibility. The principle of turbine operation is quite simple. A high-pressure gas or vapor is accelerated to a high velocity in a nozzle and then impinges on a rotor, thereby causing rotation and producing shaft power. The compactness of the gas turbine system is illustrated in figure III–21, which compares the sizes of a 1000-horsepower gas turbine

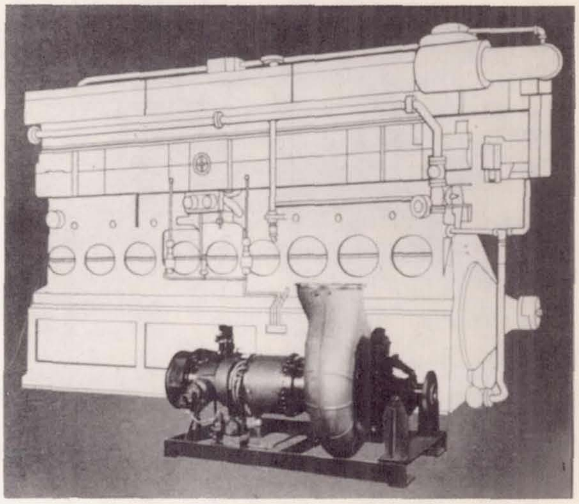


FIGURE III–21.—Comparison of turbine and diesel engines. (Courtesy Solar Aircraft Co.)

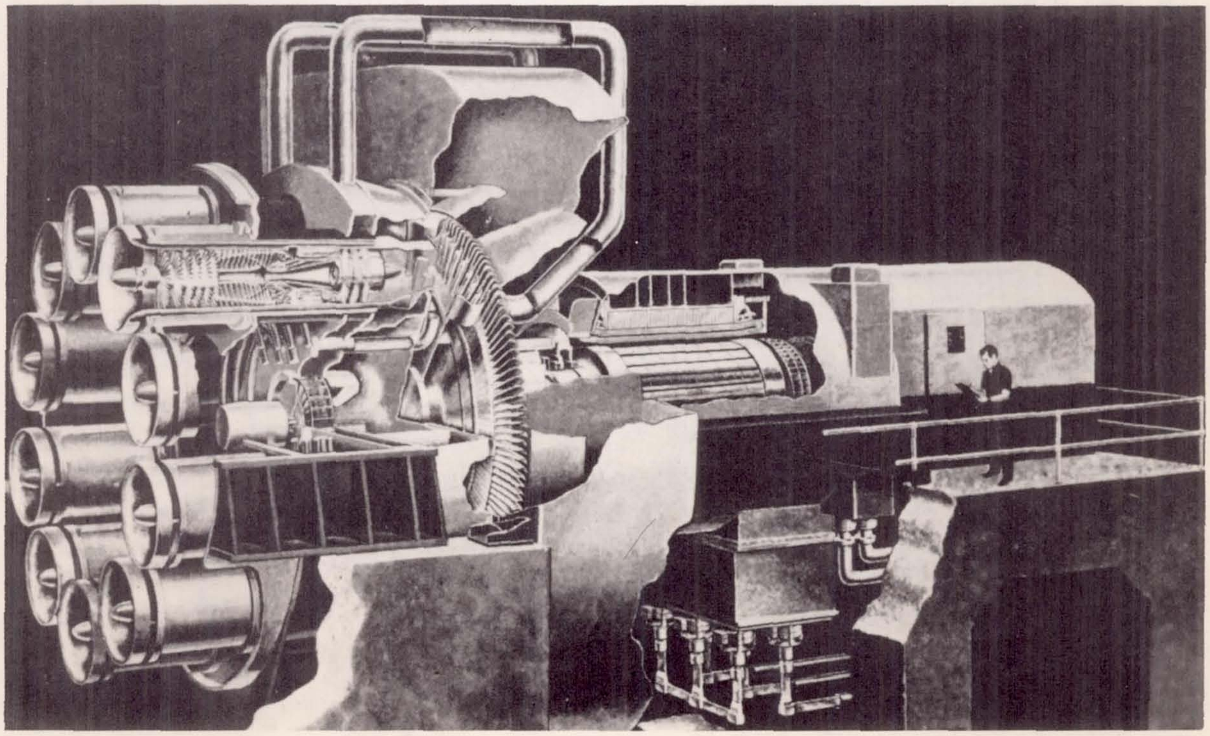


FIGURE III–20.—Turbine peaking unit. (Courtesy General Electric Co.)

engine and a diesel engine of the same power output. The turbine engine is one-tenth the size and one-twentieth the weight of the diesel engine. These features of compactness and light weight make the gas turbine ideally suited to transportation applications. In addition, there is a wide choice of fuels. The following fuels can be used in turbine aplications. The most popular fuels currently are natural gas and diesel oil.

(1) Gas
  (a) Natural gas
  (b) Blast furnace gas
  (c) Liquid gas
  (d) Coal mine gas
  (e) Sewage gas
(2) Oil
  (a) Crude oils
  (b) Diesel oils
  (c) Other distillate oils
(3) Coal
(4) Nuclear

In view of favorable features such as those previously discussed, turbine power systems are being given considerable attention in our space power program.

A schematic diagram of a vapor turbine system is shown in figure III–22. The working fluid is vaporized in the boiler and then flows through the turbine, which drives the generator. After leaving the turbine, the vapor condenses to liquid, which is pumped back to the boiler. The gas turbine cycle is similar to the vapor turbine cycle except that, because the fluid is a gas at all times, heat is added and rejected without boiling and condensing, and a compressor replaces the pump.

The differences between space and Earth turbine systems appear at the heat input and heat output ends of the loop. It is not feasible to burn coal, oil, or gas with air in space; new heat sources, therefore, are needed. The heat source shown in figure III–22 is a nuclear reactor, which supplies heat to the boiler by means of an all-liquid loop. Another energy source is the sun; in a solar system, a large mirror focuses the sun's rays on a heat exchanger that would replace the reactor in figure III–22.

In space, the heat rejection component must also change since river or lake water is not available to absorb waste heat at low temperatures. Heat must radiate away from the spacecraft; the condenser in figure III–22, therefore, must also be a radiator. If low radiator temperatures are used, very large areas are required to reject the heat and the radiator becomes very heavy. Heat removal by radiation increases very rapidly as the temperature is raised; high-temperature heat rejection, therefore, is required for space power systems in order to reduce radiator size and weight.

At these elevated temperatures, the pressures associated with the use of steam as the working fluid are quite high; much lower pressures can be achieved through the use of fluids such as mercury or potassium. These working fluids require the use of high-temperature high-strength corrosion-resistant materials such as the superalloys of nickel or cobalt or refractory metals like columbium, molybdenum, or tantalum. Two other problem areas associated with space systems are the separation of liquid and vapor in the zero-gravity environment of space and the

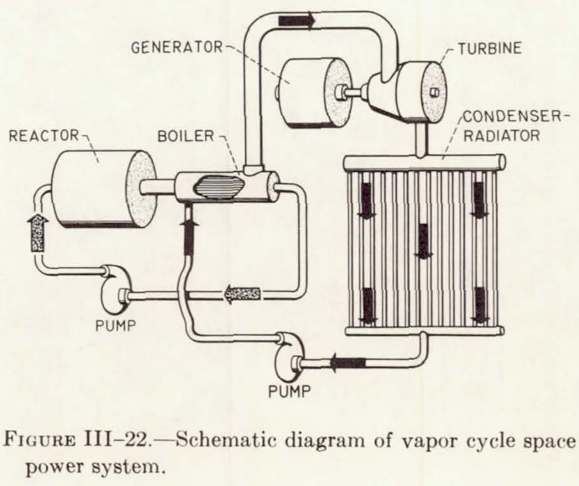


FIGURE III–22.—Schematic diagram of vapor cycle space power system.

achievement of the high reliability required for long-term unattended operation.

Much of the research associated with turbine development is concentrated on the high-temperature problems. In space this consideration is necessary, but benefits of high-temperature operation in other fields are not too difficult to imagine. In conventional systems for generating power using a steam cycle, a part of the energy of combustion is unavailable to do work because the steam turbine is limited to about 1200° F. With the development of high-temperature turbines and working fluids, this previously unavailable high-temperature energy can be converted into electrical energy and the output of the plant thereby increased.

The method wherein heat at the high cycle temperature is utilized is called topping and is illustrated in figure III–23. The high-temperature heat source, which may be a combustion chamber or a nuclear reactor, delivers heat at a temperature higher than a steam turbine can operate. A cycle utilizing potassium or mercury and a high-temperature turbine, however, can operate at temperatures nearer the source temperature. Heat is taken from the source by the liquid-metal working fluid; some of this heat energy is converted into electrical energy; and the working fluid is fed into a condenser, just as in the cycle in figure III–22. In the topping cycle the condenser, rather than being a radiator as in a space system, is a water-cooled device. Since potassium condenses at a high temperature, the water in the condenser boils and steam is produced. The steam is then used in a conventional steam turbine, and more electrical energy is generated. The condensed potassium is pumped back to the heat source, and the steam from the steam turbine is condensed and returned to the condenser-boiler. The cycle within the dotted area is called the topping cycle. The addition of this topping cycle increases the power output and thermal efficiency of the plant. This concept still must be studied with economic considerations in mind in order to determine whether such a system can reduce the cost of electricity.

One of the major technological contributions resulting from the programs involving the high-temperature liquid-metal systems will be in the area of material development. As a result of government interest in these systems, considerable effort is being expended in evolving new and exotic alloys that will provide high strengths at high temperatures and will also be resistant to the corrosive nature of mercury and potassium.

Another area where industry will have considerable interest is that of miniaturized turbomachinery. NASA is interested in turbine systems designed for power levels as low as about 3 kilowatts. One such system is presented in figure III–24. This is a solar power system appropriately called Sunflower that uses mercury as the working fluid to produce 3½ kilowatts of power. The components that can be seen in figure III–24 include the mirror, boiler, turbomachinery, and radiator. The turbine for this system is only 2 inches in diameter. A unit of this type ran approximately 4000 hours continuously without failure, thus indicating that such systems can be made to run for long periods of time.

A second low-power solar system, this one designed for 8 kilowatts, is being studied

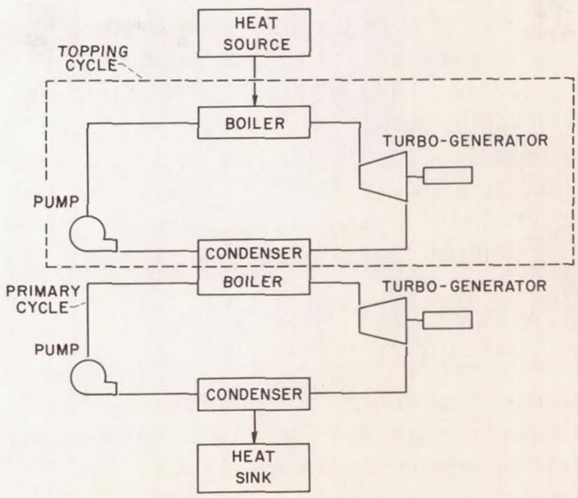


Figure III–23.—Electric power generation with topping cycle.

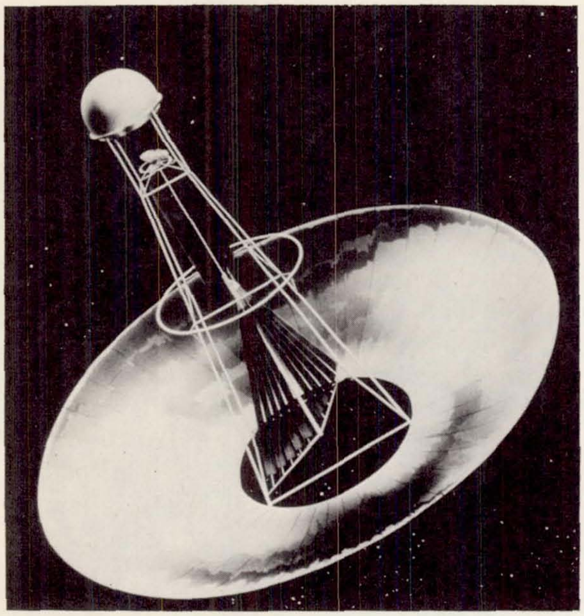


FIGURE III-24.—Sunflower. (Courtesy Thompson Ramo Wooldridge Inc.)

by NASA. This system is similar to Sunflower except that it uses an inert gas, argon, as the working fluid. The use of an inert gas eliminates any possible reaction between the working fluid and the containment materials, and thus improves chances for long-time reliable operation. One turbine being considered for this argon system is only 4½ inches in diameter.

The miniature turbines used in these systems are examples of an ever increasing number that are being evolved for low-power uses. The ramification of such programs will be to extend the useful range of gas turbines down to a low power level where, in the past, other systems such as the internal-combustion engine have reigned supreme.

MAGNETOHYDRODYNAMIC CONVERTERS

The possibility of generating electric power in space directly from a moving, electrically conducting working fluid is being investigated by NASA. The device that can accomplish this is called a magnetohydrodynamic (MHD) converter and is used in place of the turbogenerator in a conventional cycle. This device is being considered because of the high-temperature requirements placed on the energy converter by the space environment. The difficulty turbines encounter seems to be one of material limitation, that is, at higher temperatures the strength of materials decreases. Materials under high stress, such as the blades of a high-speed turbine rotor, must therefore operate at a lower temperature than materials under less stress, such as the walls of the heat exchanger. Hence, a system that would eliminate the turbine may be able to operate at high temperatures and higher cycle efficiencies. Consequently, an MHD device, which has no rotating parts, is of interest.

Let us first examine the fundamental physical principles by which a moving fluid that is an electric conductor might be used to generate electric power. Shown in figure III–25 is a schematic representation of a conductor moving at right angles to a magnetic field. As a result of this motion, an electric field at right angles both to the direction of the motion and the direction of the magnetic field is induced. This field is proportional to the product of the velocity and the magnetic field strength. If one completes an electrical circuit utilizing this voltage, a current will flow and electric power will be generated.

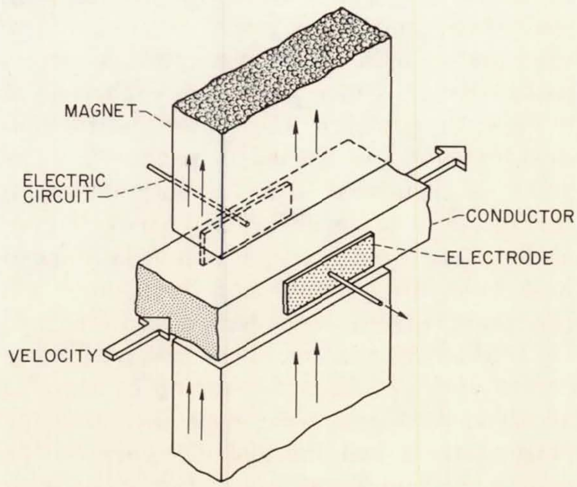


FIGURE III-25.—Conductor moving in a magnetic field.

The current that flows is proportional to the conductivity and the difference between the induced voltage and the load voltage. This technique is used in commercial power generating plants where the conductor is not continuous, as shown in figure III–25, but is formed of wires moving parallel to themselves through the magnetic field. The continuous conductor, however, makes no difference. (As a matter of fact the electrical meters in homes operate with continuous disk-type conductors in this fashion.) Not only is it not necessary to have a wire conductor, but also it is not necessary to have a solid conductor; if liquids or vapors move through the magnetic field, the phenomenon is unchanged. When a liquid or vapor conductor is utilized, the process is called MHD power generation.

By this principle, a flowing gas that is an electrical conductor can be used to generate electricity directly if it is forced through a magnetic field. A gas can be accelerated by pumping it to a high pressure and expanding it through a nozzle. Let us see how an MHD device can be incorporated into a system that has a high-temperature and high-pressure gas, such as a conventional power generation cycle. Shown in figure III–26 is a schematic representation of a thermodynamic cycle using an MHD generator in place of a turbine. The working fluid is pumped to a high pressure, heated to a high temperature, expanded to a high velocity, and forced through a magnetic field. Some of the kinetic energy is converted to electrical energy, which is dissipated in the load while the gas is cooled and sent to the pump for recirculation in the cycle. The only difference between this cycle and a conventional cycle is the replacement of the turbine by the MHD generator. We now have a thermodynamic cycle capable of generating electric power directly from a moving stream by means of an MHD converter. Because the converter has no rotating parts, it has the ability to perform at higher temperatures than a turbine; it may be possible to develop more efficient power generation plants by taking advantage of this property.

Along with this ability to perform at high temperatures is the relative simplicity of the device; it has no bearings, no seals, and no other equipment associated with rotating machinery. Under some circumstances this advantage may be more important than the high-temperature advantage.

The principal disadvantage of the MHD system is that the gases that are best suited for the thermodynamic cycle working fluid have low electrical conductivity. This is quite detrimental since the power that can be generated is directly proportional to the conductivity of the gas.

There are three ways of getting around this problem. First, since the power generated also depends upon the magnetic field strength, a poor conductor could be used if sufficiently large magnetic fields were available. Until recently, exorbitant amounts of power were required to obtain this high field strength and, consequently, this approach was considered impractical for space use. The advent of the superconducting magnet has changed the picture considerably, however. This type of magnet develops very high strengths and has very low power requirements.

The second approach is to increase the speed of the conducting gas, since the power also depends on this factor. Accompanying an increase in speed, however, is an increase

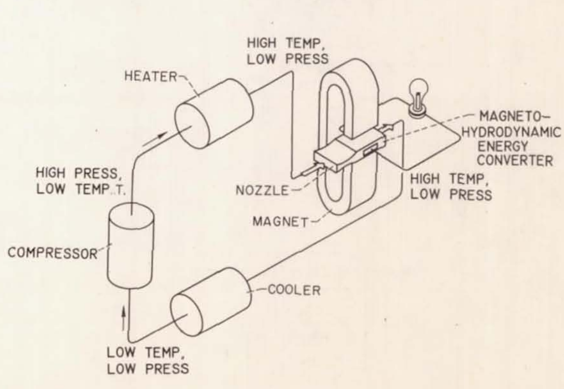


FIGURE III–26.—Power generator cycle with magnetohydrodynamic energy converter.

in friction losses. A way to minimize this effect is to make the generator large so that this loss becomes a small part of the total output of the device.

The third approach is to attempt to increase the electrical conductivity of the gases. One way would be to increase the temperature. Unfortunately, the temperatures required in most gases are much too high to be practical. If one were to mix or seed the gas with a small quantity of alkali metal vapor, however, seeding would increase the conductivity considerably and, in the case of combustion products, permit satisfactory operation at temperatures around 4500° F. Temperatures of this level can be obtained in an oxygen hydrocarbon flame. It is obvious, however, that the walls of the device would still have to be cooled considerably in order to make it practical.

It is at this point that the MHD system can be considered for applications on Earth. Products of combustion are high-temperature gases, which can be made to conduct by the addition of some alkali metal seed. Because the MHD device can utilize high-temperature heat, it can be considered for a topping application just as the high-temperature turbine was considered earlier. Shown in figure III–27 is an MHD converter used as a topping device in a conventional powerplant. The MHD converter takes some energy from the combustion gases, but the gases are still hot enough to generate steam in a boiler. Hence, if this device is inserted in the fire side of the boiler in a conventional power generation plant, it would be possible to gain more electric power without using more fuel. Estimates show that the efficiency of a good commercial powerplant can be increased from a present value of 40 percent to 50 or 55 percent.

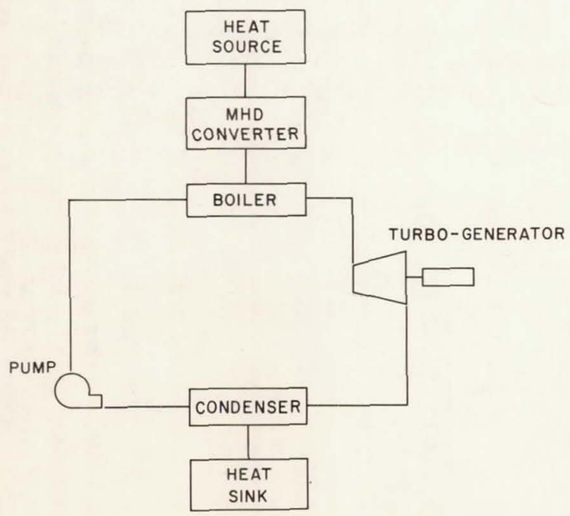


FIGURE III–27.—Electric power generation with magnetohydrodynamic topping.

Because of this possibility of using an MHD converter as part of a topping cycle in a combustion products power generation plant, several utility companies have united to sponsor research in this area. A generator has been built that has developed 1500 kilowatts of power at a generator efficiency of 45 percent for periods of about 10 seconds. The generator has graphite electrodes and ceramic insulators that are water cooled. This device has poor conversion efficiency but still increases the output of the plant. Further developments are necessary to make this useful as a topping cycle for a commercial power generation plant. One of the most important considerations is the economics of seeding the combustion gases. This seed must be recovered to make the topping cycle economical.

The topping cycle is not the only possible use for this combustion gas converter. It can be used where a short burst of direct current power is required. There may be conditions under which this device would be the most economical.

Nuclear sources are being considered for closed cycle operation both on Earth and in space. But the gas temperature obtainable from these sources is lower than that which is required for high conductivity. Consequently, methods of increasing the conductivity without heating the gas must be considered. One method which is attractive is the application of an electric field to the gas (such as found in neon advertising signs). The electric field will elevate the temperature of the electrons above that of the remaining gas. Since the electrical current is the motion of electrons, it is necessary only to increase their temperature to achieve high conductivity.

By properly building the generator and connecting the loads correctly, it is possible to utilize the electric field in the generator itself to increase the electrical conductivity of the gas. There are many experiments being carried on, both by NASA and by Government-supported industry, to develop a generator that has this increased conductivity at temperatures that are compatible with nuclear reactors. The research in this area has started only recently and in the future will explore other methods of obtaining high conductivity, various conducting fluids, schemes for generating alternating current power, other thermodynamic cycles, and other possible applications.

THERMIONIC CONVERTERS

The thermionic diode converts heat directly to electric power. The vacuum version of the thermionic diode is illustrated in figure III–28. It operates at high temperatures with no moving parts. Inside the diode are two metal plates separated by a hard vacuum. Electrons boil off the hot plate and condense on the cold plate. The cooler collector becomes negative while the emitter grows positive. The electrons from the collector then work through the load back to the emitter.

Because the vacuum diode is a sensitive thing, it was improved with the addition of a plasma as shown in figure III–29. A diode of this type is called a plasma diode. The plasma is a neutral gas of electrons and positive ions, which are fragments of atoms. Common plasmas produce the glow that is visible from fluorescent lights, flames, and lightning. But the plasma most used in thermionic diodes is cesium, a normally liquid metal that loses electrons readily. A thermionic cell that holds a cesium plasma is called a cesium diode.

How does the cesium plasma change the thermionic diode? It raises the emitted current, passes more electrons through a wider gap, and steps up the output voltage. In short, the cesium plasma brings greater power, easier fabrication, and longer life to the thermionic diode.

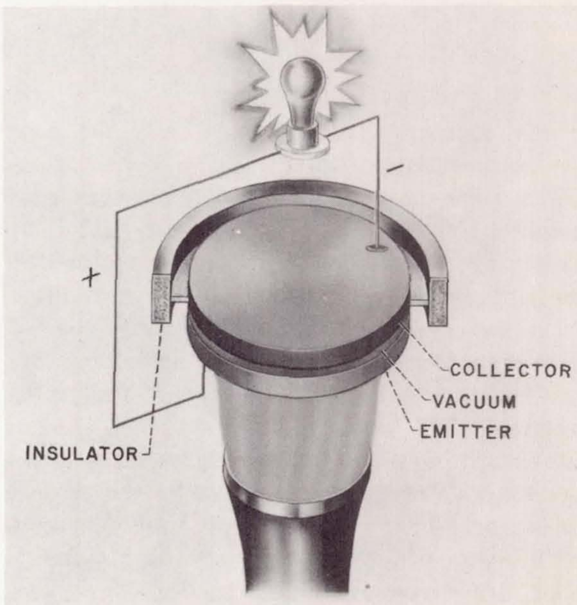


FIGURE III–28.—Vacuum thermionic diode.

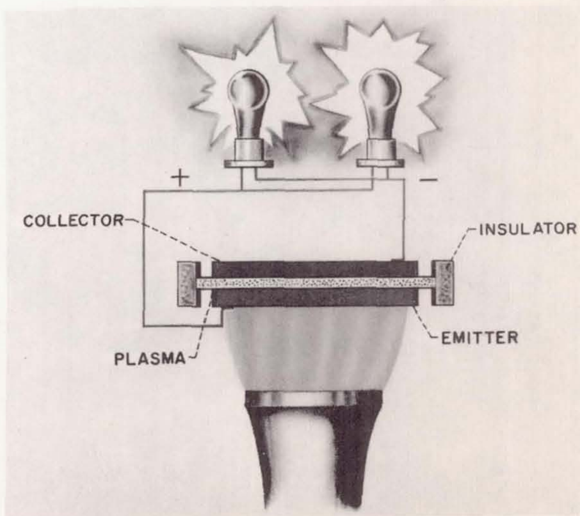


FIGURE III–29.—Plasma diode.

The following table gives performance values for cesium diodes at an emitter-to-collector-temperature ratio of 2:

When	Output, W/sq in.	Conversion efficiency, percent	Life, yr
Now	Over 360	18	Fraction
Now	Near 40	10	Near one
Soon	Over 100	20	Several
Some day	600	25	Many

Each diode operates with the emitter at twice the temperature of the collector. A diode with an emitter at a temperature of about 3140° F is described in the first row; this and the second row are experimental results. In the last two rows, theoretical numbers are presented.

Today, a cesium diode with a temperature ratio of 2 can convert 18 percent of the heat input to 360 watts per square inch during a short life. With lower temperatures, service extends to 1 year at 40 watts per square inch and 10 percent conversion efficiency. In the near future, the cesium diode should yield 100 watts per square inch at 20 percent efficiency, and it may reach 600 watts per square inch with 25 percent efficiency.

High temperature, high power, and high efficiency are promised by the cesium diode; these traits can serve spacecraft. The space program thus boosted thermionic conversion into rapid growth.

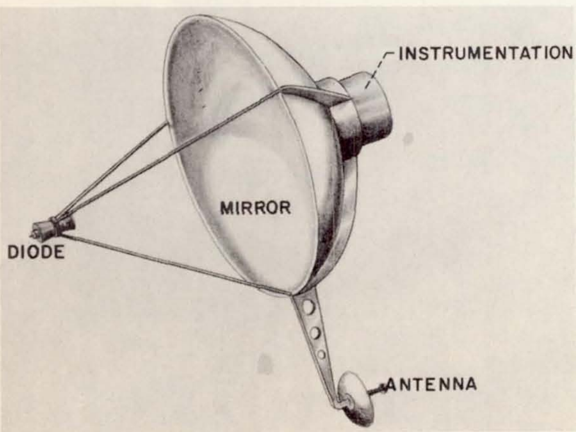


FIGURE III–30.—Solar thermionic diode.

In space, heat from the sun costs only the price of collection; therefore, the idea of driving a diode with sunshine was suggested for space applications. A solar-thermionic diode is pictured in figure III–30. A big, dish-like mirror converges rays to a diode similar to the one in figure III–30. Solar heat enters the cesium diode through the roughened target that backs the emitter, and waste heat escapes from the skirtlike radiator that flares from the collector. About 60 watts of electric power results from a mirror almost 3 feet in diameter.

"Free" heat is an advantage, but solar-thermionic problems invite competition from small, dense power sources. Nuclear energy enters here. For low power, radioisotopes can heat thermionic diodes, but big power outputs require nuclear reactors. The high temperatures and dense power requirements of the cesium diode suggest a nuclear-thermionic system; furthermore, tests indicate that the diode can operate inside a nuclear reactor. The prototype nuclear-thermionic system does not exist, however, and thus even major changes may precede practical nuclear-thermionic power generation. Let us look at the most probable nuclear-thermionic element, shown greatly simplified in figure III–31.

The cylinder combines the heat source, the cesium diode, and the heat rejector. A fissionable core supplies part of the overall critical mass and heats the diode by nuclear reaction. The fissionable material is clad with refractory metal that acts as the emitter for a cylindrical thermionic diode containing cesium plasma. In turn, the diode collector connects through an insulator to a liquid-metal cooling system. The system keeps the reactor temperature down while it cools the collector. This is a problem because reactor cooling more or less dictates the temperatures of the diode electrodes. Other difficulties for the nuclear-thermionic diode are the changing compositions of electrodes

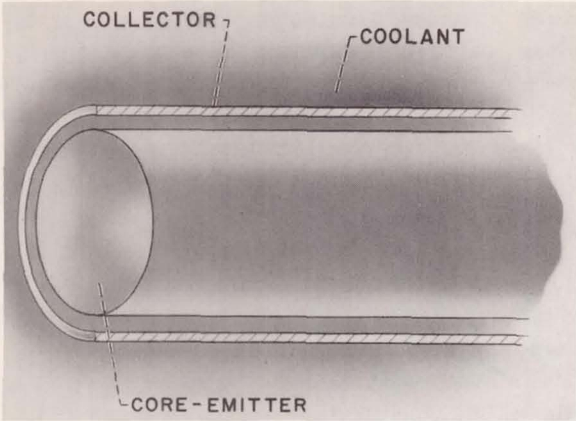


FIGURE III-31.—Nuclear-thermionic element.

and insulators and the trapping of fission products.

The thermionic converter can handle the big power densities and high temperatures of a nuclear reactor and, interestingly, the coolant can be discharged at a temperature sufficiently high to operate a steam powerplant. The combination of thermionic diode topping cycle and steam powerplant may be useful on Earth.

A recent journal article (ref. 1) from an industry engaged in nuclear-thermionic development gave one viewpoint on temperature topping. Schematically, the system discussed is similar to the one in figure III-32. The nuclear reactor, at temperatures higher than 3700° F, heats a futuristic diode that has a 23-percent conversion efficiency; the configuration is similar to the cylindrical nuclear-thermionic element discussed earlier. The diode dumps its waste heat into the steam cycle of an existing nuclear-turboelectric power station; this system, without temperature topping, has a 32-percent efficiency. The steam drives a turbine coupled to a generator. After passing through the turbine, the steam condenses in the cooler, and the water is pumped back into the nuclear-thermionic reactor.

For this case, it was concluded that temperature topping with future cesium diodes will increase the overall conversion efficiency by 12 percent, the station output by 79 percent, and the efficiency of fuel utilization by 37½ percent. It was also indicated that the 79-percent increase in electric output will be attended by a 6-percent reduction in power costs.

