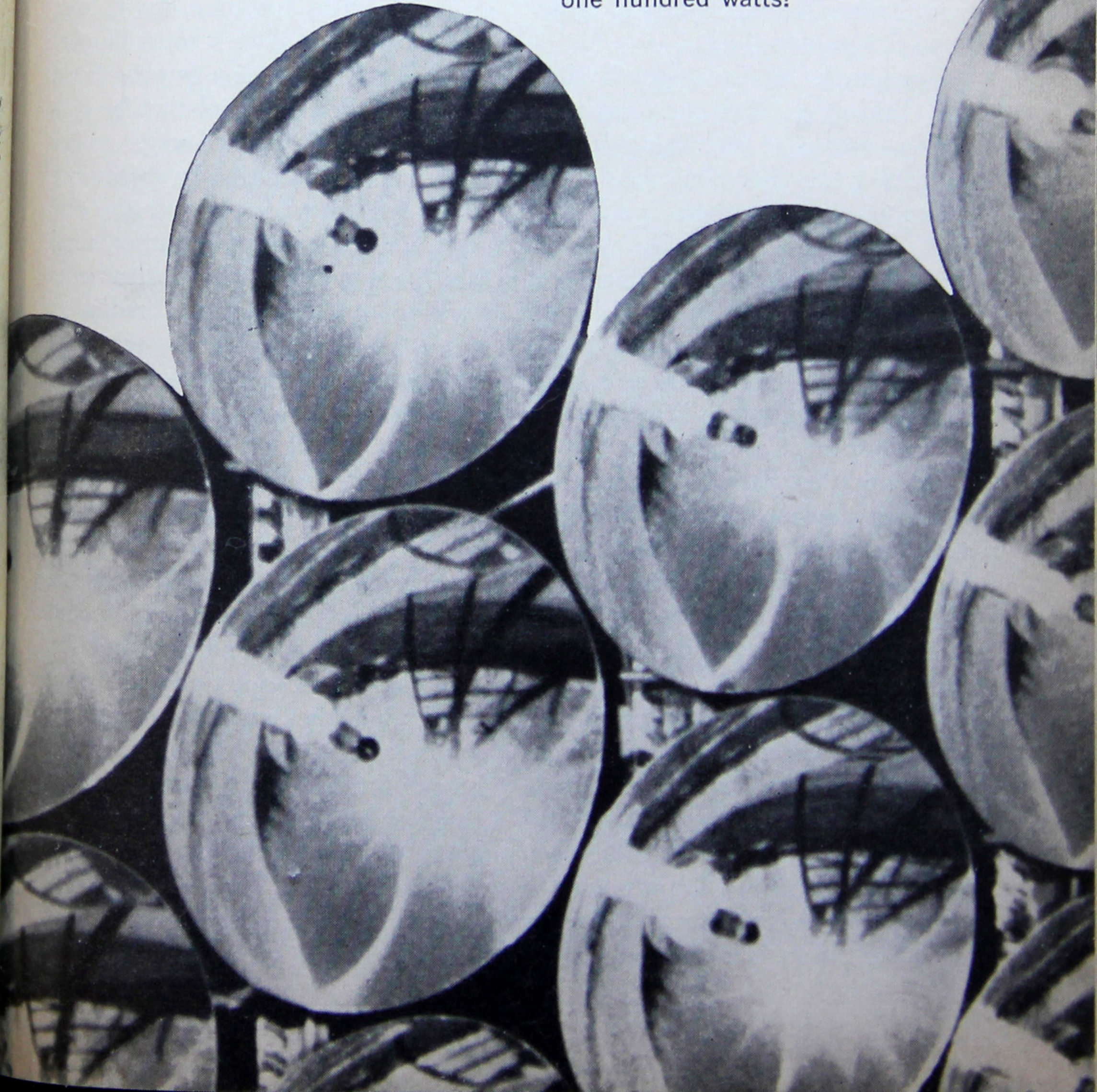
Power Supplies for Space Vehicles

BY J. B. FRIEDENBERG

It takes multi-millions of horsepower to launch a space vehicle—but once in space, a few watts of electric power becomes enormously expensive. Sure, there's one horsepower of solar energy falling on every square yard—but trapping it may cost a million dollars for as little as one hundred watts!



PART 1: NO MOVING PARTS

■ Inside, the strident, medium-fi tone reaches X-zero. A button is depressed; a switch closes.

Outside, the monster—gently sighing, clicking, gasping out a vaporous breath—comes to shattering life. It staggers a bit, lifts ponderously, becomes surer and gathers speed unto itself, then hurtles toward "that inverted bowl," the sky. A million feet later, it shakes loose a part of it that has by then become nothing but a nuisance, and—in a silence as shattering as the concert at liftoff—coasts up and up in a gentle arc.

During this period, no longer is the beast clumsy, bumbling. Now it is alive, sentient, palpably feeling for and eagerly awaiting a word of command from the planetmaster below, or from the tiny, whirring programmer in its gut.

This time of silent coasting is spent in a somewhat leisurely manner, and is a period of contemplation on the part of the beast: exactly how does my centerline point in relation to the planet below? Exactly what is my velocity at any instant? Exactly what are the instant-to-instant coordinates of my path? Exactly what parts of the earth's horizon am I seeing with my so-sensitive IR optic? Exactly what nose down-or-up push must I ask from my tiny pitch reaction control jets to assume the perfect attitude? Ditto for nose right, nose left, and roll. (Aside: it must be perfect, for otherwise how can the beast align itself perfectly and thus be prepared to fire its second-stage rocket at the one holy location in space-time which will allow it to leave the one orbit and transfer to the other, final orbit?) How are all my instruments working—accelerometers, radiation sensors, vibration pickups, temperature probes, potentiometers, gyros, pressure probes, troubleshooting instruments of all types. How is the pressure in my tanks? If it isn't just so, my propellant pumps will cavitate. How is the pressure in my high pressure helium spheres? What is the speed of my turbine? All these, and many more hypochondriacal queries.

Notice—these questions are being asked, and the answers monitored, continuously; there is no real rest period for the beast—something is going on all the time. Nothing glamorous, to be sure. The big glamour of a space shot—at least as far as lay observers are concerned—occurs at launch, when all the flame and fury is unleashed, and the vehicle "disappears in the clouds high above"—this is the part that can be seen. And there's lots of glamour in "striking in the target area, only 1.6 miles from the target," or in "the finest orbit to date, almost perfectly circular and only 7.4 miles short of the specified altitude," or "hurtling silently about our planet, watching and sending information, unseen and unheard. The next six orbits will be over Soviet territory." And so on.

Good. Let there be glamour! Glamour has a habit of begetting dollars, a very useful commodity in this business.

But what is it that permits such things as standing balanced on a thin plume of orange fire, striking in the target area, assuming and maintaining hairline attitude and altitude, watching, receiving information and sending same, continuously controlling attitude, accepting commands and acting upon them—in short, the performance of the vast multitude of small, unglamorous tasks that all sophisticated exoatmospheric vehicles must perform in the discharge of their divers duties?

Sound and fury are obviously a must; without a huge push, the beast cannot leave the ground to begin its odyssey. But this is far from enough to satisfy the intricate and far-reaching objectives presently before us, and which will become more sophisticated by several orders of magnitude in the somewhat near future.

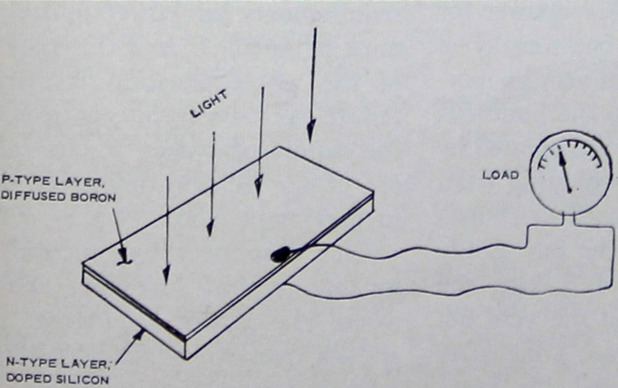


Fig I: Solar Cell

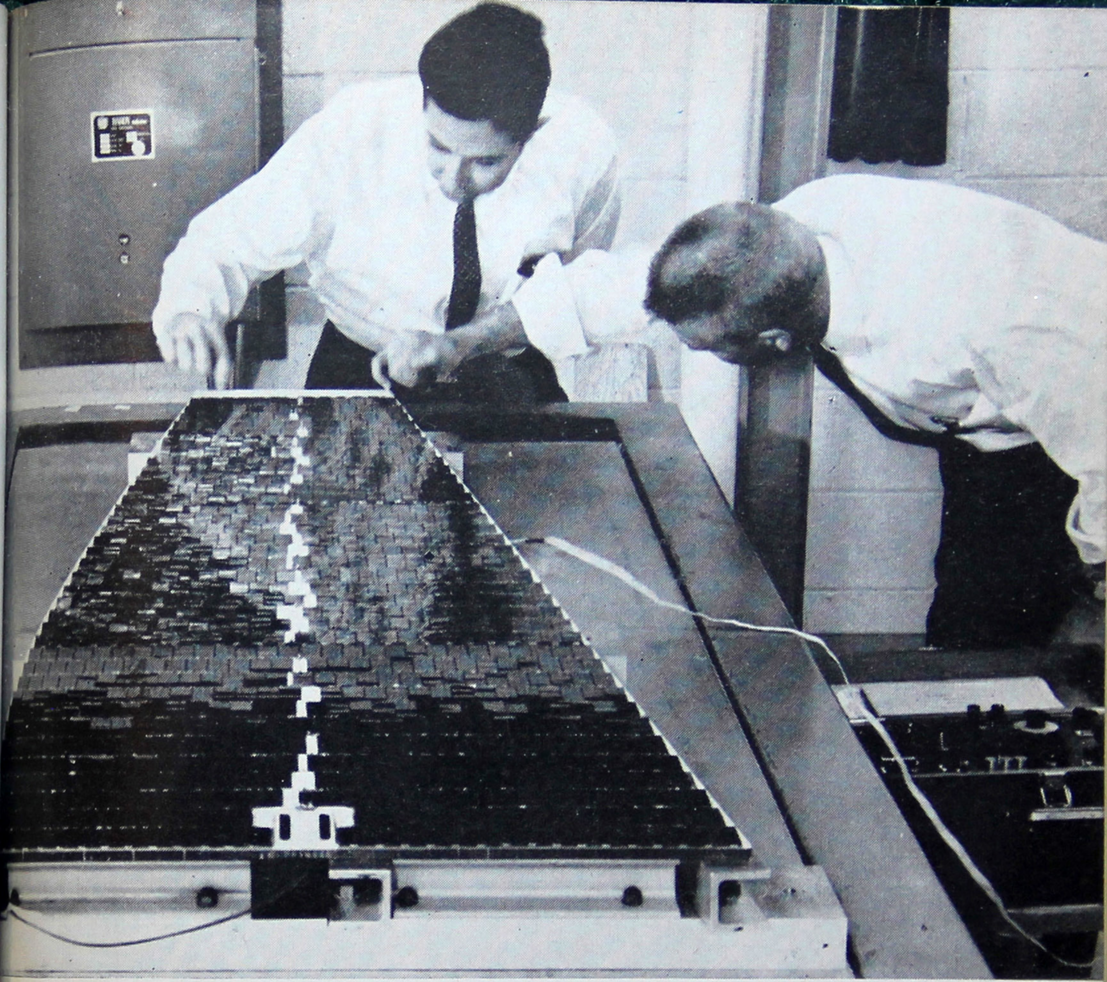
In order to satisfy these objectives, we must have available at our fingertips, pinpoint, hairline control. Control on timing, on flight path, on rocket engine start, stop, and restart, on autopilot functions, on telemetering functions, on camera functions, on IR seeker functions, on rocket engine gimballing—both first- and second-stage—on stage separation, on reaction controls, on retro rockets, and you name it. From the moment of liftoff—no, from prior to that moment—these control efforts are in process, some intermittently, some continuously.

