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SOLAR ARRAY COST REDUCTION

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INTRODUCTION

Solar cell power systems have provided yeoman service to the space program from its inception. They have reliably supplied electric power to nearly every unmanned spacecraft. They have also been expensive. Now there is a growing emphasis on exploiting our space capabilities to provide tangible benefits to society, for example by means of communication, weather, and earth resources satellites. The less expensive these satellite systems are, the greater the net benefits are. Therefore there is great interest in reducing the cost of solar arrays, which will continue to be the prime power source for unmanned spacecraft for a time to come. This paper will briefly describe the cost of solar power systems over the last decade and means by which cost reductions may be achieved in the future.

HISTORICAL COSTS

Last year NASA-OART performed an in-house study to investigate solar power system costs. The study group looked at the solar power systems for thirteen missions that represented a broad cross-section of flight projects over the past 10 years. These covered a range in average output from less than 100 watts to 4 KW. They included body-mounted and oriented arrays, a variety of orbits and trajectories, and a variety of sponsors and contractors. Some assumptions had to be made to put the costs for all the projects on a common basis. The costs were broken down into non-recurring and recurring costs for the solar array, battery, and power conditioning. The results represented total, fully-burdened costs in terms of 1971 dollars. Therefore a correction for inflation was made and in some instances assumptions were made on overhead rates. To calculate an index of total system cost the following formula was used: non-recurring cost plus recurring cost for two flight systems.

Correlations of cost with power were poor, largely because both oriented panels and body mounted arrays were included. The costs correlated reasonably well with array area, however. Not surprisingly, there was scatter in the data, presumably, due to differences in mission and schedule requirements, management philosophy, and troubles encountered in the course of the project. Nevertheless, enough of a pattern emerged to be able to make some general conclusions.

The total system cost index for the power system is shown in figure 1 as a function of solar array area. (Not shown are two projects for which non-recurring costs were low because the projects were similar to earlier projects.) This log-log plot shows a fair correlation between system costs and array area. The total costs rise more slowly than the area: about in proportion to the square root of the area. An order of magnitude increase in area results in only a factor of 3 increase in cost, or a reduction of 3 in the cost per unit area. The increase in cost with size is slow partly because the non-recurring costs increase very slowly. But the recurring costs do not rise in proportion to size either. In these projects the solar array accounted for the predominant part of the recurring costs, on the average about 2/3 of the total recurring cost.

Figure 2 shows the recurring cost per square foot for the solar array versus the total area of flight arrays built for each project. It is clear that the costs decrease as production volume increases. The cost drops from $10,000/sq. ft. if only 100 sq. ft. are built to about $3000/sq. ft. if 3000 sq. ft. are built. This reduction reflects the gains in productivity as a team gains experience with repetitive operations.

This effect can be exploited more than has been done in the past by making common building blocks from which a variety of arrays can be assembled. As it is now, not even the solar cell is a common building block. Solar cell specifications are unique for nearly every project.

If arrays are to be built from common building blocks, whether individual solar cells or modules of cells, agreement must be reached between users and suppliers as to what the building blocks will be, i.e., standardization. The more standardization that is established, the more the direct cost savings and probably the higher the quality of the product. On the other hand, standardization reduces flexibility to fit mission requirements. Can standard solar cells or modules accommodate a wide enough range of requirements to be worthwhile?

How large are the cost benefits for various degrees of standardization? Questions such as these have yet to be explored. Determination of the practical and desirable level of standardization will require a consolidated effort of the entire solar array community.

NEW TECHNOLOGY

Improvements in solar cell and array technology show promise of reducing costs also. Individual cover glasses are now used to protect solar cells from radiation in space. The cost of the covers and the labor to cement them to the cells is about three-quarters of the cost of the bare cells. FEP (fluorinated ethylene propylene) plastic is now being investigated as an inexpensive substitute for the glass covers. FEP is clear plastic available in sheets that can be bonded to the solar cells with moderate heat and pressure. The method is especially well suited to flexible arrays. Figure 3 shows a small module made with an FEP cover sheet and a Kapton substrate. Another sheet of FEP cements the cells to the Kapton. Bare cells are electrically interconnected, then assembled into a sandwich with the FEP and Kapton sheets. A single laminating process using heat and pressure yields the finished module. The material and labor costs associated with the covers would be negligible in this process, with savings on the order of $500/sq. ft. Preliminary tests under electron, proton, and ultraviolet radiation and thermal cycling have all given favorable results. Development is continuing, with the emphasis on a more comprehensive set of evaluation tests and extension of the technique to larger modules, on the order of 2 sq. ft.

