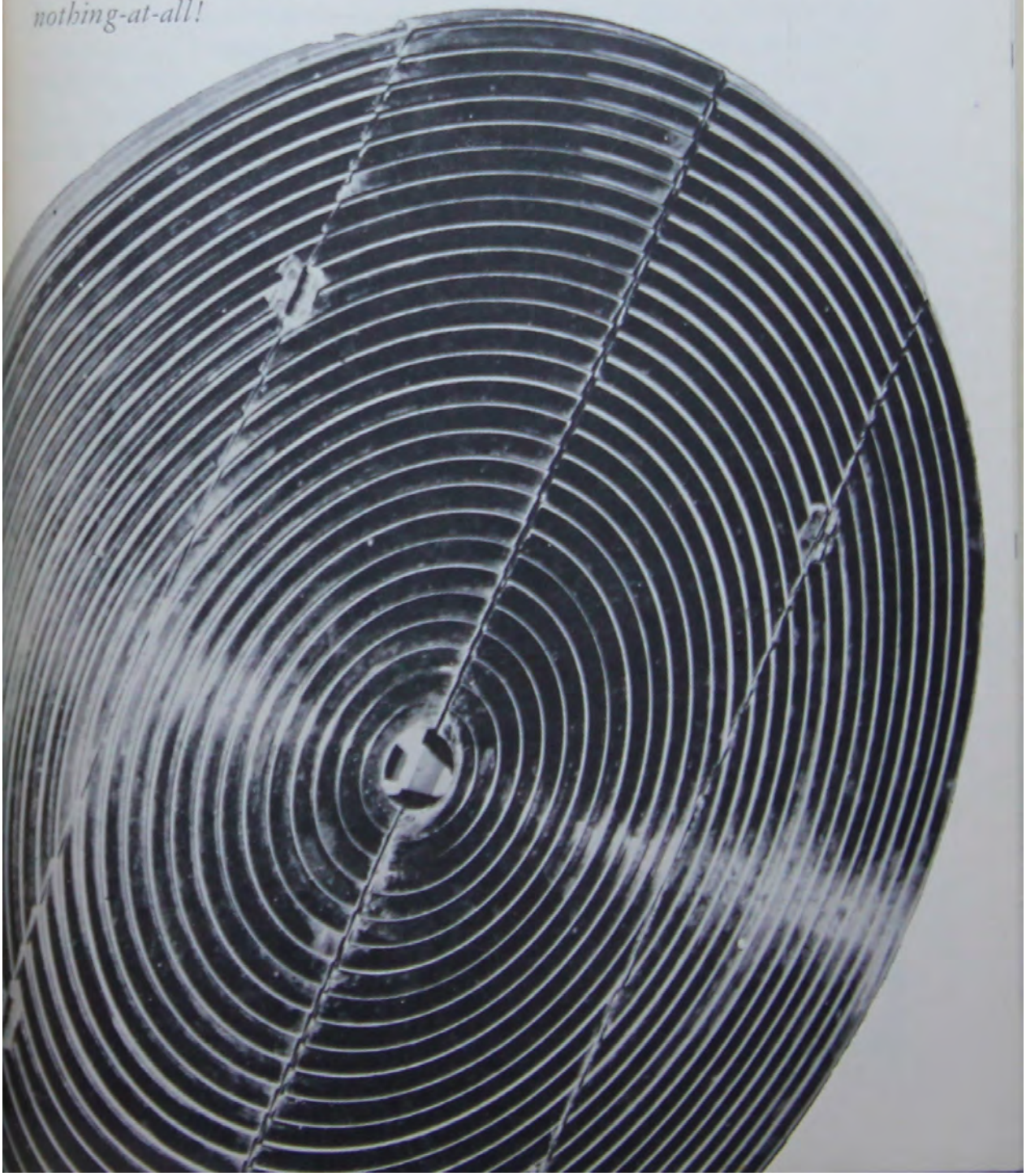
Part 2—concerning devices with moving parts, and the problems of mechanical wear in devices that you can't send a mechanic to repair! Of engines that must run without fuel and without failure in the hostile environment of nothing-at-all!

POWER SUPPLIES FOR SPACE VEHICLES

by J. B. Friedenberg



MOVING PARTS SYSTEM

■ The first mechanical solar power supply to be discussed is the *Solar Turbine Power Plant.* Variations on an old theme, this type of space power supply system probably represents the peak of technology along a particular line. Actually—and a good, solid fact that must be faced by the most rabid proponent of the "exotic" space power supply techniques—the most efficient method of generating electrical power known to us today is still the turbine-generator combination, or its reciprocating cousins. State-of-the-art for these mechanical conversion types is very advanced, having developed through the ages since Hero neatly turned the trick back in 130 B.C. However, using boiling water in a one-gee earth environment, with plenty of air or water for cooling, is quite different from boiling a corrosive medium such as rubidium, sodium, ammonia, and others, in a Zero-gee environment, using the sun as a heat source, with cooling supplied by radiation alone, and keeping the system weight in the general neighborhood of a Ping-pong ball!

Rather than discuss the many mechanical conversion schemes available, we will present a picture of the system that appears to be the leading candidate for the office of large power supplies in space. This is the solar powered, Rankine cycle turbine, using mercury or rubidium as the working fluid. As mentioned above, the turbine power system is most useful for large power requirements—as ascertained through systems optimization studies—but it really comes into its own when we talk about a space vehicle that is designed to carry a crew and maintain this crew in the space environment

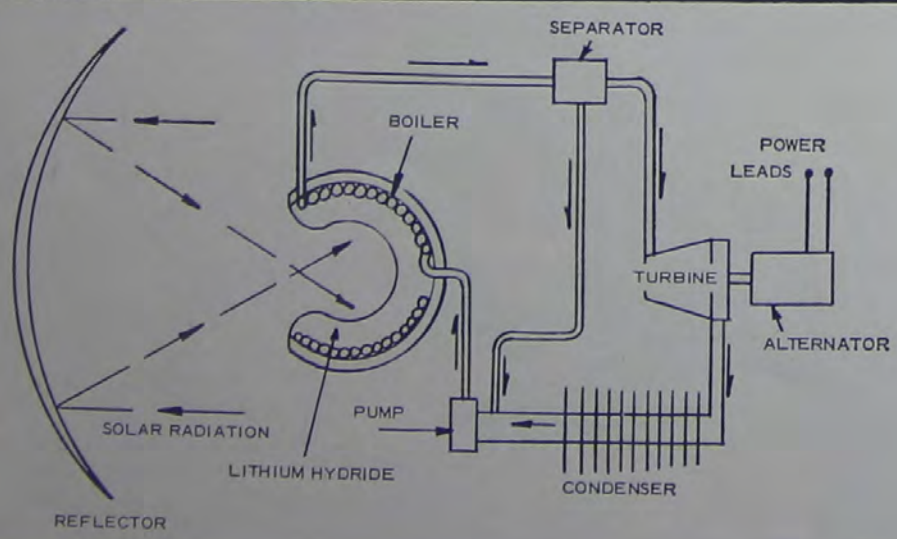


Fig. XVII: Solar powered liquid metal turbine

for weeks and months.