The basic, fundamental requirement lying at the bottom of all the activity described above is symbolized by the small word "Power." This manuscript, being interested mainly in the electrical power requirements of space missions, accordingly will present the problems and solutions from the electrical point of view.

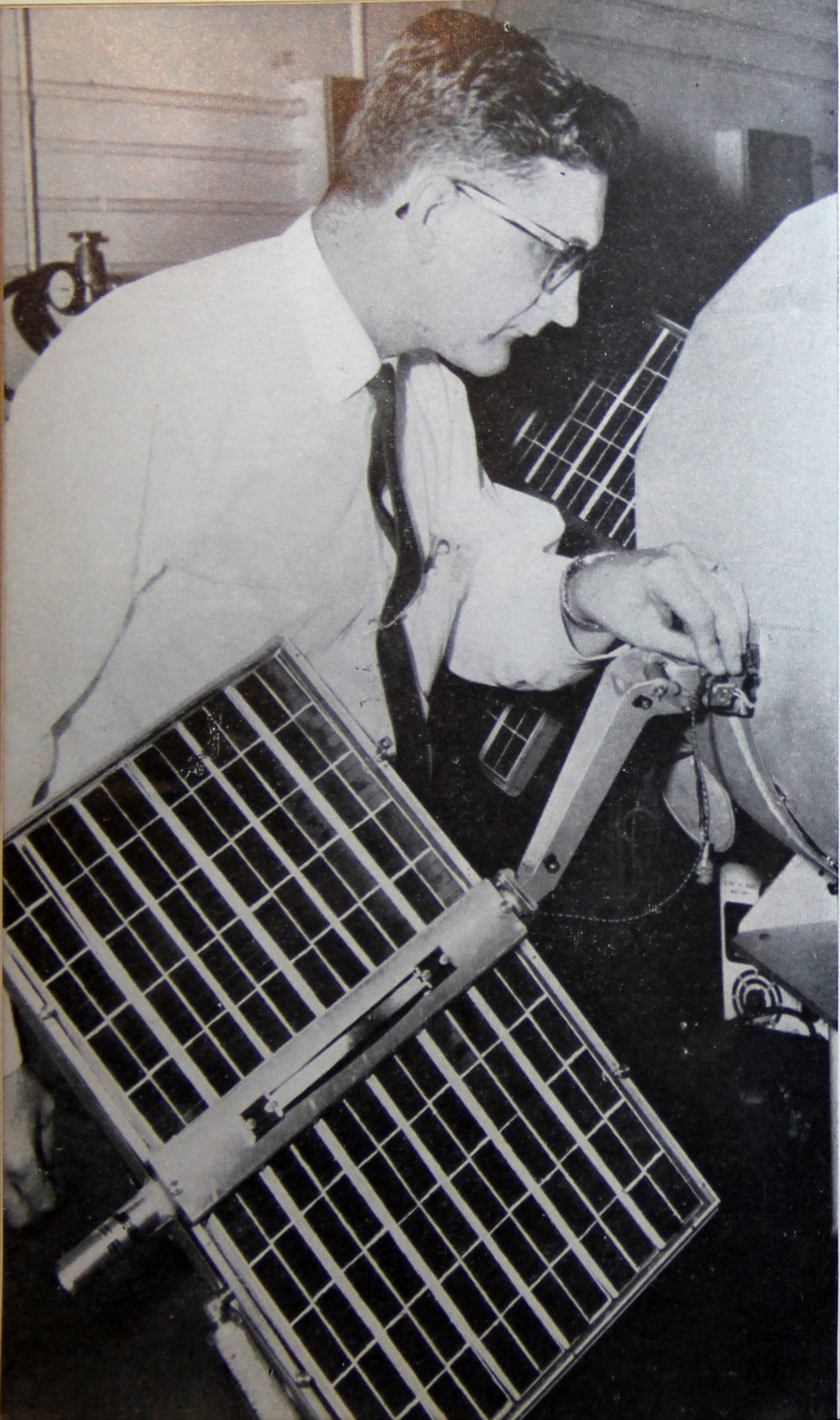
The electrical power required to perform the hundreds of long and short term jobs during a space mission is measured, for each discrete job, in fractions of a horsepower for the most part, and occasionally a horsepower or two. Not very glamorous, and a far cry from the hundreds of kilos of horsepower represented by the awesome diamonds blasting from the rocket nozzles. Quiet little chunks of power, unobtrusively but firmly going about the job of making the mission a success, from the very beginning to the very end. Long after Big Glamour has halted his bombast, long after all the air in the world is far away, the steady, everlasting requirements for power remain, and must be satisfied. And the nasty part of the whole situation is that any failure—or even intermittency—in the supply of power, results in failure of the mission objectives, either in part or in whole.

Fig. II: Checking out a solar power converter panel built for the JPL Ranger RA-1 Space Probe. The panel will provide about 90 watts of continuous electrical power, contains 4,340 individual silicon solar cells, and weighs 19 pounds. Panel was built by the Semiconductor Division of Hoffman Electronics Corporation.

Let's examine a hypothetical, reasonably typical mission, and see where the power requirements lie, and—a question which is taking up more and more time in the world of space science—how is this power de-



veloped? A representative state-of-the-art mission—which can be defined as the Best of Now—serving as a good vehicle for defining those periods wherein power requirements exist, is the overall mission of an active communication satellite. Examining the mission, we find that it breaks down into rather definite regimes, thus making somewhat disciplined the study of power requirements. In our example, we'll assume that the complete vehicle consists of an Atlas booster, on top of which is installed an upper stage of the Agena family, containing the satellite payload in its protective shroud. The Atlas is really a stage-and-a-half vehicle, consisting of a big collar holding two large thrust chambers of 150,000 pounds apiece, plus the central tank-body that holds the single sustainer chamber of 60,000 pounds thrust. The collar and its two chambers are jettisoned after about 140 seconds, and the sustainer, which has fired right along with the other two motors, continues firing for about 160



more seconds before it separates from the Agena vehicle. The Agena contains a single chamber of 16,000 pounds thrust, and in our example is an advanced type which can be restarted in deep space.

Now we're ready to break the mission down into the aforementioned flight regimes:

1. *Launch.* The launch phase lasts for about 5 minutes—the 140 plus 160 seconds mentioned above. At first boost cutoff, acceleration is about 5.6 gees, and at sustainer cutoff, about 3.1 gees. Atlas separates and falls to earth. Agena ignites, fires for 40 seconds, kicking the vehicle into coast orbit, then shuts down.

2. *Coast.* Directly after cutoff of the sustainer, the horizon sensor and a directional gyro in the Agena vehicle are actuated by an accelerometer which sensed the abrupt change from 3.1 gees to zero gees. The gyro is brought up to speed, and the horizon sensor begins to search for the preselected segments of the earth's horizon, so that when the Agena Engine does fire, the vehicle's directional reference will be aligned just so. In our case, the coast period will be scheduled as a parking orbit of perhaps six hours, to await the proper time for orbit exchange. During this period, the vehicle aligns its centerline with the programmed gyro reference, via use of its small reaction jets, and thus automatically aligns the Agena engine so that, at the proper moment, in response to either a signal from the tracking station on the ground, or from a timer-programmer in the vehicle, the Agena engine is re-ignited.

3. *Transfer Ellipse.* Under this rocket thrust, the Agena vehicle, with its satellite payload, accelerates and slides outward towards its desired final communication orbit. Now, a preset programmer, working with the axial accelerometer, tells the Agena engine when to cut off. In this case, cutoff occurs 220 seconds after restart, and the vehicle then falls into orbit. Just prior to cutoff, the acceleration is 3.75 gees. Immediately after cutoff, two actions take place: the protective nose shroud is split like an orange peel and is jettisoned by explosive bolts and/or springs, and the Agena vehicle, consisting of propellant tanks, gas bottles, structure, and rocket engine, is separated by a system of explosive bolts and is cast off by means of a small retro-rocket which gives it a backward push. Now the satellite, naked, starts its indefinitely long journey around the earth.

Fig. III: Close-up of a "paddle" on the Pioneer V satellite, showing the Hoffman silicon solar cells which convert sunlight into electricity to power the radio communications equipment on the satellite. Orbited March 11, 1960, the Pioneer V is now using solar power to send information to earth from many millions of miles out in space.

