Part 3—Solar Power

The conjunction of several events—the space program, looming fossil-fuel depletion, degrading environment, and chronic power shortages—is slowly turning man's eyes toward the sun as the ultimate answer to our energy problems. Unlimited power via solar energy, gathered and focused earthward by satellites, may yet prove to be the greatest tangible benefit from the space program.

SAMUEL WALTERS[1]

Can the sun be harnessed for large-scale electric power? The energy potential is unbounded. The thermal power intercepted by the earth's diametral plane is 1.7×10^{17} w, which is about a hundred thousand times larger than the world's present installed electric power capacity. It also has the virtue of remaining nearly constant over time periods of millions of years.

Why then has solar energy not been tapped for this purpose? Principally because it is intermittent and too diffuse when it reaches the earth. (Night, clouds, and dust reduce the "sun time" to a "use time" of about 20 percent of the full time.) To "collect" it, large amounts of real estate, including an elaborate storage system, would be required.[2]

Obviously, the flux of solar energy should be intercepted not behind the "dirty basement window" of the cloud-shrouded night-affected earth, but in a satellite orbit high above the earth's surface where "real estate" has no meaning. Such an audacious idea has been proposed by Peter Glaser, Mem. ASME, and head of engineering sciences at the Arthur D. Little Laboratories [1].[3] A large space platform composed of a mosaic of solar cells hovers in synchronous orbit with the earth's rotation at a height of 22,300 mi (35,600 km). Solar energy, converted to electrical power by

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[1] Staff Editor, Mechanical Engineering.

[2] A solar-electric power plant of 1000-MW capacity, with a conversion factor from solar power to electrical power of 10 percent, would require a solar power input of 10,000 MW, or 10^{10} thermal w. According to Daniels [15] the average solar power at the earth's surface amounts to about 500 cal/cm^2/day. This, when averaged over a full day, gives an average solar power input of about 2.4×10^{-2} w/cm^2. Then the area of the earth's surface required to collect 10^{10} w of solar power would be 10^{10} w/(2.4×10^{-2} w/cm^2) = 42×10^{10} cm^2, which would be 42 km^2, or a square area of 6.5 km per side.

[3] Numbers in brackets designate References at end of article.

the cells, flows through a flexible superconducting cable 2 mi in length to a satellite station where, converted to microwave energy, it is transmitted earthward unimpeded by atmosphere and clouds. It is then reconverted into d-c power by an antenna-rectifier array. The satellite is exposed to full sunlight all the time, except for a 1.2-hr interval every 24 hr for 25 days before and after equinox. By using two or even more satellites, properly spaced, the interruption of power during the 1.2-hr orbital night can be avoided. A continuous flow of power is thus assured, obviating the need for an energy storage system on earth.

An alternative plan is to place a space power station in a non-equatorial orbit with a seasonal rhythm pattern. The satellite power station is now no longer stationary with respect to the earth's surface but appears to move up and down above the southern horizon with a 24-hr period, the swing being the greatest during the equinox period.

How feasible is this scheme? Technological details have been discussed in various journals during the past few years. And recently the *Journal of Microwave Power* devoted an entire issue to the subject.[4] The consensus is that it is feasible, although in sheer engineering magnitude, such a system surpasses anything that has been realistically planned in the past.

Success would bring enormous rewards. An earth-girdling belt of solar cells 3 mi wide in synchronous orbit "would intercept 1.68×10^{15} watts of solar energy. *At the present level of technology,* eight percent of this power, or 1.34×10^{14} watts, could be provided in the form of d-c power to widely distributed locations over the surface of the earth. Such a power level would provide 1.17×10^{15} kw-hr of electrical energy per year, or over 200 times the...requirements for the year 1980" [1] (italics added). In addition, the directed beams could be used to hasten the evaporation of the seas or lakes, to control rainfall in selected locations, to increase hydropower potentials, to heat frozen areas, and for other beneficial uses [2].