The Samos-Midas family of satellites—even the Explorer and Surveyor types of unmanned vehicles that will eventually soft-land on the moon—require power levels that reach into the high hundreds and low thousands of watts. These vehicles can successfully use, and are designed for, the battery and solar cell power supply systems. However, when we talk about 10 or 20 kilo watts, figures which are representative of the power levels required by a manned vehicle designed for long-term missions, the minimum number of silicon solar cells needed—assuming practically laboratory temperature and orientation control—is about 1,400,000! From the point of view of the cells alone, this is a goodly number worth a goodly buck, but imagine designing the containers, joints, deployment and orientation mechanisms! It is in this range of power levels that the combination of solar collector and turbine-alternator takes over. By 1970, this type of system will actually be in use on a space vehicle.

In this type of mission, the generating system will have to supply 20 kilowatts continuously for a year, at 400 cycles. Inherent in the system must be the capability for storing energy to use during shadowed periods, similar to satellite nightside operations. A vehicle such as this will probably be used for a mission such as intercepting Mars, orbiting for surveillance, then returning to earth. In this case we would use as a design point the incident solar radiant energy felt by Mars, which is estimated to be .6 kilowatts per square meter. This is pretty poor compared to earth's fat 1.4 kilowatts per square meter, but gives us a nicely conservative design, a thing that delights the energy management engineers, but desolates the long-suffering weights people.

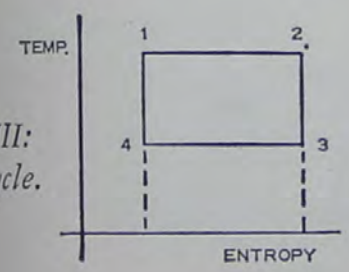


Fig. XVIII: Carnot cycle.

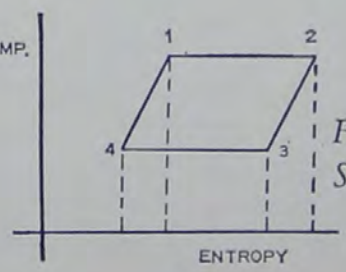


Fig. XIX: Stirling cycle.

Assuming a conversion efficiency of 10%, the total energy absorbed by the conversion system to provide 20 kilowatts will be 200 kilowatts. Calculating re-radiation losses from the boiler, we find that a total of 450

kilowatts of solar energy must impinge on the boiler. Now, assuming a collector efficiency of 85%—high, to be sure, but possible in ten years—and using the incident energy near Mars of .6 kilowatts per square meter, the collector needed to supply the 450 kilowatts turns out to have an area of 882 square meters!

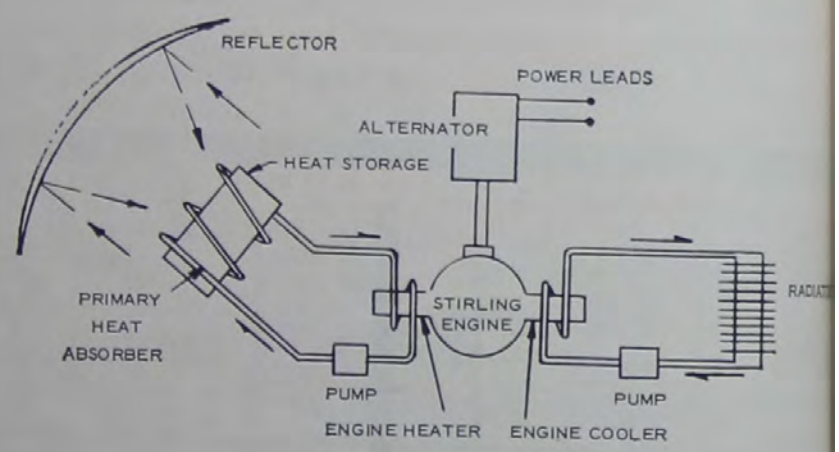


Fig. XX: Solar Stirling engine system.

If the vehicle mission is such that it will remain in the vicinity of earth, the effect of the incident energy of 1.4 kilowatts per square meter is to reduce the collector area to 388 square meters. Areas such as this are large, but are already in the design stage.

Since we've already chosen the Rankine cycle, we can examine some of the working fluids that can be used. These include mercury, rubidium, sodium, lithium, and cesium, all classed as liquid metals. The first three are already in use in systems under development. They all have boiling points below 1800-2000 degrees K, which is a practical limit based on structural considerations. Because in the Rankine system the fluid must be vaporized as fully as possible, the very high boiling temperature must be maintained constantly in the boiler. This creates rather high-order material stress problems, and going any higher in temperature would pass the practical design limits of today's metallurgy; the boiler tubes would creep, bulge, and rupture.

Schematically, a complete system such as this will appear as shown in Fig. XVII. Starting at the boiler, the fluid is vaporized as completely as possible, and the vapor flows directly to a separator. Here, the small amount of unvaporized liquid is separated

from the saturated vapor. The vapor flows into the turbine, expanding through its stages; the turbine runs up to speed, and is regulated to keep the alternator RPM within proper limits. After leaving the turbine, the vapor is condensed in the radiator and flows as a cool liquid into the pump, where it is pumped back to the boiler to start the cycle again. The radiator may require another stage for sub-cooling. Each component must be designed for lowest weight, smallest size, highest efficiency, and highest reliability. That's all!

In designing the turbine, the most important factors entering the picture relate to the corrosive characteristics of the working fluid, the extremely elevated working temperature of the liquid metal, and the very long operating duration. Exotic alloys must be used, as the operating temperatures and corrosivity dictate the downfall of ordinary metals. Even such materials as molybdenum, columbium, and tungsten are marginal, especially for long term use where the creep characteristics of the material become a major design issue. Another vital factor in the system design is the corrosivity of the working fluids. If there are any droplets of liquid in the vapor, the corrosive effect jumps sharply up. As a consequence, it becomes of first-order importance to design the boiler, and the passages from it to the turbine wheels, so that no liquid droplets are formed in these areas.

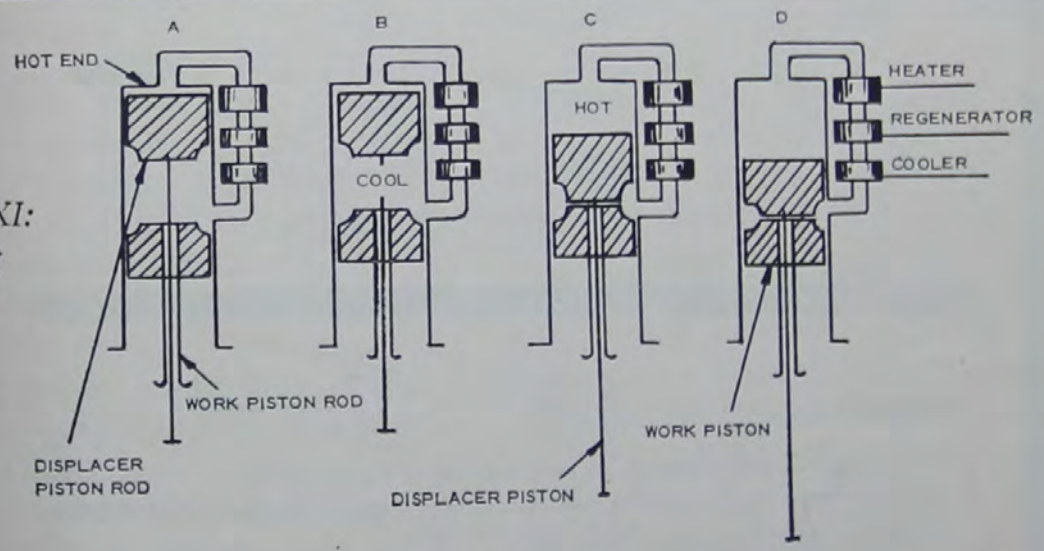


Fig. XXI: Stirling engine work cycle.

