

CAPTURING THE SUN:
THE NUTS AND BOLTS OF SOLAR CELLS FOR SATELLITE POWER

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As with the earth itself, virtually every satellite in our solar system occupied or constructed by human beings derives its power from the sun. Man-made satellites employ very large numbers of solar cells in order to convert sunlight directly into electricity.

These cells are the subject of the present brief article. Its purpose is not to engage in a scientific discussion about solar cell technology for space applications, but rather to describe some of the features of these elegant devices and their organization into enormous arrays which are designed to harvest sunlight in the most efficient and useful way. Also, some related issues of concern to the author, and perhaps to the reader, are raised.

The first figure sets the stage.¹ It portrays a space vehicle which has enough solar cells laid out in the large panels shown as dark planar surfaces to generate about 1,000 watts of power—roughly the same as a portable electric space heater. The scale of this picture attests to the huge number of cells necessary to capture even a modest amount of solar power.

At the heart of the space power package is the single solar cell. An individual cell is a thin, flat square- or disc-shaped object about the size of a credit card or a razor blade. Cells presently in space use invariably are made of silicon, the same element which constitutes the basic stuff of transistors and integrated circuits. It is not necessary to have a detailed engineering understanding of the way a silicon solar cell works in order to appreciate some of the problems associated with its use. Briefly, the cell acts as follows.

The bulk of the cell consists of exceedingly pure silicon to which a trace of chemical impurity has been added with great precision in order to modify the electrical properties. Behind this silicon plate is a solid metal layer, the back electrode of the cell, to which an electrical lead is attached. On top of the silicon bulk is an exceedingly thin layer of the same material, to which a different chemical impurity has been deliberately added. These two regions of silicon compose what is called a p-n junction. It is as if the two silicon layers, one thick and one thin, are bread slices and the interface between them is the meat of the sandwich. Atop the thin, "front" layer of silicon is an array of tiny wires which are deposited on the surface and connected to an electrical lead which constitutes the other electrode. When sunlight shines directly through the thin silicon layer into the bulk, it releases electrons within the silicon. Some of these are able, in a sense, to escape, producing an electrical current through the wire electrodes.

This essentially simple device is in fact an ensemble of design tradeoffs. The thickness of the base silicon layer and that of the thin front layer must be decided. The size of the cell itself has to be determined. Its weight is important, as every one of perhaps 10,000 cells has to be lifted with the space vehicle, and an extraordinary premium is paid for excess weight. Precise control of the chemical impurities that define

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¹Figure 1. Solar electric power panels generating about 1,000 watts for HEAO-A Observatory. All figures appear on the pages following the text of this article.

the two regions of silicon—the bread slices in the sandwich—is important. The arrangement of the front surface wires also matters. If there are too many, they will block sunlight from penetrating the silicon; if there are too few, they will not capture enough electrons from the front surface to be made available to the external circuit which is powered by the cell.

All of these chemical, mechanical, and electrical factors have been tested for years by a great many scientists and engineers in an effort to maximize the electrical power, the efficiency, the reliability, and the durability of silicon cells while minimizing their weight and size.

How much energy does a typical solar cell provide? Think for a minute of, not a solar cell, but a car battery. When little or no current is being drawn from the battery, it provides a fixed voltage of approximately 12 volts. This voltage, called the open-circuit voltage, is sustained as more and more current is withdrawn from the battery, until rather suddenly the voltage drops to zero at very high current, the so-called short-circuit current. A battery which provides a high voltage and a high current provides high power. As a matter of fact, power is merely the product of the two. Typically this product is perhaps a few hundred watts.

With a solar cell, the open-circuit voltage is about six-tenths of a volt instead of twelve volts. The short-circuit current available is directly proportional to the amount of sunlight incident on the cell (remember, it is sunlight that released the electrons), and at the level of light incident on the earth at midday is about 0.15 amperes. This product gives a maximum available power of a little under 0.1 watts in earth orbit and in direct sunlight. The efficiency, that is, the ratio of electrical energy produced by the solar cell to sunlight incident on it, is typically 15% or perhaps a little higher for the best silicon solar cells now manufactured.

