

SOLAR ARRAY SYSTEMS

William L. Crabtree
NASA Marshall Space Flight Center

SUMMARY

This paper discusses the recent past, present state-of-the-art, and future needs in the area of large photovoltaic solar arrays. In the past most attention was focused upon performance whereas in the future most of the effort should go into cost reduction. Suggestions are made regarding possible approaches to reducing cost such as on-orbit maintenance, extended lifetime, solar concentrators, and high-voltage modular concepts.

INTRODUCTION

Since the beginning of the Space age, solar photovoltaics have been the dominant source of space power. Their operation is well understood, they are not size limited and they allow considerable flexibility in design. With increased electrical load, additional arrays can normally be added. This is a definite advantage over nuclear or solar dynamic options. Weight, cost and size have always been important for solar array designers. However, in the past, because of the relatively small electrical load requirements, array sizes have ranged in the neighborhood of a few hundred watts to a few tens of kilowatts.

In general, the space budget in the 60's was of such magnitude that array cost was not an overriding consideration, and the fact that arrays were not generally large meant that weight and size were not terribly constraining. As the trend toward missions with larger electrical load requirements continues, arrays must be larger and the situation is changing. As larger arrays are required, they represent a larger part of the cost and weight of the mission; therefore, techniques are required to decrease weight and cost. One of the first significant advances in this area was made by the Air Force with the design and fabrication of FRUSA (Flexible Rolled Up Solar Array), a window-shade type array which represented a significant savings in weight of solar arrays and which could be modularized to form large arrays. FRUSA was followed by HASPS (Hardened Solar Power System) Solar Array, which although developed by the Air Force primarily to be hardened against radiation for military purposes, also represents an advance over FRUSA technology.

Array technology advancement in NASA in recent years has centered around the 66-W/kg SEPS array and 200-W/kg high performance array. These two array developments were specifically directed at multi-kW applications. Therefore, cost, weight and size are important features which have received considerable attention. The most visible contribution has probably been in

weight reduction. Future solar arrays will be larger than ever to meet missions such as large power stations, expanded public service platforms, space construction base, space processing, etc. The power requirements of these types of missions range up to several hundreds of kilowatts, making the array an even more significant part of the total spacecraft than ever before. In many cases it will be the largest part; therefore, the economic viability of a mission will depend to a large part upon the cost of the solar array. This means that ways must be found to build larger arrays for lower cost/benefit ratios. It also means that such approaches as on-orbit maintainability must be identified to allow reduction in life-cycle costs so that the technology investment may have a very high payback in terms of overall benefit. With this reasoning as the basis for the need for an advancement in the state-of-the-art of Solar Arrays, the new-initiative program alluded to in this paper was begun.

SOLAR ARRAY STATE-OF-THE-ART

Development of large solar arrays over the past decade has taken place within both the Air Force and NASA. As we investigate the current state-of-the-art of solar array technology available from these developments, we find it to be conspicuously all planar. The high state of development of 1-Sun silicon solar cells is at least one reason for this situation. However, in retrospect it appears that more development effort should have been invested in concentrators of some sort in view of their intuitively obvious advantages in deep space application. However, with the new high-flux cells being developed and increased concern for specific economic performance over specific weight performance, the concentrators will undoubtedly be given more attention in the future.

As we examine current state-of-the-art arrays, we turn first to the FRUSA (Flexible Rolled Up Solar Array) as a revolutionary departure from the prior approach to solar arrays. It was unique at the time of design in both the deployment and retraction subsystem and in its lightweight substrate design. The FRUSA Array shown in Figure 1 consists of two flexible panels 1.68m wide and 4.88m long which roll up on a common 20cm diameter storage drum. It also has a two-axis sun acquisition and tracking orientation mechanism. Deployment is accomplished by extendable metallic booms driven out by electric drive motors. These booms collapse to roll up but spring out and become rigid when deployed. The basic array is rated at 1.5 kW, with growth to 3 kW accomplished easily by adding another flexible array to one arm of the orientation mechanism. The array specific power rating is 22 W/kg without the orientation mechanism. The array utilizes 2 x 2 cm N/P silicon cells 8 mils thick. They are covered with 6-mil microsheet coverslides and are connected 81 cells in series by 222 in parallel on each panel, using a bus system which is fabricated from a copper/kapton laminate. The cells are attached to the interconnects by solder. The substrate consists of a 0.001-inch kapton H-film bonded to 0.001-inch fiberglass. The array was flown in 1971 in a 430-N.M. polar orbit and successfully completed a 6-month flight test validating the concepts and techniques used.