The function of the boiler is to transfer the collected solar energy to the working fluid. At first glance, it would appear that all the working fluid should be vaporized, as this

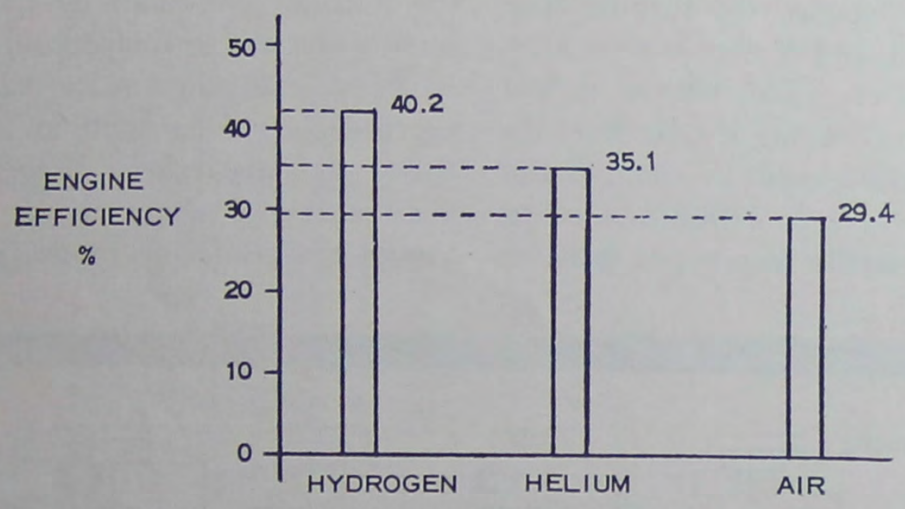


Fig. XXII: Stirling engine efficiency as affected by working medium.

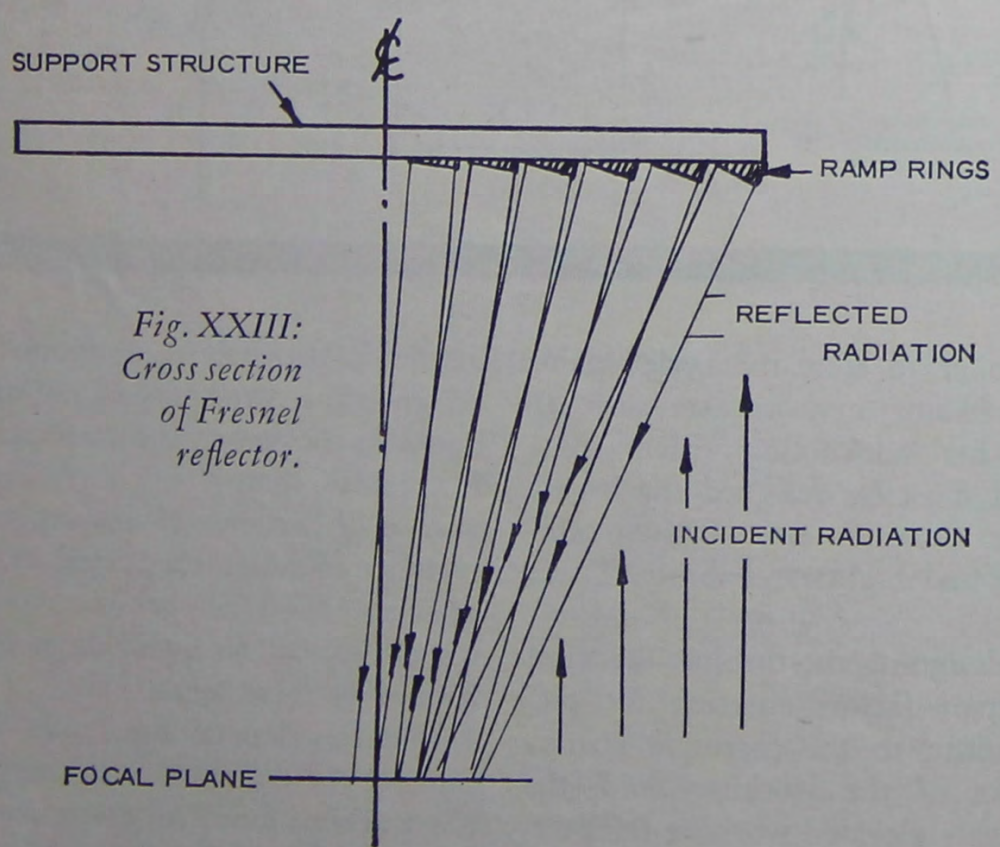


Fig. XXIII: Cross section of Fresnel reflector.

would make available the most energy in the fluid, and would also keep the corrosion problems at a minimum. However, heat transfer calculations show that while this may be practical on the ground, in a space system it becomes untenable: the heat transfer area becomes literally immense. So once again we must trade off efficiency of a single component against overall system efficiency, and accept, for example, 80% vaporization and a relatively small, light boiler. If we insist upon 100% vaporization, we will find that the boiler weight is about ten times the weight of a boiler needed for 80% vaporization!

Obviously, in this case, 20% of the fluid remains liquid. A turbine is designed—at least in this case—to operate with a vapor; liquid in the vapor, besides raising the corrosion problem, drops the efficiency alarmingly, and also cuts the turbine life. Thus, a separator is required. This can be a stationary volute or coil that bleeds off heavy liquid thrown centrifugally to the outside, or an actual motor driven centrifuge. Good separator design is a must in the liquid metal systems.

The next important item in the system is the pump. In designing the pump, once again we are faced with high speed rotating machinery that must operate at constant speed for months on end. Because we can't afford cavitation, the pump will probably be designed as a combination jet-centrifugal type. It is driven off the turbine through a gear train.

So far, we have bumped into rotating machinery in a number of places. Obviously, in this type of system there are a goodly number of rotating components. This situation means that we must have a system of bearings which will operate smoothly, without breakdown, for the long time periods of the mission. Roller and ball bearings do not satisfy; the individual parts fail under the combined high speeds, heavy loadings, and high temperatures. However, it has been found that plain, or journal type bearings, lubricated by a full film of the liquid metal working fluid, will do the job. Bearing systems such as these have been fabricated and tested, and will probaby be the type of bearing used in the turbine power system.

Probably the biggest single problem in the bearing area relates to the compatibility of the hot liquid metal with the bearing material. Some materials showing promise for bearing application are the carbides of tungsten and titanium, which are very resistant to the hot, corrosive liquid metals, do not lose strength or shape at the high operating temperatures, and will stand up to the continual abrasive action of the turbine shaft. Incidentally, as is the case with all aspects of space-oriented science, research in bearing technology has virtually become a science in itself, out of which many useful techniques will come for application right here on the ground.