The cesium diodes of today will not work in a system like this, however, thus there are a few problems.

Nuclear-thermionic diodes trap fission products and change compositions. Actually, a change in the emitter and collector compositions would be preferred—to give more current and higher voltage. Electrode problems presently hold the cesium diode efficiency at 20 percent, but small electrode improvements should come in the near future. A cesium diode must have a space of about 0.01 inch between the emitter and the collector. This tiny distance between the electrodes makes fabrication difficult, but maintaining the spaced, flat, parallel condition of the two surfaces during operation seems impossible. With the emitter temperature above 3000° F and a drop of 100,000° F per inch across the gap, thermal relaxation and shock alone seem to doom the diode, but it has been made to work. This does not end diode thermal problems, however, temperature also causes emitter materials to reorient, vaporize, and then condense and grow on the collector. Additives that oppose these processes are being studied.

The very reactive element cesium is used in diodes because it forms a plasma easily,

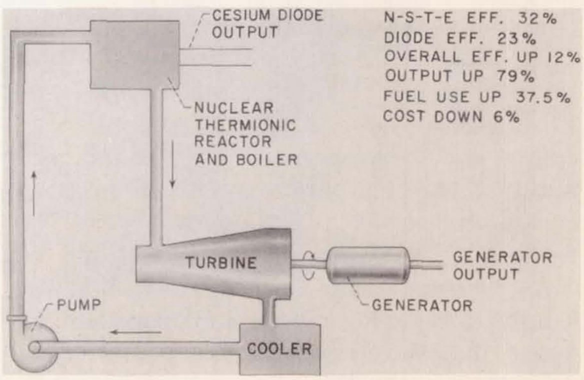


FIGURE III-32.—Cesium-diode temperature-topping possibilities.

but that same reactivity enables cesium to dissolve or combine with many metals and insulators. So diode materials must be chosen carefully or they may end as one big, hot, mixed-up blob.

The cesium diode makes considerable direct current at less than 1 volt. If direct current at moderate voltage is required, diodes can be connected in series, but if alternating current and high voltages are needed, part of the diode output must be used to change its power to alternating current. Alternating current costs 20 to 25 percent of the diode output on Earth and 30 to 40 percent in space.

There are possible plasma diodes with alternating outputs, and they may use other plasmas with or without cesium. Alternating-current diodes, however, are well behind the direct-current diode, which is yet being developed. So alternating-current diodes are future possibilties, and some of the thinking that may lead to alternating-current plasma diodes can be outlined. Some of these possibilities are sketched in extremely simplified forms in figure III–33. The hot plate on the left of each diode is the emitter, and the cold plate is the collector. The first method uses part of the diode output to run a magnetic switch that flips the plasma from one collector to the other. In the second approach, some of the power injects electrons into the plasma periodically from a hot grid. These two diodes recycle parts of their outputs to produce frequencies fixed by external circuits.

There are ideas also for plasma diodes that yield alternating power directly—without added equipment. In one, the plasma oscillates between two states at approximately 1 million cycles per second. Another interacts beams of charged particles with the plasma; ion beams produce millions of cycles per second, while electron beams yield billions of cycles per second—or microwave power. Finally, proper plasmas and mirror configurations may bring maser and laser outputs directly from heat.

This is a brief discussion of possible alternating plasma diodes; little more is warranted because alternating diodes are either ideas, early experiments, or unruly direct-current diodes at the present time, but they certainly deserve some investigation.

Only direct developments of the diode have been discussed, but as usual, an upgrading of related technologies results from any good research and development program. Research on thermionics has helped to make better vacuums, plasmas, sensors, instruments, materials, fabrication; in fact, it can be implied that all technological roads lead to the cesium diode, but that may be exaggerating a little.

It is hard to look long at a bright future for plasma diodes without prospecting a bit. Suppose 79 percent more power could be generated at 6 percent less cost. That is a nuclear-electric bonus that cesium-diode temperature topping may yield in the near future. Think of the results of direct conversion of heat to alternating power. Some day, this too should result from work that began just a few years ago as research and development on the thermionic diode.

CONCLUDING REMARKS

A limited number of applications of space power technology to everyday living has been suggested. There are many more possible applications. Consider, for example, the development of solar collectors. There are several programs under way to develop collectors with diameters up to and exceed-

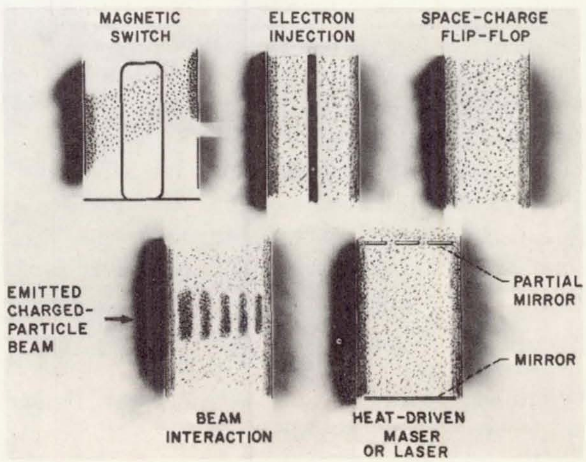


FIGURE III–33.—Diodes with alternating outputs.

ing 30 feet. No guess has been made as to the future application of this development on Earth. In a similar manner, it is felt that, in many of the areas discussed here, important new technology is being generated for which present applications on Earth are not seen. These applications will become clear at a later time.

It can be concluded that the NASA space power program and related programs of other government agencies, industry, and universities are providing a great impetus to the advancing technology of electric power generation. Promising new ideas have been introduced and old ideas and principles are being redeveloped to fill new uses. These new ideas and developments have been directed toward specific objectives of space or other limited objectives. The results of this work have applications much broader than the original limited objectives. In some cases the new development may have a revolutionary effect on our economy. Fuel cell development might lead to such a revolution. In all areas that have been discussed there are gold mines of new and useful technology.

REFERENCE

1. Wilson, Volney C.: Thermionic Power Generation. IEEE Spectrum, vol. I, no. 5, May 1964, pp. 74–83.

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N64 32771

IVa. Lubrication in Difficult Environments

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TO REALIZE THE IMPORTANCE of good lubrication, one need only ponder the significant fact that from one-third to one-half of all the energy produced in the world is lost in friction. Of course, even those in the lubrication field admit that some friction is necessary in certain processes, but most endeavors are toward a reduction in friction and wear. Lubrication problems in aerospace equipment are particularly severe because bearings must operate under a variety of extreme conditions.

Bearings must be operated in cryogenic fluids such as liquid hydrogen and liquid oxygen, which are extremely cold. The temperature of liquid hydrogen, for example, is $-423°$ F. At the other extreme, bearings must be operated in an environment consisting of combustion products or hot gases, the temperatures of which may range to 1200° F or higher. At cryogenic temperatures oils and greases become glasslike solids, and at the high temperatures they boil away or decompose. Other lubrication techniques had to be developed in response to these needs. Although these problems appear to be wholly related to space rather than to industrial problems, they are solved by the application of principles that can be applied to lubrication problems in general.

Aerospace machinery utilizes many types of bearings such as liquid- and gas-lubricated sliding bearings and ball and roller bearings operating in the environments mentioned as well as in hard vacuum and intense radiation. This brief discussion, however, will be confined to some of the work performed to develop extreme-temperature ball and roller bearings and more reliable long-life bearings.

Before discussing nonconventional lubrication methods, the functions of a lubricant will be reviewed briefly. First, the lubricant must prevent surface damage at the contact between sliding and rolling surfaces by providing a contaminating film. Second, the lubricant should remove frictional heat that is generated. Of these two functions, the need to remove frictional heat is quite obvious but what is a contaminating film? It is any sort of surface film, liquid or solid, that prevents clean metals from coming into intimate contact with each other. If clean metals do come into intimate contact under load, they will weld or stick, and severe surface damage may result. Graphically illustrated in figure IVa–1 is what happens when two unlubricated clean metals slide against each other. The materials have welded, and a piece of one material has been torn away from the main body. The lubricant must prevent this, because if it occurs in a bearing the bearing will fail. Rapid wear out is one failure mode of bearings that results from inadequate lubrication.

The components of a ball bearing are shown schematically in figure IVa–2. The ball bearing is composed of several parts. It has an inner race, which is fastened to and rotates with the shaft, and an outer race, which is usually encased in a fixed housing. In the annular space between the inner and the outer races, there are a number of rolling elements (in this case they are balls). The last part of a ball bearing is called the retainer or cage. Its purpose is to keep the rolling elements equally spaced. In a ball or roller bearing all the pure sliding contacts involve the retainer. The retainer slides on its locating race and the balls slide in the pockets against the retainer. The contact that takes place between the balls and the races is partly rolling and partly sliding. Lubrication is required at all these rolling and sliding contacts.

In applications in which oil lubrication cannot be used, a retainer made of a self-lubricating or slippery material is substituted for the standard metallic retainer. As shown in figure IVa–3, lubrication is provided directly at all the retainer contacts. Lubrication is also required at the ball-race contacts. It can be accomplished by means of a transfer film. The ball slides in the retainer pocket and continually wipes a thin film from the pocket and deposits it on the race. It is important to note that only minute quantities of lubricant are necessary. Surface films a few millionths of an inch thick are adequate; therefore, self-lubricating materials and coatings can be effective lubricants.

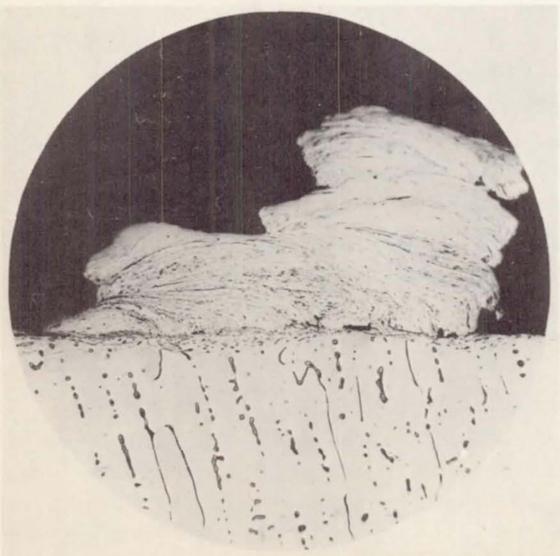

FIGURE IVa–1.—Severe surface welding resulting from unlubricated sliding; 2 percent aluminum-nickel alloy from experiment at vacuum of 10^{-9} millimeter of mercury.

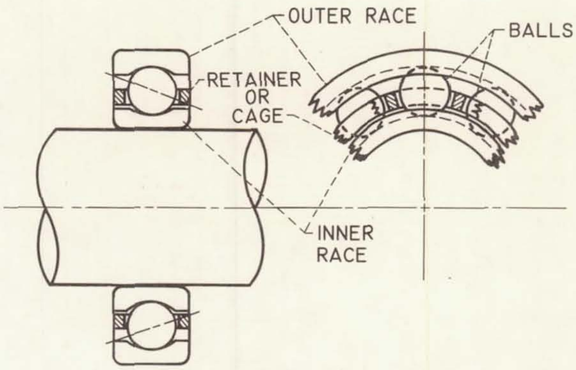

FIGURE IVa–2.—Ball-bearing components.

Materials containing fluorocarbon polymers have been highly successful when used as retainers in cryogenic applications where, as mentioned previously, conventional lubricating oils become glasslike solids. While the use of self-lubricating materials such as polytetrafluoroethylene and nylon in low-speed sleeve bearings is not new, a number of new materials containing polytetrafluoroethylene have been developed for high speeds. These materials have better strength, are easier to fabricate, and are useful in a wider variety of bearings.

Cryogenic turbomachinery must run at high speeds in order for the turbine and pumps to operate efficiently, and this requires high-speed bearings. The frictional characteristics of polytetrafluoroethylene are good, but they are not quite so good as those of oils, and, therefore, the heat generation problem becomes more acute as illustrated in figure IVa–4. The balls are rotating very rapidly and the centrifugal force developed tries to throw them out of the bearing. In standard ball bearings the force between the balls and the outer race becomes appreciable and results in considerable heat generation.

It was therefore necessary to describe mathematically what occurs inside a high-speed bearing to determine the effect of different design variables, such as bell diameter, on heat generation. One thing this analysis indicates is to use small balls; this is physically obvious because reducing the ball size reduces the centrifugal force. However, the ball size can be reduced only a

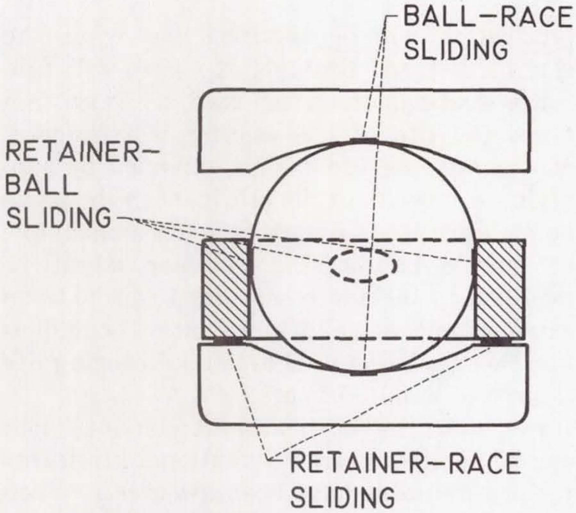

FIGURE IVa-3.—Points of sliding in a ball bearing.

limited amount before the space available for the retainer becomes too small. If the retainer cross section is reduced too much, it will break at high speed because of inadequate strength.

A possible solution to this problem is the use of hollow balls. One very promising technique being investigated for the production of hollow balls is the use of electron-beam welding to fasten two hemispherical cups together. Although hollow balls have not been evaluated experimentally, the microstructure produced by electron-beam welding appears promising.

As a result of this program, high-speed ball-bearing design philosophy has been changed considerably. The small-ball concept is now being widely used to produce more reliable high-speed bearings in which lubrication problems are less critical.

The fact that self-lubricated bearings can be operated at high speeds without the need of conventional oils has broad implications. There are many applications where freedom from the danger of organic contamination would be desirable, for example, textile and food-processing machinery.

In the extremely high temperature range, organic materials such as polytetrafluoroethylene decompose, and inorganic solid lubricant coatings must be used. Simple sprayed-on coatings containing such common solid lubricants as graphite and molybdenum disulfide are in common use, but their use is limited to the temperature at which they begin to oxidize.

Future aerospace applications may require bearings to operate white hot. To meet this requirement, coatings are being developed that are fused to the surface by firing them at very high temperatures—just as a ceramist glazes a ceramic.

The melting points of some solid lubricants suitable for very high temperature applications are too high to allow them to be fused to the surface of ordinary metals. The solid lubricant is therefore mixed with a second constituent in the proper proportions to produce a eutectic. As an example, the solid lubricant, lead oxide (melting point, 1630° F), can be mixed with lead silicate (melting point, 1350° F) to form a eutectic with a melting point of 1317° F.

A water slurry of the two constituents is first sprayed on the surface, and then the coating is fired in a furnace. Coatings may be fired in an air atmosphere, but if oxidation of the base metal is a problem and if the solid lubricant is not easily reduced, a hydrogen atmosphere may be used.

Because of the expense of conducting full-scale bearing tests, experimental coatings are

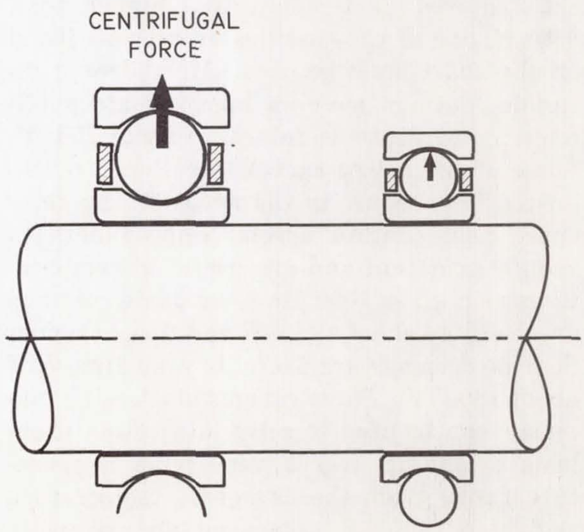

FIGURE IVa-4.—Effect of ball size in high-speed bearings.

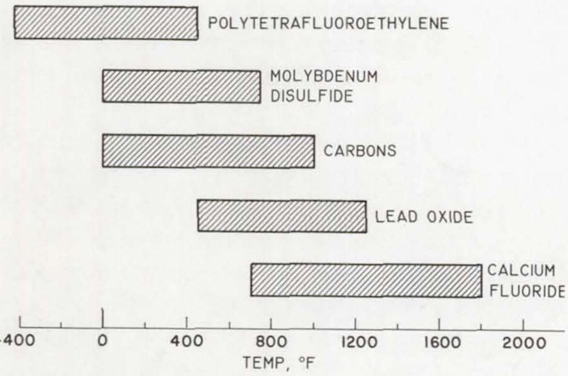

FIGURE IVa–5.—Useful temperature ranges of self-lubricating materials.

first evaluated in simple friction and wear tests utilizing a bullet-shaped rider rubbing against the face of a rotating disk. Friction coefficients and specimen wear are measured in these tests. The most promising coatings are then evaluated in bearings by applying the coating to the retainer. Bearings with lead oxide—lead silicate coated retainers have been successfully operated at 1200° F and 5000 rpm at the Lewis Research Center.

The approximate useful temperature ranges of polytetrafluoroethylene and various types of coatings are illustrated in figure IVa–5. Polytetrafluoroethylene is usable from cryogenic temperatures up to a maximum of 450° F. If self-lubricating materials are required at temperatures higher than 450° F, one of the coatings or carbons listed on the chart must be used. Molybdenum disulfide coatings have an approximate maximum temperature usefulness of about 750° F. Some of the newer carbons developed by industry in response to the needs of the aerospace field contain special impregnants to reduce oxidation and are useful at temperatures as high as 1000° F. Lead oxide coatings are useful to about 1250° F and fused calcium fluoride coatings are useful to a maximum of about 1800° F. These various lubricating materials can be used to solve lubrication problems extending over a very wide temperature range from the cryogenic temperature region to 1800° F, where metals are white hot. As long as coatings remain intact, good lubrication will be obtained, but when the coating is worn through, the part will fail. Since coatings must be used as very thin films, the life of the coating is frequently short. Bearing life can be extended by supplying reservoirs of the lubricant in the parts being lubricated. Figure IVa–6 is an example of how a ball-bearing retainer might be modified to include reservoirs to provide an extra supply of solid lubricant. Techniques like this are being used to extend bearing life to several hundred hours.

Some of the lubrication techniques that can be applied where conventional lubricants become unusable have been discussed. When an adequately lubricated ball bearing runs under load, it will fail by fatigue. Fatigue occurs when a part is subjected to stresses that are repeated until the part breaks. In principle, a bearing fails in much the same way. The pressure from a ball rolling over a given spot on a race creates a high stress in the material. As succeeding balls roll over this spot, the material is stressed again and again. Eventually, a crack forms in the material at the weakest point. This crack spreads with successive stress applications until a piece of material breaks off; this is called a fatigue spall. A typical fatigue spall

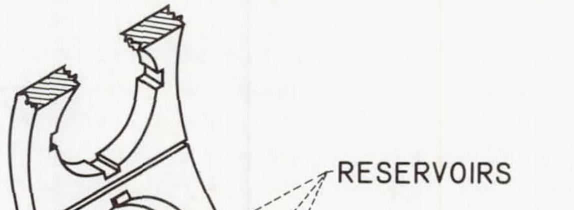

FIGURE IVa–6.—Ball-bearing retainer with solid lubricant reservoirs.

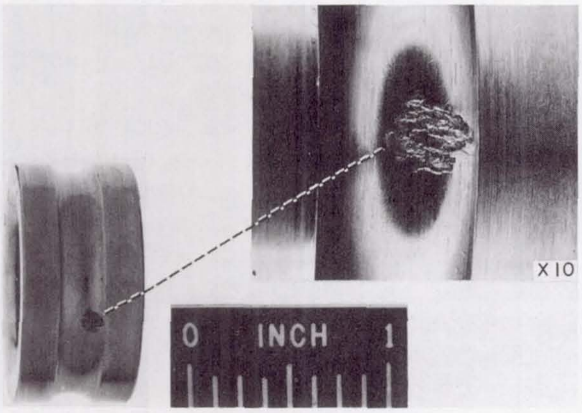

FIGURE IVa-7.—Typical fatigue spall.

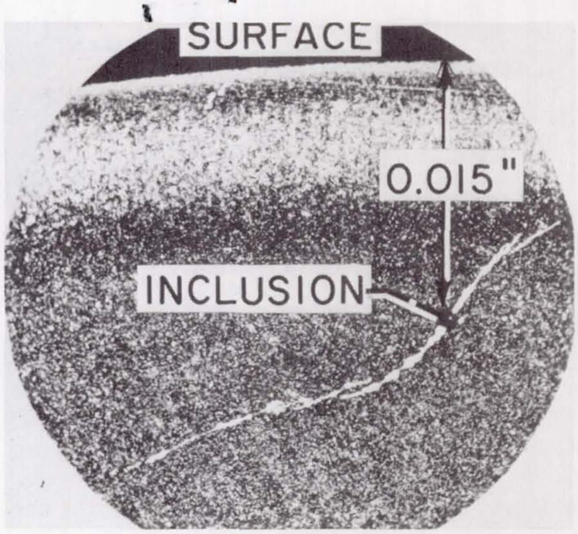

FIGURE IVa-8.—Fatigue crack originating at an inclusion.

is shown in figure IVa-7. A piece of material, roughly circular in shape, has fallen out of the race groove. The previous discussion centered on the lubricant, which was the life-limiting factor causing failure by wear and surface destruction. In the case of fatigue, the material is the life-limiting factor. Research on fatigue has shown that most fatigue cracks originate at what is called inclusions or foreign particles. Figure IVa-8 is a photograph of a typical inclusion at which a fatigue crack has started and is a highly magnified cross section of a race as seen through a microscope. The inclusion is located in the region where stresses are very high—about 0.015 inch below the surface. Although this is considered to be a large inclusion, the inclusion itself is quite small—about 0.0005 inch in diameter.

Bearing materials are complex alloys containing several metals and carbon. Some of the alloying elements react with oxygen in the atmosphere to form hard oxides when the bearing alloy is melted and fused. Hard oxides constitute one type of damaging inclusion. In conventional air melting, as illustrated in figure IVa-9, no attempt is made to control the atmosphere so that these damaging oxide inclusions can be formed. In addition, the melt is fused in a ceramic or clay crucible. Small ceramic or glasslike particles sometimes break off from the crucible and get into the melt. Until a few years ago bearing materials were melted in an air atmosphere.

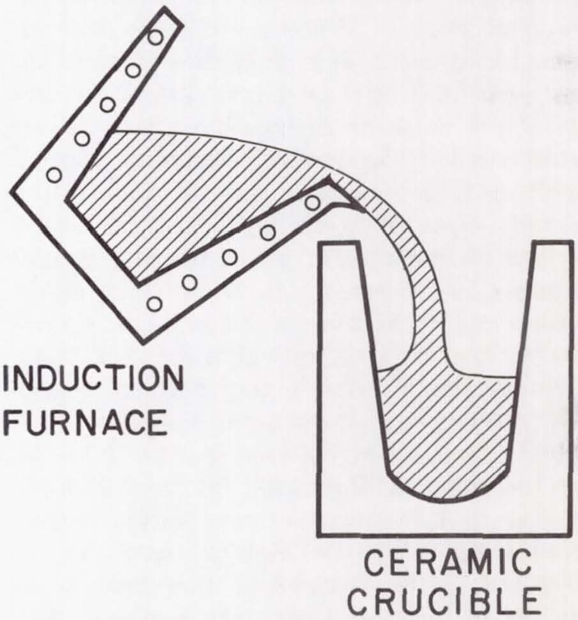

FIGURE IVa-9.—Conventional air melting.

A process known as consumable electrode vacuum melting was devised to eliminate inclusions and foreign particles (fig. IVa-10). A water-cooled copper crucible is used to eliminate the possibility of ceramic particles getting into the melt. The raw ingot is used as one terminal of an electric arc that

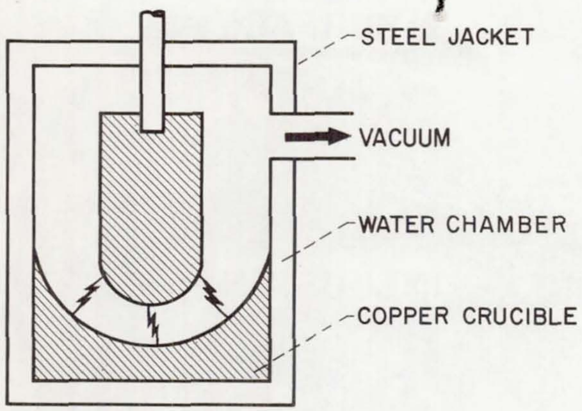

FIGURE IVa-10.—Consumable electrode vacuum melting.

is initially struck from the ingot to the copper. A vacuum is drawn to remove gases as the energy from the arc gradually melts the ingot. The melt collects and fuses in the copper crucible. Since there is no ceramic crucible present and since the oxygen has been removed by the vacuum system, the two principal causes of fatigue have been largely eliminated. Consumable electrode vacuum melting is now widely used to produce uniformly clean, high-quality bearing alloys.

The second way in which bearing fatigue life can be improved is through better manufacturing. Whenever a material is shaped by rolling, forging, or extrusion, the metal grains take on a stringlike pattern, resembling fibers—thus, the term fiber flow. The fiber flow in a bearing race that has been cut from tubing is illustrated in figure IVa-11. Research has shown that metals are weaker in fatigue when the ends of the fibers are exposed to the stressed surface than when the fibers are parallel to the surface. Note the fiber ends, which are exposed to the stress region in the race cut from the tubing.

If a special forging technique is used, a race with essentially parallel fibers in the highly stressed ball groove can be produced.

To summarize these techniques very briefly, bearing life has been extended by largely eliminating inclusions and foreign contaminants which cause fatigue. New forging techniques are being used to produce better fiber orientation in the bearing races. These two techniques together conservatively result in an increase in bearing life of about six times that of a decade ago.

Further improvements are being realized from the development of new nondestructive inspection techniques utilizing ultrasonics. These techniques are used to detect minute subsurface flaws in the material. While these methods are still experimental, they offer much promise. The net result of all these factors may be an improvement in bearing life of as much as 10 times that of a decade ago.

Let us summarize briefly what has been said. Several lubrication techniques which can be used to provide lubrication for bearings in which conventional oils and greases cannot be used have been illustrated. Self-lubricating materials, such as polytetrafluoroethylene and several types of lubricant coatings, have a potentially wide range of applications where clean bearings are required. Examples are food-processing equipment and textile machinery, where contamination from oils would be undesirable. When lubrication is adequate, improvements in materials have resulted in the extension of bearing fatigue life to about six times that of a decade ago. This increased life means that greater reliability can be obtained in machinery required to operate unattended for long periods of time.

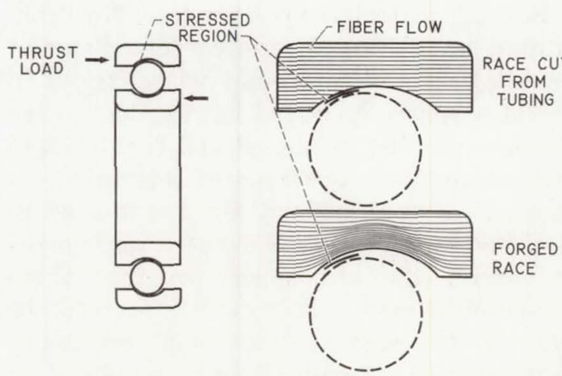

FIGURE IVa-11.—Fiber flow in bearing races.

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IVb. Liquid-Metal Technology

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WHAT ARE LIQUID METALS? Obviously any solid metal will melt if heated to a sufficiently high temperature. Liquid metals, however, are those metals that melt at a relatively low temperature: within a few hundred degrees of room temperature. Among the liquid metals are mercury and the alkali metals, sodium, potassium, lithium, and cesium.

The technological uses of liquid metals are both quite old and quite new. Applications of liquid metals go back beyond recorded history and some have yet to be fully realized. The earliest record of a liquid metal was uncovered by the famous archaeologist Schliemann, who found a small vessel filled with mercury in a tomb in Kurna, Egypt; the tomb was estimated to be from the 15th or 16th century B.C. A retrospective glimpse shows that mercury was used from early times as a medicinal agent and also as an extraction medium for the separation of gold and silver from their ores.

The alkali metals, sodium and potassium, were first isolated over 150 years ago. Almost immediately they found use as chemical reducing agents in the first commercial production of aluminum. Today, most of the sodium produced (about 250 million lb) is used in the synthesis of tetraethyl lead, an antiknock agent for automotive gasoline.

Until recently, liquid metals have been exploited primarily for their chemical properties. In the past 40 years the special physical properties of liquid metals have pointed the way to new applications. It is these special physical properties and the uses suggested by these properties that are discussed.

Figure IVb–1 illustrates that the liquid metals have a very large range of temperature over which they are liquid in comparison with other fluids that have enjoyed industrial applications, such as water and Dowtherm. The lower and the upper boundaries of the bars indicate the melting temperature and the normal boiling temperature, respectively, for each material. It should be noted not only that do the liquid metals have a wide range but that these ranges extend to high temperatures. Mixtures of two liquid metals often produce a solution with a lower melting point than the melting point of either component. That mixture yielding the lowest melting solution is termed a eutectic mixture. A mixture of 78 weight percent sodium and 22 weight percent potassium, shown as NaK

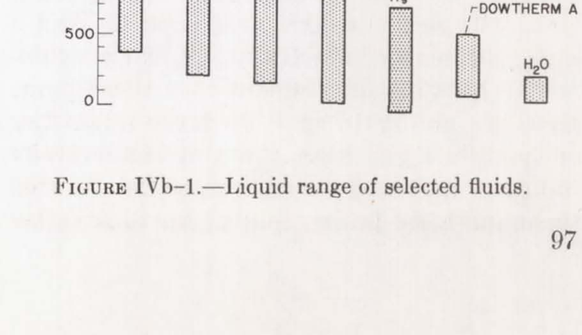

FIGURE IVb–1.—Liquid range of selected fluids.