The HASPS (Hardened Solar Power System) Solar Array is a technology extension of the FRUSA with radiation hardening being the prime motive. A slight weight penalty is paid by HASPS over FRUSA by the required modifications for radiation hardening. This array uses 2 x 2 cm cells 8 mils thick of both conventional N/P and lithium-doped variety. The cells have aluminum contacts and 6-mil fused silica covers without the magnesium fluoride coating. Conductors and interconnects are also aluminum, and cell contact to interconnect bonding is accomplished by ultrasonic welding. Each of the HASPS solar panels measures 4.42m x 2.29m when fully deployed, and the first flight of this type array will be in the early 1980's on a SIRE (Space Infrared Radiation Experiment) spacecraft (see Figure 2). It will be in a sun-synchronous orbit and the array will consist of 4 panels packaged in two drums with a total of 81,000 cells to provide an array power of 7.3 kW.

Within NASA the largest array developed and flown was the 21-kW Skylab array. This array consisted of 6 wings utilizing honeycomb rigid panels and standard N/P silicon cells. Data taken in April 1978 indicates that since its launch in 1973, the electrical performance has degraded only slightly, probably less than 10%. This array was rather heavy in comparison to the lightweight flexible designs, but it has produced probably the cheapest energy yet delivered in space at something just over \$1000 per kilowatt hour.

Aside from Skylab, the NASA solar array development in recent years has centered primarily around electric propulsion and deep space application. An example is the 200-W/kg Solar Array. An artist's concept of this array is shown in Figure 3. The solar array blanket design uses 2 x 2 cm solar cells 50u thick (2 mils). The cells are interconnected with Invar interconnects. Attachment to the interconnects is by welding. The welded assemblies are bonded to the Kapton substrate (1 mil) and the modules are encapsulated with RTV 655 plastic encapsulant 3 mils thick. The 80-cell modules which have been fabricated and tested to prove the blanket technology weigh 12.64 grams. The beginning-of-life power output at AMO, 28°C is 4.72 watts for a specific power of 373 W/kg.

The SEPS solar array shown in Figure 4 was developed specifically for the Solar Electric Propulsion stage concept. A single SEPS array wing is rated at 12.5 kW and measures 4m x 32m. It will use a quarter of a million N on P solar cells. The cell blanket consists of a printed circuit flexible solar array substrate which is a lamination of two sheets of 1/2-mil kapton with 1/2 mil of high temperature polyester adhesive. The interconnect is etched 1-oz. copper. Parallel gap welding is used to bond the 2 x 4 cm solar cell assemblies to the substrate. A cell assembly is composed of an 8-mil wraparound contact, 2-ohm-cm base resistivity solar cell with a 6-mil fused silica cover with ceria-stabilized glass as an alternate. An electrical module is 306 cells in series and 5 cells in parallel (1530 cells) and there are 82 modules in an array wing (2 modules/panel). The V_{mp} at 1 A.U., 55°C is 125 VDC. The harness is a flat conductor cable assembly attached to the two long edges of the wing on the back of the blanket. The conductors are 3-mil-thick aluminum of widths in the range of 0.050 to 0.25 in. to control voltage drops. The SEPS specific power rating is 66 W/kg.