Actual cells deliver electrical power somewhat below the product of the open-circuit voltage with the short-circuit current. The reasons for this reduced efficiency are complex and have been the topic of research for more than a decade. While it would be inappropriate to delve too deeply into this rather specialized subject, it is worthwhile to point out that some of the causes of reduced efficiency do not manifest themselves in routine testing of solar cells at the manufacturing plant or in the laboratory; rather they appear only under environmental conditions of the kind encountered in space. The chief problem is temperature. Cells which test virtually identically at the manufacturing facility vary enormously in their electrical conversion efficiency under the low temperatures that can be encountered in distant space. This unfortunate situation creates a real problem of cell selection. It is completely impractical to test every cell manufactured under the conditions that would be encountered in deep space orbit. Yet one cannot afford to have very many defective cells, once they are in place and hundreds of thousands of miles away from the earth. Research has gone into the understanding of efficiency-limiting flaws and the means to remove them from the manufacturing process.

A major concern is with the lifetime of solar cells. They are exposed to environmental radiation when in space, primarily from energetic electrons. Virtually nothing is known about the long-term effects of this irradiation on the performance of the cells. Laboratory simulations are difficult, because they need to be carried out over periods of five or more years in order to produce a realistic simulation.

Typical solar cells are perhaps eight-to ten-thousandths of an inch thick (not counting a protective cover layer) and about two-thirds of a square inch in area.

The chief problem associated with the manufacture of premium solar cells is simple breakage. As a matter of fact, breakage is the biggest single cost component of cell production. Typically, solar power installed in an array might cost from perhaps \$500 to \$1,000 per watt of available power in normal sunlight.

One cell does not make a power supply. To provide the kilowatt of power quoted earlier, for example, would take more than 10,000 cells. The mounting and arrangement of cells in arrays is in itself a challenging engineering problem. As always seems to be the case, a combination of, say, 10,000 cells does not produce 10,000 times the power of each cell; there are losses associated with electrical interconnections. In fact, if the tradeoffs involved in the design of a single cell are an ensemble, an array is an entire orchestra of tradeoffs.

Suppose, for example, one wished to design a 10,000-watt power pack for a large space vehicle. Would it be better to use 100,000 small solar cells or 25,000 larger cells? Larger cells would have fewer interconnecting wires, but the loss of a single one through a manufacturing flaw or breakage would be a more serious problem. Another question involves the heat. At 10,000 watts of electrical power, there are another 60,000 watts of heat that must be dissipated. About the only way to do so is by radiation, since the solar cell array is floating in near perfect vacuum; and radiation is not a particularly efficient means of heat transfer. Further, how can one handle the enormous fluctuations in electrical power as the cells go from sunlight to darkness and back? How, in the supporting structure, does one balance strength, on one hand, against undesirable weight, on the other? How should the cells be deployed? Some exotic means have been developed for the deployment of solar cell arrays after the satellite has been placed in orbit.

Accompanying this article are renditions of different arrangements for solar cell arrays. Some of these have been flown² and others are still experimental. They have in common the fact that they present a large unshadowed area facing the sun, and they are flat. Otherwise they are quite different in appearance. The photographs also show a closeup display of three representative cells viewed from the front, that is, from the surface facing the sun.³ The geometrical gridwork is the arrangement of metal wires used to collect the current emanating from the front surface of the cell. The rear surface cannot be seen.

The most modern array is the one shown in the picture which contains the space shuttle.⁴ This array has not actually flown as yet and will be tested within the next year or so. As depicted, it is designed to provide 12,500 watts. It, or something like it, could become a standard design. It is a rather novel arrangement. Though shown as a long, rectangular array, it actually unfolds like an accordion and can be stored relatively compactly. Expanded to full length, the array is 120 feet long by about 13 feet wide.

²Figure 2. Solar panels for Skylab generating about 25,000 watts.

³Figure 3. Closeups of three representative solar cells viewed from the front. Fine pattern is the metal gridwork which comprises the front electrode. They are 2.3 x 2.3 inches in size and represent state-of-the-art in the mid 1970s.

⁴Figure 4. Solar array proposed for testing space shuttle in 1984. About 12,500 watts.