4. *Communication Orbit.* The satellite is now positioned thousands of miles away from the earth, and is rotating about earth in a nearly circular orbit, in some definite period depending on the pre-arranged orbital diameter. From here on, it must maintain definite attitudes, so that its receiving and transmitting antennas are oriented properly at the correct times in each circuit. The various attitudes required during mission life are maintained through the actions of the horizon sensors, the gyros, autopilot system, and the attitude control system, which may be a set of tiny gas jets, a set of inertia wheels driven by small electric motors, or an ingenious combination of both. The satellite's primary mission, that of receiving a message from earth and relaying it to another spot on earth, or to an aircraft flying at a certain latitude and longitude, is henceforward its only activity.

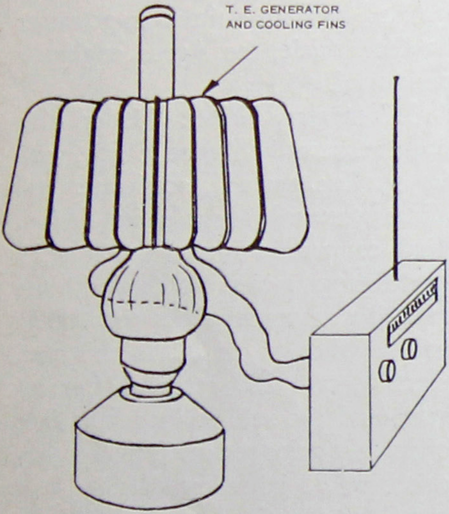
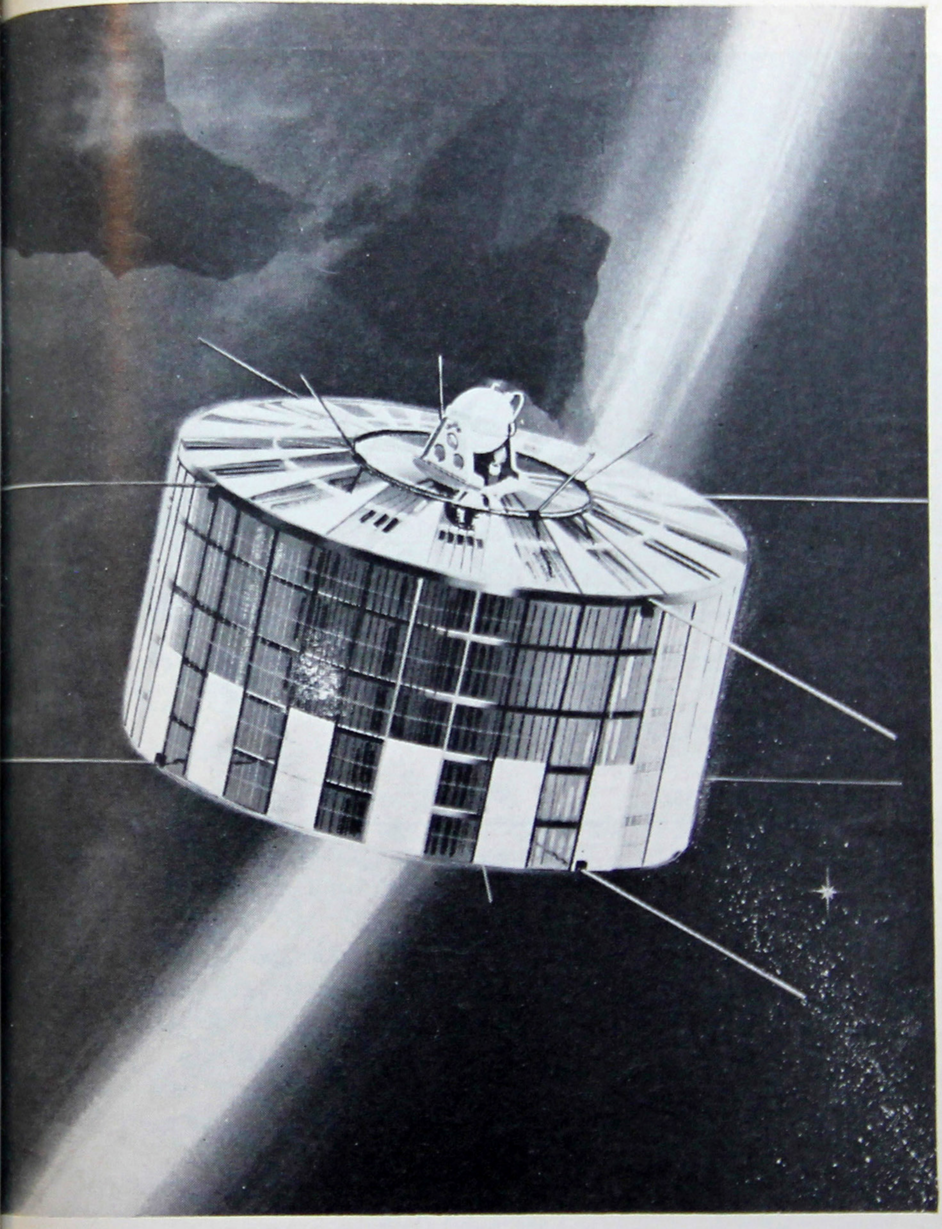


Fig. IV: Russian thermoelectric generator using heat from kerosene lamp chimney.

At present, these missions are being planned to take anywhere from a few days to over a year, by both military and commercial groups. Once again, we must point out that not one tiny portion of the mission, from launch to completion, is possible without electrical power. And this power must come from some mechanism which is part and parcel of the vehicle. How do we get the power? Where does it come from? Remember, the communication satellite may be called upon to operate for a year or more, during which time the electrical power demands of the satellite's communication apparatus are, when averaged out, relatively high. Typical power profiles for the orbital portion of the mission run from a steady minimum of perhaps thirty watts, to peaks of twelve hundred watts, with the cycle occurring many times each day.

Now let's examine the various activities going on during the flight regimes outlined previously. This will give a general picture of the myriad of jobs continually in process, that require electrical power for successful prosecution of a communication satellite mission.



The Martin Company

Fig. V: Two for the price of one. The main power supply for this Transit satellite is a silicon solar-cell array on its drum-shaped sides, essentially similar to that on the Tiros satellites. But riding on top is a small white sphere, containing a thermoelectric generator, powered by the heat from the spontaneous decay of plutonium-238 which is being space-tested as a passenger on the main instrument-package.

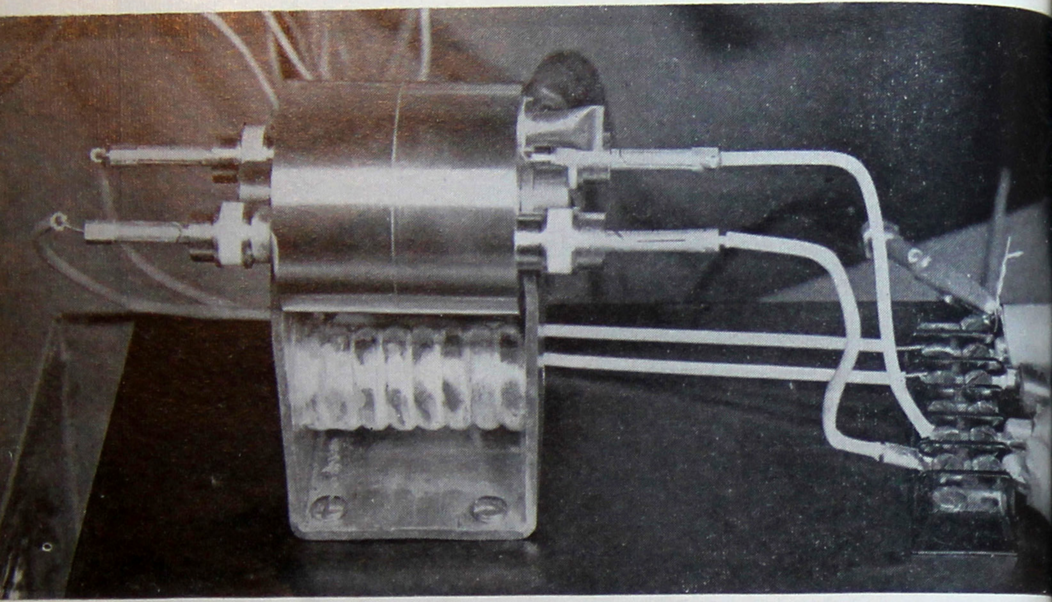


Fig. VI: Electrically simulated isotopic thermionic converter developed by Thermo Electron for the Atomic Energy Commission under a subcontract with the Martin Company.

FLIGHT REGIME	EQUIPMENT USING POWER
1. Launch.	Timers and programmers. Platform gyros, torquers, potentiometers, etc. Rate gyros. Autopilot feedback loops, amplifiers, relays. Inertial guidance accelerometers, integrators. Flight path computers. Propellant valving. Rocket engine start-stop circuits. Rocket engine gimballing mechanisms. Tracking and range safety beacons. Telemetry and instrumentation. Interstage separation system. Command receiver.
2. Coast—Parking Orbit.	Horizon IR sensors. Directional and rate gyros, etc. Accelerometers and potentiometers. Autopilot functions, circuitry. Inertial guidance system. Command receiver.

	Telemetry and instrumentation. Flight path computer. Reaction control system. Timers and programmers. Beacons.
3. Transfer Ellipse. Including rocket engine start, stop, and orbit injection.	Rocket engine arm and fire circuits. Propellant valving and sequence circuits. Command receiver. Reaction controls. Autopilot functions. Inertial guidance system. Gyros, potentiometers, accelerometers. Beacon. Telemetry and instrumentation. Flight path computer. Programmer, timers. Flight control system, rocket gimballing.
4. Final Orbit.	Stage separation pyrotechnics. Retro rocket ignition, arm circuitry. Protective shroud pyrotechnics. Satellite reaction jets. Antenna, paddlewheel erection systems. Inertia wheel motors. IR Sensors, gyro motors. Telemetry and instrumentation. Beacon. Temperature control system. Receivers and transmitters.

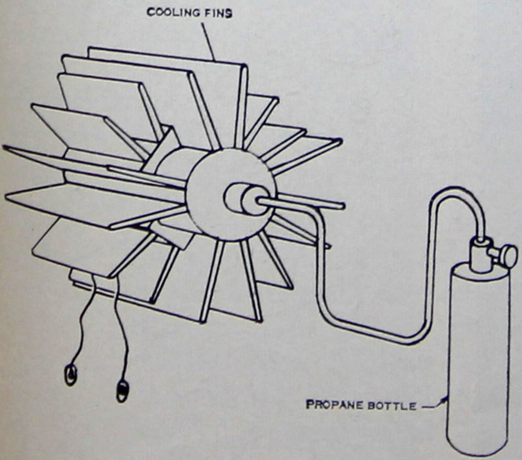


Fig. VII: General Instruments Corporation. T.E. Generator.