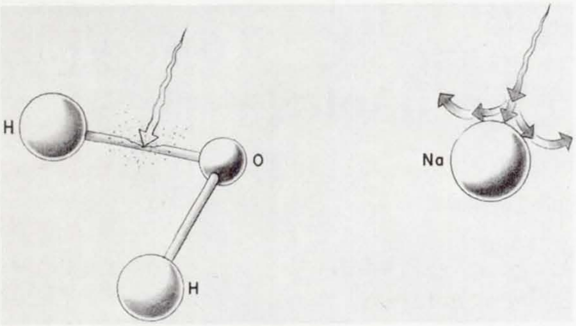

FIGURE IVb-2.—Thermal and radiation stability of fluids.

in figure IVb-1, is a eutectic mixture with a melting point of 12° F. This is to be compared with a melting point of 208° F for sodium and 146° F for potassium. The phenomenon of eutectic mixtures can be used to advantage to extend the liquid range of metals downward.

The stability of liquid metals is excellent when they are exposed to heat and nuclear radiation (fig. IVb-2). This is uniquely so because the liquid metals have a monatomic structure, while the makeup of most other liquids is that of polyatomic molecules held together by chemical bonds. Since the amount of energy required to break a chemical bond is not very large, decomposition of polyatomic molecules can be expected when they are subjected to heat or nuclear radiation. For example, hydrocarbons begin decomposing at about 500° F. The rupture of the molecular structure will usually produce undesirable changes in the fluid. Decomposition of water under nuclear radiation leads to the formation of hydrogen and oxygen gases with a resultant pressure buildup in closed systems; decomposition of organic fluids results in the formation of sludges and crud.

Liquid metals are endowed with superior qualities as heat-transfer fluids. They have both a large volumetric heat capacity and a high thermal conductivity. A large volumetric heat capacity means that these fluids have the ability to soak up large quantities of heat energy; high thermal conductivity indicates that heat energy can be transmitted through these fluids rapidly. An illustration of the capability of liquid metals to perform as heat-transfer fluids would be helpful at this point. Assume that we were to build a 1-megawatt nuclear reactor and had a choice of the three heat-transfer fluids, sodium, water, or air, to remove the heat energy from the reactor. Since there is a limit to the heat-transfer capability of each fluid, the question we may ask is, how small can we make a 1-megawatt reactor before exceeding the capacity of a particular fluid to extract heat? In figure IVb-3 are pictured three volumes bounded by the peripheries of a beer keg, a pickle barrel, and a wine tun. Imagine that each of these volumes represented the core volume of a 1-megawatt reactor. Then, each volume would be the minimum volume that could be cooled by the fluid shown below each picture. Sodium, manifestly, has the best heat-transfer capability of the fluids used in this example.

Liquid metals are good conductors of electricity second only to such well-known conductors as copper and silver. Sodium, for instance, has a specific resistance only three times as great as copper. In addition, the alkali metals can be readily ionized, since the ionization potential, or the energy required to remove an electron from an alkali metal atom, is quite low. This means that positively charged ions of sodium or cesium, for example, can be easily formed.

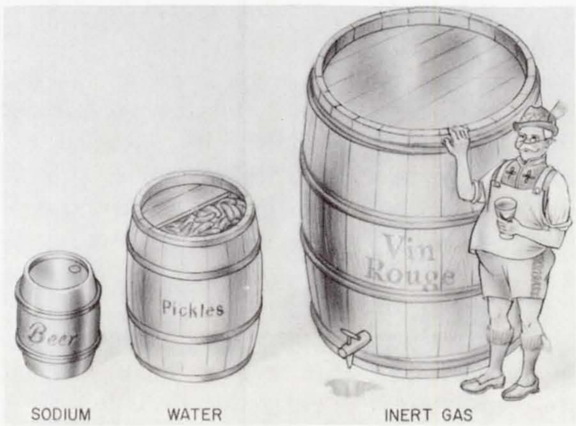

FIGURE IVb-3.—Heat-transfer capabilities of selected fluids. 1-Megawatt nuclear reactor minimum core size as determined by coolant fluid.

To recapitulate, liquid metals are technically interesting fluids because of their wide liquid range, stability, excellent heat-transfer characteristics, and special electrical properties.

One of the earliest applications of the special physical properties of liquid metals was conceived about 40 years ago—sodium cooling of exhaust valves. In an internal combustion engine the exhaust valve head is heated by exposure to the combustion process; also the exhaust gases deliver heat to the underside of the head. The objective is to transfer heat down the stem and dissipate the heat through the cooled valve guide. Sodium filled valves markedly reduce valve temperatures. Heat is transferred from the head of the valve to the stem by the splashing of the liquid sodium as the valve moves up and down. It can be seen in figure IVb–4 that the temperature of the sodium-cooled valve is 300° to 500° F lower than the solid stem valve. All aircraft engines over 300 horsepower and heavy duty truck and bus engines use sodium-cooled valves. As would be expected, temperature reduction materially increases valve life.

A logical extension of this cooling concept has been suggested for turbojet engines and is still in the experimental stages. Turbojet engines could realize increased thrust and efficiency if the temperature of the gas entering the turbine was increased. The limiting factor of the turbine-inlet temperature is the strength of turbine blade material, since material strength falls off rapidly with increasing temperature. If turbine blades were cooled, turbine-inlet temperatures could be increased without exceeding material stress restriction. Two turbine blades, one solid and the other honeycombed with liquid-metal-filled passages, are illustrated in figure IVb–5. The honeycomb blade has fins fixed to the outer side of the passage along the lower end to permit effective transfer of heat from the liquid metal to cooling air. With an 1800° F turbine-inlet temperature for the solid blade and a 2200° F turbine-inlet temperature for the liquid-metal-cooled blade, the liquid-metal-cooled blade will actually run cooler than the noncooled blade.

From jet engines let us turn to a more prosaic use of liquid metals for heat transfer. For example, how could liquid metals find use in the manufacture of glassware? Glass blanks at about 2100° F are placed in a blowing mold and are air blown to final shape. The temperature of the glass drops about 1000° F during the 5-second blowing operation. All this heat is absorbed by the mold, transferred to the outside surface of the mold, and finally dissipated by blowing cool-

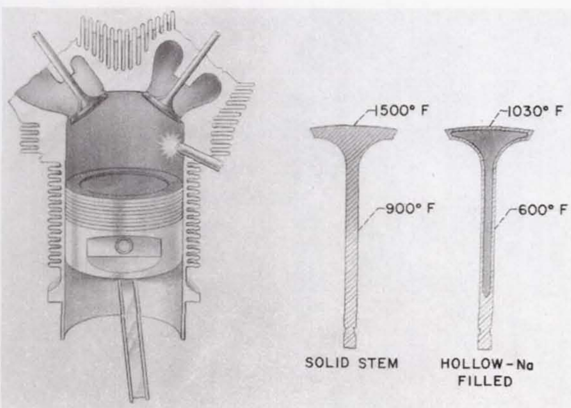

FIGURE IVb–4.—Effect of sodium cooling on exhaust valve temperature.

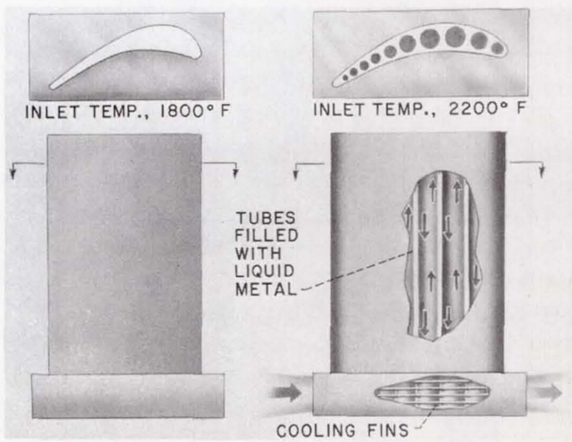

FIGURE IVb–5.—Effect of liquid-metal cooling on turbine-blade temperature.

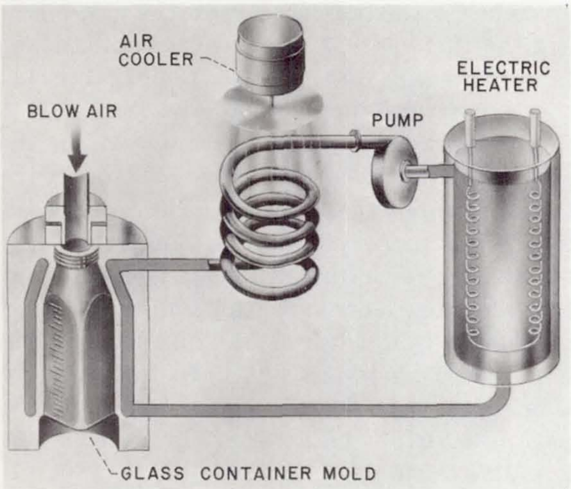

FIGURE IVb–6.—Proposed liquid-metal temperature for glass-molding operation.

ing air over the surface. It is important that there be good temperature control, because too high a temperature results in glass sticking to the mold and too low a temperature causes checking of the glass. Good operation requires a method of rapid heat transfer and at the same time the maintenance of a constant temperature of about 1100° F. Figure IVb–6 is a schematic of a proposed temperature control system for glass molds. The liquid metal circulated through the mold extracts or adds heat as required. It has been estimated that for an 8-ounce baby bottle, pictured in the figure, the liquid metal could control temperature such that the temperature of the mold would not rise more than a few degrees during each blowing operation. This is to be contrasted with a 100° to 300° F rise without liquid-metal cooling.

From baby bottles to milk is a simple jump. Also a simple jump is considering the application of the heat-transfer capabilities of liquid metals to the processing of milk, in particular, pasteurization where high heat-transfer rates are desirable. In fact, many food processing operations could similarly benefit, because high heat-transfer rates allow increases in processing capacity and lessen damage to flavor and vitamin content.

The heat-transfer characteristics of liquid metals invite their use for a whole spectrum of applications from jet engines to baby bottles. But this is only a start. Research presently being conducted under sponsorship of the AEC, the DOD, and NASA in the use of liquid metals as heat-transfer fluids in the temperature range of 1200° to 2200° F will serve to widen and extend the application of these fluids.

A second major technological use of liquid metals is as working fluids in electric power generating systems. Figure IVb–7 is a pictorial representation of a Rankine cycle power system. Such power systems are widely used for the generation of electric power. In the boiler, liquid heated by energy from a nuclear reactor or from combustion of fossil fuel produces vapor. (In the case of a steam powerplant the liquid used is water.) The vapor passes through a turbine, which converts the energy of the vapor to mechanical shaft work, which is then used to turn an electric generator. After leaving the turbine, the vapor is condensed to liquid by cooling and the liquid is pumped back to the boiler.

In general, the greater the temperature difference between the temperature of the vapor entering the turbine and the condensing temperature of the vapor, the greater is the efficiency of the power cycle. The lowest temperature attainable for condensation is set by the temperature of the coolant used; for terrestrial power systems this tempera-

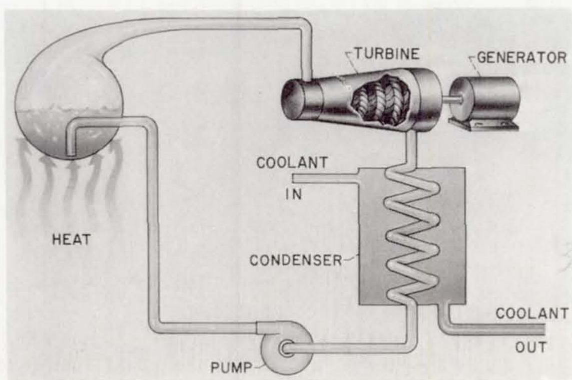

FIGURE IVb–7.—Rankine cycle power system.

ture is that of available river or lake water. The highest practical temperature that can be realized for the vapor entering the turbine depends on the particular working fluid chosen and the strength of the materials available for containing the fluid.

To clarify the role of temperature in choosing a fluid for a Rankine cycle system, let us refer to figure IVb–1, which shows the liquid range of several fluids. The normal boiling point of each liquid is given by the topmost limit of each bar. The normal boiling point is that temperature at which the pressure of the vapor above the liquid reaches 1 atmosphere (or 14.7 lb/sq in. abs). In the case of water this temperature is 212° F. The main observation to be made from this figure is that the normal boiling points of the liquid metals are generally quite high, ranging from 675° F for mercury to 2440° F for lithium.

The variation of vapor pressure with temperature for water and some of the liquid metals is illustrated in figure IVb–8. A horizontal line drawn across the plot at 14.7 pounds per square inch absolute would intersect each vapor pressure curve at a temperature equal to the normal boiling point of the respective fluid. It can be seen that as temperature increases the vapor pressure builds up rapidly. Obviously, there will be a pressure above which it will be difficult, if not impossible, to contain the vapor because of strength limitations of materials. Under such conditions it is necssary to switch to the use of another fluid with a lower vapor pressure.

The shaded areas of the figure indicate what are believed to be practical operating regions for power systems using the working fluids shown. The higher the temperature at which a fluid can operate, the greater can be the system efficiency. In figure IVb–9 is shown a measure of the dividends achievable by increasing operating temperature. Heat rate is plotted against powerplant capacity for powerplants using one of three working fluids, water, mercury, or potassium, each operating in their optimum temperature regime. The heat rate is the ratio of the available fuel energy to the electric energy generated and, as such, it is a measure of efficiency. The curves for water and mercury are derived from powerplant operation experience, while the curve for potassium is estimated. From these curves, it can be inferred that an appreciable gain is to be made in powerplant efficiency by the use of liquid-metal working fluids at high temperature.

Currently, as shown in figure IVb–8, there are two major programs on Rankine cycle

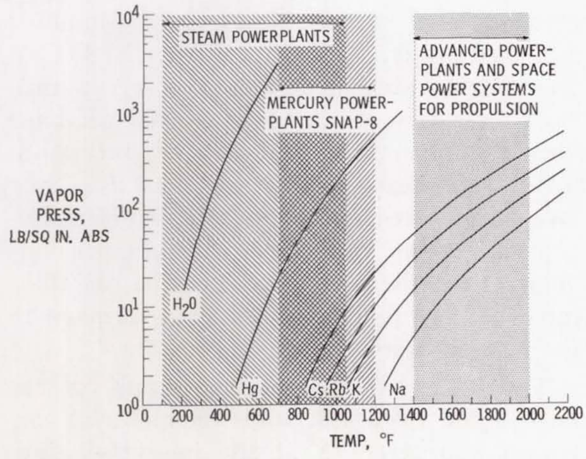

FIGURE IVb–8.—Vapor pressure of selected working fluid.

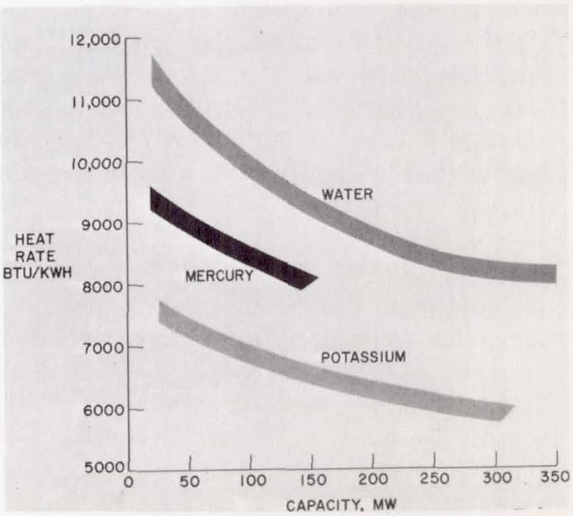

FIGURE IVb–9.—Electric powerplant fuel efficiency.

space power systems, sponsored by NASA, AEC, or DOD. The SNAP–8 space power system is a 35-kilowatt nuclear-electric system using mercury as the working fluid and is now in its early development stage. More advanced power systems that could produce several megawatts of electric power for space vehicle propulsion and would use potassium as the working fluid are still in the research and component evaluation stage. The knowledge and experience gained from these systems should have a major impact on terrestrial powerplants a decade or two from now. Higher system efficiency may allow us to reduce costs and should certainly allow us to conserve irreplaceable fuel supplies.

Some of the heat-transfer and working fluid applications of liquid metals have been mentioned. Some of the electrical uses of liquid metals are discussd in the following paragraphs. The good electrical conductivity of liquid metals enables them to be used at either high or low temperatures to carry large currents. For example, sodium filled iron pipes have been used as bus bars to carry up to 4000 amperes d.c. for several years with no signs of deterioration. Also, liquid metals can be used as frictionless brushes or switching contacts in electrical equipment. The ubiquitous mercury switch is but one example of this type of application.

In the last few years many new exotic applications based on their faculty to ionize readily have been found for the alkali metals. A cesium propellant ion engine is shown in figure IVb–10. (More detail on the significance of this engine in the space program is presented in the paper by Mr. W. D. Rayle.) In this engine, the passing of cesium vapor through a very hot porous tungsten plate results in the ionization of the cesium: an electron is stripped from the atom, leaving a positively charged cesium ion. The cesium ions are then accelerated by an electric field to high velocities, thereby resulting in thrust to the engine.

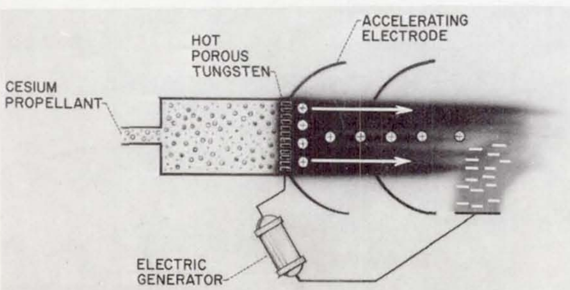

FIGURE IVb–10.—Cesium propellant ion engine.

Other futuristic electrical uses of liquid metals are as ionized working fluids in magnetohydrodynamic power systems and as an ionized vapor to dissipate current limiting space charge in thermionic devices.

To complete this discussion of liquid-metal technology, some of the hazards of, experience with, and containment material for liquid metals should be mentioned. Liquid metals are not extremely hazardous materials and when properly employed offer few difficulties. With mercury, the major hazard is the toxicity of the vapor. Mercury, however, has been used as a power system working fluid in half a dozen commerical powerplants since 1922. Safe methods have been developed to handle large quantities of mercury and to detect leaks in operating equipment.

The main hazard involved in the use of alkali metals is fire. Alkali metals react vigorously with oxygen and water and, under the proper conditions, burst into flame. The wide experience, however, with the alkali metals has shown that they can be handled and used safely. Sodium is shipped in 80,000-pound lots throughout this country in railroad tank cars. Both sodium and NaK have been used in liquid-metal—water and liquid-metal—air heat-exchange systems for over two decades as part of the AEC liquid-metal-cooled reactor programs. Experience has shown that when leaks do occur the reactions have been nonviolent, with little damage to the system other than plugging.

The choice of container materials for use with liquid metals depends on material corrosion and strength at the operating temperature. Figure IVb–11 is a bar graph of materials suitable for use with mercury and the alkali metals as a function of temperature. The identification of suitable containment materials above 1000° F is the result of many research programs conducted by the AEC, DOD, and NASA. Materials definition in the region above 2000° F is the object of current research.

In summary, the liquid metals can be uniquely employed as high-temperature heat-transfer and working fluids and in special electrical applications because of their large liquid range, stability, excellent heat-transfer characteristics, and good electrical properties. Contemporary liquid metals research and development projects are further serving to widen and extend the technological usefulness of liquid metals.

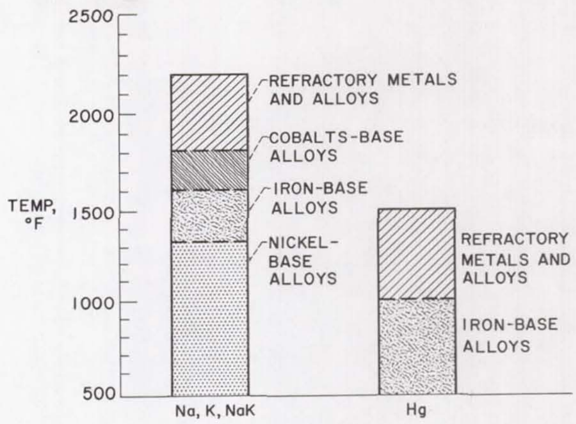

FIGURE IVb-11.—Compatibility of materials with selected liquid metals.

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IVc. Cryogenic and Superconducting Devices

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IN THE LAST DECADE there has been a tremendous interest in the use of cryogenic techniques as a means of reducing power consumption in all kinds of electrical devices. The electrical resistivity of most conductors decreases very markedly with temperature, as illustrated in figure IVc–1. Good conductors such as copper or aluminum show a decrease in electrical resistance of four or five orders of magnitude between room temperature and temperatures near absolute zero. Absolute zero is defined as that temperature at which all gross motion of the atoms ceases. There is a distinct leveling off of the resistance at very low temepratures, and there is a residual resistance of most materials at temperatures near absolute zero. A class of materials known as superconductors shows a sharp drop in resistance at very low temperatures; lead and tin are two such materials. A considerable number of elements and alloys have this property, and at some critical temperature, dependent on the material, the resistance drops to a value so low as to be unmeasurable by any techniques now available.

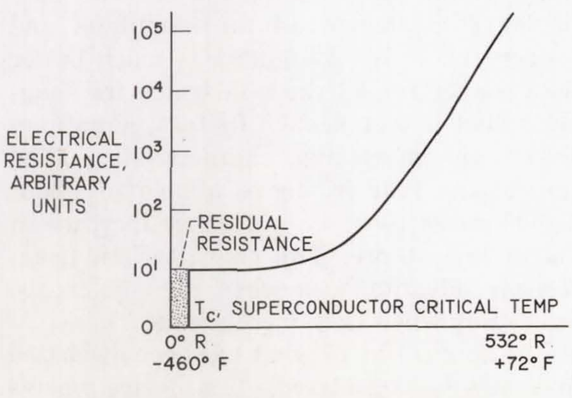

FIGURE IVc–1.—Resistance of conductors.

There are therefore two distinct classes of conductors: normal conductors and superconductors. These classes are discussed separately, with the discussion first considering (1) a decrease in resistivity by going to low temperatures with normal conductors and (2) superconductors. An interesting sidelight is that materials such as copper and aluminum, which are considered to be good conductors at room temperature, either are not superconductors at all or at least are very poor ones. Other materials that are rather poor conductors at room temperature are rather good superconductors.

The value of applying cryogenic but nonsuperconducting techniques to electrical devices is to reduce the total power consumption of such a system. It must be possible to decrease the power consumption of a particular electrical device sufficiently that the sum of the power consumed by the device and the refrigeration power is less by a significant amount. Obviously, the electrical heating losses in the device must therefore be reduced to as small a value as possible. The particular device of concern at Lewis was a large cryogenic magnet, but the same principles apply to any electrical device that has a significant power loss simply due to the resistance of the conducting material.

In general, then, the first problem is the choice of a conductor that will give the best possible characteristics at low temperatures. The characteristics of resistance R of normal materials are as follows:

$$R = R_T + R_0 + R_M$$

where R_T is the thermal resistance, R_0 is the residual resistance, and R_M is the magnetoresistance. The thermal resistance is a function of the temperature and really results from the activity of the atoms in the material. If the atoms are thought of as being in a lattice structure, tied together in a neat and orderly arrangement, it is easy to visualize what happens. An atom situated at any particular point moves up and down or crosswise in the lattice and interferes with the motion of the current-carrying electrons. As the temperature is decreased, the atomic motion decreases, and the electrons pass more easily through the lattice. The residual resistance is a function of atomic regularity and merely reflects the fact that impurities and stresses tend to disorder the lattice structure.

Practically all the resistance at room temperature results from thermal resistance (see fig. IVc–1). At very low temperatures most of the resistance is residual resistance. The residual resistance can be reduced by using very pure materials in an annealed or unstressed condition.

Magnetoresistance is probably a new term to many people, and it is a function of the magnetic field in which the conductor lies. Since magnetic fields are generated by electrical currents, it is impossible to build an electrical device that does not produce a magnetic field; many large devices such as electrical generators produce quite large

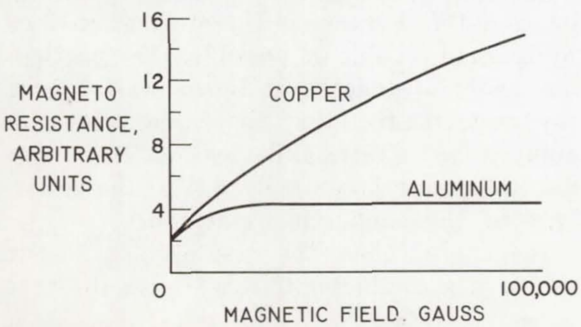

FIGURE IVc–2.—Resistance of conductors in magnetic fields. Temperature, 15° R.

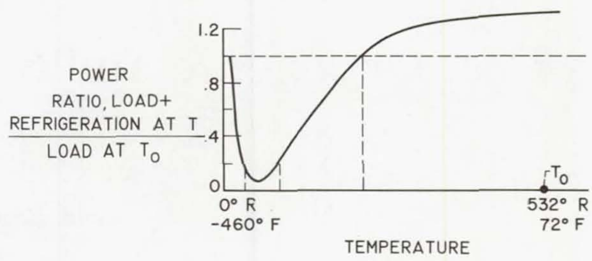

FIGURE IVc–3.—Power requirements of load and refrigeration plant.

fields. Magnetoresistance is significant only at low temperatures, but it can result in very large effects. In order to visualize how magnetoresistance produces its effect, consider the simple picture of the lattice structure filled with magnetic field lines. Since the current-carrying electrons tend to be tied to the magnetic field lines, this fact also interferes with their ready passage through the lattice structure.

For the cryogenic device, the selection of a material that has the minimum total resistance under the specified operating conditions is therefore desirable. A material with low residual resistance and magnetoresistance is needed, for if operation is at sufficiently low temperatures, that is, less than 40° R, the thermal resistance can be made negligibly small. Detailed studies have been made of the magnetoresistance of a large number of conductors, and some typical results are shown in figure IVc–2. The particular data shown are for aluminum and copper at 15° R. Aluminum is much better than copper for all cases in which the magnetic field is significant. In fact, aluminum shows an interesting characteristic called saturation; that is, above a field of about 20,000 gauss there is no further increase in magnetoresistance. This characteristic is extremely advantageous when high fields are desired or when they merely exist.

The application of what has been discussed may now be considered. If a device wastes considerable electrical power at room temperature simply because of electrical resist-

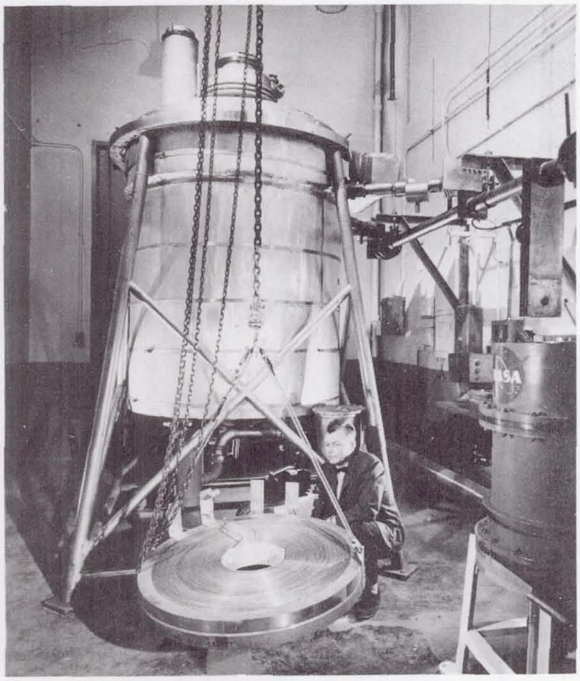

FIGURE IVc-4.—Cryogenic magnet.

ance, what advantages can be gained by going to low temperatures? Figure IVc-3 shows a particular case that was studied, that is, a magnet that produced a field of 100,000 gauss and that absorbed 3 megawatts of electrical power at room temperature. In this figure is plotted the power ratio, that is, the total power (load) of the magnet and its cooling or refrigeration plant divided by the power required to operate the magnet alone at room temperature. The power ratio goes from a value of about 1.2 at room temperature down to quite low values at about 20° R.

The fact that the power ratio is greater than 1 at room temperature merely reflects the inefficiencies in the refrigeration plant; the temperature must decrease to 200° R before the value becomes 1. The minimum value was between 20° and 50° R, and the minimum power ratio was 0.04 or 4 percent at about 35° R. The reason for the sharp rise in power ratio as very low temperatures are approached is the inefficiency of any low-temperature thermodynamic cycle; in fact, it would take an infinite amount of power to achieve operation at 0° R.

The results in this figure are shown merely to point out the large reduction in power losses that can be achieved by cryogenic techniques. Each separate case would have to be studied as to the best choice of conductor material and operating temperature.

An actual cryogenic magnet, built for operation at liquid neon temperature, 50° R or −410° F, is shown in figure IVc-4. The final magnet will consist of six pairs of coils like the ones shown and should produce a field of over 150,000 gauss. The power consumption will be about 1 megawatt compared with 100 megawatts, which would be required at room temperature. The construction of the magnet is quite interesting. High-purity aluminum is used as the conductor. Since the magnetic field is high, the stresses are large. The field of 150,000 gauss is the equivalent of 14,000 pounds per square inch of gas pressure inside the magnet bore. Construction details are shown in figure IVc-5. In order to carry the high stresses involved, the aluminum strip is bonded by a mastic or glue to a stainless-steel channel that carries the loads out to the heavy retaining ring that holds everything together. Many small spacers are provided between each turn to

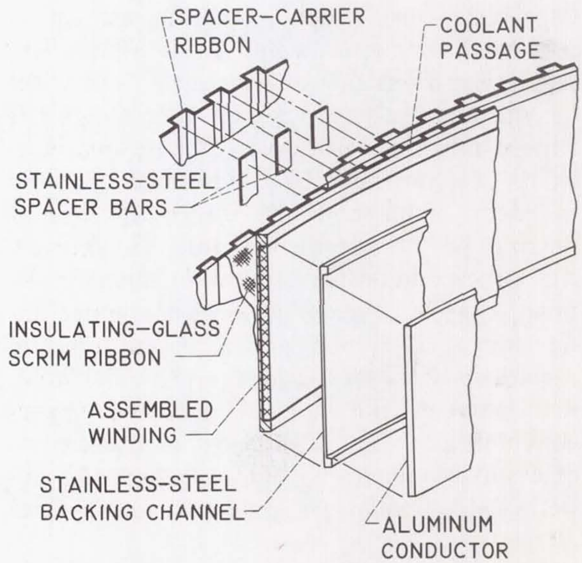

FIGURE IVc-5.—Construction of coils of cryogenically cooled aluminum magnet.

allow passage of liquid neon through the coil; cooling is accomplished merely by submerging the coils in a bath of liquid neon and allowing it to boil off as the magnet is operated.

