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ABSTRACT

A miniaturized Cassegrainian concentrator (MCC) solar array system concept is under preliminary development for the space station or for other large spacecraft/space platform mission applications that may require power at the 100 kilowatt level or higher. The concept has many of the physical attributes of planar rigid-panel solar arrays and does not require unusual deployment or thermal management methods or auxiliaries. Furthermore, it promises both lower initial cost and lower life cycle cost than state-of-the-art lightweight planar flexible blanket solar arrays. The paper briefly describes the MCC concept and presents the results of a life cycle cost comparison analysis that shows that solar array area (rather than weight) is the key cost parameter at the lowest candidate space station basing altitudes. With smaller area than its planar array counterpart, the MCC array offers a 20 to 30 percent reduction in life cycle cost.

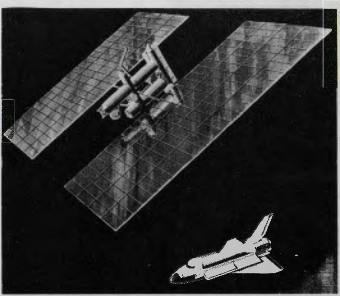


Figure 1.
A 100 kW (BOL) Miniaturized Cassegrainian Concentrator Solar Array for a Manned Space Station

INTRODUCTION

Under NASA sponsorship, TRW began the study and development in 1978 of a miniaturized Cassegrainian concentrator (MCC) solar array system concept. Targeted at very large multikilowatt solar arrays that may be required by a permanently manned space station (Figure 1) or other large spacecraft and space platforms, the development effort has a cost goal of \$100 to \$150 per watt at beginning-of-life (BOL), or about one-half of the cost of state-of-the-art flexible blanket planar (unity concentration) solar arrays.* The MCC concept utilizes high concentration (130 suns on the cell) low cost optics, and high efficiency (20 percent at 85°C at 130 suns) gallium arsenide concentrator solar cells to achieve this goal. A MCC cell with area of only 0.25 cm^2 provides an electrical output (0.43 watts) equivalent to that produced by a 30 cm^2 silicon solar cell (11 percent efficient at 68°C at one sun). Although gallium arsenide solar cells are more expensive, both in bulk semiconductor and in finished form than silicon cells, the fact that the MCC array concept requires less cell area (by two orders of magnitude) to meet a power output requirement is the key to its promise of significantly lower initial cost.

The MCC solar array system concept may also offer life cycle cost benefits for high power, low altitude missions. It requires nearly one-third less deployed area than a lightweight planar solar array system, when both are designed to yield the same end-of-life (EOL) output power. The lower area

*All references to cost in this paper are in 1983 dollars.

means that less orbit drag makeup propellant is required over an extended mission period and, therefore, that lower recurring launch costs are realized for transport of the makeup propellant to orbit.

The paper first presents a description of the MCC solar array system concept and then summarizes the results of a recent life cycle cost analysis performed in support of preliminary space station planning activities. The concept development work was performed primarily on NASA MSFC Contracts NAS8-32986 and NAS8-34131, and is continuing on NAS8-35635. Complementary work for military applications is being performed by TRW under USAF Contract F33615-81-C-2055.

CONCEPT DESCRIPTION

Early work performed by TRW showed that a significant reduction in solar array cost could be achieved with high solar concentration, provided that thermal control could be obtained by passive means and that low cost optics could be employed which did not require separate deployment (ref. 1). It was immediately clear that the solar heat input to the entrance aperture of a small optical system could be rejected to space by radiation from a thermal fin roughly equal in area to the entrance aperture, limited only by practical weight constraints on the fin design. This approach was thus completely consistent with the notion of a design that would use very small high efficiency concentrator solar cells. The materials and processes used to produce such cells might be expensive, but the smaller quantity of solar cell material than otherwise required for a planar solar array would nonetheless help to produce a major reduction in solar cell cost for the entire array.

The early studies considered compound parabolic concentrator (CPC), Fresnel, and Cassegrainian optical element designs. The latter was selected for development because it permitted the thinnest solar panel design, an important consideration for stowage and deployment, and because it offered lightest weight. A single Cassegrainian element, shown schematically in Figure 2, and a nine-element loosely packed module (Figure 3) have been designed, assembled, and tested (ref. 2).