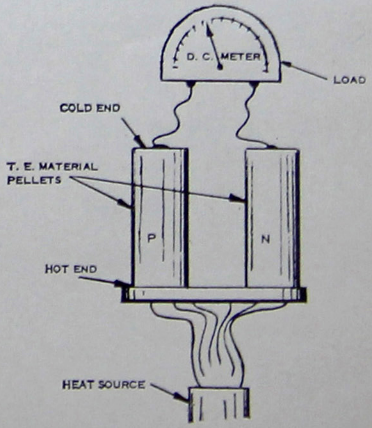
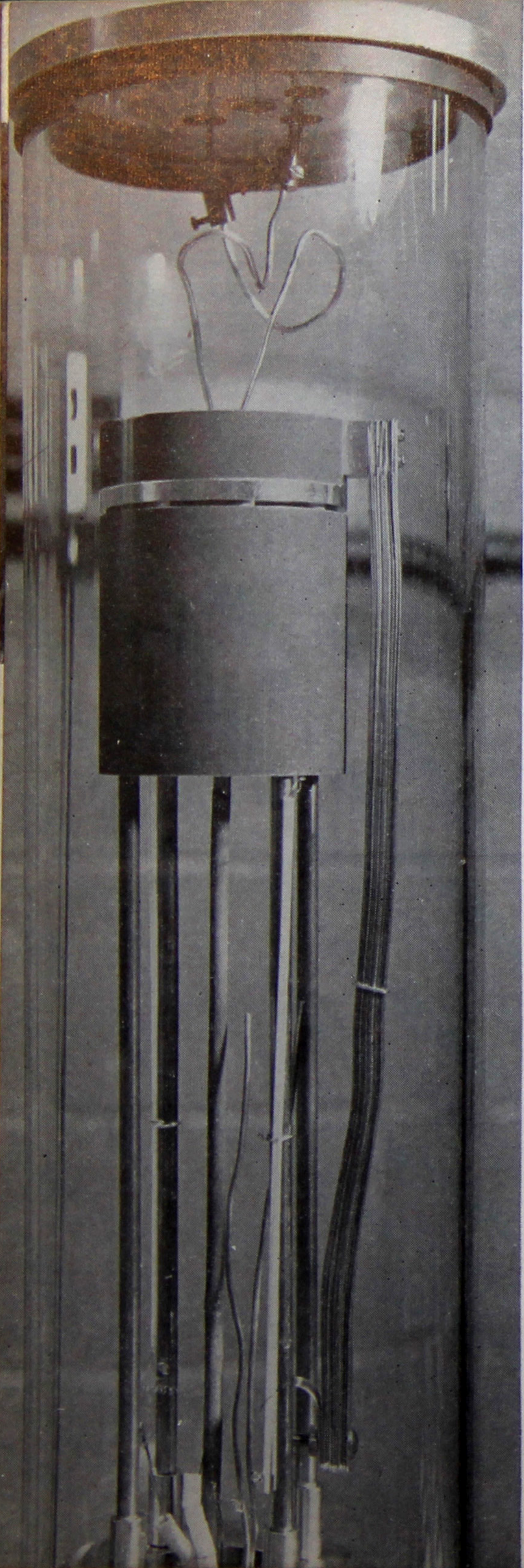


Fig. VIII: Basics of T.E. Generator, showing one junction.



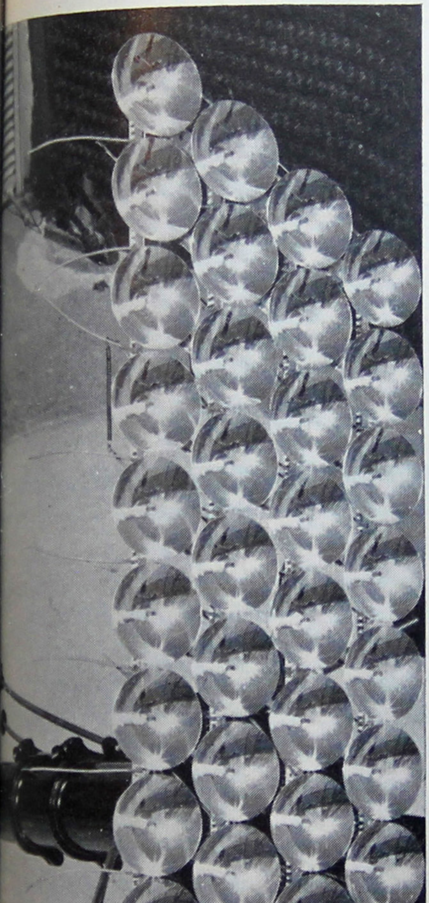
Up to now, we have cast a cursory glance at a typical communication satellite mission. This glance has told us something about the various flight phases, and some of the operations, function, and equipment that require electrical power. Once again, now, comes the pressing question: how do we supply this power, and how do we keep it in good supply for periods of a year, untended in the abysmal cold, blazing hot, pitch black, stark white fastnesses of outer space?

During certain phases of the flight, it is "easier" to supply power to the vehicle than during other phases. The "easy" phases—quotes used advisedly—start on the ground and continue throughout launch, coast, transfer ellipse, and up to the point of Agena stage and shroud jettison. For instance, during the launch phase, the big Atlas booster's large battery pack assumes the chore of providing all electrical power even before liftoff, and does all the required jobs until Agena stage separation. From this point to the disgorging of the satellite, the big Agena battery package takes over, continuing the good work.

But now things change radically. No longer is a battery pack of any

Left. Fig. IX: 200 watt 13% efficient solar thermionic converter developed by Thermo Electron for the Aeronautical Systems Division at Wright-Patterson Air Base, Ohio, under a subcontract with Thompson, Ramo, Wooldridge, Inc.

Right. Fig. X: T.E. Generator developed by Hamilton Standard.



use alone; the length of time in the communication orbit precludes this. Now we have to become really ingenious; we've got to fight Nature tooth and nail, and at the same time woo her passiontely, in order to keep the spark of life in our tiny machine. There we are, far from Mother Earth, and not an electrical socket or generator in sight.

A moment! There may be no socket, but there sure is one whale of a generator! The same generator that sparks you and me and every other living thing in the solar system. There's a key phrase: solar system, with a key word, "solar," which translates in our case into "Good Old Sol."

Let's take a look at electrical power generation.

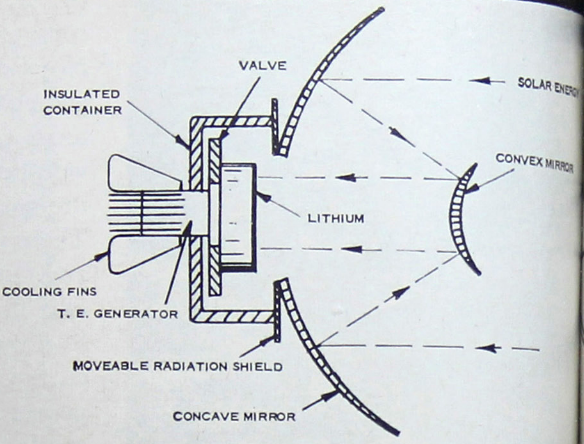
We are all familiar with the methods used to generate electrical power on the ground. These methods are all an outgrowth of Maxwell's development of the principle that a current is built up in a conductor when said conductor traverses a magnetic field in a specific manner. Really, the main differences between the various methods of present-day power generation lie not in the generators themselves, but in the prime movers.

Prime moving energy, with the exception of a few relatively unimportant methods used here and there, comes from two main sources: the combustion of fossil fuels, and the kinetics of flowing water. Oil and coal, combined with oxygen at high temperature, provide the energy for boiling fluids, or for generating gases

Right. Fig. XI: T.E. Generator using lithium for heat storage.

Center. Fig. XII: T.E. Generator—simple reflector.

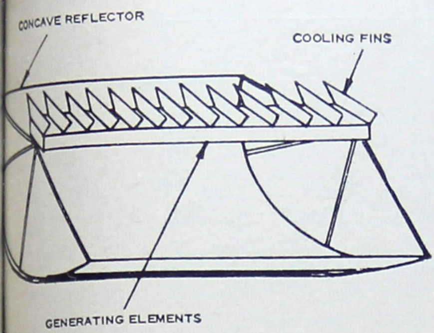
Left. Fig. XIII: Thermionic Generator—basic elements.

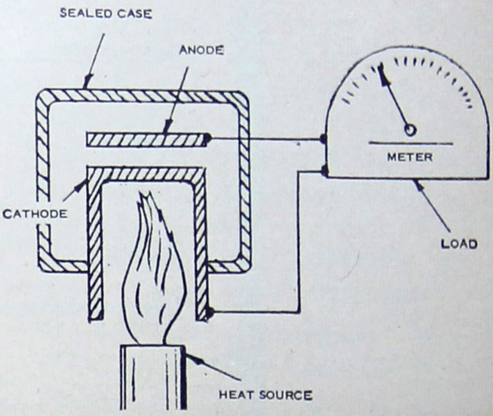


directly, which are then used to turn turbine wheels which in turn rotate generator rotors. Burning gasoline provides the energy for all sorts of small generating plants, even in moving vehicles. The flow of water is directed through turbines to turn generator armatures in large stationary generating plants. In a few localities, some slightly more exotic methods are used. There are a number of large aerodynamic generating stations—to be pedestrian, call them windmills—situated in areas where there are strong and prevailing winds, but these are mostly trial facilities and cannot compete economically with the highly developed steam, Diesel, and water-generating units. In some other particularly fortunate areas, subterranean or volcanic steam is being used to run turbine generators; the area that comes immediately to mind is New Zealand. Other methods that have been proposed were to use the motion of the tides, the temperature differential between the ocean bottom and surface, and to cover acres of southwest wasteland with surfaces that collect sun heat and reflect same onto steam boilers.

The generating methods presented above are, to be sure, good, solid, highly developed, and quite efficient. However, when we try to apply them to operations in space, we immediately run into a hitch or two that very effectively blocks us. These hitches are very simple and elemental: no oxygen and no water!