Finally, after the collector has collected, the pump has pumped, the

Fig. XXIV: AiResearch solar powered rubidium turbine system.

boiler has boiled, the separator has separated, the radiator has radiated, and the turbine has ?, we arrive at the miniaturized giant that creates the wattage—namely, the alternator. The alternator is either attached through a gear train to the turbine, said gear train operating the alternator at a specific RPM, or is driven directly by the turbine, and its characteristics are matched to the turbine speed. Because of the requirement for continuous operation over very long periods, it is not feasible to use standard alternator designs which employ brushes or commutators. Here, the problem is obviously one of wear. Therefore, we are forced to go to a brushless design, such as the inductor alternator, in which the rotor itself is forged from a magnetic material of high tensile strength. The rotor runs at a high peripheral velocity and RPM, allowing the design of a small package, with consequent low system weight penalty.

We have presented the various working components of the system as if it travels in free space without ever leaving direct sunlight. However, if the system is to supply power to a vehicle that is intended to orbit a planet for surveillance duties, it becomes necessary to add one more major component—the heat storage sink. This has been discussed in relation to the various other power systems, and in the case of the turbine-alternator system, will probably also use the lithium hydride combination. A point to note is that the heat storage component is by far the heaviest in the power supply system, accounting for about 70% of the system weight. (Here's an excellent field for invention.)

Somewhere in the neighborhood of a continuous 10 kilowatt power supply requirement, the power-weight curve of the solar turbine-alternator system catches up with, and passes, the static energy conversion devices using the sun as primary energy source. Following is a weight breakdown of a typical 10 kilowatt turbine-alternator system:

Collector-Reflector	142 pounds
Radiator	36 pounds
Boiler	10 pounds
Pump	5 pounds
Separator	5 pounds
Turbine	20 pounds
Alternator	40 pounds
Piping and Structure	10 pounds
Working Fluid	25 pounds
Orientation Mechanism	70 pounds
Voltage Regulation	10 pounds
Heat Storage	870 pounds
TOTAL	1243 pounds

Refinement of design, which will occur after the initial results are evaluated, will bring the system weight down to about 1,000 pounds. This is not a startlingly low weight, but from here on out, to the higher power levels—20, 40, 100 kilowatts this type of system walks away wit' the honors in the solar power arena

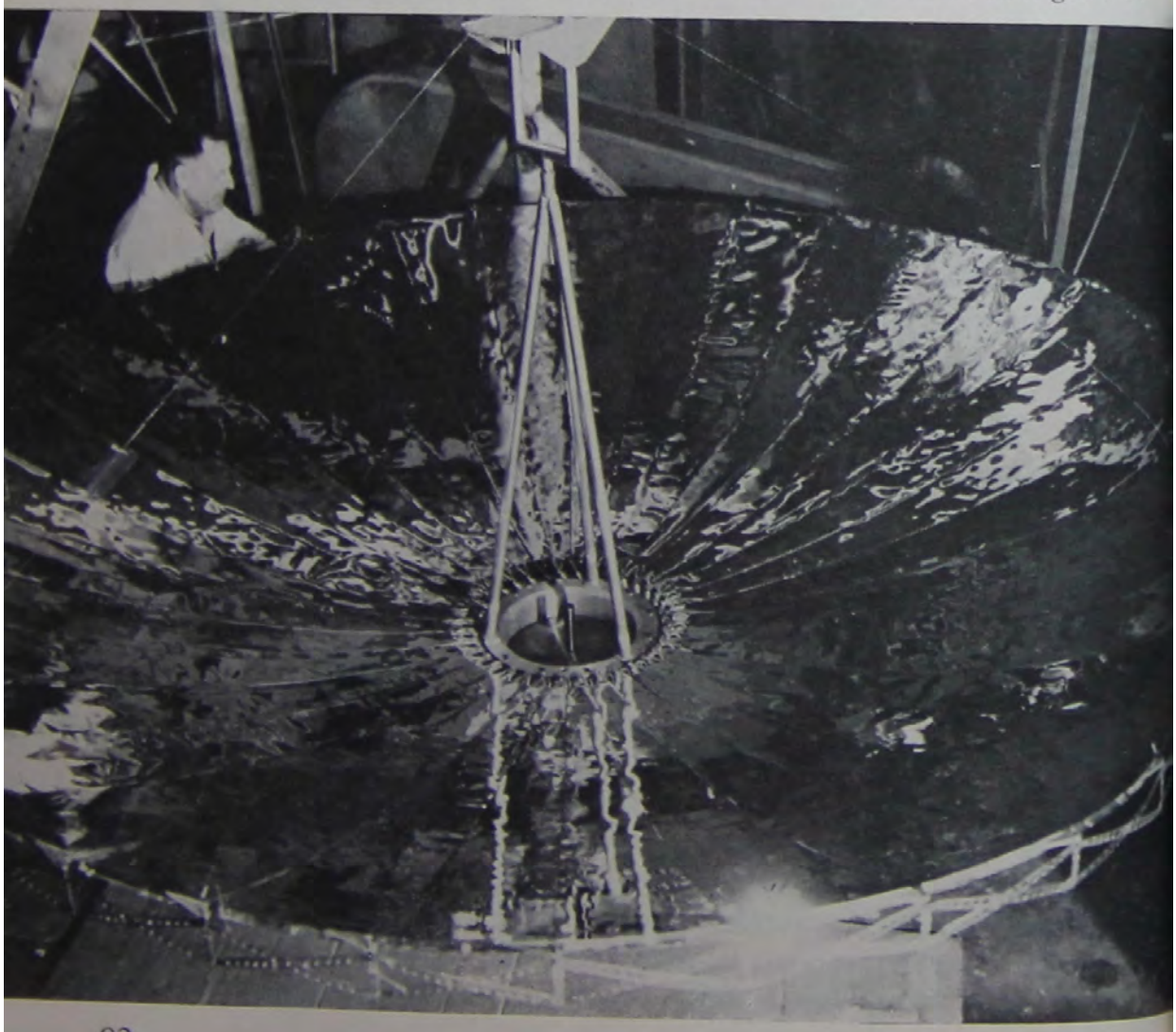
Before leaving the solar Rankine turbine system, let's see what effect the use of rubidium has on system weight, as compared to the mercury

system. In general, of course, the rubidium complex will be very similar, using the same type of components. Differences in the two systems really are created by the somewhat different design philosophies that obtain between companies.

For instance, Sundstrand Aviation of Denver, under contract with the Air Force, is well along with development of a rubidium solar turbine system which differs in design from the above-discussed mercury system, as championed by Thompson Ramo-Wooldridge, mainly in design details. The same type of components are used, in the same sequence and number, with certain modifications and additions which mesh better with the use of rubidium.

One difference is that the Sundstrand system uses a very sophisti-

Fig. XXV: Folding parabolic mirror—Ryan Aeronautical Company. It's not enough that a reflector be able to concentrate sunlight . . .