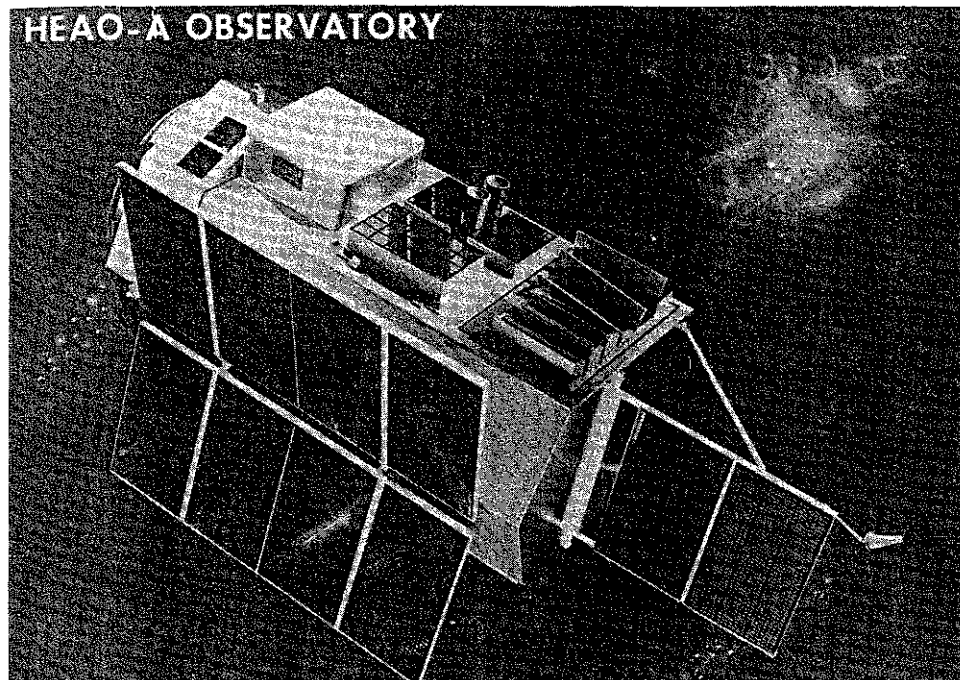
The backing material on which the solar cells are mounted is plastic, and the wires and other paraphernalia, of course, are all flexible. One interesting problem is that such a flimsy device could begin to vibrate or undulate in space. Another problem is to design a way in which it can be folded and unfolded without producing kinks or breaking wires.

Let us now turn to some of the issues associated with electrical power systems for space vehicles. The first has to do with our national posture. It became clear as early as perhaps 1981 that the United States was getting out of the solar cell research and development business. For example, at the major specialists conference which took place that year, one of the chief topics of conversation was the job market for solar engineers and scientists whose employment status was uncertain. Perhaps one-third of the 937 registrants of the conference were seeking employment. Shortly after the conference, one of the leading federal solar electrical research laboratories suffered a budget cut that allegedly was 67%.

But if the United States is getting out of this technology, the rest of the world is getting in. Some 26% of the registrants at the same conference and 19% of the papers delivered were from Europe, Japan, or other nations outside the United States. Interestingly, there were no Russians. Not too many years ago the number of foreign registrants would have been zero since the solar cell is strictly an American invention.

Of course, the status of military research and development on solar electric power systems is not accessible to the civilian scientist. But an important point should be made in this connection. Imagine satellites in some future time that can see submarines underwater or can neutralize or incapacitate guided missiles in flight. Whichever side (if indeed there are sides) deploys such satellites first has essentially conquered the world. And there are satellites designed to incapacitate other satellites. One of the most vulnerable components of a satellite is its electrical power system. Thus, it would not be prudent to disregard the technical and scientific problems associated with manufacturing efficient, robust, hardened power systems for space vehicles. In fact, it is foolish for this nation to cut back on any technology related to space. Further, the civilian benefits of such research and development can outweigh the military advantages in the long run. This certainly will be true for space technology, which is our key to the future.