In discussing auxilliary power supplies for space vehicle application, it seems fairly safe to discard such energy sources as flowing water, volcanic steam, and prevailing breezes. Which brings us to the point of choosing a logical source of energy for use in a very strange environment. What are these energy sources, how are they being used at present,





and how are they being proposed for use in the future?

First off, let's examine, in a very unspecific manner, general methods that can be used to generate power in a space vehicle. Quite simply, energy is available from two locations: external to the vehicle, or from inside it. Pressing the examination a little farther, the single major source of energy external to the vehicle is the Sun; internal energy sources are either chemistry based or nuclear. The following table gives a breakdown of these major categories into system types:

General Energy Source.	*Energy Conversion System.*
External—Solar.	Photovoltaic—Solar Cells. Thermoelectric. Thermionic. Turbine/Alternator. Stirling Engine.
Internal—Chemical or Nuclear.	Batteries. Fuel Cells. Thermoelectric. Thermionic. Gas Generator/Turbine. Magnetohydrodynamic.

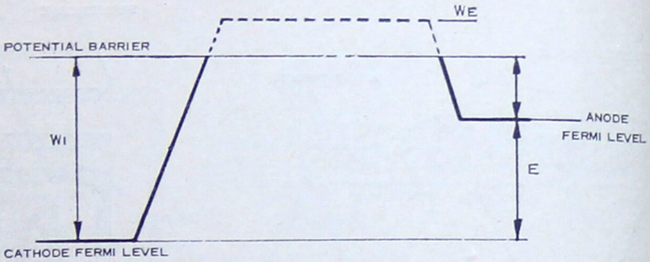


Fig. XIV: Potential energy diagram of electron moving from heated cathode to cool anode.

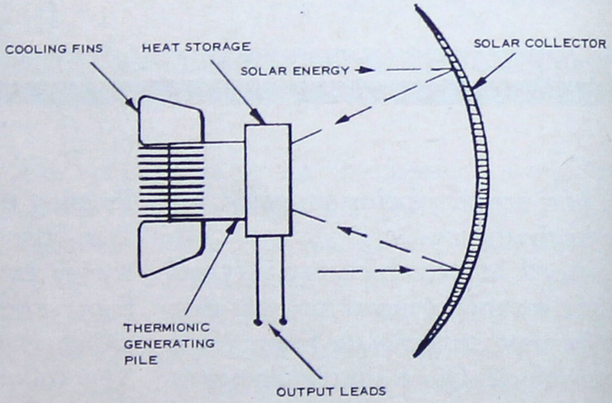


Fig. XV: Simple thermionic systems, designed for low power output.

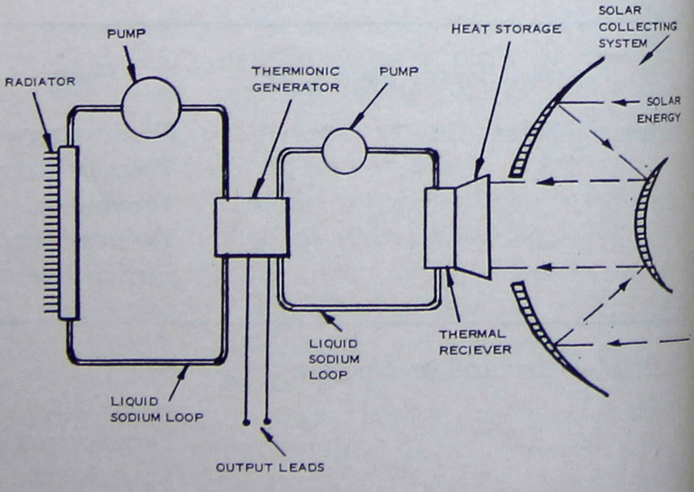


Fig. XVI: Sophisticated thermionic system, designed for high power output.

This paper will not attempt to describe chemical or nuclear systems, but will only cover the solar-powered systems, as categorized in the table above.

Photovoltaic—Solar Cells: Sometime during the early nineteen hundreds, it was discovered that a plate of metal covered with copper oxide would generate an electric current when illuminated. This discovery started a very desultory quest for a device that would deliver copious quantities of electrical power from direct illumination by sunlight. The search idled along, with the technique being mistily lost and rediscovered, until in very recent years the circumstances surrounding impending flight into space lit a big fire under it, and now the solar photovoltaic power device is the basis for a full-fledged effort in many laboratories and plants around the globe. The attractions of the solar cell are numerous: they are simple, containing no moving parts; for the same reason, they provide at least an approach to being foolproof, and with reliability of space devices carrying the importance that it does, this is no mean factor; they are easily manufactured after the initial setup, and lend well to high reproducible production rates; they are easy to package and install, and are fairly rugged; they are beginning to show reasonable efficiencies; they fit into the space environment very well.

The solar cell, as presently developed, is essentially an application of semiconductor technology. In its most common form, the solar cell is formed of a thin film of semiconductor material cemented to a wafer of metal. Semiconductor materials such as selenium, and a metal such as iron, comprise one of the standard commercial material combinations used in the "light" cells that go into the makeup of such items as photograhic light meters and some door-opening systems. These cells, when illuminated, develop enough of a signal to use in applications where tiny amounts of power are required, or where amplification is simple. In the case of a selenium cell, under the most advantageously filtered light conditions, the power efficiency is about 1.4%, the output may reach a level between 3 and 20 milli-volts.

Note usage of the term "most advantageously filtered". This is due to the fact that the efficiency of solar cells—and it depends upon the material combinations—reaches a peak at different Angstrom levels; selenium's peak is at 5461 A. However, when we apply the illumination of full sunlight, accepting the great Angstrom spread of the spectrum, the efficiency of the selenium cell drops to 0.2%, and the power output falls accordingly. It is obvious that the selenium cell will not fill the bill for a space power supply. The requirements of a space-travelling vehicle such as the Communication Satellite are relatively high, reaching a thousand watts or more. At the present time, the best material available for easily produced, reliable, high-power-output solar cells is silicon.

Silicon solar cells are being used in all space vehicles whose missions call for this general type of power supply. Available in production quantities, these cells are now giving upwards of 10% conversion efficiency, with some claims running as high as 15%, and over 20% predicted for the near future. Hundreds and thousands of them are used in each vehicle, and with mission complexities rising and power requirements going up, the few companies producing the cells have a waiting market. However, it is not all beer and skittles in the solar cell business. For instance, only about half of the cells manufactured will satisfy the applicable specifications, and this is a vast improvement over the figure of one-tenth which prevailed about three years ago! Naturally, this is a factor in the high cost of the cells; a few years ago, they were priced at somewhere between $300 and $400 per cell—yes, you read correctly, per cell! When you figure that a vehicle such as Tiros I uses 9200 cells, it becomes a bit shocking to realize the price being paid for a power supply that reaches a peak of the same order of magnitude as two of your car batteries! Total cost—$40. At the present time, due to vast improvements in production methods, things are a lot better; the cost of a high-efficiency solar cell is now in the general range of $25 to $50.

The prevailing concept of the inner workings of a solar cell is in line with present semiconductor theory. Of all the variables that affect the operation of the solar cell, those with the greatest impact pertain to the physical properties of the cell structure. Silicon in its pure state is a pretty good insulator, but fortunately can be transformed into a pretty good semiconductor by a process known as "doping." Doping is the addition of tiny quantities of impurities to the pure material; judicious selection of the impurity material and its quantity then controls the polarity, and even the "strength" of the polarity, of the resulting semiconductor crystal. Depending upon the objectives you have in mind, the doping process used to transform the pure silicon into a polarized crystal requires somewhere between one part of impurity per hundred million, and one part per billion! The process results in a crystal that has a disordered lattice structure, in which free electrons or positive-site holes can be moved about under some outside influence.

In order to manufacture a silicon solar cell, the silicon, which has a valence of 4, is initially doped with a 5-valence element, such as arsenic or antimony. This may be done in the original manufacture of the silicon crystal by adding the proper microscopic amount of the desired impurity to the melt. The resulting crystal then contains an extra electron wherever there is a finite junction between the silicon and the impurity. In the case of silicon doped with antimony, the crystal becomes a negative (n) type semiconductor. It is then sliced into wafers of about a square inch in area, and .016 inch thick. The next step in forming the wafers into solar cells is to expose one surface of the wafers to boron vapor, which diffuses into the n-type silicon. The process of diffusion is allowed to proceed until the thickness of the diffused layer is about .0001 inch. Because boron is a 3-valence element, its junction with the silicon produces the opposite effect from the antimony doping; that is, it results in electron shortages, or the formation of holes which represent positive charge sites. Now we have the complete generating unit, consisting of a positive-on-negative semiconductor wafer.

Briefly, the solar cell wafer functions like this. The doped n-type silicon surface has the characteristic of a high density of free electrons. On the other hand, the boron diffused surface is a positive (p) type semiconductor, having a deficit of free electrons, but a high density of electron vacancies, or holes, which are positive charge sites. Thus, in the p-type surface, electric current consists of an activity called a migration of holes. The vague region between the p and n type materials is called the barrier region.

Exposure of the boron-diffused surface to light results in light absorption to a depth of about one-ten-thousandth of a millimeter. Each photon absorbed displaces an electron, thus producing both a free electron at a certain energy level, and an electron vacancy or hole. Remember that the original p surface had a dearth of free electrons compared to the hole density. The effect of the photon absorption, therefore, is to increase the ratio of free electron density to hole density by a very large factor. Under these conditions, that portion of the free electrons whose energy has been raised sufficiently by collision with the photons, will move across the barrier region into the n-type material, creating an overcrowded condition, and essentially squeezing out a number of the free electrons already present in that material. These are then available to move into an external circuit and do work. Incidentally, temperature has quite an effect on the cell output; a rise in temperature results in a considerable lowering of output. At room temperature, a silicon solar cell of standard 10% efficiency will generate about .017 watts.

A simple line drawing of a solar cell is shown in Fig. I.

At the present level of space vehicle development, power supplies based upon solar cells are the only practical systems available for long duration missions. In fact, for any orbital mission lasting more than a week, this type of system is at present far and away the best from every point of view, especially if the power level requirements remain below a steady load of 200 watts, with peak loads of about 1200 watts. Of course, with the major effort presently being placed upon solar cell development, we can expect rather startling output and efficiency jumps, and in fact military people are projecting this type of system as being competitive up to power levels as high as 50 kilowatts.