Zero-g deployment of a portion of the SEPS array has been accomplished

by way of KC-135 flights. Future plans for this technology include a Shuttle flight test on an early mission (Figure 5), hopefully on one of the first test flights. This array is also the baseline for the NASA 25-kW Power Module project and is being considered for use on the ENCKE Comet Rendezvous Solar Electric Propulsion program.

TECHNOLOGY NEEDS

Having briefly reviewed the state-of-the-art in solar arrays, the question which naturally arises is "What next?" In what areas are advancements in array technology needed? A partial answer to this question can be found by an examination of the types of missions which are to one extent or the other being considered for the future. This provides only a partial answer to the question for two reasons: (1) At any given time it is very difficult to compile with confidence an "official" listing of future space missions. This is a problem inherent in the operation of a Government Agency whose budget is directly dependent upon Congressional decisions; (2) The technology itself can be the driver. That is, missions which were not previously possible can be made possible by technology advancements, particularly in an area as important to a mission as space power. To a lesser extent, technology advancements can also change a mission or class of mission which were previously marginal or undesirable into very practical missions. An example is seen in the area of many science-oriented missions which are relatively short in duration ranging up to perhaps 5 to 8 years maximum. These missions must therefore pay the penalty of an expensive short-life system. Technology advances particularly in the area of cost reduction could change this situation for the better, making such missions more viable.

Although we must understand the above limitations to determine the direction which future array technology should take, this should not prevent us from utilizing what information we do have. For instance, the Space Shuttle era allows us to expand our thinking into other areas. We no longer need to think of a solar array as inaccessible after launch. The availability of the Shuttle allows us to consider some sort of on-orbit maintainability. This might take any one of a number of forms, for instance replacement could be accomplished at a component (cell, etc.), module, panel or array level. Considerations in the determination of the direction and/or desirability of on-orbit maintainability would involve as a minimum the following: (1) The desirability to limit the number of Shuttle launches required for replacement; (2) the desirability to limit the number and complexity of astronaut operations; (3) the desirability to limit replacement to only that fraction of the system which is life limited; (4) How will an on-orbit maintainability requirement impact the original array design? The above are only a few of the areas of consideration which will need to be investigated relative to on-orbit maintainability. Logic would seem to dictate that replacement should be made at the highest possible level; however, the overriding consideration is reduction in life cycle costs, and the area of on-orbit maintainability should be thoroughly investigated to determine the benefit in reducing array costs.

Advances in solar cells themselves provide us with more options than

were previously available. A good example is the recent coming to the fore-front of cells such as GaAs whose capability to operate at reasonable efficiencies at high temperatures make concentrator arrays look more promising.

Along with the opportunities offered by the advent of high-flux cells and concentrators, however, come some problems. Since high temperatures are generated in concentrator array systems, materials to withstand high temperatures as well as methods for taking excess heat from the cell will be needed.

Another array-allied area which has impact upon array design is in power conditioning. One area needing investigation is chopping the array DC power into square-wave AC power for ease of voltage transformation and transmission. Also, an extensive investigation into allowable maximum operating voltages and optimum operating voltages is needed. Lower converter voltages may be necessary to keep down corona losses whereas higher voltages for transmission may be desirable.

From the present vantage point, one thing seems clear when future arrays are considered: they will be bigger. In the past, array advancements were dominated by weight reduction; in the future, they must be dominated by reduction in cost. The current costs of \$1,000 to \$10,000 per kilowatt hour of energy in space are unacceptable for future arrays, probably by an order of magnitude. The increase in overall array size and the present trend toward restrictively low budgets underscore the need to direct future Solar Array Technology toward the goal of lower life cycle costs.