Many of the working elements of such a system are close at hand. The first part of the project—development of the components for power generation, conversion, and transmission, would be similar to projects accomplished in the space program during past years. The other phases of the project, such as manufacturing the cells and other components in great numbers, transportation into orbit, control of attitude, orbital altitude, and temperature, operation of electric systems, and remote control of the station, would not be new in kind, but they would be of a scale and magnitude entirely without precedent. (This includes the use of humans to deploy and maintain the solar energy collector and microwave antenna.) For example, one NASA official [3] estimates that, based on present technology, a solar plant providing one-tenth of the present United States power needs would have a total mass exceeding 2[illegible]0 tons. In the not-too-distant future, improvements in efficiencies and lightweight designs could bring about "a reduction of this total mass to 50,000 or 20,000 tons, possibly even lower." These latter figures are within sight of the capabilities of earth-to-orbit shuttle systems now on the drawing boards.

System Outline

Basic elements of a solar power plant would consist of:

- Orbit characteristics to insure that the space platform is constantly exposed to solar radiation and that the radiating area can beam energy to any desired point.
- Solar energy conversion devices of high efficiency (80 percent or better).
- Transmitters capable of beaming the converted energy to an earth receiving station in a spectral region where minimum atmospheric absorption and scattering would be encountered.
- Earth receiving stations capable of accepting the required power density and transmitting the energy to power-distribution networks.

Orbit Location

The system consists of two satellites in synchronous orbit (22,300 mi altitude in an orbit parallel to the earth's equatorial plane). The satellites are about 21 deg out of phase and about 7900 mi apart to insure that one satellite is always illuminated during the time the other is in the earth's shadow, an event that occurs at least 1 hr each day for 25 days preceding and following the equinoxes. At this height and phase difference both satellites have a direct line of sight to the same point on earth.

Conversion Devices

Silicon solar cells have been the primary source of power for the Ranger, Mariner, and Surveyor spacecraft and almost all other unmanned space missions. As a commercial power-conversion device, however, the cell's usefulness is circumscribed by low efficiency and high costs, 10 percent and \$4, respectively, for a cell $1 \times 1\frac{1}{2}$ in. Large-scale use demands a price better than 4 cents and an efficiency raised to 80 percent or better. But here again, one can assume accelerated progress based on the needs of large spacecraft now being designed for missions in earth orbit and for exploration of the moon and planets.

Solar-cell arrays already have grown, in the space of a few years, from a few square feet to several thousand square feet in large lightweight deployable arrays with power levels in the tens of kilowatts. And underway are new approaches to increase cell efficiency and reduce cell cost: optical concentrators to focus solar radiation on an individual solar cell in order to reduce the number of cells required, multicellular devices, and new manufacturing processes such as the manufacture of solar cells from webbed dendrite silicon [4] or from extrusion of a ribbon of silicon single crystals.

But most promising of all is the discovery of organic-type compounds with semiconductor properties. This could open the way to a major advance in photovoltaic efficiency.

According to Glaser and others [1, 5, 6] the maximum theoretical efficiency of 24 percent inherent in the inorganic single-crystal semiconductor may not pertain to organic-type materials where charge creation and motion depend upon the long-range intramolecular charge transfer in heavy molecules found in biological systems (nerves, for example). Says Glaser: "The semiconducting properties of such molecular systems may be very different in character from those of in-

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[4] Dec. 1970 issue.

organic semiconductors, and hence may have no efficiency limitation."

The "difference in character" is based on the fact that charge creation and motion in the inorganic single-crystal semiconductor are related to the primary act of light absorption, whereas in high-molecular-weight organic systems there is a distinction between charge formation in a molecule and diffusion through the bulk medium. This means the charge may be transferred within the molecule before motion in an adjacent molecule or vacancy site occurs. Advantage can thus be taken of both the low-energy gap of such materials and a possible low rate of thermal backward diffusion of charge. Theoretically therefore, organic systems promise higher efficiency than inorganic semiconductors; they would weigh less and could be produced in large quantities at a much lower unit cost.

Attainment of a conversion efficiency of 80 percent will radically alter the prospects for commercial solar power. A space platform with 8.7 sq mi of collector area (3.3 mi in diameter) would be all that would be required to meet the power needs of the entire northeastern section of the United States [1]. The weight of the collector would then be reduced to about 160 tons, exclusive of supporting structures. This is well within the cost capability of a space program employing reusable shuttles to assemble space structures. Such an earth-to-orbit shuttle with a payload of 20 tons is now on the drawing boards [3].