Although it is evident that cryogenic techniques can result in substantial savings, the question might well be asked, "Why bother, when superconductors can reduce power losses completely?" The answer is really that in the future superconductors may well be used but that at present cryogenic-system technology is much further developed than superconductivity, which is still in the research stage. This research is vigorous and widespread, however, and is advancing rapidly.

In order to discuss superconductors, their uses, and potential, their characteristics should first be reviewed briefly.

Some characteristics are inherent in all superconducting materials. First, in the superconducting state they have absolutely zero resistance. A superconducting closed ring immersed in liquid helium, for example, has carried a continuous current around the loop for several years. The fact that no measurable decrease in the current was observed indicated a resistance so low as to be effectively zero. Such a current set up in a normal conductor would cease almost immediately when the power source was withdrawn. Secondly, the region over which the superconducting property of any material exists is determined by the temperature, the magnetic field, and the electrical current flowing in the superconductor. In general, the superconducting domain is sharply defined, that is, a material is either superconducting or it is not, and a sharp jump in resistance is observed at the critical boundary between the normal and the superconducting states. The third characteristic of a superconductor is the exclusion of magnetic field, which is known as the Meissner effect.

The region or domain over which superconductivity exists can be examined in more detail. The critical current as a function of temperature is shown in figure IVc–6. Consider a superconducting wire through which there is a current and the temperature of which can be controlled. If no current is flowing and the temperature is lowered to a value known as the critical temperature, the

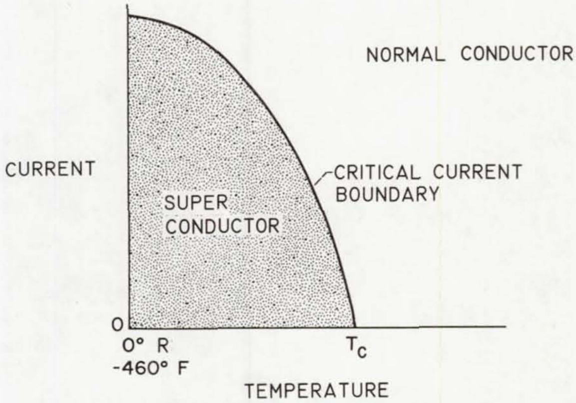

FIGURE IVc–6.—Critical current of superconductor.

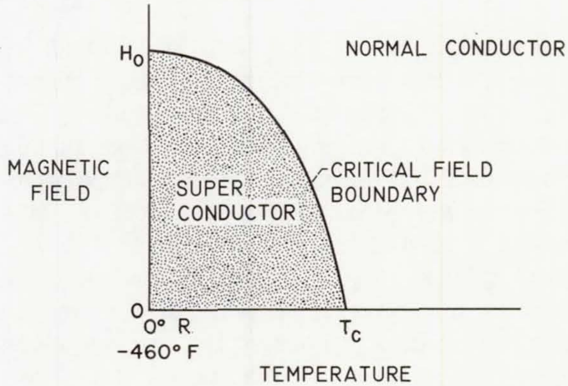

FIGURE IVc–7.—Critical field of superconductor.

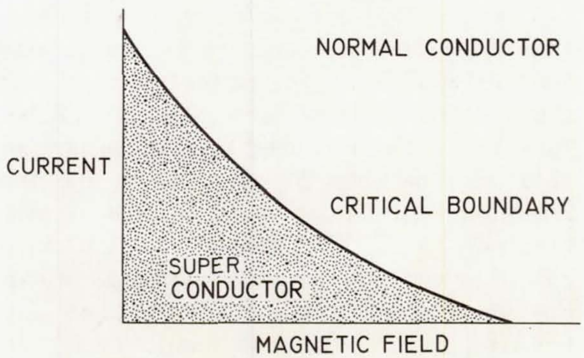

FIGURE IVc–8.—Critical current field for superconductor at constant temperature.

material suddenly becomes superconducting. For each value of current through the wire there is a particular temperature at which there is a sudden jump from the normal to the superconducting state. For any point within the shaded area, the wire will remain superconducting but outside the critical boundary the material will be a normal conductor. The highest value of critical temperature is 33° R for the alloy Nb_3Sn.

Exactly the same type of behavior is exhibited in a magnetic field (fig. IVc–7) and the same type of sharp jump is observed between the normal and the superconducting states. Finally, then, a relation for the critical current field of the superconductor is constructed. Both an externally imposed magnetic field and a current are in the sample. A typical example is shown in figure IVc–8. The critical boundary curve is for a constant temperature. Lower temperatures increase the superconducting region; that is, they raise the critical boundary. The exact shape of the curve is determined by the material, and many superconductors exhibit a straight-line relation between the two end points. The sharp boundary between the normal and the superconducting states is exactly the property used to make cryotrons. The cryotron is merely a piece of superconducting wire with a small coil wrapped around it. Current flow in the wire can be stopped by energizing the coil and producing a sufficiently large magnetic field to force the superconducting wire into the normal state.

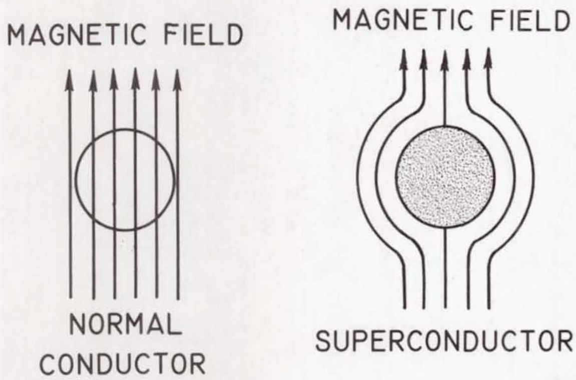

FIGURE IVc–9.—Magnetic-field exclusion; Meissner effect.

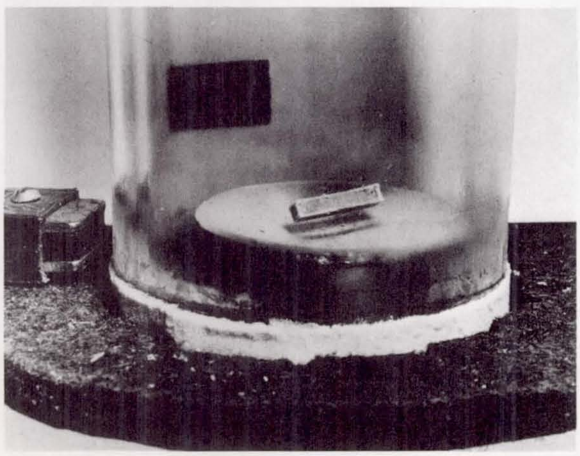

FIGURE IVc–10.—Magnet floating on its own field.

The third property of a superconductor is exclusion of the magnetic field, which is shown schematically in figure IVc–9. Consider a straight wire in a magnetic field. The end of the wire is the circle and the wire runs into the page. For most materials the magnetic field passes through the wire with no significant displacement of the flux lines. If the temperature is lowered and the wire becomes superconducting, then the magnetic lines are totally excluded. Magnetic-field exclusion exists in a whole class of superconductors to a very marked degree, but many new superconductors made of alloys show the effect only to a limited extent. The most obvious application of this characteristic is a superconducting bearing, in which a shaft would float on the magnetic field. Such a bearing would be truly frictionless. A laboratory demonstration of magnetic-field exclusion by a superconductor is shown in figure IVc–10. Floating above a lead dish is a small bar magnet. The lead has been chilled in liquid helium and made superconducting. In the normal case the magnet would lie in the dish and the flux lines from the bar magnet would pass through the dish. When the dish is superconducting, the magnetic flux lines are excluded from the dish and the bar magnet floats on its own magnetic field.

In the past, superconducting materials have had the following basic difficulties:

(1) They could not carry substantial currents without becoming normal conductors.

(2) Even small magnetic fields were sufficient to make them normal conductors.

(3) Sufficiently low temperatures were not readily available. In most cases temperatures well below 25° R are required, and only liquid helium at 8° R is sufficiently cold to give good superconducting properties.

Now many new superconducting materials carry enormous currents in the presence of high magnetic fields. In figure IVc–11 is a single superconducting wire of niobium-zirconium and its equivalent in a copper wire for room-temperature operation. The diameter of the copper wire is over 0.50 inch, while that of the superconductor is only 0.01 inch. Also shown is a very large copper wire over 0.750 inch in diameter and its equivalent in a superconducting ribbon of Nb_3Sn, which is 0.0025 inch thick and 0.125 inch wide. This is an indication of the kind of compactness that can be achieved in superconducting systems. A further illustration is a superconducting magnet. The magnet has a 2-inch bore and when operated in the Dewar filled with liquid helium produces a field of 60,000 gauss (fig. IVc–12). The magnet operates in a persistent mode without any power supply. The electric currents that produce the magnetic field simply go around in a closed path through the coil wires. It is, of course, necessary to supply the initial current to generate the magnetic field.

Achieving these kinds of fields with normal room-temperature techniques requires a considerable investment in equipment. A water-

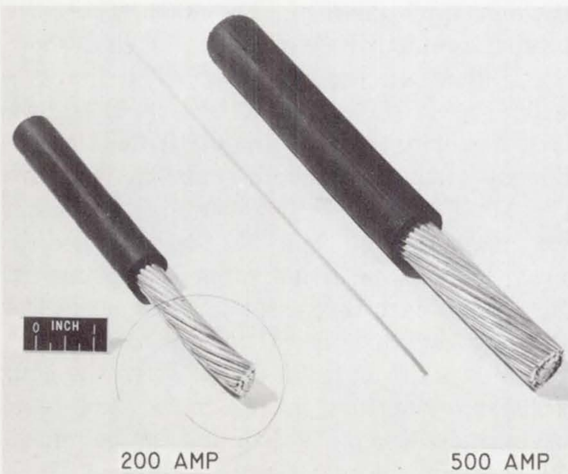

Figure IVc–11.—Current capacity.

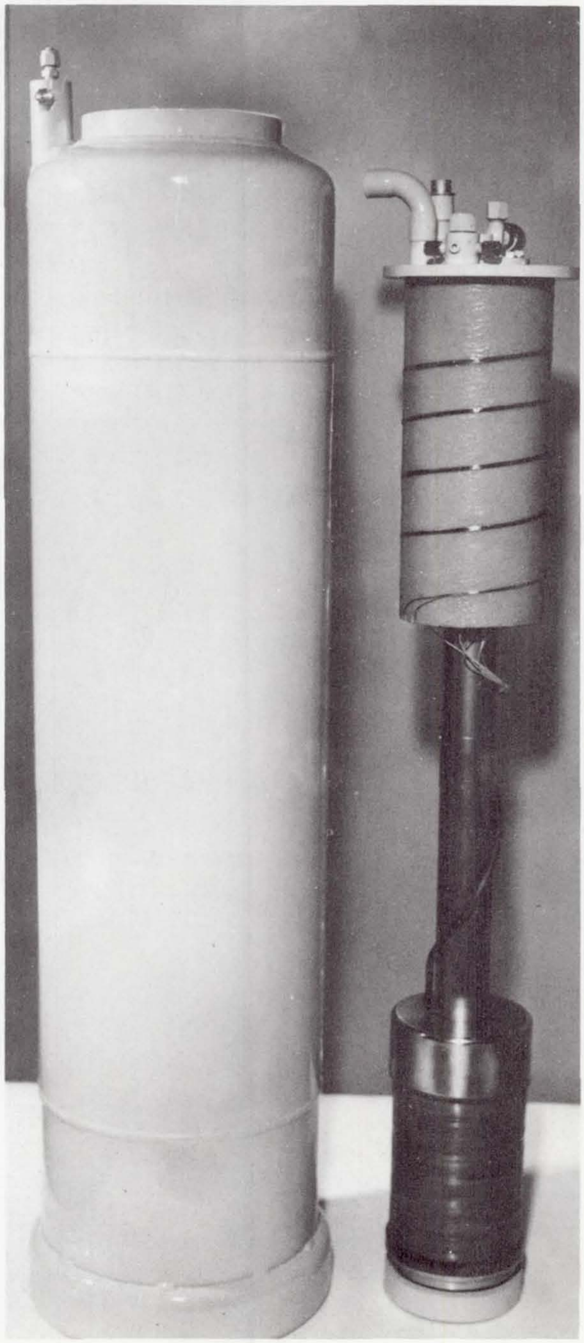

Figure IVc–12.—Superconducting magnet.

cooled magnet at Lewis that produces the same field over about the same volume is shown in figure IVc–13. Heavy bus bars are required to bring the power to the magnet. This magnet absorbs about 1 megawatt of electrical power. A room full of electrical-power equipment is needed to operate the magnet, some of which is shown in figure IVc–14. This is only really about half the total electrical-power equipment that is required.

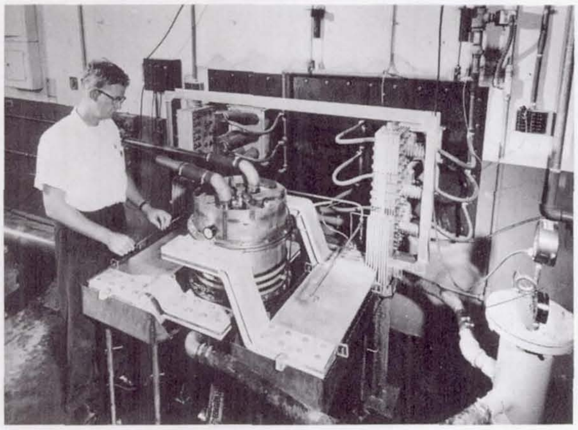

FIGURE IVc–13.—Water-cooled electromagnet.

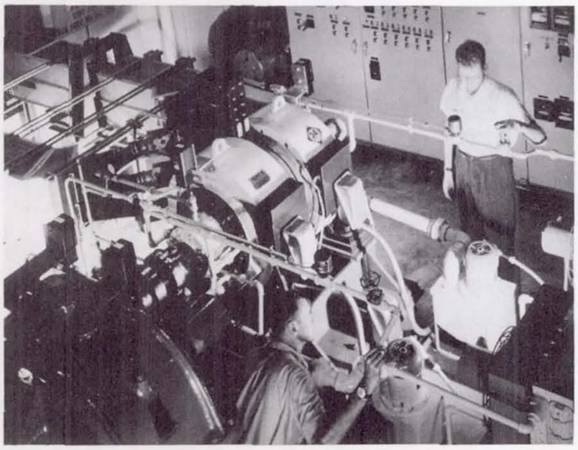

FIGURE IVc–14.—Magnet power supply.

The superconducting magnet is immersed in liquid helium, and although no heat is generated by the magnet, there are small losses due to heat leakage into the system. Replacing the helium boiloff due to leakage requires about 2 kilowatts as compared with the 1 megawatt required for the Lewis water-cooled magnet.

Numerous studies have been made of the application of the new superconducting materials to all types of electrical devices; even such prosaic and well-developed items as transformers can be significantly improved. Furthermore, such systems would be greatly reduced in size by factors of 10 to 100. Detailed studies have shown that the normal electrical substation, for example, which now occupies one-quarter or one-half of a city block could be compacted into a unit about the size of an office. This reduction in size would certainly be of great value in downtown areas of large cities.

Another application of superconductors is energy storage. Large amounts of energy can be stored in the magnetic fields of superconducting magnets and this energy can be withdrawn as electricity. So far, the Lewis studies indicate that such devices can possibly be considerably better than ordinary battery power.

Another interesting application is an a–c—d–c rectifier. A device has been built with two cryotrons or gates. These gates operate alternately at 60 cps, and 1 ampere of alternating current has been converted into 500 amperes of direct current and stored in a magnet. The device is about as large as a man's fist. The usual techniques would require a solid-state converter about 100 times as large.

The future of the whole field of superconductivity is bright, and it will undoubtedly have a marked effect on the electrical industry.

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IVd. Ion and Plasma Technology

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PREVIOUS DISCUSSIONS have mentioned both ions and plasmas. However, at the risk of being repetitive, these terms are redefined with the aid of figure IVd–1. At the top is symbolized a normal gas, with the dots representing neutral atoms or molecules. The process of ionization is shown in the center—the removal of an electron from the neutral atom or molecule leaves a positive ion. At the bottom is symbolized a plasma made up of ions and electrons.

Such charged particles can be acted on by electric and magnetic fields. They can be accelerated to very high velocities. A plasma can be heated, confined, or squeezed without contact with material bodies. The plasma ions and electrons need not have the same temperature—processes are known which can heat either species selectively. The quantities most important in signifying the state of a plasma are (1) the temperature of the constituents, and (2) their densities—the number of ions or electrons in a given volume.

The plasma state is involved in any electric arc or spark. Familiar plasmas include the gas in a neon light or in the core of a lightning bolt. Very high temperatures will also bring about ionization and hence the plasma state. The sun itself is a huge mass of plasma; the stream of charged particles flowing from the sun through the solar system may be considered a very tenuous plasma. Plasma temperatures may range from a few thousand to hundreds of millions of degrees; plasma densities vary from near zero as in interplanetary space up to the very compressed matter in the cores of stars.

The work being performed in developing the ion and plasma technology is aimed at specific objectives. In figure IVd–2 are shown some of the processes and development

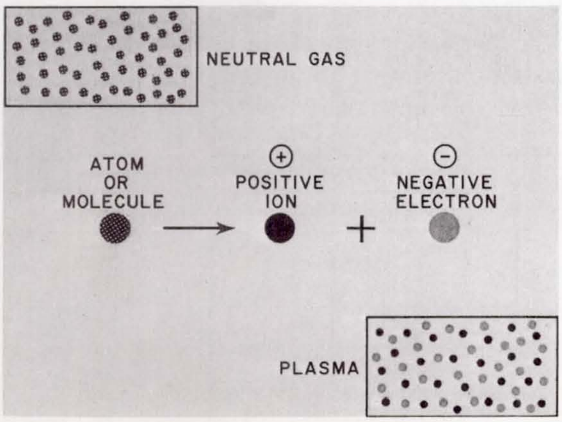

FIGURE IVd–1.—Ionization.

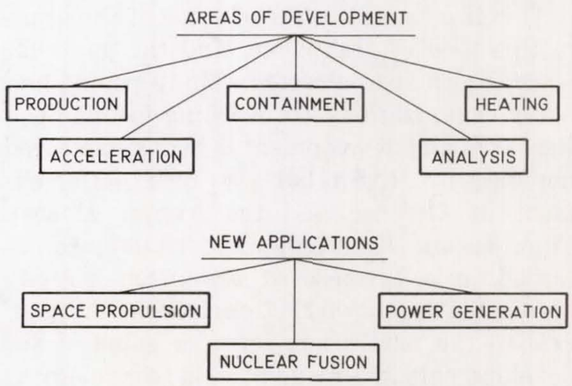

FIGURE IVd–2.—Ion and plasma technology.

areas, as well as some of the direct applications. The space propulsion, nuclear fusion, and power generation applications are not the only applications; they are the most interesting from the viewpoint of the space program. The space propulsion system requires the production, acceleration, and confinement of plasma or ion streams. Analytical techniques are needed to determine the character of the streams at various locations.

The use of plasma in power generation—sometimes referred to as a MHD generator—takes advantage of the electric conductivity of the plasma. Conventional devices use metallic conductors moving through magnetic fields. A plasma can be used in a similar manner. This involves the production, acceleration and deceleration, confinement, and heating processes.

Nuclear fusion is the reaction which powers the H-bomb. It is also the source of the Sun's power. To obtain a controlled fusion reaction, with light atoms combining to form heavier ones and releasing energy, it is necessary to generate and confine an extremely hot plasma for an appreciable time. The required temperature runs to hundreds of millions of degress. Mr. E. E. Callaghan has described the generation of extremely strong magnetic fields using superconductors and cryogenic techniques; such strong fields will be essential to the confinement of thermonuclear plasmas.

This is a broad outline of some of the areas in this field of technology and the goals toward which it is directed. Many people and many organizations are working in this field. Research and development is being sponsored not only by NASA but also by the Department of Defense and the Atomic Energy Commission. Knowledge and techniques obtained in a given area are often directly applicable to another. Going from the general to the particular, consider some of the developments in ion and plasma technology as it relates to the space propulsion application.

During the next decade men are to land on the moon. This feat will be accomplished using chemical rockets. Such rockets are limited in performance, both in theory and in practice. Looking to the future, toward interplanetary missions or to deep space probes, we can see the need for more potent propulsion systems. Both nuclear and electric rockets offer, in theory, substantial improvements.

Any rocket provides a thrust depending both on the amount of matter being ejected and on the velocity with which it is ejected. By accelerating our propellant to higher velocity, we can reduce the amount of propellant required. Chemical rockets have maximum exhaust velocities in the range from 10,000 to 15,000 feet per second. With electric rockets there is effectively no upper limit on the velocity attainable. Velocities from 100,000 to 200,000 feet per second are most appropriate from powerplant considerations.

For space missions, electric rockets use relatively little propellant but give low thrusts—on the order of a few pounds for a major mission. Such low thrusts are effective because they are sustained over long periods of time that typically approach a year. The electric rockets for major missions require large powerplants—of the order of 10 megawatts. Many systems and processes are being developed in the area of electric power generation. The eventual applicability of electric rockets depends most strongly on these developments leading to lightweight, reliable space powerplants.

A block diagram of an electric propulsion system is shown in figure IVd–3. Here, a rather conventional power system is assumed.

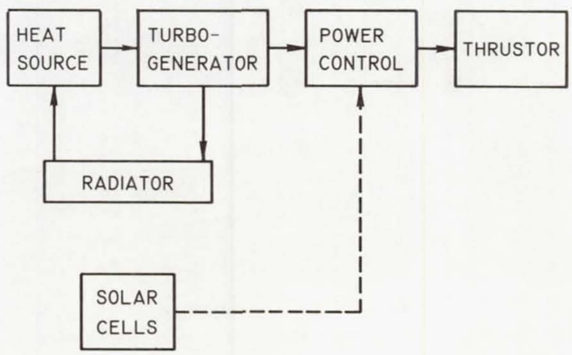

FIGURE IVd–3.—Electric propulsion systems.

A nuclear reactor serving as a heat source heats a working fluid; this drives a turbogenerator and then passes through a radiator back to the reactor. The electric output then passes through a control system to the thrustor. One alternative sketched here would use a bank of solar cells to provide the power to the control system.

What might some of these electric rockets or thrustors look like? The ion rockets that have been most extensively investigated fall into two categories, according to the means used to produce the ions. The first is the contact ion engine (fig. IVd–4). The propellant used is the metal cesium, which forms ions on contact with the hot porous tungsten electrode. The ions are accelerated by an electrode structure, which is similar to that used in some radio or television tubes. Electrons are added to neutralize the beam. The development of these engines has had ramifications especially in the fields of materials handling and fabrication and in the porous metal technology.

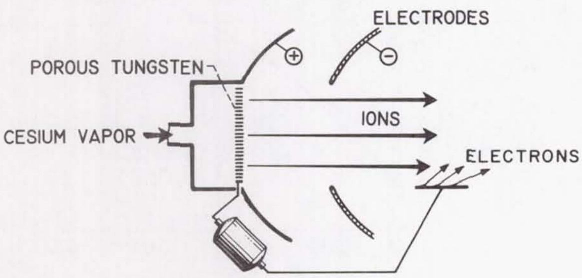

FIGURE IVd–4.—Contact ion engine schematic.

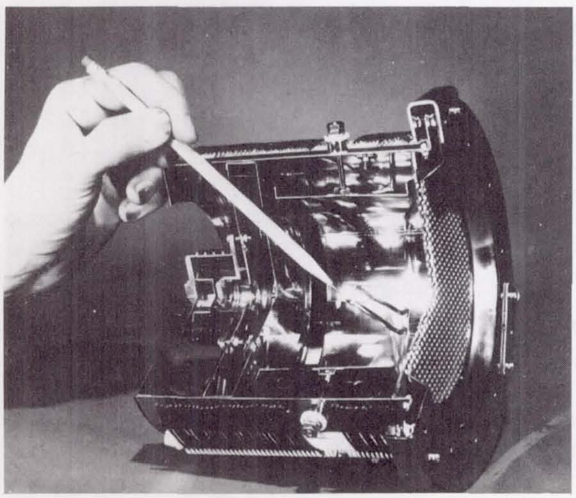

FIGURE IVd–5.—Cutaway view of electron bombardment engine.

The other category of ion engine uses electron bombardment to produce ions. Figure IVd–5 is a cutaway view of such a bombardment engine. This one uses mercury as a propellant, although in principle any material could be used. The propellant is ionized within the chamber and the ions are accelerated through the perforated plate structure. In this system a considerable amount of work has been devoted to the cathode, which is shown as a metal hairpin in the figure. The cathode supplies the electrons used in ionizing the propellant; the development of durable cathodes for this engine may have applications in other fields.

Both engines require systems for controlling and metering the extremely low propellant flow rates. As mentioned before, the development of the accelerator structures has used existing radio tube technology and, in turn, has contributed to it.

Another type of thrustor is one called a hybrid arc jet. Figure IVd–6 is a simple schematic of such an engine. This thrustor operates by passing a large electric current, and arc, through the propellant. The resulting plasma is accelerated by electromagnetic forces to very high velocities. The jet emerg-

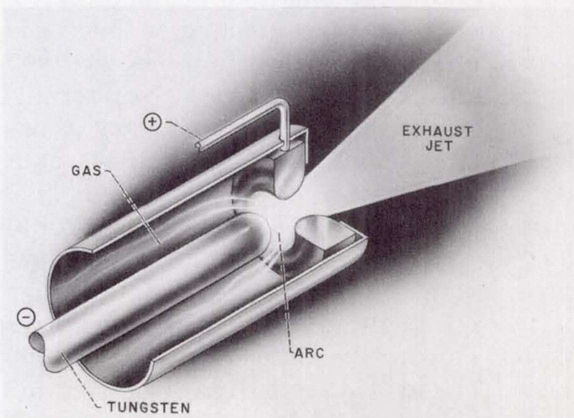

FIGURE IVd–6.—Hybrid arc jet.

ing from this arc may have an effective temperature approaching a million degrees. Again, it appears likely that a beam of such hot matter may well have other applications.

Suppose an unmanned space station is to be sent to Mars. How can a decision be made about which system is the better of those discussed? It cannot be decided because sufficient information is not available at this time. Estimates based on extrapolation of existing technologies can be made. The result of one such estimate is shown in figure IVd–7, which is a curve representing the relation between trip time and payload for an electric rocket system. It shows that about three times the payload could be obtained with electric rockets as compared with the chemical rocket, or the extra capability of the electric rocket could be used to reduce the trip time and keep the same payload. Even more favorable comparisons have been made for more difficult missions—interplanetary round trips, for example.

How does the present state of the thrustor art compare with some of the proposed mission requirements? Power and durability requirements for three applications are illustrated in rough form in figure IVd–8. Thrustor powers over 1 megawatt are needed for manned interplanetary trips, with operating times over 10,000 hours. Unmanned probes need about the same durability, but may get by with power levels of tens of kilowatts. Station keeping and attitude control might need only a few hundred or thousands of watts with operating lifetimes of 1000 hours and up. Such use would be intermittent, so that such engine operating times could correspond to satellite lifetimes of a few years.

Also indicated on the chart are some typical current performances. Single ion engines have already been run at powers in the range of tens of kilowatts, with smaller engines having shown durabilities approaching 1000 hours. The hybrid arc jet has been operated at power levels of hundreds of kilowatts, with very long operation not yet attempted.

Obviously, the higher levels of power could be obtaind by the operation of more than one engine simultaneously. Similarly, the operating lifetimes could in theory be obtained by using replaceable engines. There seems little reason to doubt, however, that the needful lifetime can be obtained.

One caution should be made—the power levels and operating times are not by any means the only qualities required. Another crucial measure of the electric rocket performance is the efficiency with which it converts its power into thrust. As of this moment, the ion engines possess an efficiency advantage over the more powerful arc jets. At typical operating conditions set by mission requirements, the ion engines may approach 80 percent efficiency, while the arc jet as yet has shown only about 40 percent.

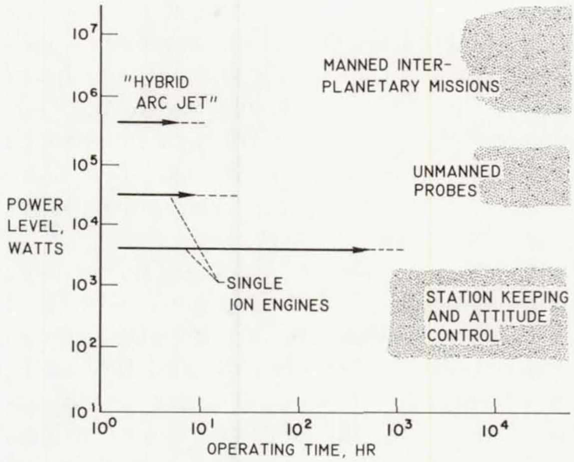

FIGURE IVd–8.—Electric rocket requirements.

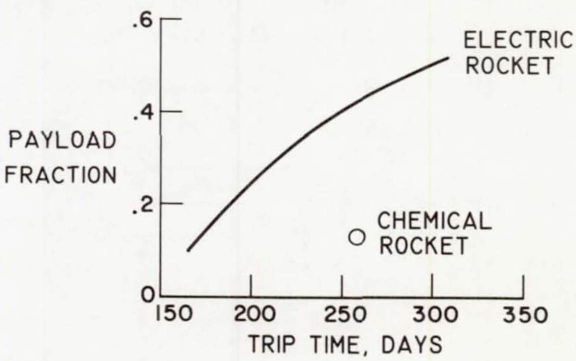

FIGURE IVd–7.—Payload to Mars orbit.

In summary, our existing technology seems already nearly adequate to provide thrustors for the station-keeping and attitude-control missions. Systems to propel unmanned probes appear readily attainable and even the manned mission application appears within the range of the continuously developing technology.

The development and testing of such thrustors will now be considered. The natural habitat of an electric rocket is space, that is, an environment with lots of sunshine, a few micrometeors, and very little else. The "very little else" constitutes an extremely hard vacuum, one which is almost impossible to duplicate on Earth. The appropriate place to develop electric thrustors is space. This is not practical. The next best method is to create a reasonable facsimile here on Earth. Such a testing facility is a large vacuum tank such as is shown in figure IVd–9. This 25-foot-diameter tank produces a vacuum of the order of one-billionth of an atmosphere. The pumps in this view are capped to prevent contamination. To help maintain the vacuum, a large cryogenic baffle is used inside the tank. This is a system cooled by liquid nitrogen wherein such propellants as mercury or cesium freeze out, thus reducing the load on the pumps.