One of the nasty problems with which this system must contend is the complex one of orienting the cell array. The array panels must be oriented within about plus or minus 10 degrees of perpendicularity with the sun for optimum results. This rather large tolerance on angularity before the output drops alarmingly off the top of the curve is accounted for by the fact that power output drops as the cosine of the angle of incidence. Much development is now going into the orientation problem, and the solar cell arrays will do even better than they are presently doing as soon as a reliable, accurate closed-loop orientation system, that can be easily packaged, is developed. At present, paddlewheel designs provide enough cell area to take care of non-optimum conditions. This sort of problem also occurs on the solar cell arrays used on satellites such as Tiros, in which the array covers most of the surface of the satellite itself. Tiros I rode in its orbit in a spin stabilized condition, with its spin axis fixed inertially, and as a consequence, only a small part of its array could feel direct sunlight at any instant. It is pretty obvious that a nonoriented system requires many cells than does an oriented system. Nevertheless, it certainly is a simple way to do the job, and right now is probably the most reliable cell configuration.

Orientation is only one of many problems. For instance, what do we do when the satellite is traveling, during its orbital period, in the earth's shadow? This is a problem that is relatively simple of solution: we install chemical batteries, and we charge the batteries from the solar cells during that period of the orbit when sunlight is plentiful. Now we have a well regulated system which can operate for long periods at a high level of reliability. And system reliability is not harmed one whit by the fact that the prime source of energy is good old evershining Sol. The batteries in this system are very special silver-zinc or cadmium-zinc units, designed so that hundreds of current drains and recharges will not harm them. The development of these batteries is another story.

There is a universal problem that besets any mechanism that lifts from the earth: everything, but everything, weighs too much. In the case of solar cells, this is just as acute as in any other flight system. Weight must be kept at a very minimum; at first glance, the paddlewheel array doesn't look too bad from this point of view. Flat solar arrays can be designed and fabricated to weigh about a half a pound per square foot, including cells and structure. However, this is not the full story. The very radiation energy field that provides the energy for electrical power generation also contains other types of radiation which are destructive to the solar cells, and must be protected against. At the same time, the extremely active Van Allen belts create similar radiation hazards. Remember, all types of radiation except light in specific spectral bands are harmful—infra red, ultra violet, cosmic rays, Xrays, et cetera—even stray micrometeorites which happen along. Much work is being performed to develop protective coatings which are feather light, but for the present generation of solar panels, the method used is to cover each cell with a thin cemented wafer of glass about .05 inch thick, including a 15-layer interference film. Paddlewheel panels must be covered both front and back; integral arrays only on the front.

Recently, a big advance in overcoming the radiation problem has been scored by the Army Signal Corps, through their development of a new cell that resists four times more radiation than the standard silicon-boron cell, for ten times longer periods, and still exhibits the same or slightly better efficiency. The new cells do not use boron, but instead diffuse phosphorus into the surface of silicon which has been doped so that it exhibits p-type semiconductor characteristics. We have here, then, a negative-on-positive cell, which is the reverse of the standard cell configuration. Work is in process now to uncover the reasons for the remarkable radiation resistance of this new solar cell, which will soon be in quantity production for space vehicle use.

Now we are confronted with the usual system-type problems that occur when a new element is injected into a design situation. The radiation protection raises the weight of the cells, which automatically creates a requirement for heavier structure, until the panel weight finally stabilizes at about two pounds per square foot. At present, solar cell powered systems run about 1200 pounds per kilowatt, an admittedly unhappy figure. However, all is not lost, as higher power solar cell systems, using reflectors to concentrate the light, now point the way to system weights of perhaps 300 pounds per kilowatt.

At present, solar arrays are costly. A glance at two typical satellite arrays will give a picture of approximate costs. Tiros I, the meteorological satellite that uses two TV cameras and a picture transmitting system, is shaped like a squat cylinder. The top and sides are covered with silicon cells—only the bottom is not. Total number of cells is 9200. We can assume a cost per cell, at the time of development of the Tiros system, of $100 per cell, and not be too far off. This results in a cost somewhere around $900,000 for a system that delivers a steady output of less than 100 watts!

The active repeater communication satellite that the American Telephone and Telegraph Company has proposed as part of their commercial communications network will also be powered by a solar cell array. One design is spherical in configuration, and its surface is virtually covered with 11,552 cells. At the current going price of about $25, the cost of the cells for this array comes to a spanking $288,800! The price of wattage out there is high! And this does not take into account such items as wiring, installation, test, breakage/replacement, and the batteries and charging circuits. Figures II and III show solar cell arrays built by the Hoffman Electronics Corporation for our satellite programs.

Also on order by the military is a huge array of twelve panels, totaling 50,000 cells of a slightly newer design and higher efficiency; the cost of this little item is estimated at $600,000. The latter two cost estimates are based upon the latest production prices; obviously, production methods have come a long way since the time when each cell cost $400!

Despite the problems and expense, solar cells are now, and are destined to remain for a long time, the number one conversion method for use in space vehicles. Interestingly enough, the U.S.S.R. seems to be in about the same situation as we are—perhaps a little more advanced in their orientation techniques, although this is very debatable. Actually, we don't know many details about their power supplies—only a few generalities. The following is a quote from Pravda of February 26, 1961, in an article about the Russian Venus probe, named by them AIS, or Automatic Interplanetary Station: "Two panels of solar batteries, constantly oriented on the Sun, ensure the uninterrupted charging of the chemical sources of current over the entire trajectory of the AIS; ensuring power supplies to all systems and equipment."

Now let's go on to the next type of power conversion system.

Solar Thermoelectric Generator. In 1821, about a year after the discovery of the electromagnetic effect, Thomas Johann Seebeck stumbled across a very interesting phenomenon. He discovered that a magnetic needle held near any leg of a circuit made up of two different conductor materials, will deflect when any part of the circuit is heated. Naturally, he got excited, and started a lifetime of investigation which led him down a wrong road, and set back the science of energy conversion by about a century! Seebeck unfortunately decided that what he had discovered was a method of generating magnetism via establishment of a temperature differential, and he used up the rest of his life in trying to prove this fact alone, in a bitter fight with the scientists who believed that the magnetic effect was secondary, and that the temperature differential actually created an electrical current flow in the circuit. However, even though Seebeck was to a large extent mistaken, he certainly was a painstaking investigator, and left very few stones unturned in his studies. In fact, he not only investigated metals, but wound up actually creating some semiconductor materials which show an electrical conversion efficiency of over 3%. At that time, this was directly comparable to the efficiency of existing steam-powered engines. The unfortunate aspect of Seebeck's interpretation is emphasized when we realize that successful generation of electricity, through use of a steam engine and wire-wound generating coils, was not established until the 1870s, about half a century after Seebeck's discovery! Then, development of the rotary generator provided the final impetus that put thermoelectricity into a state of suspended animation.

The kiss that aroused this sleeping beauty into a state of wakefulness, and probably a long life of usefulness, was the USSR's requirement in the 1930s for the capability of developing electrical power in the many small communities lying undeveloped in the hinterland. During this period, scientists all over the world were attracted by the electrical properties of the class of materials called semiconductors. Investigation showed that some of these materials acted in a similar manner to unlike metals when heated, but produced a much greater voltage. In the late Thirties, Westinghouse's Dr. Maria Telkes developed and patented a number of semiconductor materials for use in thermoelectric generators which delivered conversion efficiencies approaching 6%. These were cast mixtures of zinc plus antimony, with small additions of silver, bismuth and tin, and bismuth plus antimony. The former formed the negative leg, and the latter the positive. However, in this country, these alloys were considered a scientific curiosity, and a help in understanding semiconductors, but little else.

Meanwhile, back on the steppes, one A. F. Joffe had been placed in charge of a project to develop thermoelectric generators for the Russian back country. At present, according to all reports, Joffe and his workers have come a long way in the development of practical thermoelectric generators. In fact, a generator was manufactured and handed out to back-country farmers. This item develops 5 to 6 watts, and receives its heat from a kerosene lamp chimney; it is used to power a radio receiver. Fig. IV shows a picture of this generator.

A glance at the research and development efforts to date in the field of TE power generation shows that a goodly number of groups have already developed working models of TE generators. In the U.S.S.R., as mentioned before, Joffe and his associates have manufactured the 5-watt back-country generator for general distribution, and by 1958 had attained power outputs in larger generators of 200 watts at about 10% efficiency. We don't know exactly how far they have gotten by now, but rest assured that TE power generation in Russia is not standing still.

In this country, Westinghouse has on hand a series of practically off-the-shelf propane heated TE generators up to 500 watts and has also built for the Navy a large shipboard generator which uses seawater to cool the cold junctions. Also in development for the Navy is a multi-kilowatt generator, and built-in generators for submarines are being designed and tested. Minnesota Mining and Manufacturing Corporation, fabricators of semiconductor pellets for TE generators, has an 11-watt, 10% efficient generator in the laboratory. General Instrument Corporation has a 5-watt generator using propane gas as a fuel, which can run to fuel exhaustion unattended, a feature that interests the Signal Corps. The SNAP-III generator produces 5 watts at an efficiency of 6½%, using a decaying isotope as the heat source; one of these was orbited in late June, 1961, as a passenger on a Transit shot. A small, ingenious generator has been developed by ATI Associates for use as a classroom demonstrator, constructed of metal, and rugged enough to take classroom treatment. At the other end of the scale, Bell Telephone has for sale a parametric amplifier which uses a tiny built-in bismuth telluride TE refrigeration unit for cooling the diodes.

These are some of the developments that have been accomplished to date, and are in reality the first steps that research people must take to generate the required "feel" for a subject. They are connected by rather tenuous, but very tough, ties to the space effort.