Power Generation and Transmission

The illustration below shows the main elements of a system designed to beam 10,000 MW earthward, enough power to supply the city of New York and its environs. Because of the inefficiency of present-day solar cells, the solar collector spreads over a 25-sq-mi area. Solar energy is here gathered, converted to d-c electric power, and transmitted to the microwave generators along a transmission line 2 mi long. The line is superconducting to reduce weight and power losses. Along its entire length, multiple-stage refrigerators maintain the proper temperature. The line is also articulated to provide relative movement between the solar collector, which must maintain its orientation toward the sun, and the microwave generators, whose radiating antennas are beamed to a receiving antenna on earth.

The microwave power transmission system consists of three major parts:

- Microwave generation, that is, the conversion of the d-c power output from the solar cells into microwave power.
- Beam forming, that is, the forming of the microwave energy into a sharp beam by means of the transmitting antenna.
- Microwave collecting and reconversion, that is, a means of collecting the energy at the receiving point and then reconverting it back into ordinary electric energy.

At first glance, the very high power levels involved—10,000 MW of microwave power—appear incongruous. Microwave technology is usually identified with the low power levels common in the communications industry. However, efficient high-power tubes have been developed. The assumed 10^7 kw of microwave power can be generated in a phased array of 10,000 amplitrons, each with an output power of 1000 kw [7, 8]. Such an array would reduce the rating of the individual tubes to the point where their design would be consistent with a modest extension of existing tube technology.

Earth Receiving Station

The capture and conversion of the 10,000 MW of microwave power beamed earthward from space is by "rectenna" (contraction for rectifying antenna), a device that combines the functions of a receiving antenna and rectifier. It is a large dipole receiving field several square miles in area made up of highly efficient solid-state rectifiers dispersed throughout the array and terminating in small apertures. The array, as a consequence, is relatively non-directive, which eliminates pointing problems and minimizes mechanical tolerances [7, 9]. The converted d-c power is then fed into a distribution network through superconducting transmission lines. Such networks have already received considerable attention, and research is being performed on this method for electric power transmission in this country and abroad.

Although the power densities in the microwave beam (roughly 1 w/sq cm, an order of magnitude greater than the solar radiation received on earth) may damage objects or living tissues that might enter the beam, they are not high enough to cause major destructive effects. Safety devices would have to be devised and regulations established to prevent entry of objects or living beings into the beam. The problem of safety

Courtesy of Arthur D. Little Inc.

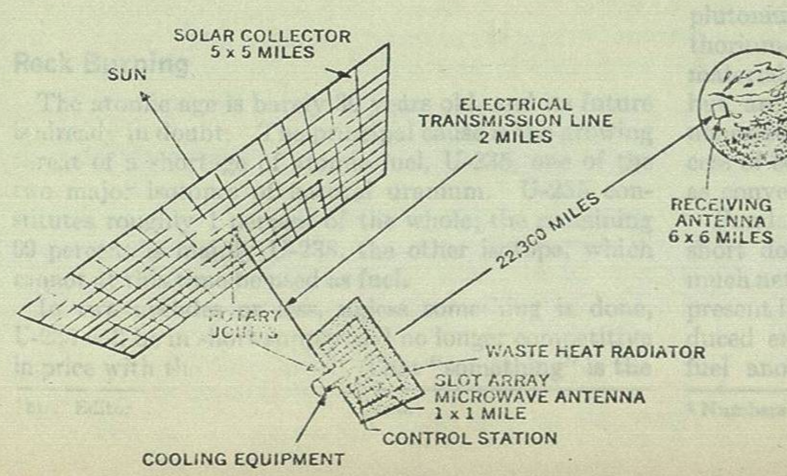
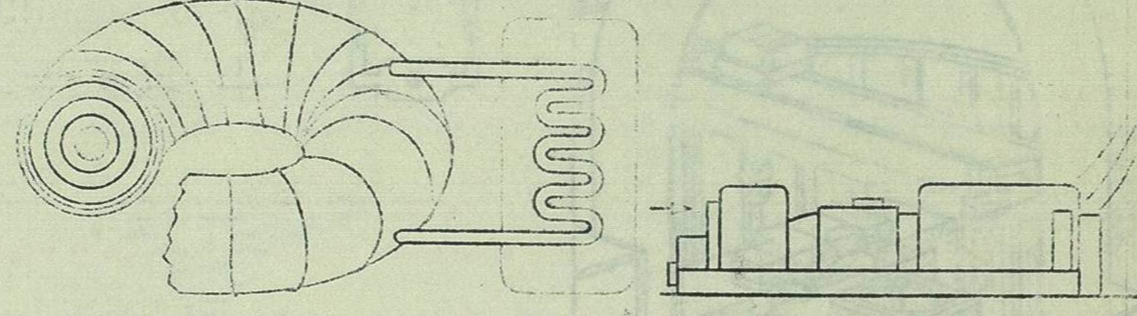