Recently, interest has been renewed in wraparound cells. Figure 4 shows a conventional cell and the front and back of wraparound cells. Wraparound cells, with both of their electrical contacts on the back of the cell, will make electrical interconnection of the cells much easier. Since the interconnector can be flat, it will probably be less prone to failure, as well. Furthermore wraparound cells are far more amenable to highly mechanized or printed circuit techniques of interconnection. Recently the American cell manufacturers have produced wraparound cells with efficiencies comparable to conventional cells, in some cases above 11 percent.

There are some research efforts underway that may eventually yield cost reductions. A long range program has been started to improve substantially the efficiency of silicon cells. Calculations based on ideal diode characteristics and small allowances for series resistance and reflectance losses indicate efficiencies approaching 20 percent are theoretically possible. Figure 5 shows the calculated maximum efficiency as a function of the resistivity of the base region. The theoretical efficiency goes from 14 percent for 10 Ω-cm material to 18 percent for 0.01 Ω-cm material. Average efficiency for present 10 Ω-cm cells is about 10.5 percent, with some cells reported up to 12 percent. Past attempts to get high efficiency with low resistivity material were unsuccessful. Possible reasons for the poor results are impurities or defects in the material, poor junctions, or surface leakages. The approach in the present program is first to identify what loss mechanisms are responsible and how they arise and then to eliminate them if possible.

Some small efforts are underway or are planned to explore ways that might make possible fabrication of very cheap solar cells by continuous processes. These include growth of continuous thick films or ribbons of single crystal silicon, deposition of polycrystalline silicon on flexible substrates, and formation of tiny single crystal spheres of silicon that can be assembled into solar cells. These are all high-risk explorations, but they illustrate the ultimate intent to make very inexpensive solar cells.

One major hindrance to cost reduction is that the volume of production required to satisfy the space program is not enough to justify a high degree of mechanization or automation. The emergence of a terrestrial application that would increase the market many-fold would have a profound effect on costs. Unfortunately, no large scale terrestrial applications appear economically practical until the array costs are substantially reduced. One of the goals of the cost reduction programs is to reach the point where terrestrial applications will proliferate. There would then be reverse spinoff - terrestrial applications directly benefitting the space applications.

CONCLUDING REMARKS

Solar power systems have indeed been expensive, the arrays alone costing several thousand dollars per square foot. Some degree of standardization is called for and will certainly lead to lower costs. New technology is evolving that will also reduce costs in the near future. The renewed interest in exploratory research indicates recognition of the long-term importance of solar cells both in space and on the ground. We may yet see the day when solar cells make a direct contribution to our daily living.

FIGURE CAPTIONS

Fig. 1 - Solar Power Systems Cost Index versus Solar Array Area

Fig. 2 - Recurring cost per square foot for solar array versus total area of flight arrays built.

Fig. 3 - FEP-covered solar cell module.

Fig. 4 - Wraparound solar cells and conventional front-contact cell.

Fig. 5 - Theoretical efficiency of silicon solar cells as a function of base resistivity.

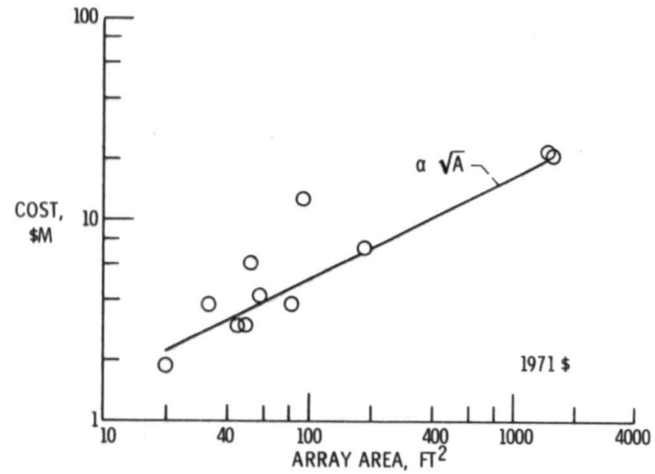

Figure 1. - Solar power system cost index versus solar array area.