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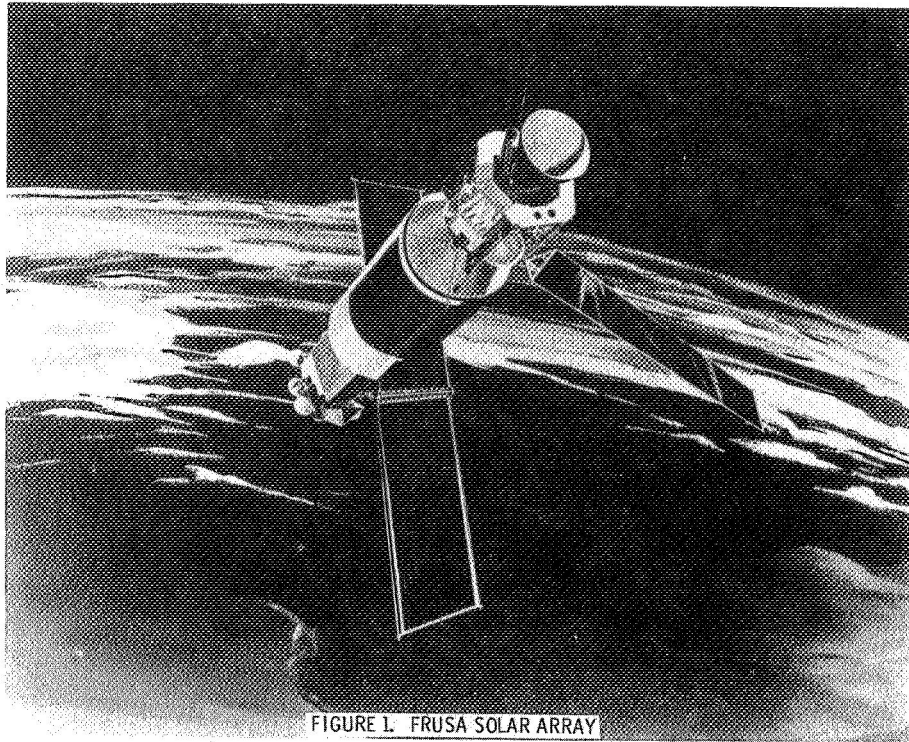