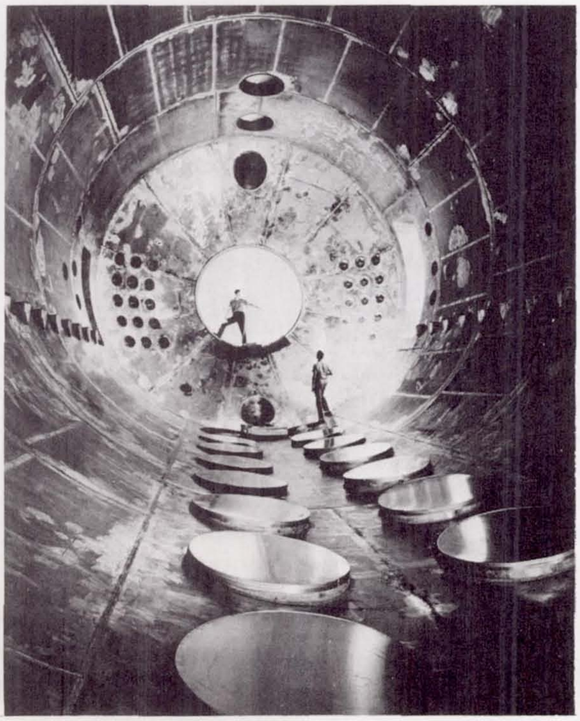

FIGURE IVd–9.—Vacuum facility.

FIGURE IVd–10.—Three-engine array in vacuum facility.

The ports visible along the front of the tank provide access for instrument and power leads. Although the pressure quoted is not nearly so low as that in space, experience leads us to believe that the performance of an ion engine in this tank should be about the same as it would be at lower pressures. In operation, the rocket is mounted in a 10-foot-diameter chamber at the far end of the tank. A closer view is given in figure IVd–10, where an array of three ion engines is being installed for testing.

The use of vacuum facilities cannot prove conclusively that a given system will perform in the same manner in space. Such final proof demands that an engine be first tested on the ground—in a tank—and then be operated in a similar manner in space. Such a test has been designed and should be launched this summer. Figure IVd–11 shows the Space

Electric Rocket Test (SERT) payload in the vacuum tank with one of its two ion engines visible. This payload carries one contact (cesium) ion engine and one electron bombardment (mercury) engine. It will be launched by a solid rocket and remain above the atmosphere for over 30 minutes. The very small thrusts of the ion engines will be used to cause the spin of the payload to increase and decrease. Performance data will be telemetered to ground for comparison with previous tests. The major bulk of this payload comprises the batteries, power control subsystems, and telemetry.

As mentioned before, the plasmas of interest to the nuclear fusion process are extremely hot with temperatures of hundreds of millions of degrees. Work in this field has been concentrated on the twin problems of confinement and heating. Figure IVd–12 is a schematic diagram of a plasma confined by a magnetic field. The two coils form a magnetic field, which is strongest directly under the coils. The flux lines follow the pattern shown. Such a configuration has been called a magnetic bottle, because these strong fields tend to prevent the plasma from leaking out of the central region. Naturally, the devices being used for fusion research are considerably more complex. The figure serves merely to illustrate the principle. The extent to which the plasma is confined depends on the strength attainable in the magnetic field. The rapid development of cryogenic and superconducting magnets, which Mr. Callaghan discussed, should contribute the intense fields that seem needed. Fields of hundreds of thousands of gauss are very difficult to acquire otherwise.

Producing a thermonuclear plasma in such a bottle can be attempted in two sequences; one might try first generating the plasma in the field, then heating it. Alternatively, very high-velocity particles can be generated externally. These can then be injected and trapped in the field, remaining hot while their density increases. Both approaches are being pursued.

In this brief discussion, a sample of some of the accomplishments in the field of ion and plasma technology has been presented. Obviously the field is still in a relatively early stage of development. What sort of capabilities can be foreseen as this technology, matures? In general terms, one can say that the ability is being acquired to produce and use very energetic beams of matter, as well as the ability to heat appreciable quantities of matter to extreme temperatures. The direct applications mentioned — space propulsion, power generation, and nuclear fusion—will certainly not be the only applications for such capabilities.

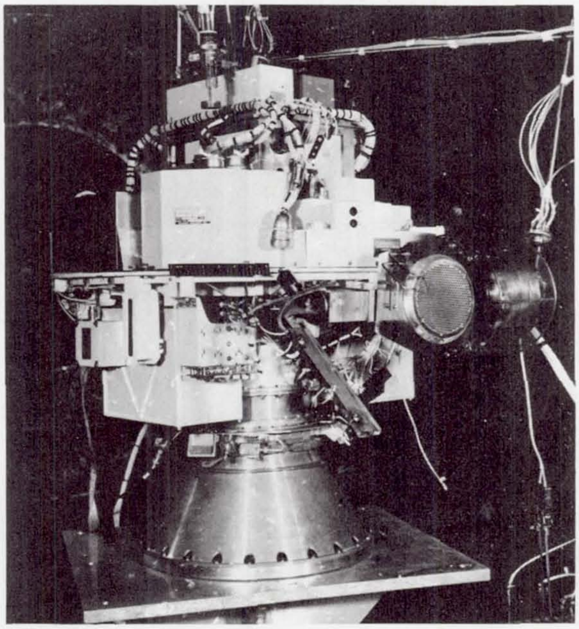

FIGURE IVd–11.—SERT payload in vacuum tank.

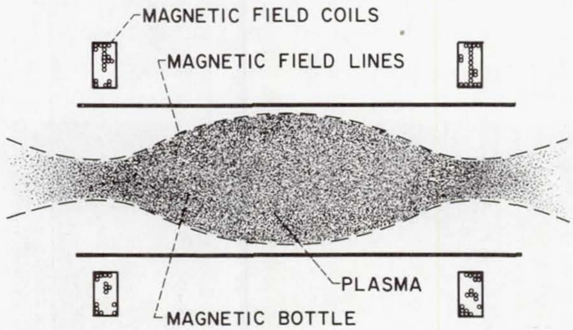

FIGURE IVd–12.—Magnetic confinement.

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V. Instrumentation for Measurement and Control

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Isidore Warshawsky, and Kirby W. Hiller
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The need for instruments to measure and to control enters into all fields of human endeavor, from ordinary household operations to those of the advanced scientific laboratory. To meet these needs, an instrument industry has evolved whose annual sales are close to 1 billion dollars. Northeast Ohio has a considerable stake in this industry; there are many local instrument manufacturing companies, some of them credited with pioneering innovations in instrumentation for measurement and control.

Such instrumentation is vital to the aerospace field. For example, an unmanned space probe, like Mariner, represents an automatically conducted and controlled experiment to acquire information about Venus and about interplanetary space. In fact, the entire NASA may be considered as an information processing system whose final output is merely information. The research laboratories, the space vehicles, and the space missions themselves provide only this final output. The design of measuring and control equipment to produce this product requires the design engineer also to utilize equipment and techniques originating in nonaerospace industries. The information finally derived becomes universally available. Thus, a great two-way flow of knowledge occurs between the aerospace and the nonaerospace fields. This conference is a means of promoting that flow.

The substance of this presentation is outlined in figure V–1, which likens the functions of measurement and control instruments to human functions. First, there are sensors, like the eye, to detect and measure qualities of the physical world. The signals containing information acquired by the sensor are transmitted to the brain, or to a calculator, which makes sense out of the information, makes decisions, and issues commands. The command is issued to some device that can accomplish some action, like the human hand; in the terminology of control engineering, it is an actuator. The actuator acts on some device or process; thus, the hand might steer an automobile.

In many instances, the sensor, or eye, can see the effects of the actuator's action, so that new information enters the system as a result of the action of that system. This circulation of information is termed *feedback;* the control is then said to be a *closed-loop control.*

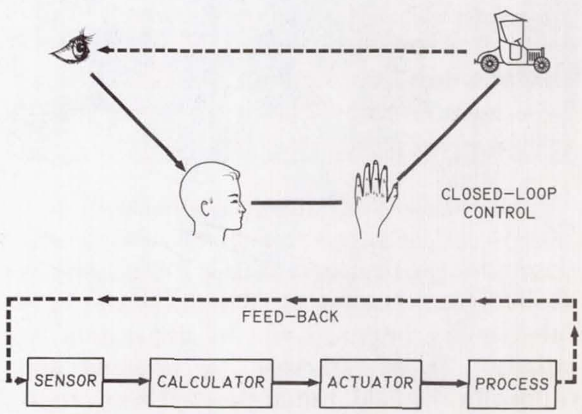

Figure V–1.—Control loop.

On a flight such as that of Mariner (fig. V–2), there were several such closed loops. In one loop concerning the electric-power system, the sun sensor detected the position of the Sun and sent a signal to a control system, which then actuated jets that oriented the spacecraft so that the solar cells (and the Sun sensor) faced the Sun. In another loop, a second group of jets was used to point the transmitting antenna toward Earth. In a third loop, the radiometers were pointed toward Venus, when the probe was near to the planet.

All of these control loops were only means to an end: the acquisition of information about Venus.

The path of this information is represented in figure V–3. The signals from numerous sensing instruments were collected and assembled in proper sequence for transmission, by radio, to an Earth-based computer that analyzed the information and presented the final results in tables and graphs that could readily be understood by man.

A similar sequence is followed in ground-based information processing (fig. V–4) with the exception that the radio link is generally replaced by a wire cable.

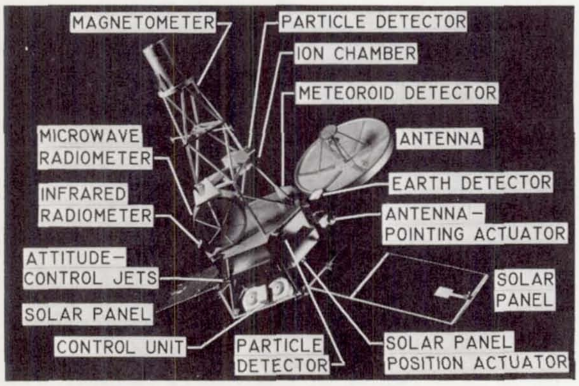

FIGURE V–2.—Mariner space probe.

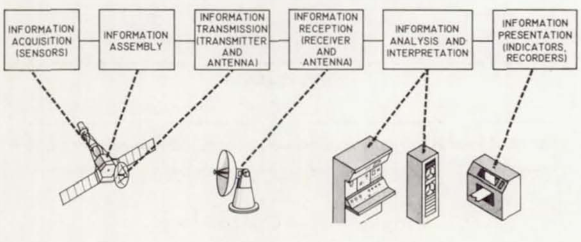

FIGURE V–3.—Information processing in spacecraft.

Figures V–1 and V–4 outline the presentation to follow. First, the principal elements of the loop will be treated: sensors, the information-processing chain, actuators, and final elements. Then, the entire control loop will be considered as a complete system.

SENSORS

The first step in acquiring information is to measure the physical quantities of interest. These measurements may in themselves represent the desired knowledge, or else they may provide the basis for exercising control actions or making decisions.

The instrument panel of a modern jet airliner is filled with instruments, the pointers of which tell the pilot his position, direction, speed, the condition of the air around and ahead of the plane, and the condition of the engines, cabin, airframe, and controls. These measurements enable the pilot to navigate, to take off and to land, to communicate, and to make decisions.

Similarly, the instruments on the panel of a Mercury capsule provided information to the astronaut that enabled him to establish the conditions inside and outside the capsule, to control its attitude, on occasion to control its speed and direction, to communicate, and to make decisions.

Spacecraft Measurements

On scientific spacecraft, like Mariner, there are no instrument pointers because there are no human eyes to see them; but there are

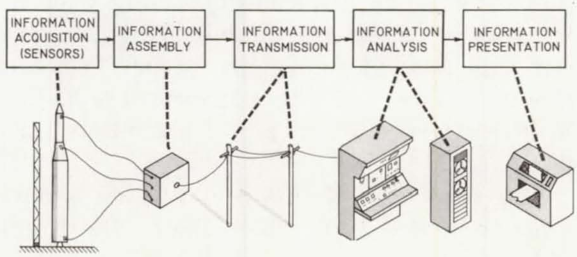

FIGURE V–4.—Ground-based information handling.

many sensors, or transducers, that make a variety of measurements, converting each of these into a voltage that can be radioed back to Earth. These measurements are rarely ends in themselves; they are merely the steps to a better understanding of our Earth, our solar system, and our galaxy. Thereby, they also furnish information about the conditions for which we must prepare in undertaking manned extraterrestrial flight.

In the broad context of the scientific exploration of space, the desired measurements are as follows:

To learn about a planet's environment

- Fields:
  - Gravitational-field strength
  - Magnetic-field strength
  - Electric-field strength
- Radiation:
  - Reflected sunlight (albedo)
  - Thermal radiation from surface
  - Thermal radiation from atmosphere
- Atmosphere:
  - Composition
  - Density

To learn about extraplanetary space

- Particles:
  - Electrons
  - Protons
  - Neutrons
  - Ions
  - Mesons
- Waves:
  - Gamma rays
  - X-rays
  - Ultraviolet rays
  - Visible light
  - Infrared rays
  - Radio rays
- Dust:
  - Meteoroids

Some of the measurements on the Mariner flight illustrate how the resulting knowledge transcends the mere acquisition of numerical data. Thus, the magnetometer measurements indicated that Venus was rotating very little and that it should not have a dangerous Van Allen belt. The measurements of thermal radiation, provided by infrared and microwave radiometers, helped to estimate a little more closely the probability of biological life on the surface of the planet. Three different kinds of detectors of charged particles and a meteoroid detector yielded measurements that provided a better understanding of solar activity and of the hazards of manned interplanetary flight.

A few specific spacecraft sensors will be discussed in brief detail, and an indication given of how these have their industrial counterparts in Earth-based technology.

Magnetometers.—The magnetic field of the Earth extends far out into space; like the gravitational field, it gets weaker at greater distances from the Earth. A planet that does not rotate is unlikely to have a strong magnetic field. This appears to be the case for Venus, on the basis of the single Mariner flight.

Some of the magnetometers that have come into use in the last few decades are

- Search coil
- Flux gate
- Hall effect
- Cathode ray
- Precessing types
  - Proton spin
  - Rubidium vapor
  - Metastable helium

All are characterized by the fact that they can operate on board a ship, an airplane, or a spacecraft.

The search coil magnetometer operates on the same principle as the electric generator—that a coil of wire moving through a magnetic field develops a voltage between the ends of the wire that is proportional to magnetic-field intensity. Search coils were used on the Pioneer series of space probes to explore the Sun's magnetic field. Synchronous-motor-driven search coils are used to map magnetic-field intensity in large magnets used in science and industry.

The flux-gate magnetometer uses a specially designed electrical transformer whose output voltage is a distortion of the input voltage. This distortion is affected by the magnetic field that is present; the magnitude of the distortion is a measure of magnetic-field intensity. This same principle is applied, in a slightly different manner, to constitute the flux-gate compass used extensively in military and commercial aviation and navigation.

The Hall-effect and cathode-ray magnetometers have lower sensitivity than the other instruments and have not been used in spacecraft.

The precessing instruments use a principle analogous to that of a spinning top. If a top, initially spinning about a vertical axis, is tilted so that it is acted upon by gravity, it will wobble, or precess, about the initial vertical axis. For the magnetometers using the precession principle, we go inside the atom for the analog of the spinning top, and a magnetic field is used to force the precession, rather than a gravitational field.

The proton-spin magnetometer uses the spinning nucleus of the hydrogen atom (fig. V–5). A coil of wire is wrapped around a cell containing water or other hydrogenous liquid. The spinning nucleus is disturbed by connecting the coil to a d–c power supply for about 0.0001 second. The nucleus recovers from this disturbance by precessing slowly

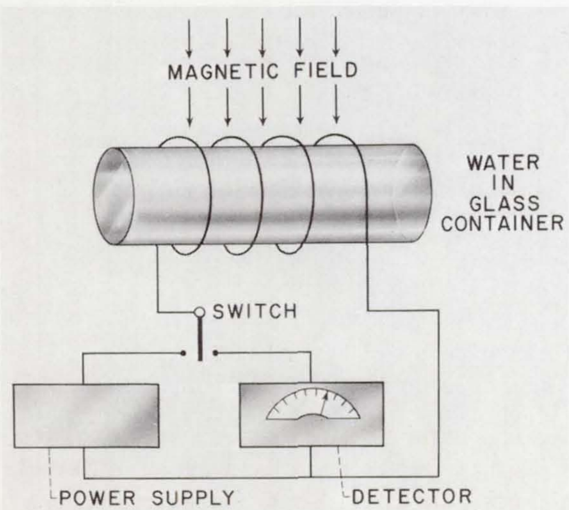

FIGURE V–5.—Proton spin magnetometer.

back to its original condition; this precession produces audiofrequency waves that can be picked up by connecting the coil to a suitable detector. The recovery takes several seconds —long enough to permit accurate measurement of the frequency of the waves; this frequency is proportional to magnetic-field intensity. The physical process involved is also termed *nuclear magnetic resonance;* this process is used in chemical analysis.

The rubidium-vapor and metastable-helium magnetometers differ from the proton-spin magnetometer in the following respects: the electrons in the atom are used, rather than the nucleus; the disturbance is created by using a strong light, rather than a strong magnetic field; the recovery produces higher-frequency radio waves or light waves, rather than audiofrequency waves; and the processes of disturbance and recovery go on simultaneously, so that the indication is continuous rather than intermittent. The physical process involved is termed *optical pumping;* it is the same process involved in masers and lasers.

The optically pumped magnetometers are hundreds of times more sensitive than the proton-spin unit, but are also more complex and more costly. The order in which the three precessing-type magnetometers are listed is also the order of decreasing sensitivity to rotation and vibration; thus, the last two are more suited to airborne use than the first.

A portable proton-spin magnetometer has been demonstrated in Switzerland as useful in finding a person buried under the snow in an avalanche. A person traveling in dangerous country must carry a small magnet clipped to one of his boots. The presence of such a magnet sufficiently disturbs the normal magnetic field of the Earth so that a person buried under 10 feet of snow can readily be found. When subfreezing temperatures preclude the use of water in the cell of the magnetometer, alcohol is a suitable hydrogenous substitute.

Rubidium-vapor magnetometers have been flown in airplanes to make rapid and extensive surveys, in geophysical prospecting for oil, where constant altitude above sea level must be maintained. The sensitive cell of the magnetometer is often carried at the tip of a boom extending from the tail of the airplane, in order to be far from magnetic parts of the airplane.

Optically pumped magnetometers have also been towed at the end of a cable extending from an airplane or helicopter. The helicopter not only can make a slower and therefore more detailed survey, but also is better suited to being flown at constant altitude above ground level, as is required in geophysical prospecting for minerals. These magnetometers have also been towed under lake surfaces, to make geomagnetic surveys, and they have been used to trace deeply buried iron pipes.

Charged particle detectors.—Most of the charged particles encountered in space appear to come from the Sun, within the core of which temperatures of millions of degrees exist. Violent solar activity results in a stream of protons, electrons, and ions that constitute the *solar wind*. This wind is strongest at a time of high sunspot activity. (The interaction of this wind with the Earth's magnetic field concentrates many charged particles into the Van Allen belts.) The identity, number, and energy or speed of these particles must be determined.

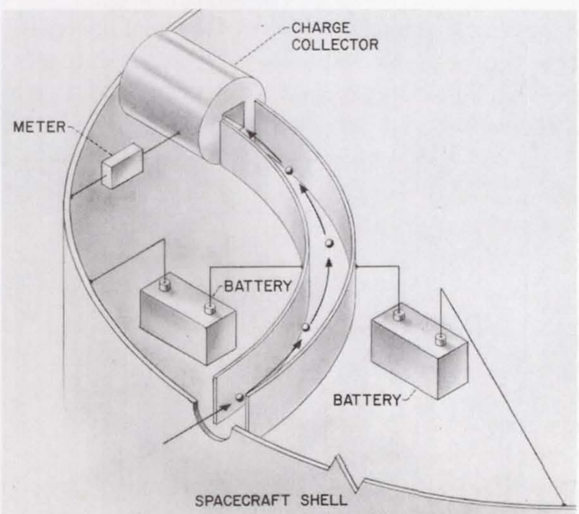

FIGURE V–6.—Energy discriminator for charged particles. Electrostatic deflection method.

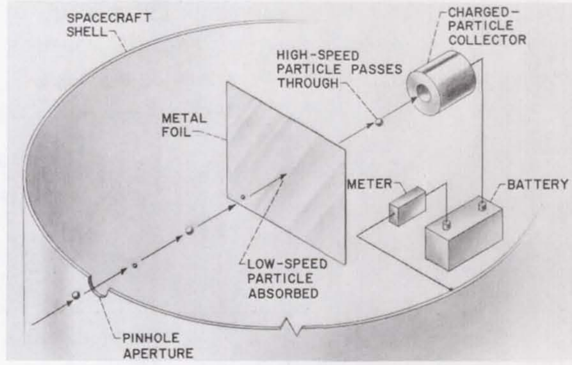

FIGURE V–7.—Energy discriminator for charged particles. Absorption method.

The number of charged particles entering an aperture on the spacecraft shell can be determined by collecting the particles in a cup-shaped electrode that is connected to the spacecraft shell through a suitable current-measuring device and a battery or its equivalent. Such an electrode is sometimes termed a *Faraday cup*. Other detectors often used are ion chambers and Geiger-Mueller counters.

One of the methods that may be used to segregate particles of a particular energy is to require them to pass along a path between two charged, curved plates (fig. V–6). Only particles of a particular energy pass through to the collector without hitting and being collected by one or the other of the plates. Particles with different energies are collected when the voltage on the plates is changed.

Another method of measuring particle energy is to place various thicknesses of metal foil between entrance and collector (fig. V–7). The more energetic particles will pass through greater thicknesses of metal. From physical laws and laboratory experiments, the particle energy required just to penetrate a given thickness of metal can be computed. The spectrum of energies can be estimated by using a series of foils, each of different thickness, in turn. Such a selective-absorption technique is used in thickness gaging in industry; it has been particularly useful in measuring the thickness of rapidly moving sheets of metal, paper, or plastic, because it involves no mechanical contact with the specimen.

Charged particles are deflected by magnetic fields as well as by electric fields. A combination of both is used in some *mass spectrometers* for the identification of ionized chemical elements; such a combination is used also in the ordinary television tube for the two-dimensional deflection of electrons. In the Nier-type mass spectrometer (fig. V–8), ions are bent through a circular path while they pass between the pole pieces of a magnet. The radius of the circle is dependent on the mass of the ion and on the voltage applied to the collecting electrode; changing the voltage permits collection of ions of different mass, which is generally equivalent to a different chemical element.

Such mass spectrometers exist in considerable variety, ranging from comparatively simple devices that are tuned to a single ion, as in the helium-mass-spectrometer-type leak detector, to those that provide a fairly crude chemical analysis in a few minutes, to still others that provide highly detailed resolution or that provide a complete spectrum in a few milliseconds. Such mass spectrometers have been used in television- and radio-tube processing, in vacuum melting and brazing of metals, and in monitoring chemical processes. They supplement the gas chromatograph by providing an exact calibration for it and by providing more detailed resolution of chemical components.

Infrared radiometers.—Infrared radiometers were particularly important on the Mariner flight because they provided information about the clouds of Venus and about the temperature that might exist at the surface. This information was obtained by using two radiometers: one equipped with an optical filter that allowed entrance into the radiometer of the characteristic infrared radiation from carbon dioxide, which is believed to be the principal constitutent of the clouds, and the other equipped with an optical filter that rejected this carbon dioxide radiation and instead permitted entrance into the radiometer of the type of infrared radiation that could be expected from the surface itself.

The technique of determining how a gas absorbs infrared light, by use of radiometers equipped with narrow-band filters, is a popular industrial method of analyzing the composition of a gas. The technique is simpler than mass spectrometry, but is limited to only those gases that have a unique ability to absorb infrared light. Such absorption, when present, is usually pronounced only for certain "colors" of infrared, the "color," or wavelength, being characteristic of the gas.

Infrared radiometry also provides a means of measuring the temperatures of solid objects without touching them. It is therefore suited to measuring the temperature of rapidly moving objects, such as railroad hot boxes, metal strip in rolling mills, and paper in high-speed printing presses. It has been used to map the temperature of the sea from an airplane. It has been used to find local points of infection near the surface of the body, because these points are at slightly higher temperature (a few hundredths of a degree); for example, it has detected bone cancer in the knee at an earlier stage than was possible by X-ray diagnosis.

Infrared light has also been used to gage the thickness of sheets of plastic that are translucent to infrared. This method is an alternative way of measuring the thickness

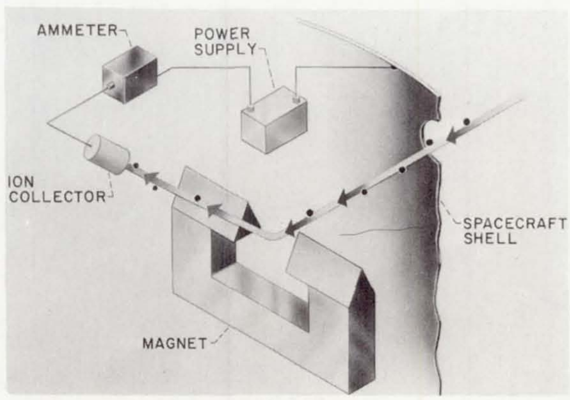

FIGURE V–8.—Nier type mass spectrometer.

of moving sheets, often competitive with nuclear-radiation methods.

By means of infrared cameras, hot spots in electronic and industrial equipment can be detected in time for remedial action before failure. Figure V–9 shows an electronic circuit board photographed by ordinary light and by infrared light. An overheated component appears bright; the coldest components (e.g., the transistors) appear black. The temperature of the overheated component may be estimated by comparing its brightness with that of a series of metal strips, each heated to a known temperature and photographed at the same time as the circuit board. These strips appear at the top of the figure.

The U.S. Air Force, in research on Arctic clothing, has photographed a human subject exposed in a chamber held at 32° F, to determine how different parts of the body cool

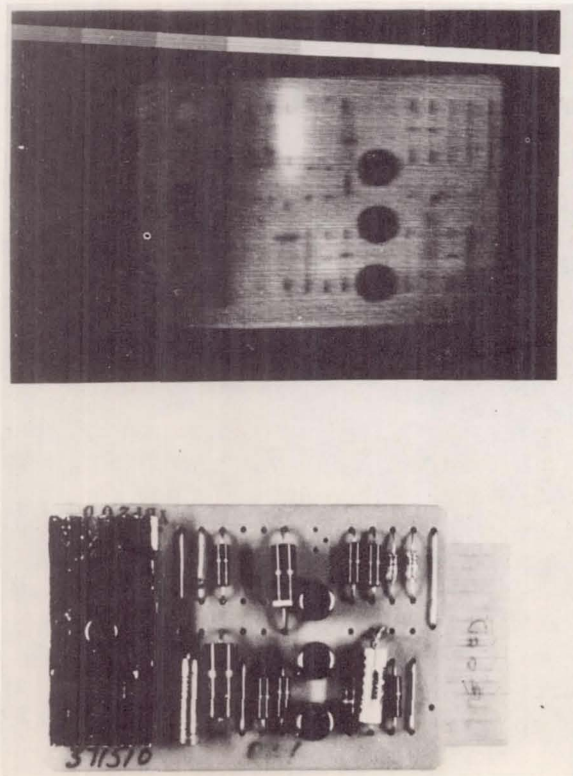

FIGURE V–9.—Electronic circuit board. (Courtesy of Barnes Engineering.)

down at different rates. Thus, in a 45-minute test, the knees are found to feel the cold very soon, while the neck appears more resistant to chilling.

Ground-Based Measurements

Advanced instrumentation is needed also in ground-based research on launch vehicles, their rocket motors, the ground-support equipment, and, most extensively, in the backup engineering research such as that conducted at NASA research centers. Among the host of sensors involved, brief discussion will be made of some of the sensors for force, torque, pressure, flow, and temperature.

Force sensors.—During rocket development, an accurate measure of engine thrust is required. Prior to launching, while propellant tanks are being filled, an accurate measure of the changing weight of the launch vehicle is required. The needs of the aerospace program for both of these measurements, and for related ones, have fostered the development of electrical weighing devices, colloquially termed *load cells,* to a degree of perfection well in advance of what was available a decade ago. These load cells use the principle that the electrical properties of materials change when they are stressed by loads and that this change of properties can be converted into a measurable voltage that is proportional to the load.

Existing, commercially available load cells have capacities ranging from a fraction of a pound to 1 million pounds. With appropriate electrical circuits, secondary indicating instruments, and careful engineering, weight changes of one part in 10,000 are readily detected. Their advantages are compactness (cells having capacities of 250,000 lb can be lifted by two men); hermetic sealing, making them adaptable to outdoor installations; and an electrical output that permits remote indication of weight that is adaptable to automatic computations.

Typically, load cells have been used to weigh trucks on toll roads and airplanes on hangar aprons. Another representative example is their use in a batch process of preparing solid propellants for solid-propellant rockets, in which the operations of weighing out the components, mixing, pouring, and packaging are controlled automatically, in proper sequence, so that there is no need for the proximity of personnel in these hazardous operations.

Torque sensing.—One of the recent developments of the Lewis Research Center has been an optical method of measuring the torque in a shaft turning at high speed. The method involves no contact of the measuring instrumentation with the shaft and is superior to older optical methods and other noncontacting methods. The principle of operation, illustrated in figure V–10, is that the light from a stationary lamp is reflected, successively, from two polished surfaces on the shaft and forms an almost stationary image. The two reflecting surfaces are separated by several inches along the shaft. The twist of the shaft, proportional to torque, produces a slight but accurately measurable displacement of the image of the lamp. Measurements on high-speed machinery with shafts turning at 20,000 to 100,000 rpm are readily possible.

Pressure sensors.—Almost entirely as a result of the needs of aerospace research and development, there now exists a great variety of compact pressure sensors, most of which use the same operating principles as the load cells. These can remotely indicate pressure from a fraction of an inch of water, as occurs in ventilation practice, to thousands of

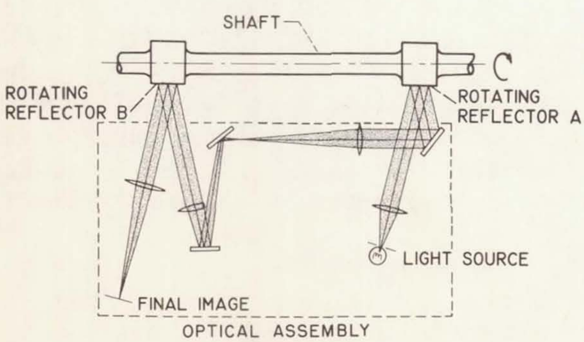

FIGURE V–10.—Optical torquemeter.

pounds per square inch, as may occur in the operations of forming, forging, and molding. They variously combine some of the following features: sensitivity, high speed of response, vibration resistance, resistance to highly corrosive liquids like nitric acid, and ability to operate at high temperatures. Water-cooled models can measure the pressure inside rocket engines, where temperatures of thousands of degrees exist. High-speed units can follow pressure during every moment of an injection-molding operation. Their electrical output makes them adaptable to use in computing networks for the exercise of automatic control functions.