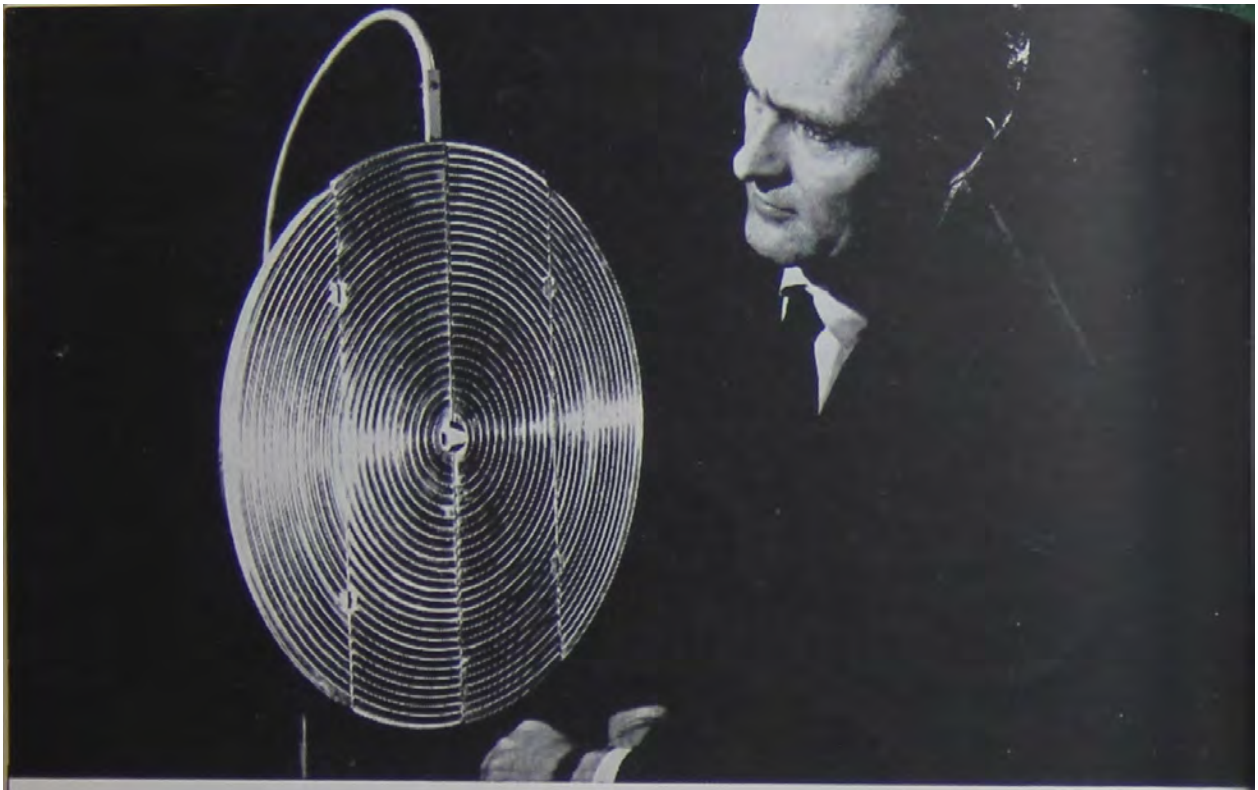
catedly designed combined heat storage-boiler section; this section contains two heat sink cavities, one utilizing the familiar lithium hydride, and the other holding sodium fluoride. These work as a two-stage heat sink: the solar enery is reflected through a fancy energy flux trap into both stages, where the heat is held at two different temperatures by the two molten salts.

Fig. XXVI: . . . It's got to fold to fit in a rocket vehicle, too!

The rubidium is circulated first through the lithium hydride, where it is boiled and brought to a temperature of 1,200 degrees F. It then continues its journey through stage two, where the sodium fluoride superheats it to about 1,800 degrees F. In this state, the vaporized rubidium is then expanded through a four-stage axial flow turbine, which turns at a design speed of about 24,000 RPM, which in turn drives the alternator and coolant pump. All bearings are lubricated by the rubidium working fluid itself. A thin metal meteoroid shell protects all working machinery. The turbine exhausts rubidium vapor into the center of a circular platelike radiator, where it moves through passages to the rim, and condenses at a temperature of about 650 degrees F. From here it is pumped to the bearings and the boiler, to start the cycle again. The big thirty-six foot diameter solar reflector is made of aluminized mylar—the same stuff that the Echo satellite is made of—and is rigidized by injection of a forming plastic that sets hard.

The use of rubidium in the Rankine turbine system allows a larger spread of working temperature than in the mercury system, due to the higher allowable working temperature of 1,800 degrees F, as compared to mercury's 1,200 to 1,300 degrees F. The increase in latent energy results in higher overall system efficiency, with consequent savings in size and weight for a given power requirement.

For instance, the weight of a com-



plete rubidium system designed to deliver 10 kilowatts in space is close to 750 pounds, as compared to the 1,243 pounds quoted for the mercury system previously. This sort of weight saving, it almost goes without saying, gladdens many a heart during the development cycle of a satellite system that always seems to be pulling a Topsy. Of course, it should be pointed out that the really nice thing about the *mercury* system is that it has a long history of ground usage in stationary power plants behind it; consequently, many of the problems have been worked out. On the other hand, the problems associated with the use of rubidium are still being uncovered.

Fig. XXX shows a photo of a ground-based working model of the rubidium turbine system developed by Sundstrand Aviation—Denver. An artist's conception of a space system is shown in Fig. XXXI.

Also in the solar rubidium turbine business is the AiResearch Manufacturing Division of The Garrett Corp. These people have embarked on an ambitious development program in the Phoenix area, where they are making good use of the exceptionally plentiful solar energy reaching the ground. In Fig. XXIV, we have an artist's conception of the AiResearch rubidium system in space.

The last type of space power supply system to be discussed in this article is the *Solar Stirling Power Plant.*

In 1827, Robert Stirling, a thermodynamically inclined English preacher, dreamed up a rather odd engine based upon a new gas cycle which was also invented by him. Looking

Fig. XXVII: Fresnel reflector—
Allison Division of General Motors.

Fig. XXVIII:
Fresnel reflector—Allison Division of General Motors.
Incidentally—for the home experimenter—equivalent Fresnel lenses, made of sheet plastic, capable of acting as solar furnace units, are available from scientific supply houses such as Edmond Scientific, at very modest prices. They look like transparent phonograph records—and act like ten- to twelve-inch lenses!