Sunlight reaching an element is reflected from a primary parabolic reflector to a secondary hyperbolic reflector and finally to the solar cell. The solar cell is mounted to a molybdenum heat spreader which is mounted in turn to a 0.25 mm thick aluminum heat fin. The primary and secondary reflectors are designed such that they have a common focal point in the plane of the entrance aperture, an f-number of 0.25, and a rim angle of 90 degrees. This design yields a height of 13 mm which is similar to the panel thickness of conventional rigid sandwich panel planar solar arrays.

The optical reflectors used for the demonstration hardware were made of electroformed nickel with a 2000 angstrom rhodium primer coating, a 1200 angstrom aluminum reflective coating, and a 2500 angstrom silicon monoxide protective coating. The reflectors used for flight hardware will have a silver reflective coating to enhance performance.

Test results obtained from the demonstration hardware have established that the concept is technically feasible. Misalignment tests have shown that required optical component alignment can be achieved by mechanical design without the need for individual element optical adjustment. Off-pointing tests have shown that the auxiliary light catcher cone improves off-axis performance over that predicted without a cone. Reflectance measurements on the electroformed parts have

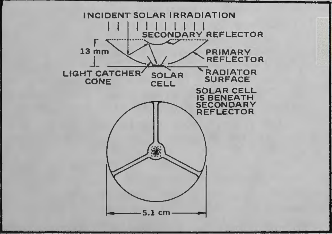


Figure 2.
A Single Concentrator Element

Figure 3.
A Nine-Element Demonstration Module

verified specification compliance and have shown good coating reproducibility. Heat balance tests conducted with a single element have confirmed initial thermal models and temperature predictions. The steady state operating temperature of the concentrator cells will be in the range of 64 to 95°C depending upon particular combinations of the radiometric properties of the cell and the optical components, the cell operating efficiency, the element geometry, and the parameters of the mission orbit.

Other technology issues have been identified and work addressing them either is under way or is being planned. For example, the environmental stability of reflector optics is an important issue as well as contamination both before and after launch. Reflector samples aboard STS 8 showed no significant degradation during short-term worst-case exposure to atomic oxygen. Other samples will be given greater exposures aboard the long duration exposure facility (LDEF). Other flight experiments being planned will also provide similar data as well as information regarding plasma interaction effects. It is also worth noting that a MCC array is much less subject to self-contamination since it contains very little adhesive (by comparison to planar solar arrays).

A 100 kilowatt MCC solar array, configured with two wings for the space station as shown in Figure 1, has beginning-of-life performance characteristics of 160 W/m^2 and 28 W/kg (ref. 3). Figure 4 illustrates the deployment concept for one wing. Each of the four subwings contain 24 panels. The panels are deployed using a folded box beam approach that was successfully applied on Skylab and which is being employed on the Gamma Ray Observatory (GRO) spacecraft. Array retraction is also possible using the folding beam design. The entire array requires approximately eight lineal feet of Shuttle cargo bay in the fully stowed configuration. Figure 5 shows a section of one of the panels. The elements are in a closely packed hexagonal arrangement supported by a graphite epoxy structure to minimize thermal distortion. A panel will be fabricated in the current phase of this development program to demonstrate the concept.

Other array configurations have been examined and found feasible, including one that uses a tetrahedral deep truss structure that has been developed by NASA Langley. The structure is erected in space using nestable graphite epoxy column elements; hexagonal MCC array panels are subsequently attached by an astronaut team (Figure 6).