FIGURE 1. FRUSA SOLAR ARRAY

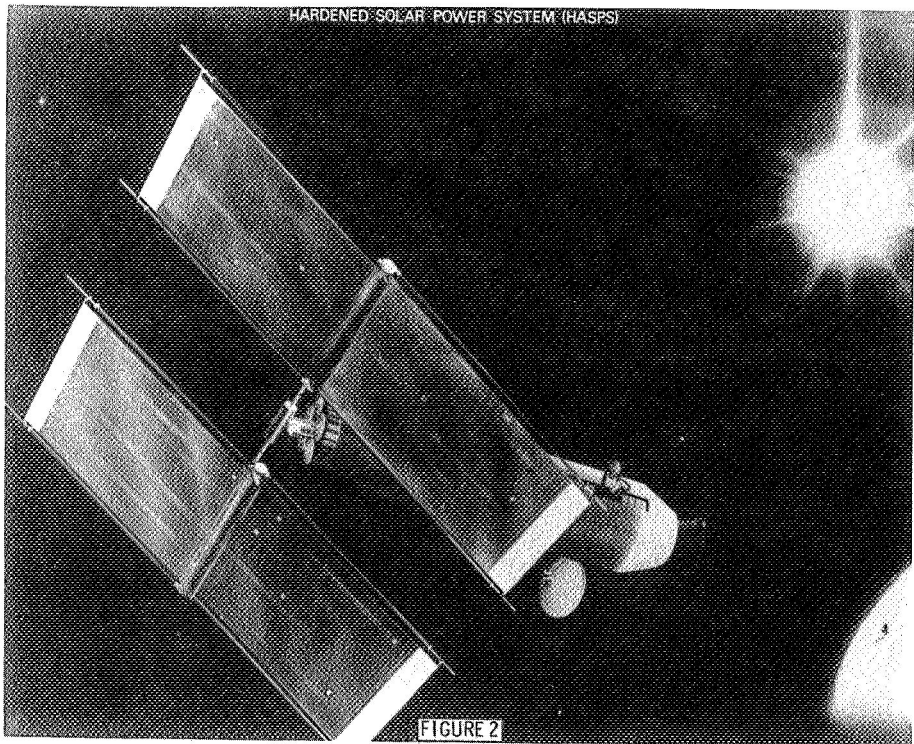


FIGURE 2

GE 200 WATT/KG SOLAR ARRAY

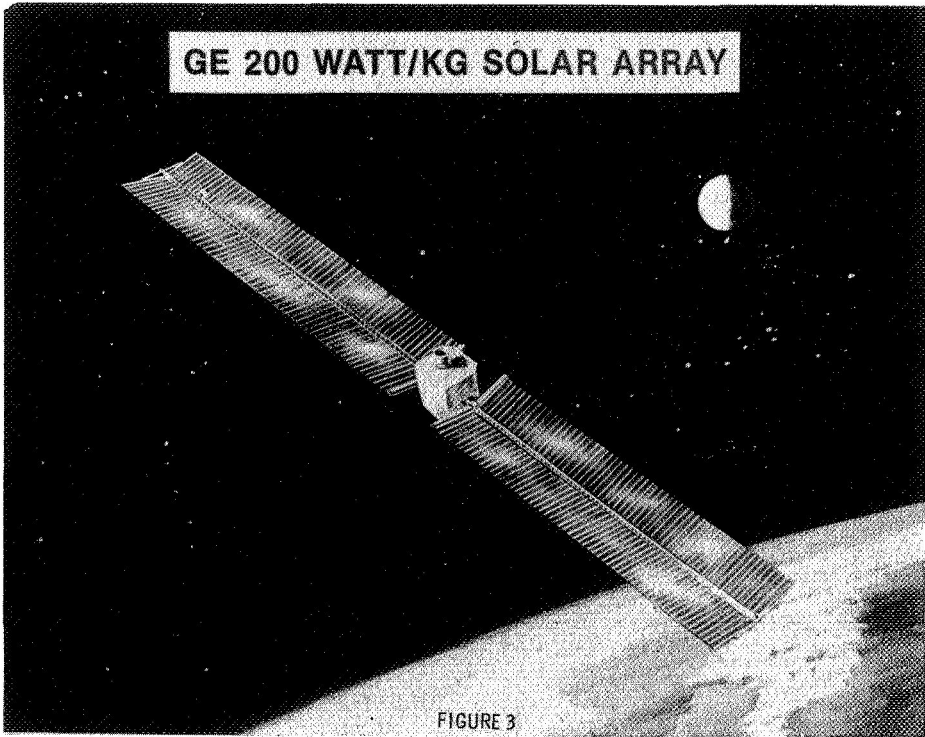
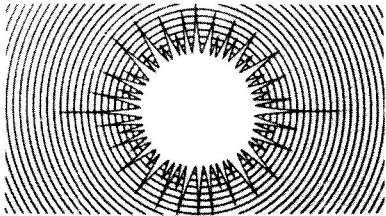