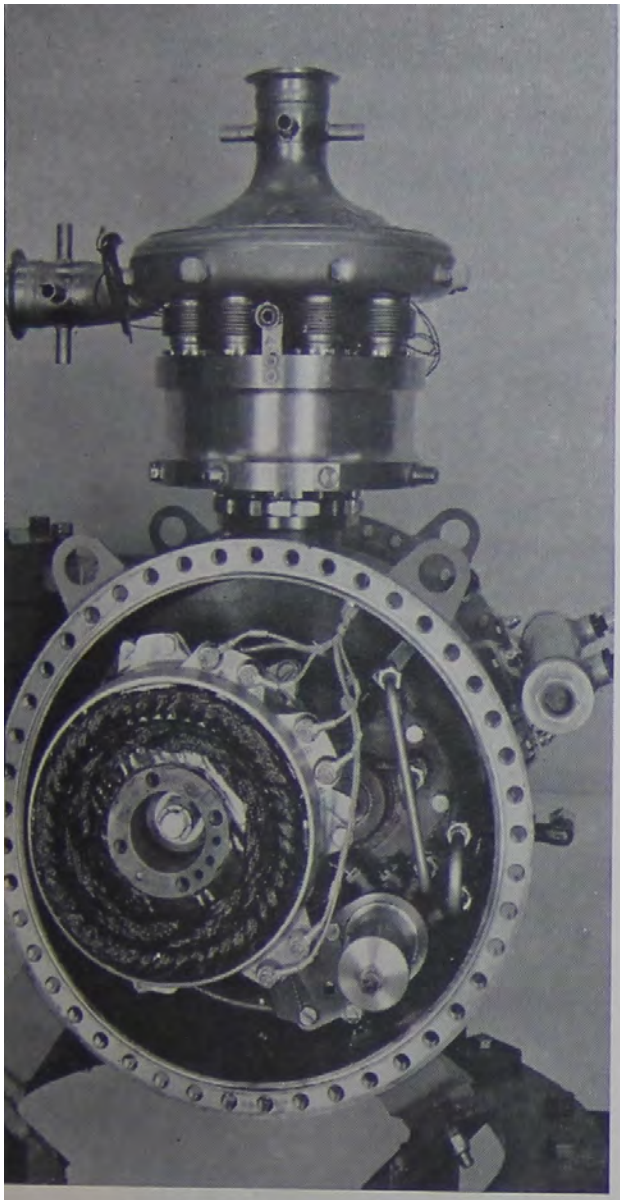


Fig. XXIX: Stirling engine and integral alternator—Allison Division of General Motors.

back on Stirling and his development efforts from the vantage point afforded by the ensuing century and a half, it appears as if he deliberately tried to force the gas cycle into following, as closely as possible, the classical Carnot cycle which delivers —on paper, anyway—maximum heat engine efficiency. We can even imagine his excitement and delight when his paper work showed that his cycle did indeed approach the Carnot heat utilization, although the method he used was obviously a forced and artificial one.

So artificial was the method, in fact, that the contemporary scientific professional types snickered loudly, and pointed out the impossibility of ever achieving high speed action with the Stirling cycle. Fatuously, they concentrated on development of the sturdy steam engine, and of another silly little item that showed much promise—the internal combustion engine. Snickers changed to condescending laughter when Stirling's huge, cumbersome external combustion engines were demonstrated. Although they worked, as predicted by the brethren they chuffed ponderously through the

Fig. XXX: Model of rubidium solar turbine system—
Sundstrand Aviation, Denver.

Fig. XXXI: Artist's conception of rubidium turbine space system in orbit—Sundstrand Aviation, Denver.

strangely artificial cycle invented by the good preacher. After a few short years, development petered out, and it was concluded that the cycle, while interesting on paper, was impossible to implement.

Obviously, with the working medium—a gas such as air—separated from the heat source by the cylinder walls, it is not possible to transfer heat rapidly from the gas to a heat sink and back again in a closed cycle. Thus, one could never achieve rapid reciprocation, and the development of high powered engines would necessarily result in huge machines—too large for practical use in a world which was searching for smaller and smaller power packages. Indeed, that intrepid and remarkable engineer, Ericson, of Monitor fame, built a 3,000 horsepower engine for the United States Navy, using a modification of the Stirling cycle, the modification invented by himself and appropriately called the Ericson cycle—which operated at 9 (nine, that is) RPM! It never went into service.

However, time proceeds, and various and sundry milestones of technical development come to pass. New materials appear on the scene, making possible activities that once were termed impossible. Twenty-five or thirty years ago, an enterprising outfit named N. V. Philips Research Laboratories, in the Netherlands, decided that the Stirling Gas cycle looked very interesting. Being knowledgeable, they connected the new-found high-strength steels with the Stirling cycle, and came up with an amalgamation that seemed to deserve another look-see. Accordingly, they instituted a long-term development program which has continued to this day, and has been used as a foundation for a remarkable power conversion system planned for space use.

Let's look at the Stirling cycle.

It is the usual thing to compare all gas cycles to the classically unattainable Carnot cycle, thus checking their possibilities and further assuring the non pareil nature of the Carnot diagrams. On a Temperature-Entropy chart, the Carnot cycle is represented by two isothermals and two isentropics, as shown in Fig. XVIII. The heat rejected during operation 2-3 returns during 4-1, and the ideal cycle continues unabated. In the Stirling cycle, the adiabatics of the Carnot cycle are replaced by constant volume slopes, and the cycle diagram looks like that shown in Fig. XIX.

In the actual Stirling engine, the approximation of the Carnot cycle is accomplished by the ingenious incorporation of a device called a heat regenerator, which is expressly designed to store the rejected heat—usually thrown overboard, thus killing chances of approaching Carnot—so that it can be returned during operation 4-1. In the ideal case, the heat absorbed from the source is the same as in the Carnot cycle, and the efficiency possibilities are also the same—if we have an efficient regenerator.

As stated before, the Philips people saw this potential, and decided to exploit it. The engines they have developed, using heat resistant steel alloys, elevated gas temperatures, and the latest heat transfer techniques, operate at efficiencies equal to or better than internal combustion engines. Operating medium—air or some other cheap gas—reaches a temperature of 1,200 degrees F, and the working pressure reaches as high as 750 psi. Design of the heater, regenerator, and cooler, and the use of high heat transfer rates, small gas volumes, and passages designed for low aerodynamic resistance, has given operating speeds of over 3,000 RPM.

The regenerator—development of which was one of the keys to success—consists of porous coils of wire, is 95% efficient, and can raise or lower the gas temperature 900 degrees F in .01 second! The amount of heat saved in the regenerator is 75% of the heat required to raise the temperature of the gas from its working cool level to its working hot level. And right there is the reason why the Stirling cycle has become so attractive.

Using all this work as background and foundation, the Allison Division of General Motors has had under development, since early 1959, a 3 to 5 kilowatt space power system based on the Stirling engine. The sponsoring agencies are ARPA and the Air Force. So far, in this program, the Allison people have demonstrated a 40% efficient Stirling engine.

Actually, the defunct Stirling cycle was resurrected because when all the gas cycles were investigated for application to space missions, the Rankine and Stirling cycles proved on paper to be just about as practical and efficient as could be found in the field of mechanical heat engines. Also, in the case of the Rankine turbine, other companies were already into development, and the Stirling cycle was still dormant. Both of these systems are closed cycle types, a definite requirement for space missions of any extended duration. Both systems use an external heat source, and don't much care what kind of source it is.

The Rankine cycle has the advantage of being an old-timer on the scene, with its mechanics very well known; the main point of beauty about the Stirling engine is its high inherent efficiency, derived from the particular thermodynamic characteristics of the Stirling gas cycle. Unlike the Rankine cycle, which uses a two-stage working fluid, and must, therefore, change state on the way up to vaporization and on the way down, the advanced Stirling engine uses a pure gas as the working medium. Whereas the Rankine cycle using mercury works best at a radiator temperature of 500 to 600 degrees F—it would be foolish to run the liquid mercury down any further in temperature and then have to heat it all the way back up again—the Stirling cycle is not limited in its maximum and minimum temperatures by cycle considerations, al-

though it is obviously limited in the hot range by structural considerations.