Flowmeters.—*Turbine-type flowmeters,* developed to measure the flow of jet-engine and rocket propellants, are extremely popular in rocket engineering because they are small and easy to install, do not require a high degree of skill on the part of the installation technician, and provide remote electrical indication. They consist of a threaded or flanged casing, a multibladed rotor *(turbine* or *propeller)* supported on two bearings, and an electrical pickup coil leading to appropriate electrical rate-measuring equipment. Such flowmeters are part of the standard line of many manufacturers of instruments for the process industries. They exist in sizes of inside diameter from ⅛ inch to over a foot, the largest having been built for such applications as measuring the flow of propellant to the 1,500,000-pound-thrust F–1 rocket engine.

An interesting new development has evolved in the last 2 years from efforts to improve the performance of these meters in measuring the flow of liquid hydrogen. Since liquid hydrogen is so light that it behaves more like a gas than a liquid, manufacturers' development efforts have produced a line of industrial turbine-type flowmeters for measuring gas flow that retain the advantages of simple construction, simple installation, and remote indication.

The *electromagnetic flowmeter,* of particular value in aerospace research, has the advantages that it introduces no obstruction

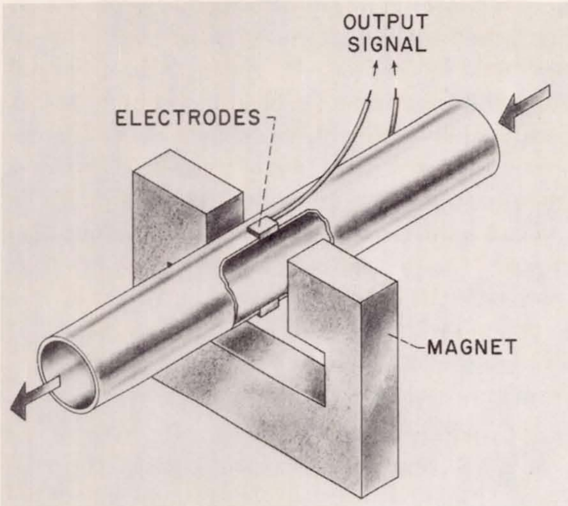

FIGURE V-11.—Electromagnetic flowmeter.

into the pipe, has negligible pressure loss, and provides remote electrical indication. The flow of a conducting liquid between the poles of a magnet producs a measurable voltage at two electrodes, located as shown in figure V-11. This voltage is proportional to flow rate. In medical research, it has been used to measure the flow of blood in the veins. In 1949, a larger scale version was developed at the Lewis laboratory to measure the flow of nitric acid and other rocket propellants. It has since found wide application in industry.

Its principal limitation has been that it could be used only with liquids that were electrical conductors; it could not be used with insulating liquids like oils. However, a current NASA-sponsored research and development program has produced a version that is usable with insulating liquids; this version may soon be commercially available.

Temperature sensors.—The field of temperature sensing has seen rapid progress during the past decade.

The traditional industrial thermocouple (fig. V-12) has always been one of the more convenient ways of measuring temperature. The ends of two dissimilar wires are twisted together, the junction welded, and the whole surrounded by a protective metal sheath. The voltage developed at the open ends of the wires is a measure of junction temperature; the relation between voltage and temperature is very reproducible, if the metallurgical quality of the wires is carefully controlled. Millions of feet of thermocouple wire are used each year.

An advance in thermocouple design occurred when it became necessary to measure the temperature of the exhaust gas of a jet engine. Not only were temperatures higher than those in industrial practice, but it was also necessary to have thermocouples that would rsepond very quickly. To this end, as shown in figure V-13, the ends of the wires were joined by butt-welding in order to minimize the mass that had to be heated, and the bare wires were exposed directly to the gas stream, without the obstruction of the protective sheath. The butt-welded construction is now common in industrial "fast-response" thermocouples.

New approaches were needed when it became necessary to measure temperatures of the exhaust gas of rocket engines. These temperatures often exceeded 5000° F and were thus above the melting point of any thermocouple material that would not be oxidized and consumed in the hot gas. Satisfactory solutions of the problem were obtained by controlled cooling of the thermometer bulb.

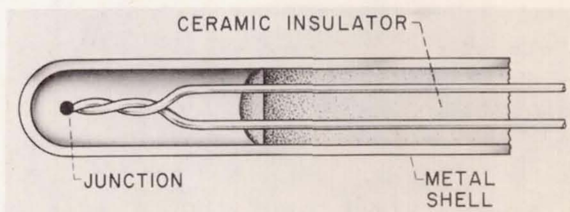

FIGURE V-12.—Industrial thermocouple.

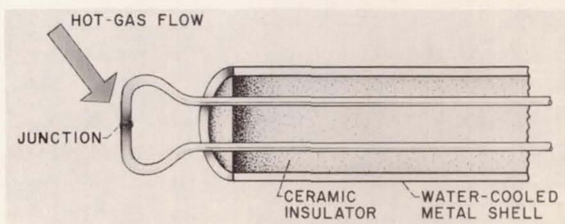

FIGURE V-13.—High-speed thermocouple.

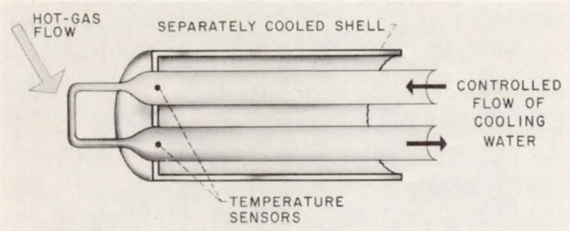

FIGURE V–14.—Cooled-tube thermometer.

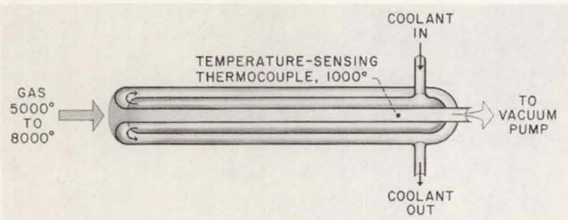

FIGURE V–15.—Cooled-gas thermometer.

The success of this apparently self-defeating technique is due to the fact that, if the mathematical laws of heat transfer between gas and bulb are adequately known and if the cooling is accurately controlled, it is possible to calculate the true gas temperature even if the thermometer bulb is at a considerably lower temperature.

One successful cooling technique is represented by the *cooled-tube thermometer* (fig. V–14). Through a small tube (resembling the external configuration of the bare-wire, butt-welded, high-speed thermocouple), sufficient cooling water is passed so that the tube temperature rises only about 100°. The rate of water flow is carefully controlled, and the rise in water temperature is accurately measured by thermocouples immersed in the water. The external gas temperature that produced this rise in water temperature can then be calculated accurately, if the gas velocity is also known by some independent measurement.

A second cooling technique is represented by the *cooled-gas thermometer* (fig. V–15). Here, the gas is cooled by sucking it through a long tube by an appropriate vacuum pump. The long tube is separately cooled by a secondary water-cooling system so that its temperature rises only a few hundred degrees; the concentric-annuli construction shown in the figure represents a typical cooling-passage design. After the hot gas has passed down the tube for a sufficient distance, it has been cooled to the point where its temperature can conveniently be measured with a thermocouple. An adequate knowledge of the laws of heat transfer then permits computation of the external gas temperature that produced the measured temperature of the downstream thermocouple. Variations of this method have been used to measure temperatures in industrial coal and gas furnaces.

A third technique that permits measuring a 5000° F gas temperature with a thermocouple like the high-speed thermocouple of figure V–13, which would melt at 3000° F, is to insert the thermocouple momentarily into the gas stream, and then withdraw it before its temperature rises above about 2000° F. By rapidly cycling such a thermometer bulb in and out of the gas stream several times a second, the average temperature assumed by the thermocouple can be related to the true gas temperature.

The successful developments of the high-speed thermocouple and of the controlled-cooling techniques have been made possible by fundamental research in the laws of heat transfer between solids and gases in the near-sonic, transonic, and supersonic regimes; much of this work was performed at the Lewis laboratory. These laws, once established, have had far wider applicability than just to thermometry.

The *infrared radiometer* is also applicable to the measurement of very high gas temperatures; an instrument of this type has recently been built at Lewis. Although the technique is less accurate than the probe-type methods described, the convenience of a method that does not require that anything be inserted into the gas is often a dominant consideration.

Infrared radiometry is only one of several optical techniques for gas-temperature measurement. All possess the merit of convenience and the fault of reduced accuracy.

Concluding Remarks

Numerous listings exist of commercially available sensors. The ISA Transducer Compendium, the result of a recent industry-wide survey by the Instrument Society of America, lists over a thousand different kinds of sensors that are commercially available today. They range from older, well-established devices to others that have recently been developed, perhaps for a single special application. The wealth and variety of these tools of measurement is sufficient that the measurement requirements of industrial operatitons and engineering development can adequately be met from this storehouse, if the tools are properly chosen, and properly applied, with adequate understanding of the overall system and of the end result to be provided by the measurements.

INFORMATION PROCESSING

The signals provided by the numerous sensors used on any one project must be assembled in a form suitable for transmission. or telemetering, to an appropriate facility where computations can be performed to analyze the data, and a final presentation made in a form useful to man. These steps of data assembly, transmission, analysis, and presentation (fig. V–4) are illustrated by a particular example, a nuclear test.

Nuclear-Rocket Test

In the nuclear rocket (fig. V–16) liquid propellant from a storage tank is first passed along the wall of the rocket, to be preheated and converted into the gaseous form. (Simultaneously, this process serves to cool the rocket walls.) The gas is then passed through the reactor core, where it is heated to a very high temperature, and then expelled through an exhaust nozzle to produce thrust. Such a system can generate five times as much thrust per pound of propellant as can be generated by a conventional chemical rocket, such as the one used to launch Mariner.

As a first step in nuclear-rocket development, the reactor core is replaced by one that is electrically heated, in order to reduce hazards and expense. Nevertheless, the test remains sufficiently hazardous so that it cannot properly be conducted near a populated area. For this reason, such tests are performed at the 6000-acre Plum Brook facility of the Lewis Research Center, near Sandusky, Ohio.

Central Data-Processing System

In a particular test, 300 sensors are used to measure force, pressure, flow, temperature, and vibration. Auxiliary equipment required to create an appropriate environment for the test is monitored with additional sensors. The wires from these sensors and from asso-

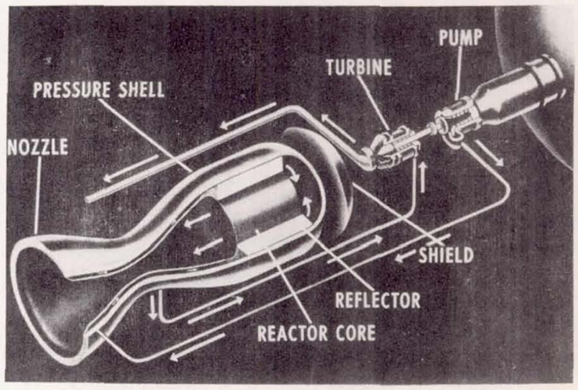

FIGURE V–16.—Nuclear rocket engine.

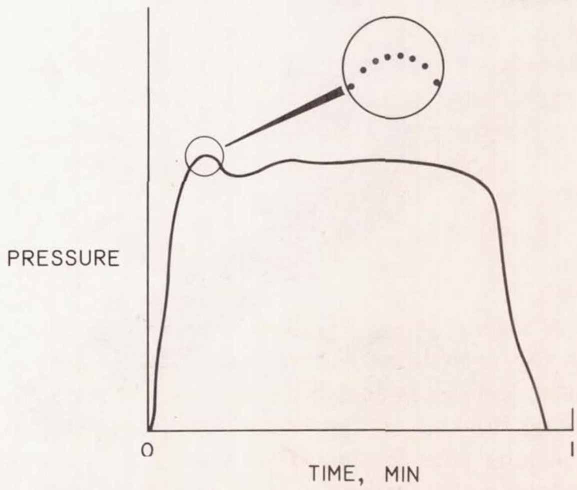

FIGURE V–17.—Sampling.

ciated control equipment terminate in a remote blockhouse, from which the test can be controlled by human operators and by automated equipment. At this location, also, the signals from the sensors are prepared for recording on magnetic tape.

One of the operations of such preparation is *sampling*. If the signal from a particular sensor varies continuously with time, as indicated in figure V–17 the value of the pressure is sampled at discrete times, as shown in the enlargement on figure V–17, and these sampled readings recorded on magnetic tape. Samplings from several sensors may be recorded on a single channel of magnetic tape. The recording is in the form of magnetized bits on the tape (fig. V–18), which will be described more fully later.

The building in which the recording of data takes place serves all of more than a dozen rocket test facilities at Plum Brook; any one facility can be connected to the recording equipment at any one time. This centralization of recording effects appreciable improvements in cost, reliability, and efficiency.

After the test information has been recorded on tape, the project engineer can play the tape back at a slower speed and observe on an oscilloscope the manner in which each test variable behaved. The oscilloscope display then resembles the curve of figure V–17. Portions of particular interest can be selected for further analysis; this process is termed *editing*.

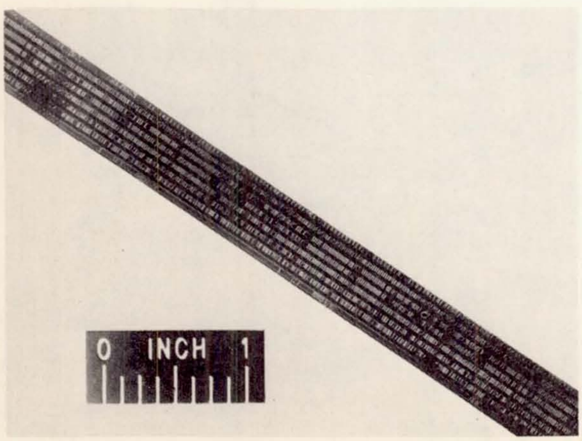

FIGURE V–18.—Seven-channel magnetic-tape record. Eighth channel is a timing and run-identification trace.

The data-sampling system takes about 15,000 samples in a second, or about 1 million points in a minute, the duration of an average test. Since it is not possible to determine in advance what portion of the data is important, the editing process is used to assure that only that portion of the data is selected for further analysis that is of greatest importance. This editing process is essential to prevent our being swamped in data and is one of the keys to the success of our data-processing system.

The magnetic tape containing all the data of the test run, together with a sheet on which the engineer has identified those portions that were determined to be of paramount interest during editing, are taken to the central computing center in Cleveland. The identifications, together with predetermined instructions for analysis of the data, are programed into the computing machine; the output is in the form of tables and graphs that describe the results of the test in a form easily interpreted and understood by the engineer. In the case of the test of a nuclear-rocket system, the results may be a visual depiction of the dynamics of the system, final data on the performance of the pump and of the turbine, or a graph of the variation with time of the heat-transfer rate between the propellant and the wall of the rocket chamber. Such results may be compared with those predicted by an earlier analysis, so that prediction methods for future tests may be improved.

The information handling and computing system records and analyzes 20 million data samplings per month. Final results of any one test are available a few hours after a test is completed. By hand methods using slide rules or desk calculators, the same analysis would have required three people working for several weeks and a four fold increase in cost.

Modern Tools of Data Processing

The modern high-speed computer makes such rapid data analysis possible. Over 50 percent of the U.S. computer industry income is derived from the aerospace field. Conversely, present-day space flight would be impossible without the computer. The manned Mercury flights relied on computers that could keep up with the 18,000-mph flight, while making intricate computations of the trajectory and movement of the spacecraft.

These elaborate computers have been made possible by such electronics-industry developments as the transistor and other solid-state devices. These have largly replaced the vacuum tube and provided advantages of smaller size, reduced weight, and lower power consumption.

These new developments have also made possible much of the intricate electronics used on board spacecraft. Speed and reliability have been increased. More data can be collected in a given time, and they can be assembled and analyzed in less time.

In many cases, this increased speed is due to the smaller size of transistors and the consequence that they can be placed closer together, because speed is often governed by the time it takes an electric current to travel along a wire from one point to another. Basic operations in some computers take place in only 10 billionths of a second, the time it takes an electric current to travel 10 feet.

Figure V–19 is a symbolic representation of the relative performance obtainable with devices using (1) the conventional vacuum tube, (2) ordinary solid-state devices in a conventional manner, and (3) microminiaturized versions of these same solid-state devices, as they might be constructed for use in space flight. Improvement factors for size, power, and weight are indicated, relative to the vacuum-tube devices.

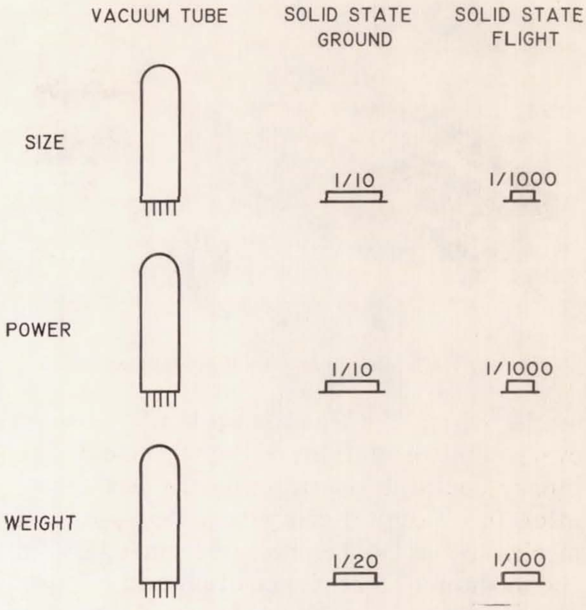

FIGURE V–19.—Relative performance of computing devices.

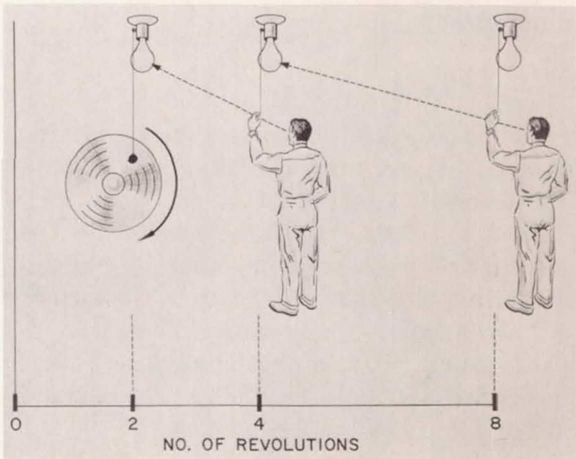

FIGURE V–20.—Counting with flip-flops.

Binary Counting

Speed and reliability are often increased when the solid-state devices are used to perform binary counting by means of off-on switching circuits called "flip-flops." Figure V–20 shows a mechanical analogy of this counting operation. The pull-chain electric sockets are actually mechanical flip-flops. To use them to count the revolutions of a wheel, the first lamp socket is arranged so that the lamp will light at every second revolution of the wheel. Each of the men is instructed to pull his lamp-socket chain whenever the preceding lamp is lighted. Thereby, the second lamp lights once for every four revolutions

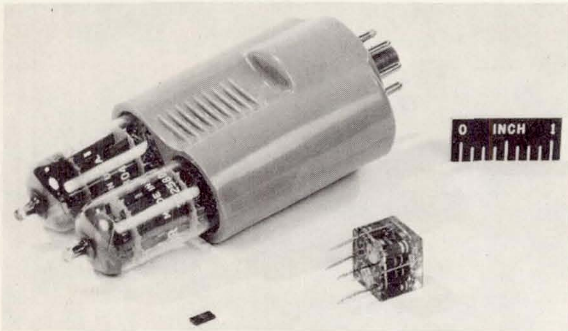

FIGURE V-21.—Relative sizes of flip-flop modules.

of the wheel, the third lamp lights once for every eight revolutions of the wheel, etc. This binary counting operation is the basic operation in all digital computers, because a numerical result can be presented solely through the medium of a sequence of on-and-off operations, that is, yes-and-no operations; on magnetic tape (fig. V-18) yes-and-no corresponds to whether the tape is or is not magnetized.

Circuit Developments

A modern, large computer may contain a million basic flip-flop circuits, each consuming a certain amount of power that is dissipated as heat. This heat raises the temperature of the transistors, thereby reducing reliability, since the reliability of a transistor is halved when temperature is raised 20°. This problem is exceptionally serious in spacecraft applications, where it is very difficult to get rid of the heat.

A refined circuit technique has recently been developed at Lewis that changes the efficiency of the basic flip-flop circuit from its usual value of 15 percent to a value of 90 percent, corresponding to an eightfold reduction in heat developed. Twice as many transistors are required, but any decrease in reliability for this reason is more than offset by the increase in reliability due to the lower operating temperature. Figure V-21 shows the relative sizes of (1) a conventional flip-flop module using vacuum tubes, (2) a conventional flip-flop module using transistors and the newly developed circuit, and (3) what a microminiaturized version of (2) would look like. By using the newly developed transistorized flip-flop design, a computer containing 15,000 such flip-flops could be operated with no more power than is consumed by an ordinary three-cell flashlight and could fit into an ordinary suitcase.

Magnetic Devices

Modern developments in magnetic devices have also reduced the size and increased the speed and reliability of information-processing equipment. Magnetic-core memories now have the ability to store vast amounts of information, in a relatively small volume, with little power consumption. Figure V-22 shows one plate out of a cubical stack that constitutes a magnetic storage unit. The plate contains 1024 tiny rings of magnetic material, each ring laced with five wires that perform the functions of input, output, location, and erasure of on-off information. A stack of 33 of these plates can store 32 nine-digit numbers.

Modern high-quality magnetic tape, such as that shown in figure V-18, also provides a high storage density of information. The video tape recorder, which allows recording and rebroadcast of television programs, has been made possible partly because of this improvement in the quality of magnetic tape.

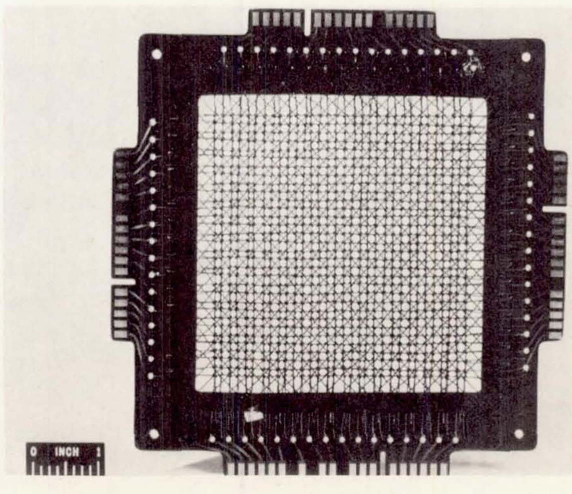

FIGURE V-22.—1024-Core magnetic-core memory plate.

Concluding Remarks

The rapid developments of the instruments and techniques for the assembly, recording, and presentation of data, together with the modern high-speed computer, have made possible an increase in the scale of information processing beyond that which was practical a decade ago. Thereby, tasks can now be performed that were once too complex to be feasible. Manned space flight is an outstanding example of such a task. Other examples may be expected to develop, in commercial and industrial operations, as knowledge and skills are disseminated more widely.

CONTROL COMPONENTS

Another subject to be considered is that of control. As noted in figures V–1 and V–23, the control has within it information-processing functions, such as those previously discussed, as well as data assembly and computation. The output of the computing system in basic control, however, is a command that must be executed by some device such as an actuator. Shown in figure V–23 is the information-processing chain consisting of sensed data, data assembly, and calculation, which has been discussed. The output of the computer in this case feeds an actuator that operates on the process that we desire to be controlled. In the case of closed-loop control, as mentioned before, the sensor observes the result of the control action. Thus, two new thoughts have been introduced. One of these concerns the components of a control system and the other concerns the closed-loop control. Consider first the subject of control components.

The special requirements of control components for space vehicles have made it necessary to develop a group of devices with considerable industrial interest. Some of the requirements that must be satisfied by a typical aerospace control component are lightweight, low power consumption, high performance, environmntal tolerance, long operating period, and low cost. These same features incidentally are, in general, desirable for most control components, aerospace or otherwise. For example, for high performance, a fast response device may be needed for an aerospace application like a rocket-engine gimbal actuator. This actuator swivels the rocket engine to keep the missile from tumbling. The accuracy of the mission depends on having a fast-response actuator. Since this is an expensive mission, a development program can be afforded to advance the state of the art for fast-response actuators. The resulting actuator will also be advantageous for industrial applications like a machine-tool-positioning actuator. Before going further, however, it would be appropriate to show some examples of aerospace control components that might be of industrial interest.

Hot-Gas Actuators

One example of control components of interest is the group called hot-gas actuators. These actuators are flight-weight instruments that combine high performance with simple power supply requirements. Originally, they were developed for use with small missiles. Their source of high-pressure gas is obtained from the combustion of a grain of solid propellant. This solid propellant, in a small pressure vessel, was ignited seconds before the flight of the missile. These actuators have since been adapted to a wider range of applications. They can be made to operate with fluids of any temperature, down to that of liquid hydrogen, but the name hot-gas actuators still is used.

One example of a hot-gas actuator is a

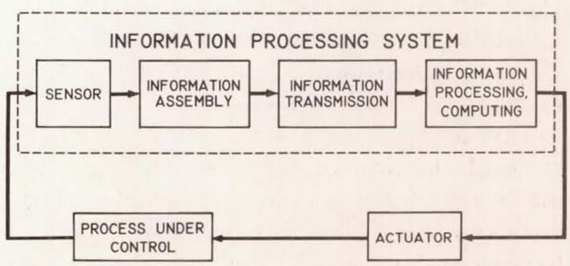

FIGURE V–23.—Elements of a control.

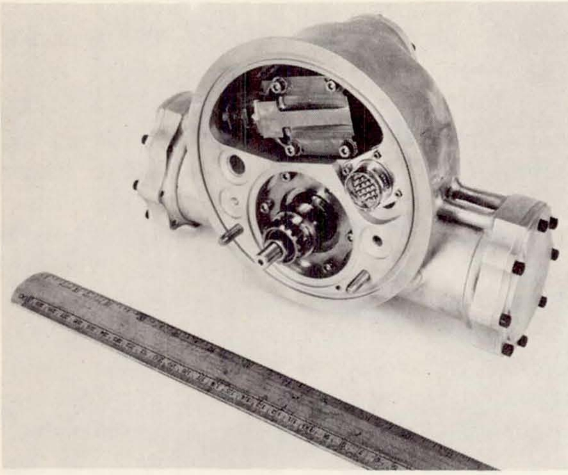

FIGURE V–24.—Electropneumatic mechanical actuator. (Courtesy General Electric Co.)

rotary position actuator (fig. V–24). Its source of power is high-pressure gas that is fed into the ports on the mounting face. Control signals are supplied to the connector on the mounting face of the actuator from a remote amplifier. This actuator was developed for the nuclear-rocket program. The construction techniques are similar to those of conventional automotive engine construction; however, high-level engineering has adopted the construction to satisfy a stringent set of specifications. This simplicity of construction is probably responsible for operation over such a wide temperature range. If it had been built like a precision clock with close tolerances, thermal expansion would have caused it to seize and malfunction. It is built with solid-film internal lubrication so that nuclear radiation can be tolerated. It is fail-safe so that on loss of pneumatic or electric power it will turn to the closed position. The speed of response exceeds most commercially available hydraulic actuators. Also construction is of the plug-in type so that by releasing a single clamp it can be disconnected mechanically and electrically.

This actuator represents an advance in the state of the art for high-performance pneumatic actuators. As was mentioned, it is only one example of a hot-gas actuator. Actuators have been developed to run from the gas that might be available on their spacecraft. They avoid the complexity of other types of power supplies like turboelectric generators or hydraulic supplies.

Fluid-Interaction Devices

Another class of control components that should be of considerable industrial interest is called fluid-interaction devices. These devices are sometimes called pneumatic amplifiers with no moving parts. These new devices can, in fact, be either pneumatic or hydraulic amplifiers. The principle of operation of a fluid-interaction device is explained in figure V–25. The device consists only of passageways in a block of solid material. The geometry is fixed and depends on the interaction of fluid streams for operation. First a source of fluid pressure is needed to create a jet that divides equally on the sharp edge. If flow is passed into the right control port, the jet is deflected to the left, and the flow is no longer equally divided. Thus, the left output pressure becomes greater than the right output pressure. There can be an amplification of the pressure change; in other words, a small change in control pressure can create a larger change in output pressure. Thus, the device is said to have a pressure gain.

As mentioned earlier, the fluid-interaction-device field is rather new. It is well known that fluid amplifiers with moving parts such

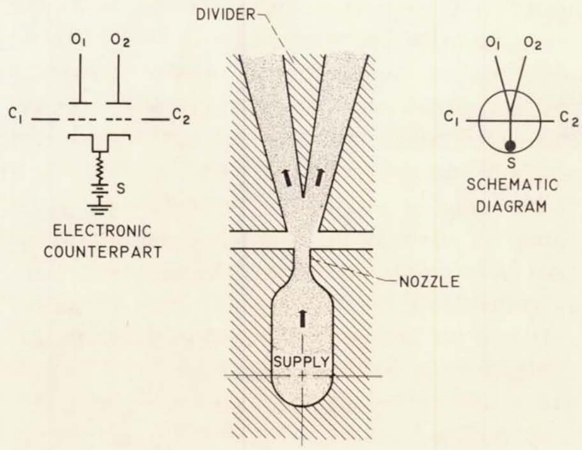

FIGURE V–25.—Typical fluid jet amplifier.

as bellows, variable orifices, and jet pipes have been in use in the process control industry for many years. Thus, only the nonmoving-part fluid-interaction-device field is represented as being a new field. This field first became of serious interest in 1960 when the Diamond Ordnance Fuse Laboratories of the Army Ordnance Department, as well as the Massachusetts Institute of Technology, released information about this important new area of work. Widespread interest by the Government, universities, and industry followed. It is likely that fluid-interaction units will eventually become incorporated into the pneumatic process controllers that were mentioned earlier. A new market can be created by the new types of functions that can now be performed pneumatically.