FIGURE 3



SOLAR ELECTRIC PROPULSION (SEP) SOLAR ARRAY

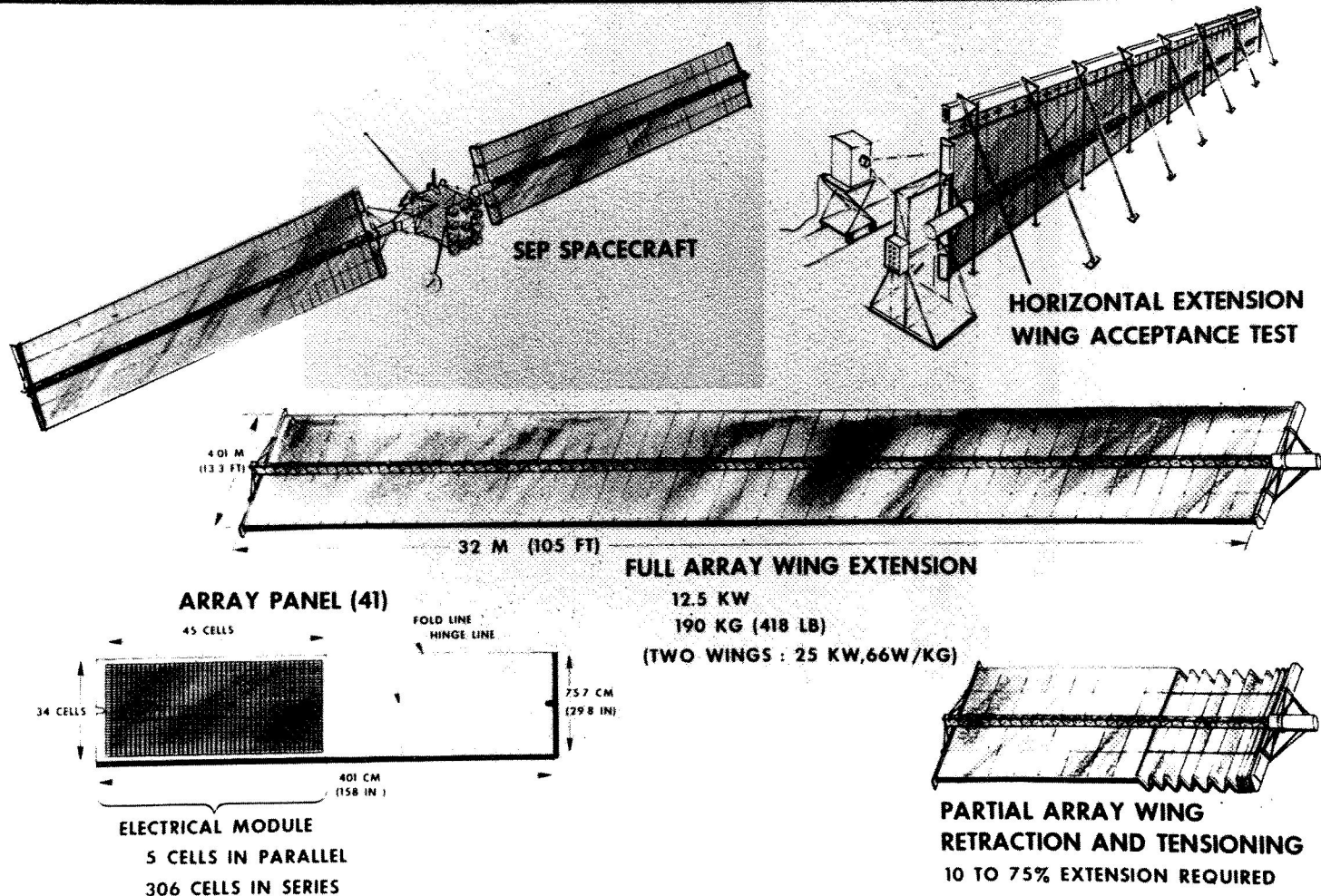
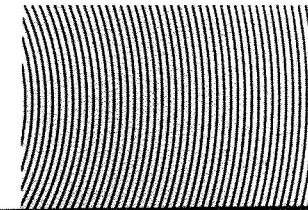