The 100 kilowatt MCC array concept has been analyzed to determine the effect of pointing errors. Thermal distortion errors, manufacturing tolerance buildups, and dynamic distortion errors are at a maximum at the array wing corners furthest from the space station body. Pointing control sensing errors apply uniformly to the entire wing. Figure 7 summarizes the results of these analyses. The "average" off-pointing error for an entire array wing can be determined by performing an integration over the wing area. The integrand is a function of the contributing errors at each concentrator element and the off-pointing performance characteristics

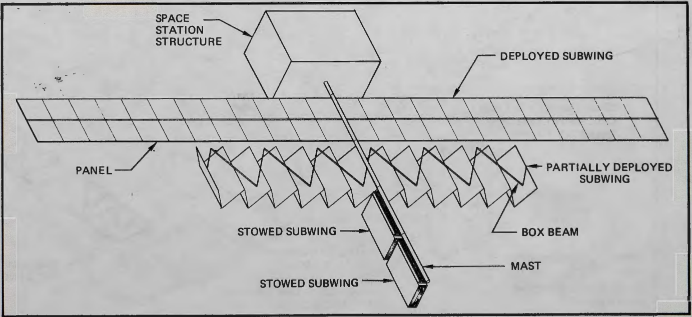


Figure 4.
Deployment Sequence of MCC Solar Array Subwings

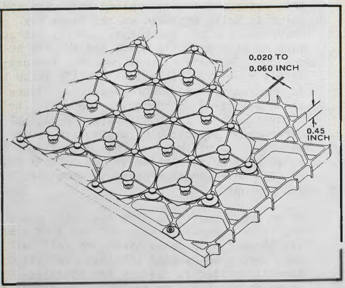


Figure 5.
Panel Concept with Tri-Hex Grid Element Support Structure and Integral Frame

of the element. These functional relationships have not been sufficiently defined to perform the integration. Thus, as a conservative estimate of "average" off-pointing, the worst-case pointing error components have been combined on an RSS basis. The RSS pointing error of 1.1 degrees corresponds to a performance factor of 0.98 based upon single element analyses; the algebraic sum of all worst-case contributors (1.8 degrees) corresponds to a factor of 0.94.

PERFORMANCE COMPARISONS

Table 1 compares the performance characteristics for the flexible blanket, carbon fiber/epoxy sandwich panel, and MCC array types. The MCC solar array and the other flatpack foldout planar solar array systems have each been sized to deliver 75 kilowatts after 10 years operation in low earth orbit (250 nmi, = 30 degrees) (ref. 4). Both conventional designs and lightweight versions are presented for each array type. The planar solar arrays defined for this comparison incorporate state-of-the-art 10 ohm-centimeter silicon solar cells with a back surface reflector (BSR) and a back surface field (BSF). The BSR feature results in lower operating temperatures and higher output powers; incorporation of the back surface field results in a cell with higher

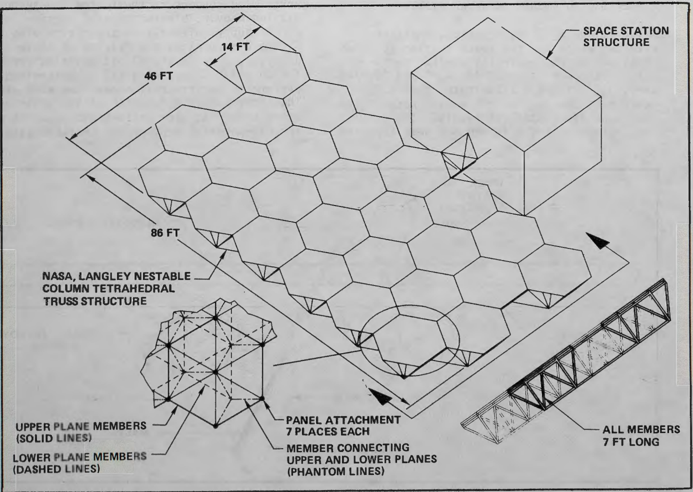
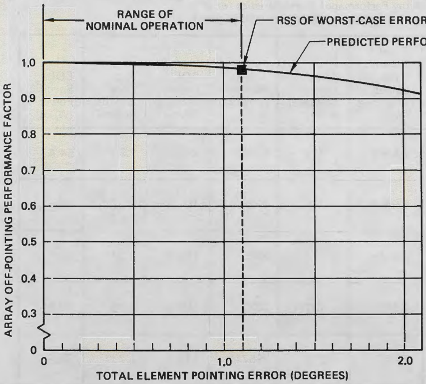