In fact, an analysis of this cycle shows that the minimum weight for a Stirling space power system using a nice conservative upper limit of 1,250 to 1,300 degrees F, occurs with a radiator temperature of about 150 degrees F. In the case of the advanced Stirling system, the high engine efficiency has a very beneficial effect on the overall system weight. Actually, the Stirling engine alone is heavier than a mercury Rankine turbine that develops the same power, but a comparison of the overall system weights, optimized to deliver 3 to 5 kilowatts, shows the Stirling system to be about 40% lighter than the Rankine system. Table I gives the breakdown for this comparison. Table II shows a comparison of the weights of a Rankine and Stirling system designed to the same radiator surface area.

TABLE I.

	Rankine	Stirling
Solar collector diameter—feet.	32	19
Radiator area—square feet.	100	160
Radiator temperature—degrees F.	500	150
Maximum working temperature—degrees F.	1250	1250
Engine efficiency.	13%	38%
Weight of components in pounds.		
Solar collector	300	110
Primary heat absorber	50	20
Heat storage	125	45
Radiator	25	35
Engine/Alternator	125	235
Liquid metal	55	40 (coolant)
Structure	115	75
TOTAL	795	560

TABLE II

	Rankine	Stirling
Radiator area—square feet.	100	100
Radiator weight—pounds.	25	25
Total system weight—pounds.	795	622

Taking a look at the complete Stirling system and its various components, we find that, in general, it carries the same labels as does the Rankine system shown in Fig. XVII, with the exceptions that no liquid droplet separator is needed, the primary heat absorber is not a boiler, and of course the prime mover is a reciprocator, not a turbine. A schematic of this system is shown in Fig. XX.

Basically, the system works in a manner similar to the Rankine system, and in fact to all the other solar systems. The sun's radiation is collected by a reflecting surface and concentrated on the heat absorber. Here, liquid metal picks up the heat, and is then pumped to the engine heater, which then performs the function of heating the working gas. The liquid metal then returns to the heat absorber to start its cycle again.

As in the other systems, heat is stored in a lithium hydride reservoir during the sunlit portion of the orbit, and the excess designed into the reservoir is released to the engine during shadowed portions of the orbit. The cool end of the engine is kept that way by a liquid metal system that picks up engine heat and circulates through a radiator. The solar reflector is kept continuously oriented sunward within narrow limits by an automatic servo system. Incidentally, the reflector which has been designed as a part of this system is very interesting; we'll delve a little deeper into that further on in this discussion.

Obviously, the heart of the Stirling system is the engine itself. At this point, we can examine—somewhat cursorily, to be sure—the dynamic and mechanical considerations that form the basis of a working advanced Stirling engine design.

To repeat, the Stirling engine uses a closed cycle, a working medium consisting of gas only, and an external heat source. Very high reliability can be attained, as there are no valves, and the engine can be adapted to a mechanical arrangement in which there are no piston side loads, and all torque, gyroscopic forces, and vibrations are canceled or balanced. The absence of an ignition system insures freedom from electrical interference, and also does no harm from a reliability point of view. Once again, praise be to Good Old Sol!

Fig. XXIX shows a photograph of Allison's advanced Stirling engine, with its integral alternator, specifically designed for space power application. The work cycle of this advanced Stirling engine is shown in Fig. XXI. As shown, the cylinder is closed at the hot end, and the work piston seals it at the cool end. In the space between the work piston and the cylinder head, is a displacer piston, whose function it is to move the working gas from the hot end of the cylinder to the cool end through a passageway consisting of, from top to bottom, a heating system, a regenerator, and a cooling system. The working cycle starts with the displacer piston against the hot closed end of the cylinder, and the work piston at

the bottom of its stroke. In this position, the cylinder volume is at its greatest, and the maximum amount of gas is in the cool space, as in Fig. XXIA.

The work piston now moves up toward the closed end of the cylinder, where the displacer piston is being maintained at what might be called top dead center, as shown in Fig. XXIB. This is the "cold" compression end of the cycle. Following the compression of the working gas in the cool chamber, the cool compressed gas is displaced out of the cool chamber by the motion of the displacer piston downward toward the work piston, as shown in Fig. XXIC. As the cool gas moves through the passages toward the hot end, it passes through the heat regenerator and heater. Remember, the gas moved in this manner is a constant volume, so that this portion of the cycle is really a heat addition at constant volume.

At the end of this phase, the pressure has been raised considerably, by the addition of heat, over the pressure attained at the end of the cool compression stage. Now, this pressure increase moves both the displacer piston and the work piston downward; this is the work portion of the cycle, as shown in Fig. XXID. It can be seen that this phase results in expansion of the working gas in the hot chamber, with a consequent heat loss. The displacer piston now returns to the closed end of the cylinder, displacing the gas from the hot chamber to the cool chamber; in transit, it picks up heat from the heater and then deposits it in the regenerator matrix for use in the next cycle.

Naturally, as in all high-speed machinery—especially when the design pushes the state-of-the-art limits as in space applications—there are some tough problems to overcome. For instance, the zero-gee environment creates a lubrication problem which is over and above the already bad lubrication problem associated with operating reliably for periods of a year or more. Under investigation at the present time are two systems which are specifically designed to operate in zero-gee; these are a pressure lubricated system, and an ingenious system that uses a controlled oil mist. In these configurations, plain or roller-type bearings work.

Another area which has forced some ingenious design is that relating to seals. Problems are encountered during engine operation, especially in trying to prevent gas flow around the displacer piston, around the work piston, and along the two independent-but-mutually-sliding piston rods. Also, any oil mist must be prevented from entering the working zones. Some very fancy arrangements are being evaluated; promising designs include such items as spring-loaded Babbitt rings, piston rings made of glass-impregnated teflon, and fabrication of the pistons with a soft metal coat plated on, containing a small amount of dry lubricant.

The advanced Stirling engine efficiency is directly affected by the heat absorption and rejection properties of the working gas. Fig. XXII illustrates the engine efficiencies relative to the use of hydrogen, helium, and air. It appears that hydrogen should be the obvious choice as the working fluid, and for short term operations, say up to a month, it is. However, all gases have the nasty habit of diffusing through the walls of thin-walled containers, even the type of metals used in these space engines, and from this point of view, hydrogen takes the cake. Therefore, we can expect a continuous, fairly rapid, and quite respectable drop-off in engine power after a relatively short period of operation at high pressure, and for periods of a year, hydrogen does not look attractive. Therefore, we have to go to other gases, and accept a lower engine efficiency. Helium, while it also diffuses through metal, can still probably be used in this engine for the required durations, as its rate of diffusion is low enough so that system performance degradation is tenable.

For many of the communication satellite missions, the orbital electrical power requirements do not vary greatly with time-in-orbit. That is, power needs do not change radically from one hour to the next, but remain fairly constant. When we examine the overall aspects of such a mission, one of the recurring items that keeps hitting us is reliability. If our mission involved large variations of power, we would probably have to get pretty fancy in our engine control system design, and try to make the engine put out exactly enough power to cover the minute-by-minute requirements. This would mean adding quite a few complex electronic and mechanical components, such as sensors, timers, feedback circuits, switching elements, actuators, and the like, and would immediately result in lowering the probabilities of success.