FIGURE 4

NASA SEP SOLAR ARRAY
SHUTTLE FLIGHT EXPERIMENT

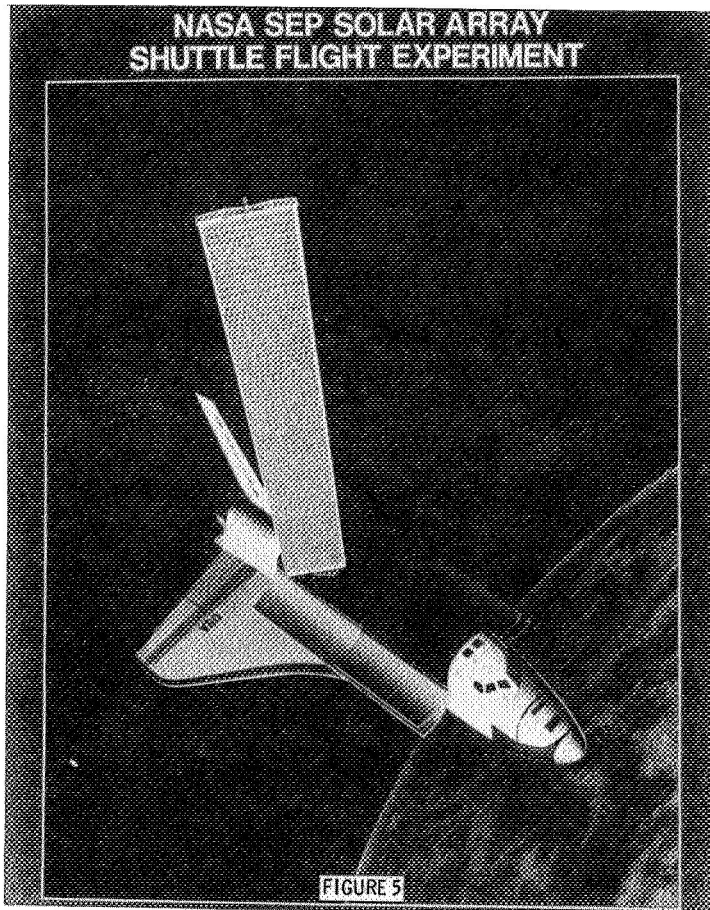
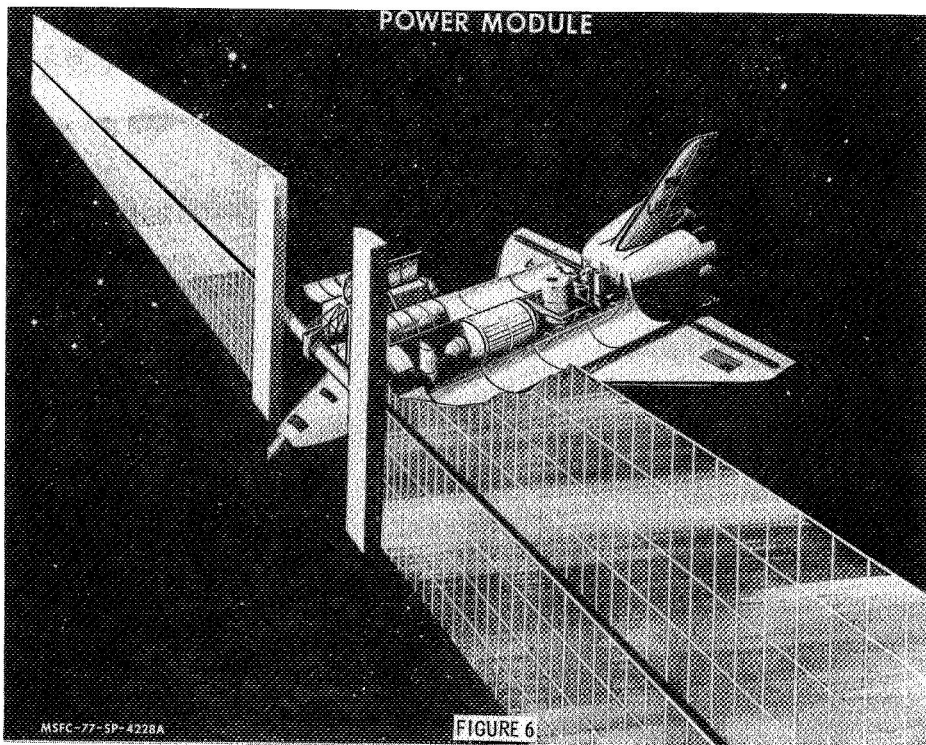


FIGURE 5

POWER MODULE



MSFC-77-5P-4228A

FIGURE 6