Diagram of the main elements of a satellite solar power station designed to produce 10,000 MW, enough power to supply the city of New York and its environs.

POWER IN THE YEAR 2001



Part 4—Rock Burning and Sea Burning

Dispersed in the rocks of the earth are enormous quantities of "fertile" low-grade uranium and thorium ores. These will be converted to fissionable fuel in an experimental breeder reactor, a power plant that produces more nuclear fuel than it consumes. Success would assure a supply of low-cost energy for thousands of years. Our finite reserves of coal, oil, and gas would then be used as sources of organic molecules rather than as sources of heat. As for "sea burning," the process of extracting energy through fusion of the heavy isotopes of hydrogen, this is still a physicist's dream, but the lineaments of a practical device can be discerned in the emphasis on its scientific feasibility and some rudimentary thought on the technological, economic, and social aspects of commercial fusion power.

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Rock Burning

The atomic age is barely 30 years old, and its future is already in doubt. The principal cause is the growing threat of a shortage of atomic fuel, U-235, one of the two major isotopes of natural uranium. U-235 constitutes roughly 1 percent of the whole; the remaining 99 percent is mainly U-238, the other isotope, which cannot at this time be used as fuel.

In two decades or less, unless something is done, U-235 will be in short supply and no longer competitive in price with th[illegible]. That "something" is the breeding reactor, so called because it produces more nuclear fuel than it consumes. The now-wasted U-238, along with low-grade thorium ores, would be converted through neutron bombardment into fissionable fuel from the dwindling supply of U-235.

At the present time, U-235 in the form of a 5-lb fuel rod is already worth about a third of its weight in solid gold. The refining process—separating U-235 from U-238—is an expensive operation because both have the same chemical characteristics. Huge $800-million separation plants do the job. The end product is a slightly enriched uranium containing about 3 percent U-235. The utilities pay the price because the potential of a single fuel rod is the heat equivalent of 6000 tons of coal [1].[2]

Breeding Reaction

The breeding reaction goes as follows: Uranium-238 (or thorium-232) is subjected to neutron bombardment in a reactor whose initial supply of fuel is uranium-235. Uranium-238 absorbs a neutron and is converted to U-239. The latter, by two short-lived radioactive transformations, changes spontaneously, first to neptunium-239, and then to plutonium-239. Likewise, thorium-232 absorbs a neutron and is transformed into thorium-233. This, in turn, changes radioactively into protoactinium-233 and then into uranium-233 [2].

Because they are fissionable, U-233, U-235, and plutonium-239 are called fissile isotopes. U-238 and thorium-232, on the other hand, are known as fertile materials because they are not themselves fissionable, but are capable of being converted into previously nonexistent isotopes which are fissionable. The process of converting fertile into fissile materials is known as conversion.

Fundamental to a successful breeding program is a short doubling time (the time required to produce as much net additional fissionable material as was originally present in the reactor). The reactor thus w[illegible] duced enough fissionable material to r[illegible] fuel another identical reactor. An efficient b[illegible]

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[1] [illegible] Editor, [illegible]ING.

[2] Numbers in brackets designate References at end of article.