It would be appropriate before proceeding further to consider some of the functions that can be performed by fluid-interaction devices. Figure V–25 shows an amplifier that could be capable of making a feeble signal from a sensor powerful enough for transmission, recording, or control action. It is therefore similar to the triode vacuum tube or the transistor. Likewise, the functions of other electronic components in information-processing circuits have their fluid-interaction counterparts. For example, it is possible to build fluid-interaction diodes, flip-flops, counters, commutators, and oscillators. In the case of pneumatic oscillators and flip-flops, cycling frequencies between 1000 and 10,000 cps have been demonstrated. This is slow compared with electronics by a factor of 10,000, but for many control or simple computer applications, it can be more than adequate. Since it is possible to build fluid-interaction counterparts of many electronic devices, the possibility presents itself of the growth of a fluid-interaction industry that could be a small-scale counterpart of the electronics industry. Naturally, fluid interaction will never make electronics obsolete. Fluid interaction, for example, will never be used in communications equipment or high-speed computers because it is too slow; however, it may be applied in connection with manipula-

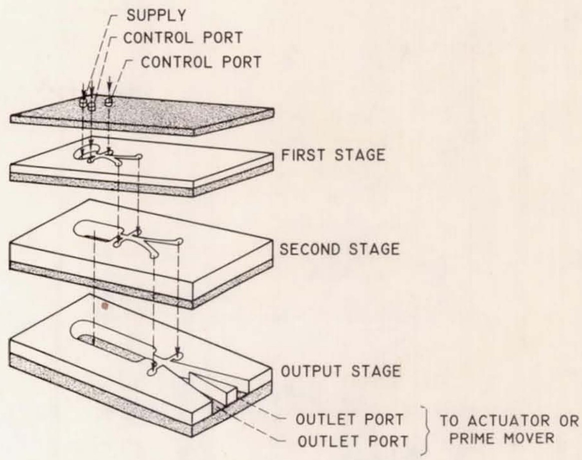

FIGURE V–26.—Laminar construction of fluid interaction amplifiers.

tion of physical objects in actuators, servosystems, or with liquid- or gas-flow systems.

An interesting similarity between electronics and fluid interaction is in the area of what might be called printed-circuit-board construction. Fluid-interaction stages can be made by laminar construction techniques. Figure V–26 shows a three-stage power amplifier that is built in the laminar configuration. The input stage is in the top layer. Its output ports feed into the control ports of the second stage, which is in the middle layer. The output ports of the second stage, in turn, feed into the control ports of the third stage, which is in the lower layer. The external connections to this modular three-stage power amplifier are the two input ports to the first stage, the two output ports from the last stage, and the connection to a source of pneumatic pressure. These five ports could be brought out as tubes on the same side of the cube so that the unit could be a plug-in power-amplifier module. This laminar construction of fluid-interaction devices opens the prospect for fabrication of the lamina at a very low production cost. For example, it is possible to make the lamina by pressure-injection molding of plastic, the way plastic toys are made.

The following table summarizes some of the advantages and disadvanatges of fluid-interaction devices:

Advantages	Disadvantages
High environmental tolerance	Careful design required
Very long service life	Limited range of adjustability
Unlimited shelf life	Low signal-to-noise ratio
High density packaging	Slower response than electronics
Low production cost	Wasteful of driving medium
Driving medium readily available	
Explosion proof	

The devices have considerable advantages in the area of environmental tolerance, long service and shelf life, high-density packaging, and low production costs. On the side of disadvantages, careful design of fluid-interaction stages is required at the present time. Fluid-interaction stages can be plagued by parasitic oscillations, and the problems of aerodynamic noise cannot be neglected. The advantages of fluid-interaction devices are so attractive, however, that further development is anticipated to continue in this field.

CONTROL SYSTEMS

As shown in figures V–1 and V–23, the control system or control loop consists of the sensor, the information manipulating or calculating equipment, the actuator, and the process. Information from the process is fed back to the sensor to close the loop. These closed-loop configurations are commonly called servomechanisms or servos.

Servo Theory

In the closed-loop configuration, the system can take on characteristics that could not have been easily predicted by someone knowing the characteristics of the components that compose the loop. In fact, one thing that probably is the most impressive to those who have had only occasional experience with closed loops is the fact that servomechanisms can malfunction in very extraordinary ways. One of the most common types of malfunction is oscillation, and there are a number of words that describe the different types of oscillations, such as diverging oscillation, marginal stability converging oscillation, etc. Because of this situation, the field of servo theory or closed-loop control theory has grown. Most of the development of this field has taken place during and after World War II. By the use of the servo theory and some specialized equipment, it is now possible to design control systems that work properly on the first try. In fact, it is possible now to design control systems for processes that are only on the drawing board.

This presents an interesting contrast to the 1930's where automatic controls were rarely used even to operate something like a chemical plant. Later partial automatic control was incorporated. The plant came first and the controls were adapted to it. This did not always produce the optimum combination. If a few well-selected changes had been incorporated into the design of the plant, as could have been disclosed by a proper servo analysis, the result would have been more controllable.

Analog Computers

A tool that is being used extensively by the modern controls engineer is the analog computer. The servo theory that was mentioned before makes it possible to handle many control-system designs by pencil and paper analysis, but the use of the analytical approach becomes difficult for systems that exhibit nonideal behavior like backlash or stiction. Also, for multiloop systems where many loops like the one shown in figure V–23 are interconnected and interact with each other, the analytical approach finally becomes too laborious. At this point, the use of the analog computer comes into its own.

Analog computers have found widespread applications in the aerospace effort. The name analog computer is derived from the fact that if two quantities are similar or analogous to each other, they are called analogs. An example of this is a topographical map of the United States. This is a small analog of the actual physical topography of the countryside. It has a scale factor such as 1 inch equals 50 miles, which explains the relation of the analog to the real thing. In a similar fashion, analog computers are used to build models of physical systems. For example, the flight of an airplane can be simulated on an analog computer so the voltages in the computer behave just as the airplane would. In this case, voltages in the computer are made analogs of physical quantities such as speed, altitude, and angle of attack. In the case of altitude, the scale factor might be 1 volt equals 1000 feet.

The science of analog computers has developed largely within the last 15 years. The first analog computer at Lewis was purchased in 1948. It was one of the first in the country. The improvements that have been made in analog computers since then are so vast that the 1948 model computers have become completely obsolete. Present-day analog computers are being used to solve problems where the solution is a time-varying quantity. Some examples of these problems are the evaporation of propellants after injection in a chemical rocket engine or the time history of start-up of a nuclear-rocket engine. These types of problems are of a complexity to utilize a large quantity of analog computer equipment. They could not be solved by hand calculations and do not readily adapt to digital computer solution. With the use of the analog computer in these applications, a prediction of the behavior of a future propulsion system like a nuclear rocket can be made years before its first actual flight. In fact, it can be said that, previous to actual flight of any of our present-day aircraft or missiles, enough analog computer simulation was done to give good prediction of their in-flight behavior. It is worthy of note that the analog computer is not strictly an aerospace tool. Its use in many industrial applications is now becoming more feasible. A recent development that is making this possible is the simplification of large computer consoles into small transistorized desk-top versions. These are much less expensive and do not require the special air-conditioned installations required by the large computers. This area of transistorized analog computers has developed within the last 3 years. It holds the prospect for many interesting applications.

An interesting example of the use of analog computers to solve control-system problems is in the case of the nuclear-rocket engine. The operation of this engine can be illustrated by the use of figure V–16. Liquid hydrogen, under pressure, flows out of the supply tank through the turbopump. It is pumped up to the high pressure and flows into the regeneratively cooled expansion nozzle. It passes over the outside of the engine and then flows through the hot reactor core. It then is ejected from the expansion nozzle and produces thrust. A small quantity of high-temperature hydrogen, as it comes out of the reactor core, is ducted into the turbine to drive the pump. For control of this engine, it is necessary to control the flow of liquid hydrogen to the engine, and it is also necessary to control the power generated in the reactor core. These two parameters, flow rate and reactor power, are controlled by two control loops; these are closed-loop control systems. This is an example of the design of a control system where quick response and stable operations are required. It is a control that is more complicated than can be easily handled with pencil and paper analysis.

How the analog computer is used to solve the design of a control system for this nuclear rocket can be explained as follows: First, the system characteristics are simulated on the computer. In other words, one part of the computer is patched together so that it behaves as the system would behave. After this is done, it would be possible to try to operate the rocket without any kind of control. In this case, it might run away or explode. If this happens on the analog computer, no harm is done; the computer is protected against runaway conditions. The rocket can be restored and operation can resume. Next, another part of the computer is patched together so that it behaves as a controller. The controller and nuclear rocket are mated to determine how well-behaved the closed-loop system really is. It is possible to try out different control schemes to find the one that is the best adapted to the requirements of this rocket engine.

The most important point about the previous discussion is that it is necessary to do this analysis before the actual flight of a nuclear-rocket missile. The nuclear rocket cannot frequently be run on the ground because of the hazards and the expense involved. It is therefore necessary to simulate the major parts of the system beforehand to learn how well the system will behave when it is operated. This technique of defining a control system is called breadboarding a control system. In the breadboard approach to designing control systems, the analog computer is used as a control, and it is allowed to run some of the actual hardware of the system. Several control schemes can be patched into the computer, and this computer can be used to control the real process. At Lewis this principle of control has been used to run aircraft engines. Turbojet engines and ramjet engines have been run with analog computer control systems. After the control requirements were more closely defined by this technique, the control could be miniaturized into a smaller box that was called a prototype. This prototype can still be somewhat experimental, but ultimately it is miniaturized into a flight-weight version.

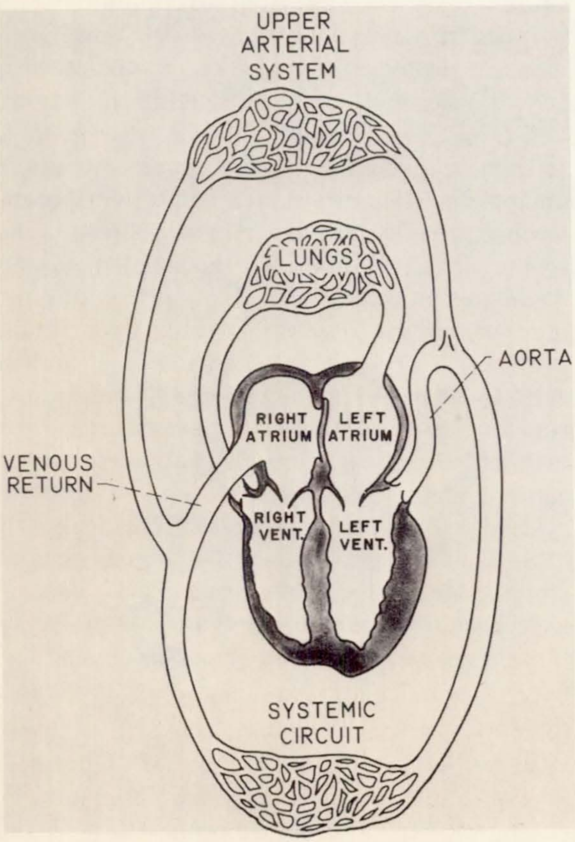

FIGURE V–27.—Normal circulatory system.

Artificial Heart

An example of the advantage of breadboarding a control system was recently demonstrated by NASA Lewis engineers in a project to control an artificial heart. This medical engineering project was conducted in cooperation with the Cleveland Clinic. In this case, the variable to be controlled was not hydrogen gas flowing through a nuclear engine but blood flowing through a circulatory system that was connected to an artificial heart. The function of a normal circulatory system can be explained by use of figure V–27. The path of the flow of blood around the circulatory system can be traced. Return flow from the body is ducted to the venous return and into the right heart. It is pumped out of the right atrium and right ventricle to the pulmonary artery, passes through the lungs, is oxygenated, and is ducted to the left heart. It is then pumped out of the left atrium and ventricle into the aorta and circulates through the body.

Finally, it is returned through the veins to the right heart and starts the circuit again.

Where the heart has become diseased, the medical people would like to replace it with an artificial heart pump. A circulatory system connected to two artificial heart pumps is shown in figure V–28. The normal heart has been replaced by two pumps. For convenience, the functions of the left and right heart have been separated. The right artificial heart now performs the same function as the right half of the normal heart, and the left artificial heart performs for the left normal heart. These heart pumps are really lightweight plastic bags equipped with artificial valves. When pneumatic pressure is ducted to one of the pumps, the air pocket expands and forces blood out of the artificial ventricle or blood chamber. The artificial valves behave like check valves permitting unidirectional flow of blood. Carefully controlled pneumatic pressure to actuate the pumps is ducted in through small diameter plastic tubes from our control system.

It should not be concluded that NASA Lewis is building these heart pumps or conducting this type of artificial heart research. This project is being done at the Cleveland Clinic, but they are using some of the Lewis control system know-how drawn from aerospace technology. Also, it should not be concluded that this artificial heart system is fully developed and ready for use. Its exact status will become more apparent as the discussion proceeds.

Figure V–29 shows these two plastic pumps after being connected to a circulatory system of a calf. The plastic bag pumps are made of silicone rubber reinforced with woven Dacron.

A point that should be made in any discussion of an artificial-heart system is that it should not be confused with the heart-lung machine. There are some important differences. This is a pump, not a pump-oxygenator combination. It is intended for permanent heart replacement, not a temporary bypass as in the case of the heart-lung machine. Also, it is not to be used external to the body, but it is an in-the-chest artificial heart.

The fact that this system is for permanent heart replacement makes the control problem more exacting. Simply to pulsate the pneumatic pressure in the pumps by use of an on-off valve connected to a source of constant pressure was not sufficient. This would cause pumping, but just to pump in this simple fashion was not sufficient. In trying out

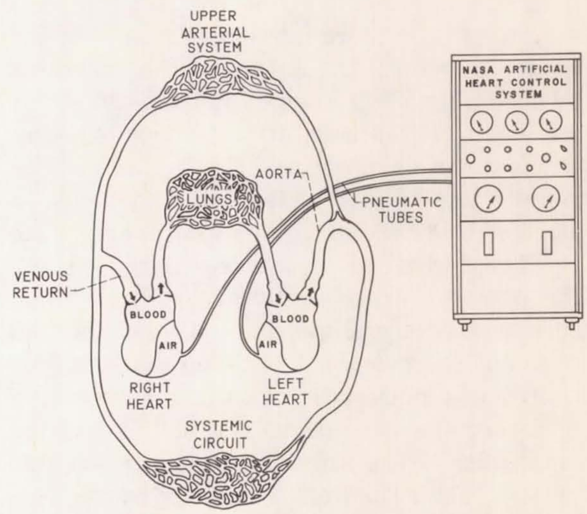

FIGURE V–28.—Circulatory system driven by pneumatic artifical hearts.

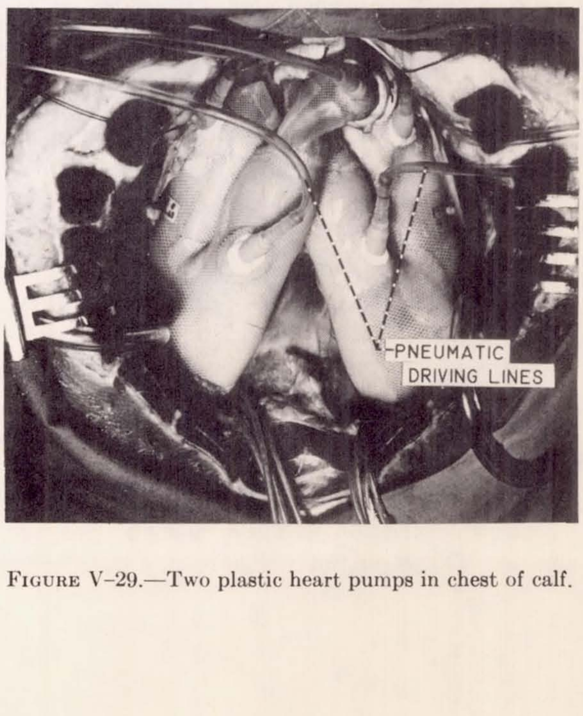

FIGURE V–29.—Two plastic heart pumps in chest of calf.

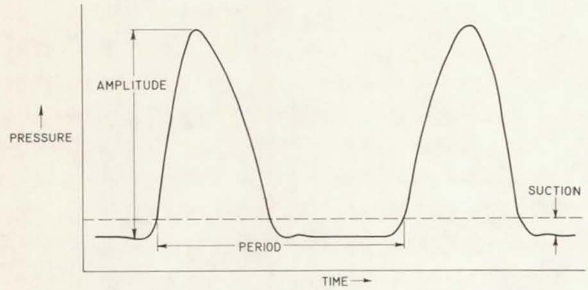

FIGURE V-30.—Pumping pressure of heart.

such a scheme, it was found that the experimental animals did not survive for more than 6 or 8 hours. This is why it was necessary to go to a more flexible system with the ability to control the nature of the heartbeat by adjusting a few knobs. Figure V–30 shows an idealized representation of the pressure in the ventricle of a heart. The pressure rises rapidly to a positive value and drops back to atmospheric pressure. This first phase of the heartbeat is called the systole. After systole, the pressure drops below atmospheric pressure to create a slight suction. This second phase of the heartbeat is called diastole. For control of a pneumatic heart pump something is needed that will permit adjustment of the amplitude of the pressure excursion and the period. By adjusting the period, it is possible to adjust the frequency of beating or the pulse rate. It is also necessary to be able to adjust the waveform of the pressure pulse. Thus, a sharp high peak or low broad peak in pressure during systole can be obtained. In this way it is possible to try physiologic waveforms of pressure or something that is more experimental.

A breadboard control system was used to do this job. It was built from analog-computer-type equipment and designed to provide the maximum degree of adjustability. A block diagram representation of the artificial-heart control system is shown in figure V–31. A function generator receives instructions so far as desired pulse rate and the desired waveforms for the left and the right hearts. The two output voltages from this function generator are fed to two pressure servos. These output voltages are indicative of the waveforms of desired left and right heart pumping action. The pressure servos translate the voltages they receive into corresponding pneumatic pressures, which are sent to the two heart pumps. The system has several internal feedbacks so that it corrects itself for varying conditions in the circulatory system. The actual control system that was built by using these principles is shown in figure V–32. The engineer shown in the figure is adjusting some of the controls that are used to set up the waveform of pressure that is fed to one of the hearts. Figure V–33 shows how this equipment is used in an operating room where a survival experiment is being conducted. The animal shown has had his normal heart replaced by two artificial hearts.

Numerous survival-type experiments with animals have been conducted at the Cleveland Clinic with this equipment. Current experiments are being done with calves.

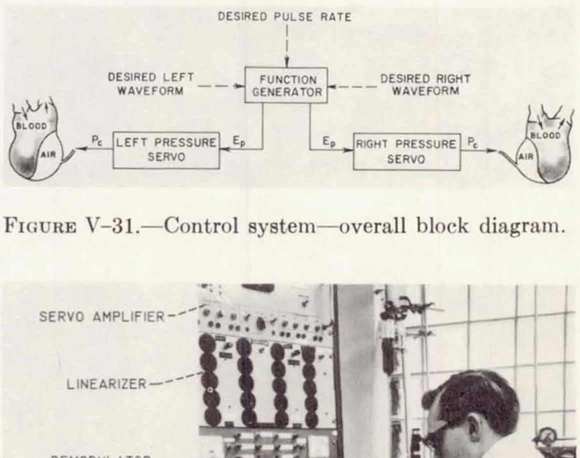

FIGURE V-31.—Control system—overall block diagram.

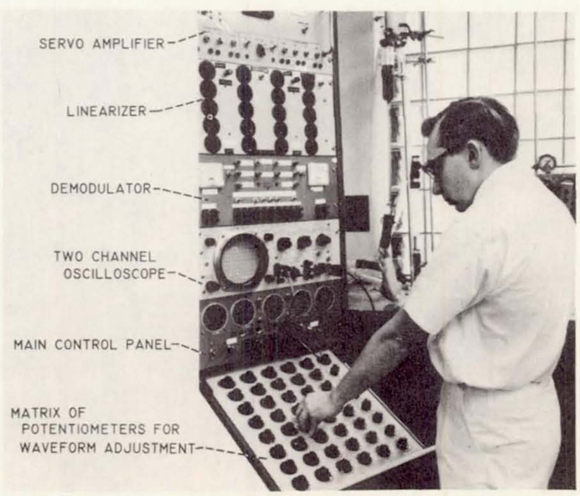

FIGURE V-32.—NASA artificial heart control system in use at Cleveland Clinic.

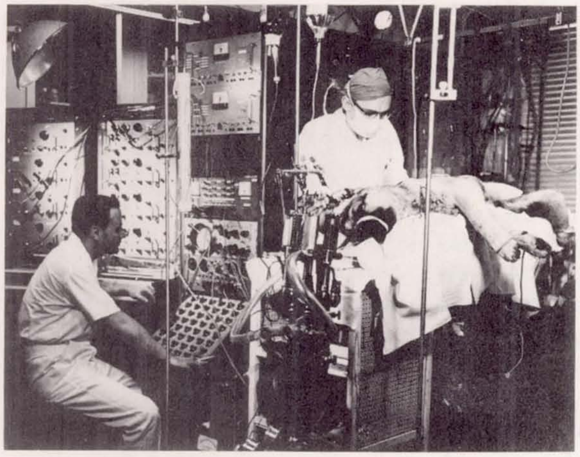

FIGURE V-33.—NASA artificial heart control system being employed in heart replacement experiment at Cleveland Clinic.

With the use of this equipment, the longest survivals on record have been achieved with animals that have had their hearts replaced by plastic pumps. In the past, numerous kinds of artificial-heart devices have been tried, but this system with pneumatic hearts and a feedback control system seems to work the best. Typical survival times of the order of 24 to 30 hours have been achieved.

Supervisory or Automation Systems

It is now appropriate to leave the field of automatic control of such devices as the nuclear rocket and move to a grander subject, that of supervisory control or automation systems. This is control of systems where a variety of decisions are possible and must be made by the control system. These supervisory controls incorporate all of the components that have been discussed previously—sensors, information-processing devices, actuators, and closed-loop controls.

One type of supervisory control system that has been placed into effect in several locations around this country is the automatic dispatching of electric power in electric powerplants, which are part of large distributing networks. This *economic dispatch* of power is governed by the time of the day, the day of the week, the season of the year, the actual load on several stations of a single complex power system, and the generating capacity of each of those stations. As many as a dozen stations might be tied together by a single automatic dispatching computer.

Another example of a supervisory system is computer checkout of one of the data systems here at Lewis. A computer has recently been installed the function of which is to check the operation of the information handling system. This computer will determine the condition of everything in the system, other than the computer itself, that is being used for the analysis. This includes such items as continuity of electrical lines, proper electric supply to the sensors, and the proper functioning of the electronics in the data assembly area. The computer performs this check on 300 channels, that is, on 300 sensors, in a fraction of a second and tells the operator which measurements are not satisfactory. While the measurements are being recorded, the computer can determine whether each sensor output is within satisfactory limits.

An example of a supervisory or automation system that is involved in the daily lives of individuals is a self-correcting traffic control system. Figure V-34 shows the console

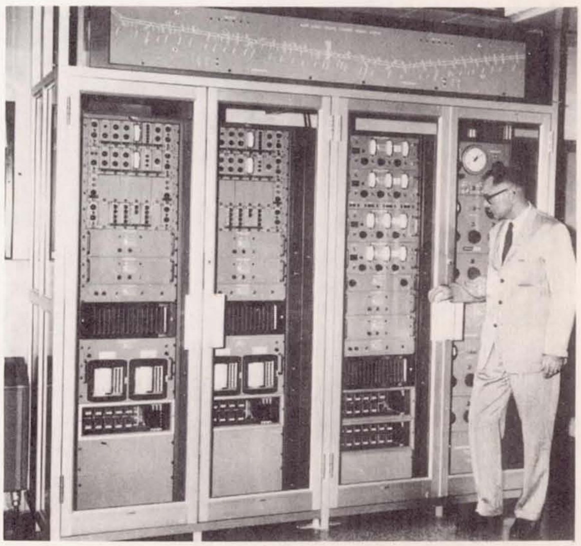

FIGURE V-34.—Traffic control computer used in Buffalo, New York. (Courtesy Railway Signal Co.)

of such a system. It is being used to control traffic-light timing along the main thoroughfare in Buffalo, New York. A map of the street with the locations of the traffic lights is shown above the console.

This system is different from a simple preprogramed system that merely adjusts stoplight timing according to the time of day and the day of the week. In this case, sensors look down on the traffic lanes to determine the percentage of lane occupancy for each lane. If the lane is jammed with bumper-to-bumper traffic, the lane occupancy number becomes 100 percent. This information, together with numbers that tell the direction of major traffic flow, inbound or outbound from the city, is fed to a computer and to recorders. In this case, the computer is an analog type. This computer then directs the traffic lights both in cycle length, that is, the time between each green light, and in offset, that is, the ratio of red to green duration. The characteristics of this traffic-control systems permit continuous readjustment of traffic lights to meet changing demands. Thus, traffic loads can efficiently be moved inbound or outbound from the city. Such a traffic-control system will not be "surprised" by an unexpected event; instead, it will automatically compensate for a traffic burden like the termination of a holiday parade or a stalled vehicle.

An example of a supervisory system that is space related is one that can automatically perform the countdown operation of a missile system. In the countdown procedure for missiles in the past, most of this work was done by a team of human operators who make the decisions one at a time concerning whether or not the missile is ready for launch. The checkout of present day missile systems, however, is becoming so complicated that a human operator or a number of human operators cannot perform the necessary jobs in the time allowed. Because of this situation, an automatic checkout and acceptance system is now being built for NASA that can automatically perform the checkout of the Apollo space vehicle. This is a computing system that has a schedule built into it of all the conditions that must be met prior to launch of the vehicle. The computer checks through these items in sequence making quick calculations and comparisons as it goes. It summarizes these calculations and presents them visually to a human operator. In each step of the countdown the machine can make a decision whether to continue the countdown or whether to proced to alternative checks before continuing the countdown. An advantage of such an automatic system is that the complete countdown can be performed more quickly. The machine is able to back up its decisions with more thorough calculations, thus making its decisions more objectively than the human operator can. The major decisions, however, that would involve knowledge not built into the computer, or judgment that is felt the computer is not capable of making, are left to the human operator.

CONCLUDING STATEMENTS

Systems Engineering

It would be appropriate to distinguish between advanced measurement problems and the routine measurement problems that constitute the majority of industrial needs. In advanced measurements, generally, the sensor is the device that requires most development for the solution of the problem. In the great majority of routine applications in industry and in research, however, there already exists a wealth of sensing devices that could be applied to any given measurement problem, provided that these devices are properly chosen and properly used by qualified and experienced engineers. In other words, the tools generally do exist; men must learn how to choose the proper ones and how to use them correctly.

Manpower Requirements

In any discussion of systems engineering, it should also be pointed out that there is a need for a great number of qualified people of two types. On one hand are the instrument engineers who have a good systems knowledge of what the problem truly is as well as a knowledge of the capability of parts that are available to do the various aspects of the job. After the system has been built, there is a need on the other hand for people who might be called *technologists*. These technologists can skillfully operate and maintain the type of equipment that has just been described. They occupy a position between that of the professional engineer and that of the journeyman trades worker. They would have a training similar to that provided by some of the better technical institutes in the country.

Consumer Products

In the preceding discussion, instrumentation and control equipment has been mentioned both on the basis of the opportunities for using it to do something better than before and the opportunity for making it to be used by others who, in turn, want to use it to do something better than before. In this latter category, the increased use of automatic equipment in consumer products should be mentioned. Thirty years has produced a dramatic change in this area. At that time, most homes had little automatic equipment. Today, most homes employ closed-loop control of room temperature and of the temperatures of appliances like refrigerators, ovens, and clothes dryers. Timers are used to turn these same appliances off and on automatically. This use of automatic equipment, simple as it is, in the home has made a revolution in the daily activities of the housewife, but this is just a beginning.

It was indicated previously that control of traffic lights can be timed automatically. It was also indicated that when something becomes too difficult to be done by a human operator, like the countdown of a missile system, a computer can be made to perform this same function more quickly and effectively. In a similar fashion, some of the things that individuals are asked to do in modern living are beginning to exceed the capabilities of the human. One example of this is driving an automobile. The traffic death toll over the 1964 Memorial Day weekend of 360 seems to prove this point. Many of those persons died because drivers encountered situations where their native sensing, calculating, and actuating equipment was not really fast enough for the occasion. The highway safety people indicate that the solution to the problem is in better driver training. This, of course, cannot be discounted. Another solution to the problem that perhaps holds the prospect for more dramatic improvement is in the area of the topics discussed in this paper, namely, sensors, computers, and servomechanisms, that is, the use of automatic equipment to drive the automobile.

Adaptation of automatic devices to the automobile has already started. We have power steering, power brakes, and automatic transmissions. These are primarily the actuating end of the control system. They can manipulate the automobile but they cannot make the necessary observations or issue the necessary commands. Thus, what is required is only to develop the sensors and computers to go along with these actuators. Many of these sensors and computers are, in fact, within the state of the art.

It was mentioned that automatic devices in the home have revolutionized life for the housewife; similarly, automatic devices may some day revolutionize life for the automobile driver.

Summary

In preparing material for this paper, the authors were impressed by the wealth of instrument technology now available, by the vigorous growth of the instrument and control industry, by the opportunities for new development, by the growing importance of instrumentation to our society, and by the prospects for a greater growth of this industry in the future.

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VI. Information Sources

JAMES J. MODARELLI
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A TREMENDOUS AMOUNT of technical information results from NASA activities. However, the gathering of technical information, or to rephrase it, the effort to increase our sphere of knowledge, is an incomplete thing in itself. This knowledge, recognized as a critical national resource, is not useful unless it is reported, announced, and shared. After the information is made available, it is hoped that the material will be understood and used.

Consider the various methods utilized for reporting information. These methods include conferences, seminars, technical society meetings, exhibits, motion pictures, and most important, the technical publications.

The material published in the technical publications can be broadly divided into two major areas: first, the documents prepared under the auspices of an organization and, second, those primarily reported in the technical society journals.

The organization or in-house generated reports issued by NASA are of a rather wide variety of types (fig. VI–1): Technical Memorandums, Technical Notes, Technical Reports, Technical Translations, and Special Publications. Each serves a specific function in the dissemination of technical information. They range from quick reports on raw data to incremental progress reports, state-of-the-art reports, translations of foreign literature, and the Special Publications, which are, in part, directed towards technology utilization.