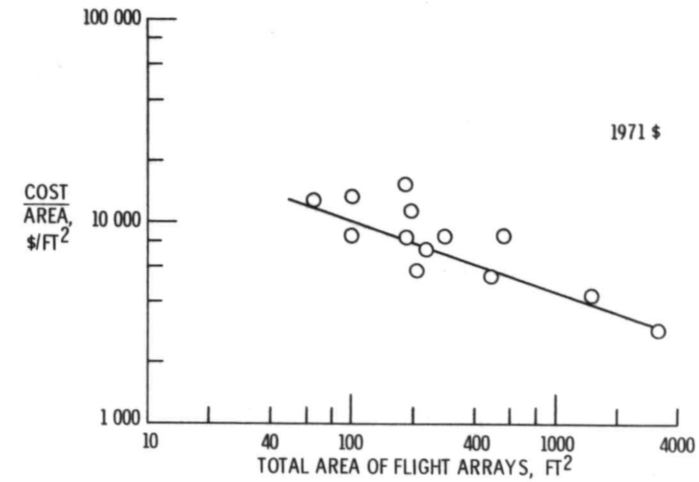

Figure 2. - Recurring cost per square foot for solar array versus total area of flight arrays built.

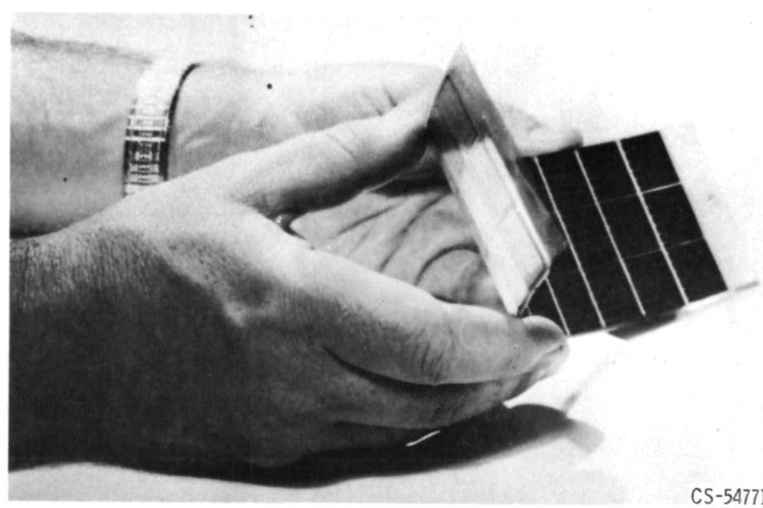

Figure 3. - FEP-covered solar cell module.

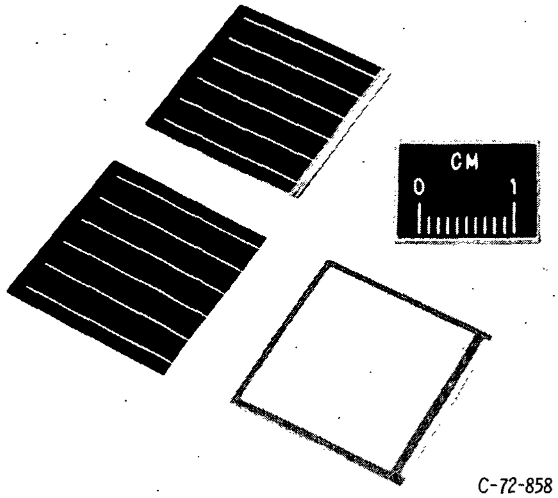

Figure 4. - Wraparound solar cells and conventional front-contact cell.

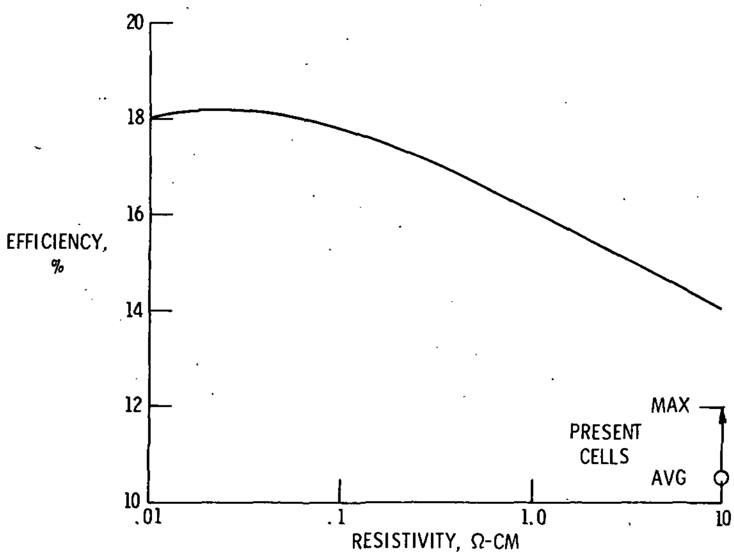

Figure 5. - Theoretical efficiency of silicon solar cells as a function of base resistivity.

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