Fortunately, many missions maintain a steady requirement, and in these cases, we can use an engine control system of minimum complexity, which will operate the engine continuously at its rated design level. This is designed to cover the peak power requirements, and during periods of reduced requirements, the excess electrical power generated is simply switched out and radiated into space as heat loss. Although this requires a slightly larger radiator, once again a trade-off study shows that this type of control system is undoubtedly the most practical and reliable from a systems point of view.

Some time back, it was mentioned that we'd look at the solar reflector being designed to go along with the Stirling system. To date, there has been a rather special reflector designed, and built in large model form, for evaluation. This reflector can be used, of course, with any other system just as well, but in this case, reflector design was undertaken by the same company that put together the generating system, and the re-

flector design was integrated from the beginning into the complete system. Therefore, it seems logical to talk about this reflector at this point.

As usual in a space power supply system that has a duration of more than a week or so, the design of this system wound up with a requirement for a heat storage sink; also as usual, further study dictated the choice of lithium hydride. Now, lithium hydride has a melting point of 950 degrees K, and when various heat losses and temperature drops through container walls are taken into account, the design temperature at the heat storage sink must be about 960 degrees K. Thus, in this and other systems using lithium hydride, reflector design has centered about the problem of designing a reflector that will concentrate solar radiation onto a heat sink at a temperature of 960 degrees K.

Some of the problems that we bump into concern requirements relating to high optical efficiency, low weight, low cost, low storage volume, ease of deployment, good capability to withstand the special environment, and reliability. Among these factors, there exists a systems relationship, and the final choice of design always winds up as a sort of optimum set of engineering compromises. After a thorough investigation of reflector theory, reflector state-of-the-art, manufacturing techniques, material technology, and so on, it was decided that the reflector for this system would be a Fresnel type, modified for specific application to the Stirling space system.

The Fresnel reflector is a very interesting configuration, coming close to parabolic reflector efficiencies while using a perfectly flat structure. In fact, many researchers contend that the Fresnel type reflector will afford a greater percentage of radiation being reflected to a desired area, than will a parabolic reflector, especially when you have to use large surfaces of exceeding lightness, due to the extreme difficulty of maintaining the required accuracies in a large parabolic surface.

Essentially, the Fresnel reflector consists of a series of concentric rings in the form of ramps or serrations, the surfaces of which are arranged to reflect into a focal area. Fig. XXIII is a sketch of a cross section of a Fresnel reflector. Each ramp ring is relatively small, and for that reason can be built quite accurately, even if the diameter is large. Because of its flat design, the Fresnel reflector can make use of some of the more exotic lightweight construction materials, for example, the cemented plastic-and-metal honeycombs. Also due to the flat plate design, folding for storage becomes a fairly simple chore—much simpler than for a metal parabolic reflector—and the whole deployment mechanism can be of rather straightforward design.

Figures XXV and XXVI show photographs of a deployable all-metal parabolic mirror, designed and built by the Ryan Aeronautical Company as a working model of a future solar reflector for space use. The

photos in Figures XXVII and XXVIII show some of the working models of Allison's Fresnel reflector development program, which is progressing along with the Stirling engine power conversion system. It looks as if this combination will be tested in space in the foreseeable future, at least in this decade.

It seems that Robert Stirling, the foolish English preacher, was right.

* * *

This paper has presented some of the engineering aspects relating only to those systems using the sun as an energy source. It should be understood that there is as much effort going on in the development of power supply systems using man-made nuclear energy sources, and a major effort is going into the very promising field of fuel cells. The reciprocating engine has not received the brush-off either.

Small thermoelectric and thermionic power generators, using the heat of decay of radioisotopes, have been designed and built as prototype feasibility models. These have been operated very successfully on the ground, and are providing the basic data for design of space vehicle systems. In fact, as stated before, an experimental generating unit of the SNAP family has recently been orbited, and its power is helping to send signals to earth. Also, both thermoelectric and thermionic systems using fast reactors for heat sources are being developed. The use of reactor heat is also being studied in relation to a liquid metal turbine-alternator system. In fact, it can be said that for every solar powered system, there is a nuclear powered counterpart—except, of course, for the solar photovoltaic cell. For the very high power requirements, ranging into the megawatt region, the nuclear fission reactor becomes the paramount energy source, outstripping even the best solar powered systems in power weight ratio by a large amount.

Oxygen and hydrogen are also being investigated as fuels for space power supplies. Included in this group are the fuel cells, which promise fantastic conversion efficiencies because they are not heat engines and do not have to go through the Carnot cycle, and some dandy, tiny reciprocating engines burning oxygen and hydrogen at high efficiencies.

Details of these space power supplies cannot be given in this paper, as they are a complete study in themselves. Suffice to say here that they are all being studied, most are being built, and many will be tested in near and deep space during this decade. ■

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« *Continued from page 82* »

Marghem found it a relief to be able to talk about something other than the robot question for a change. Maybe he oughtn't to have been so dogmatic about keeping Ira away. He sighed and repressed temptation.

"Oh, wonderfully. Courtship customs, for instance. I'm in the best possible place to observe those, because I'm being courted wholesale. But not just that. This big party tomorrow, for example—it's just like a peasant party in Central Europe, like a christening or wedding feast, crossed with a celebration in the old days in the steel communities of America. There's a tremendously strong substructure of folk tradition binding these people together, which even bringing them off Earth hasn't weakened. In fact, it's strengthened by their having left home, because it's what they most rely on to keep their communal identity."

She hesitated. "By the way, I think the answer to this problem of Joe and the other robots—"

Colville looked at the ceiling, as if to say, *What in the name of all that's holy can she know about it?* Marghem ignored him.

"Go on," he encouraged Ira. After all, he and Colville had drained themselves of ideas. Anything, no matter how wild, was better than nothing.

"Well, I mentioned that folklore contains many legends of mechanical men. One of them—"

Under the dome everything was as festive as it could possibly be on New Earth, in Eisenberg. All the families in town had turned out their store of rags and scraps, hoarded as such things had always been hoarded, and chosen the most colorful odds and ends to make into flags and streamers. Red, yellow, blue, green, they looped in festoons above the tables, some of which were groaning under the weight of the carefully prepared delicacies because they were ordinary tables people had brought from home, others of which couldn't because they were lengths of rail or even unfinished billets brought from the mills where they were awaiting shipment.

Barrels of beer and tanks of prunejack were racked around the wall of the dome behind the tables. Through amplifiers at the highest point of the dome poured music from tapes that had been made at home on Earth—a kind of last souvenir before departure. The music was wild and gypsylike. In the center of the floor the young people were dancing equally wildly, shrieking with laughter and sometimes yelling the words of the songs which came over the amplifier.

In a place of honor facing the dance floor sat Nagy, looming tremendously over his little wife, who blushed like a girl every time one of the dancers paused in passing to cry congratulations and thanks for the party. On the other side of her husband from her, Ira Bell sat—and indeed Nagy seemed as proud of hav-