For example, some typical documents in the Special Publications group are pictured in figure VI–2. They vary from major project summaries to handbooks and bibliographies. Of special concern is the SP–5000 series, which is devoted to formal publications on

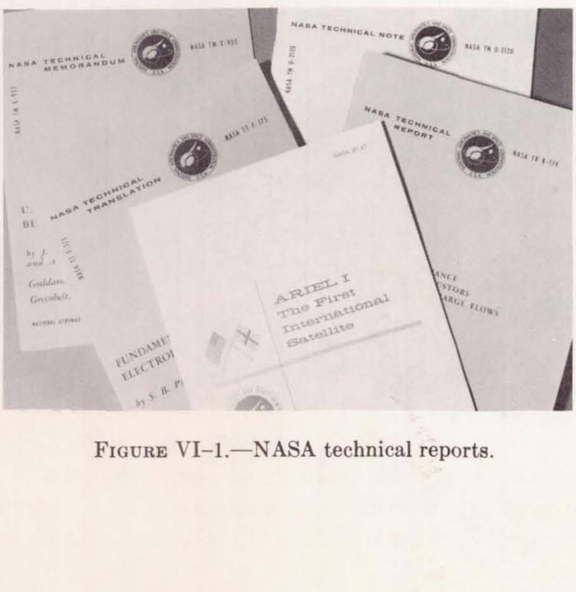

FIGURE VI–1.—NASA technical reports.

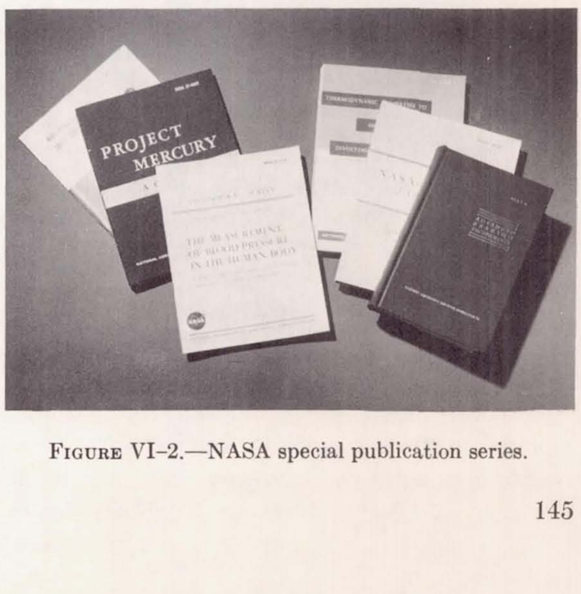

FIGURE VI–2.—NASA special publication series.

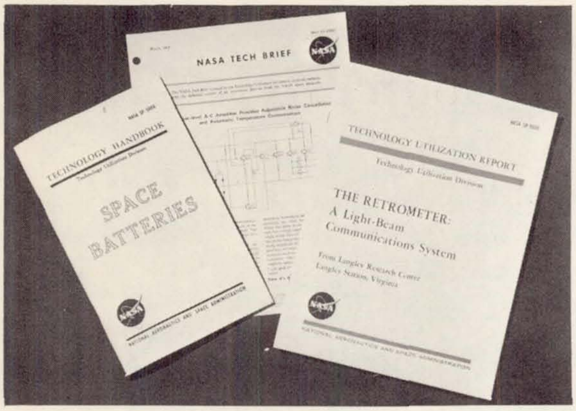

FIGURE VI-3.—Technology utilization publications.

FIGURE VI-4.—NASA contractor reports.

technology utilization for distribution to business and industry. In this area, an effort has been made to eliminate the complex mathematical equations and data figures and to describe the subject in terms of industrial application. Typically, a fabrication technique is emphasized rather than the aerospace problem and its solution.

Illustrated in figure VI-3 are two more examples of the technology utilization SP-5000 series. In addition, one- or two-page announcements called NASA Tech Briefs are published. These are simply flyers that are distributed free to acquaint industry with a potential innovation resulting from a NASA project.

There is one other group of NASA reports that are different in that they are not written by NASA authors; however, they are monitored by NASA and are under NASA management. This group is composed of the Contractor Reports (see fig. VI-4). It is interesting to note that 90 percent of NASA's $5 billion plus budget this year is being spent on research and development contracts. Research and development imply activities in new, unexplored areas, and NASA contractors in many cases must conduct research and experimental tests before they can proceed with the design and fabrication of hardware. This new information is typical of the content in the Contractor Report series.

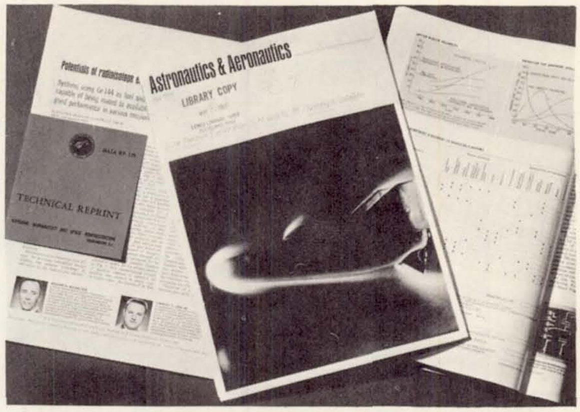

FIGURE VI-5.—NASA reprints.

NASA authors are quite active in submitting journal articles and participating in conferences and symposiums supported by the various technical societies. In most instances, the society publishes the papers in its journal. In these cases, NASA purchases reprints from the original publisher for subsequent distribution in response to individual requests. This type, called RP's, or Reprints, is the last type of NASA report (fig. VI-5). The reprints are purchased to avoid the expense of dual publication and to assist the technical society.

So much for the reporting of technical information. Writing and publishing these documents, which represent a major portion of NASA's end product, are only part of the job. The potential user must become aware that a new report in his specific area of interest is available. NASA employs two digest or abstract compilations for announcing new technical literature. Basically, one covers the organization literature and the other, journal literature, both national and international. The common requirement is that the material fall into the broad subject of aerospace. Both publications consist of abstracts of aerospace material in 34 principal categories and include pertinent information to easily identify and obtain any of the documents listed.

The first of the abstract publications and the one covering organization literature is Scientific and Technical Aerospace Reports or "STAR" (fig. VI–6). It is a semimonthly publication that announces abstracts of all NASA reports as well as other national and international documents associated with aerospace activities. While the number of reports abstracted and reported in STAR varies from issue to issue, a typical copy might list over 800 items from the following contributors: about 100 from NASA Headquarters and its 10 field installations, 50 from NASA's contractors, and perhaps 15 from NASA's grants to Universities; about 100 from other Government agencies including the military, their contractors, and University grants; about 50 from Universities; about 100 from industries associated with aerospace; and perhaps 400 foreign translations from a score of countries. Figure VI–7 is a typical subject index page from STAR. As mentiond earlier, an effort has been made to include as much information as possible on each item, including the price if appropriate. The price shown is $2.50 for a full-size (110-page) document. Later this year it is hoped that you will be able to purchase a microfilm at a cost under $1.00.

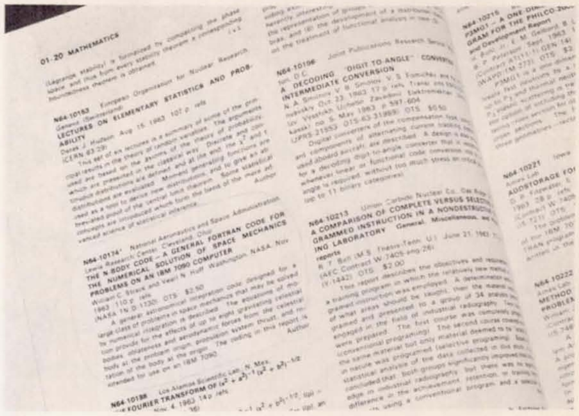

FIGURE VI–7.—STAR.

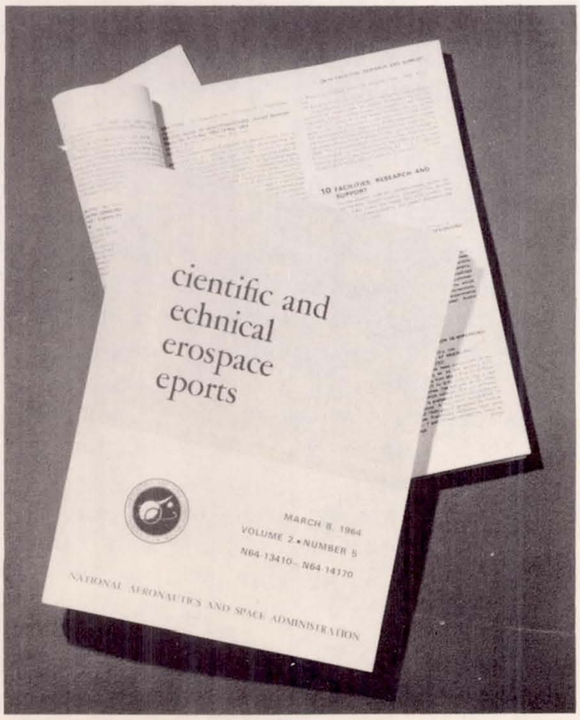

FIGURE VI–6.—NASA abstract journal.

The second abstract document, devoted primarily to journal literature, is called International Aerospace Abstracts (fig. VI–8). It is published semimonthly under NASA contract by the American Institute of Aeronautics and Astronautics. It includes abstracts of books, technical journal articles, and technical society presentations, both national and international. Here again the total number of articles abstracted will vary from issue to issue. A typical copy might contain abstracts from over 300 journal articles, 80 society presentations, and over 300 papers and journal articles from foreign authors.

This discussion, thus far, has covered the reporting of the technical literature and the announcement methods. How is this information shared? How are the reports obtained?

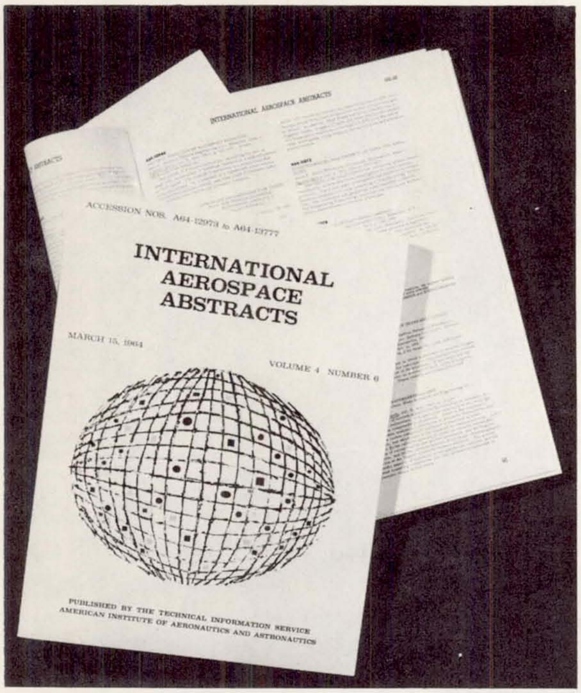

FIGURE VI–8.—IAA abstract journal.

STAR (fig. VI–9) is issued semimonthly and may be purchased from the Superintendent of Documents for $25.00 per year. The public may purchase NASA documents listed in STAR from either of two sales agencies, as specifically identified in the abstract section. Documents not originated by NASA may be obtained by writing to the originating source or to the other information systems. Documents not originated by NASA are abstracted only as a service. NASA is vitally interested in keeping its personnel and STAR recipients aware of recent aerospace literature, but obviously cannot assume the burden of making available copies of non-NASA documents.

International Aerospace Abstracts (IAA), also issued semimonthly, may be purchased for $25.00 per year from the IAA subscription office in New York City (fig. VI–10). Items listed may be obtained from them for the reproduction service charge. STAR and IAA abstract journals utilize the same arrangement of abstracts and the same indexing system. In essence, these journals are

Purchase of *STAR*

The semimonthly issues and the cumulative index issues are available postpaid on subscription and in single copy from the Superintendent of Documents, United States Government Printing Office, Washington, D.C., 20402, United States of America.

Semimonthly issues. Annual subscription rate: $25.00, domestic; $31.00, foreign. Price per single copy: $1.50, domestic; 25c extra for foreign mailing.

Cumulative index issues. Annual subscription rate: $30.00, domestic; $34.00, foreign. Price per single copy varies according to the number of pages.

Domestic subscription rates apply to the United States, Canada, Mexico, and all Central and South American countries, except as noted below.

Foreign subscription rates apply to Argentina, Brazil, British and French Guiana, Surinam, British Honduras, and all other countries throughout the world.

Payment should be by check, money order, or document coupons, and must accompany order. Remittances from foreign countries should be made by international money order, or draft on an American bank, payable to the Superintendent of Documents, or by UNESCO book coupons.

FIGURE VI–9.—Purchase of STAR.

standardized on treatment and complement each other. Combined, they announce the bulk of the current aerospace technical literature.

Unlike NASA reports, which are abstracted in STAR, NASA Tech Briefs are not abstracted in either STAR or IAA, but a company can be placed on the automatic distribution list for free copies through the NASA Technology Utilization Division in Washington.

As mentioned earlier, the avalanche of technical literature has created many problems in handling and distribution. One innovation that promises to relieve some of the problems is microfilm, or more accurately, microfiche.

Figure VI–11 is a view of the negative film, which can accommodate a document up to 60 pages, along with the equipment that enlarges the individual page for viewing.

NASA is planning through the Office of Technical Services, Department of Commerce, in the near future to provide the user with the option of requesting either the actual document or the microfiche, since full-size copies can be made from the film at a reasonable cost.

At the Lewis Research Center Library, the microfiche has been used to some extent. It has been found in many instances that the requester may want full-size reproductions of only a few pages rather than the complete document. Also after viewing the report, he may find it unnecessary or unrelated for his use.

Technical [illegible]
and Space Administration.

By special arrangement between NASA and the American Institute of Aeronautics and Astronautics, IAA is issued in coordination with the twice-monthly schedule of STAR, which appears on the 8th and 23rd of each month.

IAA and STAR utilize both identical subject categories and indexes, which are described below.

Thus the two services provide comprehensive access to the national and international unclassified report and published literature of current significance to aerospace science and technology.

Arrangement of the Semimonthly Issues

IAA is arranged in two major sections:

(1) Abstracts Section. This section contains complete bibliographic citations with informative abstracts,

[illegible] index.

Information regarding SCIENTIFIC AND TECHNICAL AEROSPACE REPORTS and the availability of INTERNATIONAL AEROSPACE ABSTRACTS to organizations having contractual arrangements with NASA may be obtained from the following address:

National Aeronautics and Space Administration
Scientific and Technical Information Division
Attention: Code AFSS-A
Washington, D.C. 20546

Abstracts of published literature in the field of aerospace medicine are provided, for the most part, by the Aerospace Medicine and Biology Bibliography Section, Science and Technology Division, Library of Congress.

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Telephone 212-TN-7-8300

SUBSCRIPTION INFORMATION.
Semimonthly issues: United States and Possessions, 1 year, $25 postpaid; Foreign Countries, 1 year, $33 postpaid.

Cumulative Index Volumes: United States and Possessions, 1 year, $25 postpaid; Foreign Countries, 1 year, $33 postpaid.

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FIGURE VI–10.—Purchase of IAA.

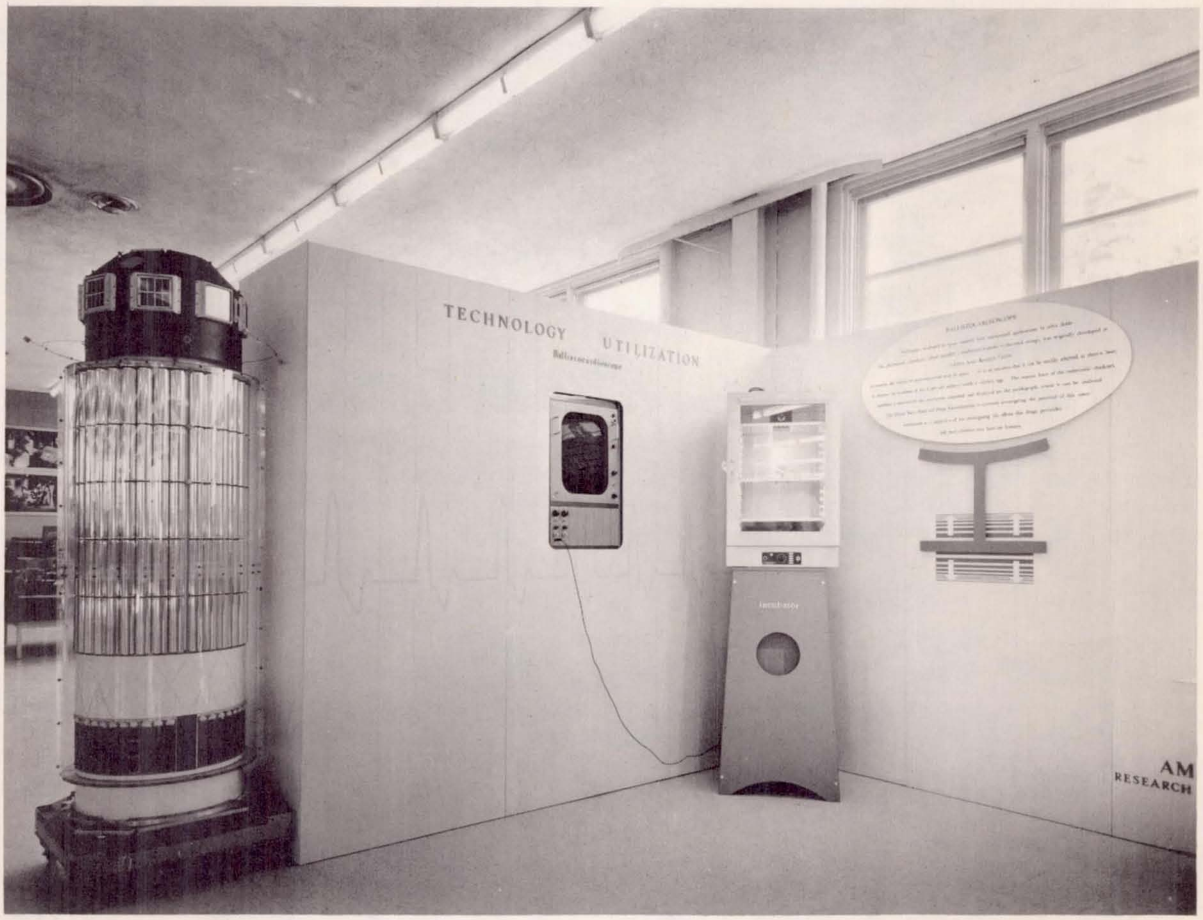
FIGURE VI–11.—Microfiche program.

An additional item that may be of interest is the availability of technical literature in public libraries and depositories. Locally, selected series of NASA reports are in the collections of the Cleveland Public Library, Case Institute of Technology, Fenn College, and Western Reserve University and are available for reference use.

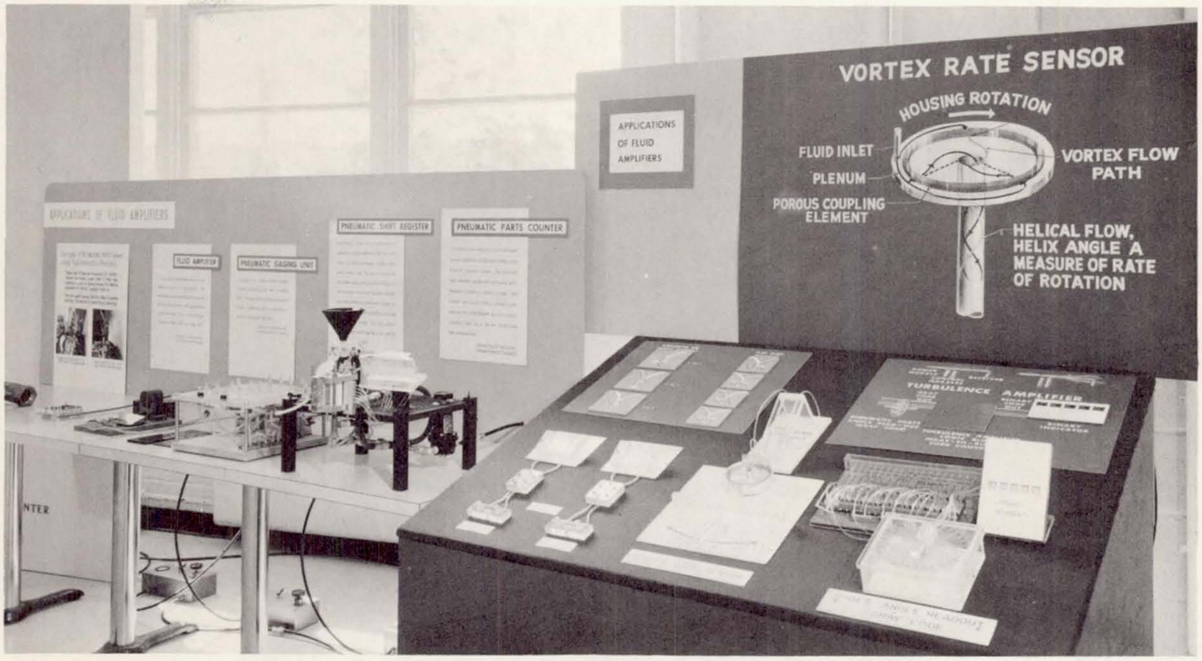
Twelve universities and libraries in the United States have been selected as Regional Technical Report Centers to make widely available the unclassified results of federally sponsored research and development. An interesting note is that less than 2 percent of last year's NASA authored reports were classified. Three agencies, AEC, NASA, and the Department of Defense, produce an estimated 90 percent of the government's unclassified technical reports and are supplying copies for deposit in each of these 12 centers. The depositories can provide you with reference services, interlibrary loan, photocopy service, and assistance in obtaining retention copies.

The depository serving Ohio, Kentucky, West Virginia, and Pennsylvania is the Carnegie Library in Pittsburgh. The John Crerar Library in Chicago serves Michigan, Illinois, Indiana, Minnesota, and Wisconsin.

Appendix—Conference Scenes

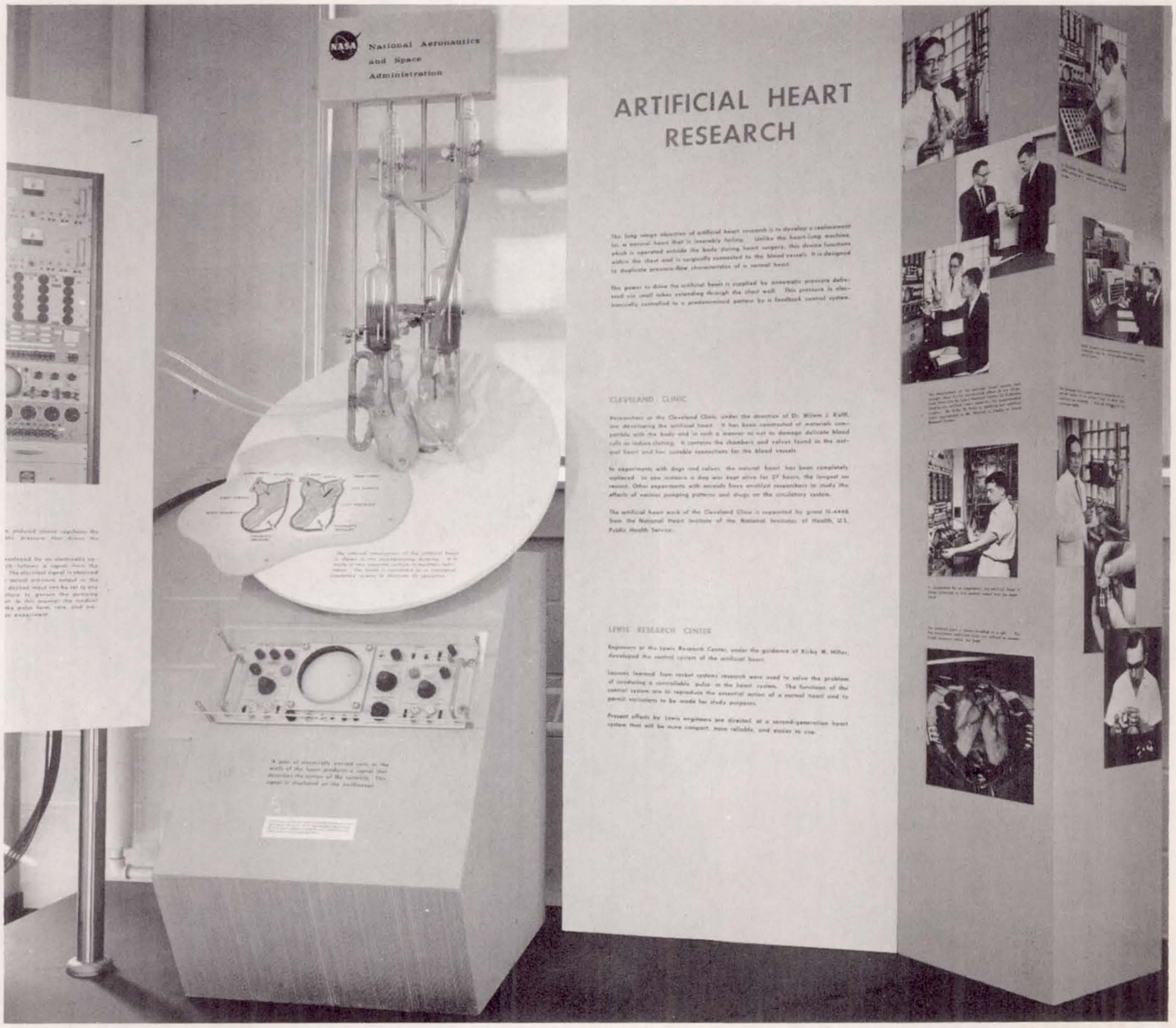


A piezoelectric momentum detector developed for micrometeoroid research is sufficiently sensitive to measure the heartbeat of a chick embryo. This adaptation assists research on drugs and vaccines.



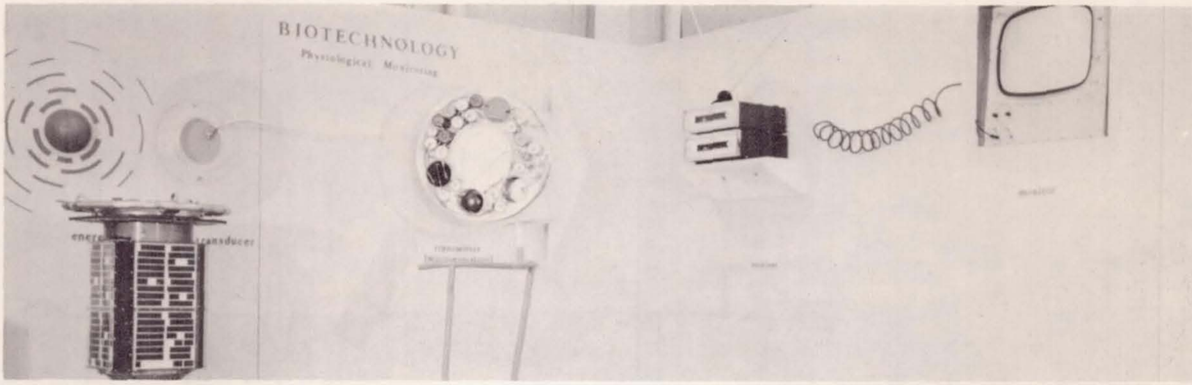
Fluid interaction devices having no moving parts and operating by the controlled interaction of moving gas or liquid streams are displayed. This new field of technology can be viewed as analogous to electronics—with fluid flow in place of electron flow—and the devices displayed show a similarity in function and nomenclature: counter (500 parts counted per second), shift register, diverting valve, rate gyro, shaft encoder.

Displayed here are a number of parts and assemblies selected to demonstrate the versatility of certain of the newer fabrication techniques and equipment: magnetic forming, electron beam welding, electric discharge machining-------.

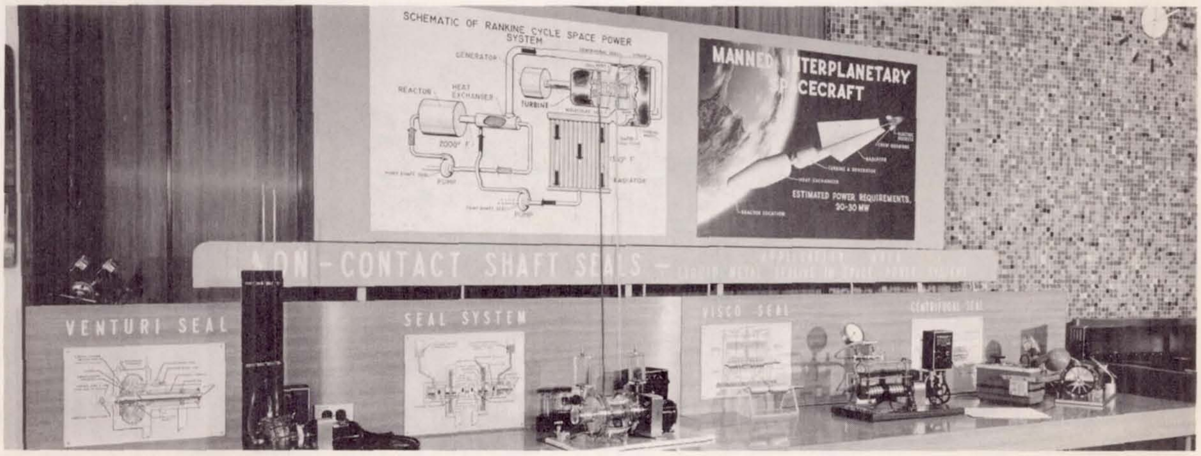


Artificial heart research at the Cleveland Clinic is benefiting from aerospace technology applied to the design and building of an electronic control system to provide a predetermined heart pulse pattern.

The exhibit displays the two key abstracts of aerospace technical literature, STAR and IAA; typical; technical literature; and items prepared to assist technology utilization.



Instrumentation required for physiological monitoring of astronauts in flight has shown possible application to remote monitoring of hospital patients. Displayed is an FM transmitter, smaller than a 25-cent coin, including battery and antenna. It senses and transmits the millivolt electrical signal from the nerve pulse preceding heart contraction.



A display of noncontact shaft seals technology demonstrates the principle of sealing by forces induced in the fluid. Models shows application to liquid metal systems (second from left) and demonstrate three different types of seals.

Lewis is the principal NASA field center for research and development in propulsion and electric power generation. This display briefly outlines Lewis propulsion work in airbreathing engines, chemical rockets, electric and nuclear thrust devices. Advanced work in many scientific and engineering fields is required to accomplish both the propulsion and electric power generation responsibilities.

The Honorable James E. Webb, Administrator of NASA, addresses an audience of industry and university executives on the evening of June 4, 1964.