An impressive number of companies in this country are engaged in full time research and development on TE generators. The heaviest effort is being directed toward military and space operations, although, as usual, there are a number of offshoots already being applied in industry. •

Once again, let's take a look at the application of an external energy source to conversion machinery. As in the case of the solar cells, the sun is the prime source of energy, only in the case of thermoelectric conversion, it is the long wavelength end of the solar radiation spectrum that is used. In general, in order to take advantage of the fact that conversion efficiency rises as the temperature differential increases, a collector/reflector becomes a part of the generating system, focusing the sun's radiation on the hot junctions. The present TE materials cannot accept anywhere near the temperature that the reflector is capable of supplying, due to their predilection for deterioration above 600 degrees C. At the same time, other limitations inherent in TE materials create sticky design problems. The new TE materials, such as Bismuth Telluride and Zinc Antimony, are amalgams which are cast into pellets. The cast material is extremely brittle, and very low in tensile strength, a structural combination that forces the use of short pellets, which is also forced by the fact that the internal resistance of long pellets becomes intolerable. The shortness of the pellets in turn creates the nasty problem of trying to maintain one end of the pellet cool, when the other end is an inch or less away and is at about 500 degrees C. Thus we find present designs sporting huge and fancy cooling fins on the cold end of the generator, the hot end of which is enclosed in a relatively small heated chamber. Good illustrations of this are the Russian kerosene lamp generator, and the small General Instruments' 5-watt generator. (Figs. IV and VII.)

In examining a sun-powered TE generator designed to deliver a steady output of, say, 200 watts, to be carried aloft by a space vehicle, it becomes evident that a series of very knotty design problems must be solved, especially on a systems basis. Remember, this generating system consists of a large reflector, the generating pellets, a heat exchanger which spreads the heat evenly over the hot junctions, the cooling system for the cold junctions, the connecting cabling, the rechargeable storage battery system, the power regulation system, a servo to maintain the small tolerance orientation of the reflector, and the structure that ties the whole business together. Add to this complex of problems the high order of expense of the TE materials, the difficulty of handling same, the possibility of the pellets cracking under the heavy vibration loads imposed during the boost period, the difficulties in maintaining surface tolerances in the large, flimsy reflector, and it is no idle statement to say that there are many long months of arduous labor ahead before the first generation of solar powered TE generating systems starts supplying power to space vehicles. Of course, as in most other technological efforts, development of this type of system is only a matter of time, and when that point is reached, we will have a power supply system which not only has the advantages of solid state devices—namely no-moving-part reliability—but also makes use of the very abundant and very free radiant energy pouring continuously from the sun.

The question may be asked, what can this system offer that the solar cell system doesn't have? Briefly, the answer is that it is much easier to use the very broad infra-red band of the radiation spectrum, without the problems of careful filtering that attend the solar cell, and into the bargain, the TE generator delivers more voltage per junction, and requires far fewer individual pellets than there are solar cells. This means a considerably smaller system, which in turn reflects back into the overall system design in a very favorable manner.

Thermoelectric energy conversion can be defined rather simply as the direct conversion of thermal energy into electrical energy, or conversely, the direct addition/subtraction of thermal energy from a junction by the application of electrical energy. The basic building blocks of a TE generator are 1) the use of two connected dissimilar materials, one being a positive (p) type, and the other a negative (n) type; and 2) the maintenance of a marked temperature differential between the hot end of the junction and the cold end to which the load is wired. These basics are shown in the diagram of Fig. VIII.

The p and n materials used in present TE generators are doped semiconductors such as Bismuth Telluride and Zinc Antimony. These materials act in a manner similar to the solar cells, with the obvious exception that heat replaces light as the prime energy source. Theory states that there is a similar migration of free electrons and holes, with the heat input creating the exciting conditions for both the electron migration in the n leg, and for the hole migration in the p leg. There are four well-known major parameters which have a gross effect on the efficiency and output of a TE generator. We want the lowest resistance to electron flow, the highest resistance to heat flow—or more familiarly the lowest thermal conductivity—to keep the heat from flowing too easily to the cold end, the highest thermoelectric coefficient, meaning the intrinsic ability of the material to supply a certain amount of voltage-per-degree, and the ability of the junction to develop more and more voltage as the temperature differential increases. The two latter items Joffe combined into what is called the Seebeck coefficient, measured in volts per degree. Joffe also derived the thermoelectric Figure of Merit, which combines all four parameters, and gives a direct view of the generation efficiency of any TE material. The equation for Figure of Merit is

$$Z = \frac{S^2}{\rho K}$$

where S is the Seebeck coefficient, in volts per degree, ρ is electrical resistance in ohms per centimeter of pellet length, and K is thermal conductivity in watts per centimeter per degree.

It must be realized that the TE generator is a heat engine, and as such partakes of those efficiency losses that any Carnot cycle engine is subject to during the inevitable temperature exchanges that take place. Thus, even before we can begin to convert heat into electricity, we lose well over 50% of the available heat energy to the Carnot cycle losses. In an actual design, we can assume a Carnot efficiency of 30%, and a thermoelectric conversion efficiency of 10%, resulting in a system conversion efficiency of 3%. This doesn't look so good on the face of it, but the saving factors are the free presentation of energy, and the extreme simplicity of the TE generator.

One of the problems with the thermocouple as an electricity producer is that it is inherently a high-current, low-voltage device. For instance, a TE junction formed of Lead Telluride will provide .0006 volts per degree C. At a temperature differential of 400 degrees C, the output of this junction will be only .24 volts, although its wattage is .2. Consequently, if any reasonable voltage level is required, the junctions must be wired in series or series-parallel. In order to generate enough power for a satellite mission, quite a large number of junctions are needed, although fewer than the number of solar cells by one and a half orders of magnitude. As with the solar arrays, a rather fancy design of the thermocouple assembly/heat exchanger/structure is required, unfortunately.

Also unfortunately, the good semiconductor materials used in thermoelectric generators cannot take anything like direct flame temperature without deteriorating to the point of destruction.

An intensive materials research effort is underway, both here and in Europe, to uncover semiconductors which have higher Figures of Merit than the present-day 1.2 or so, say about 3.0, and which can withstand temperatures of 1000 degrees C or more. It is estimated that a material such as this will deliver a conversion efficiency of 30%. When this development comes about, we can look forward to some rather fantastic mechanisms, not only for space applications, but doing everyday jobs right in the home. Certainly the job of the secondary space power engineer will be made easier, and who knows, it may even arrive at the point where that harassed gentleman will be reluctantly accepted as a member of the human species by structures and weights engineers, although this might be stretching the point a bit.

At the present time, TE generators have not reached the levels of cost, reliability, structural integrity, or producibility wherein they can be used for the generation of sizable quantities of electrical power in space vehicles. Lots of intensive R and D work is going on, and in fact working models of TE generating systems for space application have already been demonstrated on the ground. An excellent example of a TE system that has been developed specifically for space use is the one being developed by Hamilton Standard, which uses a large number of small parabolic reflectors on a light frame, each reflector pinpointing one, or several, TE junctions. This framework will be mounted in a similar manner to the familiar solar cell arrays or panels, and will probably be oriented continuously sunward. It will be used in conjunction with a battery pack, and will be large enough to supply power during dark periods. This configuration is shown in Fig. X.

Another type of solar powered TE generator which to a certain extent gets around the problem of carrying enough batteries for the dark periods of orbital trajectories is shown in Fig. XI. In this generator, the solar energy is collected by a large concave mirror which reflects it onto a focusing surface. From this surface, the energy is played on a container filled with Lithium Hydride in liquid form. The container is surrounded with TE junctions, and the Lithium Hydride gives up its heat to the junctions at a rate regulated by a valve in such a way that it is optimum for the particular TE materials used. During the sunlit portions of flight, the radiation shield is open, allowing the Lithium Hydride heat storage sink to be bathed continuously in the solar radiation. When the satellite moves into the earth's shadow, the insulated shield automatically closes, effectively encasing the heat sink and the hot ends of the TE junctions in an insulated container. The cold ends plus their cooling fins are all outside the container, radiating heat into space. The amount of Lithium Hydride to be used as a heat sink for the radiant energy, and then as a heat source for the TE junctions, is governed by the mission flight plan; in this case, how many minutes will be spent in darkness, and how many bathed in solar radiation. Analysis shows that this type of system actually has a distinct weight advantage over the type which carries extra batteries for daytime charging. On the other hand, it also requires a development period which the batteries have already gone through.

Fig. XII shows a simple solar powered TE generator. A cylindrical convex mirror system collects and concentrates the solar energy on a row of TE junctions connected in series or series-parallel, as required. The system design maintains a temperature differential of about 350 degrees C. A fairly large model was fabricated and operated at ground conditions, and achieved a Carnot efficiency of 25%, a conversion efficiency of 8%, and a consequent system efficiency of 2%. This was a combined Westinghouse-Boeing effort, and was used only to test the feasibility of the concept. It used a sun-oriented drive, water cooling at the cold junctions, and was operated in a chamber to simulate space conditions. The semiconductor materials used were Zinc-Antimonide, (p), and Indium Antimonide, (n), and the number of junctions came to 16. The cylindrical collector-reflector measured 20 by 50 inches, and a power output of 3 watts was attained. In actuality, a solar TE array such as is shown in Fig. XII can be made any length. Probably the critical factor in the design of the panel length is the ability to break the array up into modules which can be folded and packaged to take flight accelerations and vibrations, and which can then be unfolded easily into a large array without too many tricky joints.

One point about system efficiency. It may be that in order to achieve high values of Carnot efficiency—25 to 30%—we will have to design very large radiators. The radiator then becomes very heavy, and although the system efficiency is high, the system weight climbs to a point where we have to do away with some of the communications equipment, or some of the precious propellant, or something else that will ruin the mission. In this case, we lay efficiency aside as a controlling design factor, and shoot for a high power-to-weight factor. Therefore, we design the cold-end temperature higher, and let the efficiency fall off; the radiator weight comes way down, with a consequent drop in overall system weight. Up to a certain point, this works fine, and this point is reached through a systems optimization study, which results in a good power-to-weight ratio, a reasonable efficiency, and no removal of equipment.

There are a surprising number of solar TE generators being designed for space vehicles. Some will need backup from extra chemical battery systems, and some will have built-in heat collectors to obviate this need. Some will use multiple small reflectors in large panels, and some will use a single huge reflector which will unfold, petallike, when in orbit, to a diameter of as much as 45 feet. These impressive, simple-in-principle, expensive machines will provide unfaltering electrical power for space vehicles during missions which last months and years. Furthermore, there isn't much doubt that these systems will act as the basis for—I hesitate over a badly beaten word—a breakthrough in power supply methods for ground use in military, commercial and home applications.