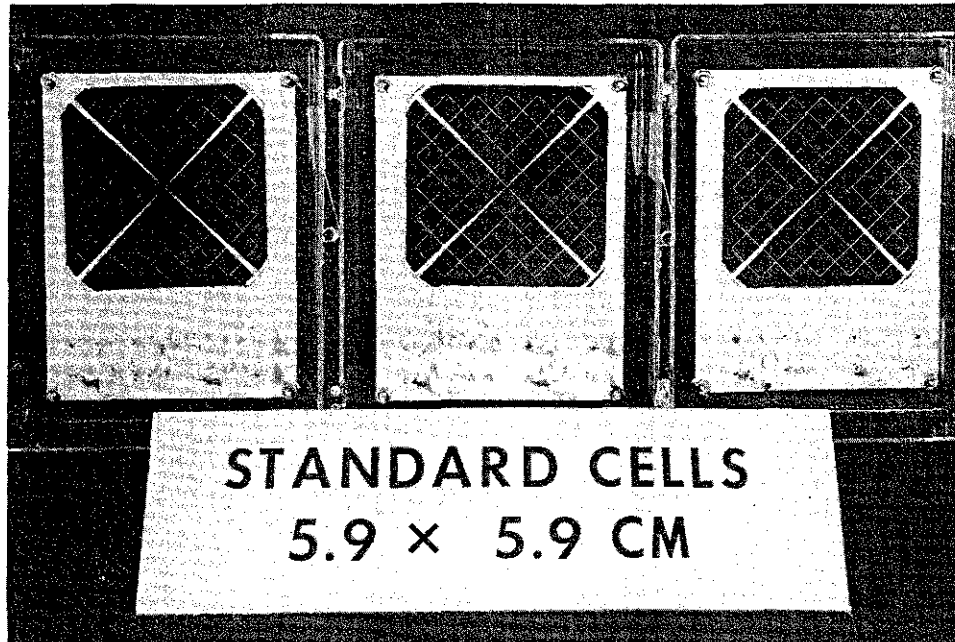
In closing, I would like to cite a quotation by Horace Walpole in the 18th century, who said, "The best sun we have is Newcastle coal." If that were still true, man would have never left the earth.



1. Figure 1. Solar electric power panels generating about 1,000 watts for HEAO-A Observatory.

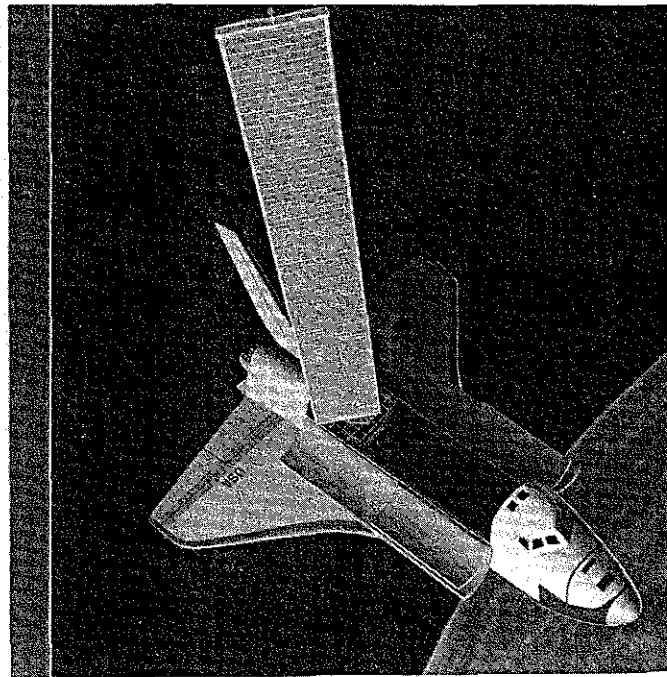


2. Figure 2. Solar panels for Skylab generating about 25,000 watts.



3. Figure 3. Closeups of three representative solar cells viewed from the front. Fine pattern is the metal gridwork which comprises the front electrode. They are 2.3 x 2.3 inches in size and represent state-of-the-art in the mid 1970s.

SEPS
SOLAR ARRAY
SHUTTLE
FLIGHT
EXPERIMENT



4. Figure 4. Solar array proposed for testing space shuttle in 1984. About 12,500 watts.