The next type of power generating system which we will examine is the *Solar Thermionic Generator.*

Just before the turn of the Twentieth Century, Thomas A. uncovered a characteristic of metal which has been heated to incandescence. Appropriately enough, this was called the Edison effect, and it states simply that electrons boil off the surface of incandescent metal, and the number of electrons boiling off increases as the temperature increases.

In our present electronic age, this statement may not create pandemonium among the brethren, but it presents a phenomenon which has only recently been pressed into service in another type of oddball heat engine that threatens to open new energy-supply vistas to an energy-greedy world. This engine has come to be called a thermionic generator or converter, and sometimes a thermoelectron engine. In principle, the thermionic generator is, like its cousins, a very simple machine. Basically, the generator hardware consists of a sealed chamber, a cathode, an anode, and a heat source. As can be seen, it strongly resembles a diode. Fig. XIII gives a picture of these elements.

There are two major types of thermionic generators: In one, the chamber is evacuated. In the other, the chamber is filled with a gas such as cesium vapor. Briefly, the thermionic generator works in the following manner: the electrons that boil off the heated cathode reach certain energy levels during the process. Certain of these electrons reach energy levels high enough so that they escape from the cathode, and migrate across the intervening space to the anode surface, which is relatively cool. If these electrons, which have been lifted to a high potential by the thermal energy, migrate to a surface which is made of material with a low work-function, some of this potential can be recovered and used to move the electrons through an external circuit. The cathode and anode materials are selected so that the electrons emitted from the hot cathode require more energy for escape than would be required for anode electrons to escape from the anode surface. This results in a stream of electrons that land on the anode with a fund of energy which allows them to do work in the low work-function environment of the anode.

A crude analogy might be the difference in work potential that an earthman would display on the moon, compared to his work potential on the earth—provided that he has been supplied with enough energy to escape from the higher gravitational field of the earth. To illustrate the availabiliy of energy in the thermionic generator, Fig. XIV presents an idealized potential energy diagram of an electron migrating from a hot cathode to a cool anode. In the diagram, W_1 is the work-function of the cathode, and W_2 that of the anode. In order to escape from the cathode, an electron must be raised above the energy level represented by W_1 to the level of W_E. Having escaped and migrated to the anode, the electron gives up energy equal to the anode work-function W_2, which then appears as heat in the anode. However, after having fallen from the level of W_E through the potential barrier and down to the Fermi level of the anode, the electron still has an amount of energy left over equal to E, the difference between W_1 and W_2. This leftover energy appears directly as electrical energy when a circuit between cathode and anode is established.

It's hard to conceive of a much simpler machine. Two pieces of metal, a small chamber, and a candle! However, some little problem always seems to rear up and take all the joy out of living, and the label on this particular problem reads "Space Charge".

When we heated the cathode and boiled the electrons off the surface, we naturally expected, as per theory, that a certain percentage would make it across the intervening vacuum to the anode. Knowing the work-functions of the cathode and anode, the temperatures of both, and their spacing, we can calculate the electron flow, and the consequent developed current or voltage. But we failed to reckon with the very large number of electrons that didn't quite reach escape-energy level. These, in an ever-increasing number, clog up the *Space* between cathode and anode, and form a cloud which has an overwhelming negative *Charge*. In turn, this negative space charge tends to repel electrons that boil off the cathode, and only a very few of exceptionally high kinetic energy content can get through. Therefore, although the thermionic generator described above will stabilize at a certain level of output, said output will be very low in comparison to the input of heat; this makes for a very inefficient system.

Independent workers at MIT, General Electric, and RCA came up with a few excellent answers to the space charge problem. An extremely simple method which has resulted in conversion efficiencies approaching the 15% mark, is to fabricate the cathode and anode from a material such as tungsten, very carefully machined, and place them as close together as .0005 to .001 inch! This requires pretty careful machining and assembly, but it can be done, and as stated, good conversion efficiencies have been attained with this procedure.

Another very promising method of overcoming the space charge barrier is to neutralize it. Ingeniously, the researchers reasoned that somehow or other, a positive-particle cloud should be introduced, so that each electron in the space charge cloud would be attracted to a positive particle, resulting in a nulling of the space charge. Ions fit this bill, and a vapor made of cesium provides an excellent source of ions. When cesium atoms strike the hot surface of the cathode, which has a higher work-function than the cesium, they lose an electron. This electron then becomes bound to the cathode, and the newly formed cesium ions bounce out in the form of a positively charged cloud. Enough of these result in neutralization of the negative space charge, and at the proper cesium vapor pressure, with the space charge virtually absent, the flow of energetic electrons can be started and maintained at a high level by heating the cathode to temperatures easily reached by simple heat sources. There are other tricks to increasing the life, efficiency, and practicability of the cesium vapor thermionic generator. These are being pursued with utmost diligence, and in a few short years we are sure to see the utilization in space—and no doubt in ships and on the ground—of thermionic generators which will be simple, reliable, and will deliver efficiencies in the neighborhood of 30%.

It is well and expedient to point out that there are other problems which bedevil the researcher and engineer in this field. One of the obvious, and most difficult to solve, pertains to materials. Because of the basic requirement to boil off many electrons and to give them a high level of kinetic energy, it is necessary to raise the temperature of the cathode to a high value if any sizable current is to be realized. For instance, some thermionic generators have been operated as high as 3000 degrees K, and the standard operating temperature range runs between 1400 degrees K and 2000 degrees K. At temperatures such as these, the tungsten cathode doesn't last very long; it vaporizes rapidly and deposits on the anode. In a cesium vapor generator, at certain pressures the problem can be taken care of by the fact that the cesium atoms condense on the cathode, thus coating it. In this case, the cesium atoms on the cathode boil off at a great rate and migrate into the cesium cloud, but are replaced continuously via the condensing process. In this way, cesium vapor thermionic generators can operate for many hours at the high temperatures needed for decent efficiencies.

Two other prominent problems are the containment of the alkali vapors at high temperatures, and the prevention of breakdown in the electrical insulation between the cathode and the anode. However, as stated before, the concentrated attack on these and other problem areas will soon result in materials and methods that the engineer can put to good use in the process of solution. In fact, very recently one company has solved the problem—to a certain degree—of material failure at high temperature, by simply devising a thermionic generator that works at far lower temperatures.

At the present time, a number of working thermionic generating systems have been built by quite a few companies. Many of these, of course, are laboratory models, but some are prototypes of future space power supplies. Some have delivered up to 200 watts for hundreds of hours. An intensive study and development program is underway at companies such as General Atomics, RCA, General Electric, Thompson Ramo Wooldridge, Martin, Thermoelectron, and others, with the prime objective of coming up with actual space-flyable power supply systems. These systems will incorporate the same type of solar collectors, orientation systems, heat storage sinks, et cetera, as has been presented previously relative to thermoelectric generators. Some of these are approaching the ready stage now, as far as laboratory testing is concerned, and final designs for the actual space-solar thermionic systems are well along. Just recently, after an industry-wide competition, a contract for a 135 watt thermionic solar powered system, using cesium vapor generating elements, was let to Electra Optical Systems, Inc.

The solar-powered thermionic generating system consists of a number of major components, among which are the solar collector for concentrating solar radation on a receiver adjacent to the cathode, the thermionic generator itself, a radiator to reject heat from the anode to space, heat transfer loops or thermal conductors to transport heat from the receiver to the cathode and from the anode to the radiator, control mechanisms to regulate and modulate the generated electricity, and a means for storing either thermal or electrical energy during periods of orbital shadow. Systems of this type are very similar in configuration to the TE generating systems, except for the generating element itself. Figures XV and XVI show drawings of simple and sophisticated thermionic generating systems. As in the other types of solar generators, the thermionic types use a multiplicity of generating elements, connected in series or series-parallel.

It is interesting to examine some of the design problems and their solutions, in this particular field. As noted before, the thermionic generator operates at fairly high temperatures; in fact, thermal power rates are on the order of 25,000 BTU's per square foot of cathode area. The solar collector-reflector must be designed to concentrate solar energy to match the temperature and BTU requirements. At the same time, the reflector must also supply solar energy to the thermal heat sink, and must compensate for any heat that leaks from the thermal receiver into space via radiation. Because of the many areas in a solar space power system which represent drains on the transfer of solar energy into usable heat energy at the cathode, the collector should be close to optically perfect relative to surface deviations and reflectability. This is possible if we can afford a carefully ground surface on a stiff structure; however, the bugaboo of system weight requirements limits us to a weight of about one-tenth pound per square foot of reflector surface. This exceedingly light structural requirement virtually dictates rather poor optical qualities, followed by the need for an enlargement of the reflecting surface. Add to this the immense job of stowing the reflector in a folded condition during the flight from earth to orbit, and the necessity for erecting the structure in orbit and keeping it oriented, and it can be seen that the solar reflector alone represents a major developmental effort.

Some of the collectors presently in work have been designed in the form of a folding umbrella, some as inflated plastic structures, others as flower petal structures, and the like; please recognize that these designs run as large as 100 feet in diameter!

Another sticky design area is the radiator. Because the thermionic generating elements convert only a small percentage of the applied heat into electricity, the rest of the BTU's must be dumped overboard. In space, radiation is just about the only practical method, and radiator design becomes of prime importance. One design that shows promise consists of a very thin stainless steel sheet formed to allow passage of liquid sodium. The sodium picks up heat from the anode through a heat exchanger, and is then pumped through the radiator in a loop which returns it, after cooling, to the anode. Some radiator designs incorporate a meteorite barrier covering the thin stainless; others attempt to solve this problem by designing the radiator with thick walls to begin with. In any case, all radiators are too heavy, clumsy, and complicated; ask any of the engineers who are working on these systems.

Let's look at a solar thermionic generating system designed to deliver about 6 kilowatts continuously, during a mission that comprises a 100 minute orbit, 35 minutes of which are spent in the earth's shadow. An average thermionic conversion efficiency of 10% is available, at a cathode temperature of 2500 degrees K. For this generating system, the thermal receiver will have an area of 12 square feet. At an efficiency of 40%, the reflector-collector area will be 2800 square feet. The radiator will weigh 120 pounds, the reflector 180 pounds, the controls 30 pounds, the thermal receiver and storage sink 200 pounds, and the thermionic generating pile 280 pounds. Altogether, the system weight comes to 810 pounds. An overall system efficiency of approximately 3% can be expected. Naturally, system weight will drop when we develop generators with conversion efficiencies of 30%. ■

Moving machine power systems will be discussed in our next article.