Figure 6.
One Wing of a 100 kW Erectable MCC Solar Array



POINTING ERROR COMPONENT	POINTING ERROR (DEGREES)
THERMAL DISTORTION	± 0.2
MANUFACTURING*	± 0.8
CONTROL SENSING	± 0.1
DYNAMIC** DISTORTION	± 0.7
SUM	1.8
RSS	1.1

* WORST-CASE SUM

** WORST-CASE CREW MOTION (NOT TIME PHASED)

Figure 7.
MCC Solar Array Design Factor Due to Pointing Error is 0.98

output at both BOL and EOL than a comparable BSR-only cell. Specific power and power density trends obtained using planar gallium arsenide cells are not shown because these cells are likely to be at least three times more costly per unit area than silicon cells. The planar gallium arsenide solar cell thus is not a candidate cell type in low altitude, low radiation orbit applications where low cost (lower than conventional planar arrays) is a major design driver, but it may be considered as potentially enabling technology along with the MCC solar array for higher power missions in orbits that result in higher levels of exposure to natural radiation.

Table 1 shows that the MCC solar array requires about 30 percent less area than the planar arrays considered. Although the baseline MCC array concept is 20 to 60 percent heavier than the planar arrays, its lightweight version results in an array system weight quite similar to those obtained with composite rigid panels.

Similar design comparisons have been conducted for other missions and orbits. The studies further illustrate the potential of the MCC array concept in achieving reductions of solar array area and weight where exposure to natural radiation is high. For example, at geosynchronous altitude the MCC array requires approximately 40 percent less area than silicon cell planar arrays. The area reduction is even more dramatic at Van Allen belt altitudes where 60 to 70 percent reductions can be achieved relative to planar arrays of comparable output power.

LIFE CYCLE COST MODELS

Parametric analyses of manned space station solar array life cycle costs have been performed for a flexible blanket planar array and the MCC solar array system concept (ref. 4). Life cycle costs include recurring array costs, launch costs associated with the array system, and launch costs associated with drag makeup propellant. Other aspects of the electrical power system (e.g., energy storage, power conversion and control, and power distribution) and other factors affecting space station architecture were not considered. Key parameters analyzed were mission lifetime, atmospheric density, STS launch cost, and space station basing altitude. Table 2 presents the key assumptions and data that formed the basis for the life cycle cost projections.

Figure 8 presents life cycle cost as a function of STS launch cost for a 185 nautical

Table 1. Comparative Solar Array Performance Characteristics for a 75 kW (EOL) 10-Year LEO Mission (250 nmi, i = 30 degrees)

Array Type	Cell Type	Cell Thickness (mil)	Front* Shield/ Back Shield Thickness (mil)	Array Area (2 Wings) (m^2)	Array Weight (2 Wings) (kg)	EOL Power Density (W/m^2)	Array Area Density (kg/m^2)	EOL Specific Power (W/kg)
Flatpack foldout flexible blanket	10 ohm-cm BSF/BSR (13.9% at 28°C)	8	7.5/6.5	724	1376	103.5	1.90	54.4
	10 ohm-cm BSF/BSR (13% at 28°C)	2	4.5/6.5	742	1128	101.1	1.52	66.5
Carbon fiber/ epoxy sandwich panel foldout****	10 ohm-cm BSF/BSR (13.9% at 28°C)	8	7.5/25	714	2335	105.0	3.27	32.1
	10 ohm-cm BSF/BSR (13% at 28°C)	2	4.5/25	731	2032	102.6	2.78	36.9
Miniaturized Cassegrainian Concentrator	Gallium Arsenide (20% at 85°C)	10	50/50	515	2957**	145.6	5.73**	25.4
	Gallium Arsenide (20% at 85°C)	10	50/50	515	2194***	145.6	4.26***	34.2

*Equivalent fused silica.
**10 mil thick nickel optics.
***5 mil thick nickel optics.
****5 mil carbon fiber/epoxy facesheet, 0.80 inch aluminum honeycomb sandwich.

mile basing altitude for 10, 20, and 30 year missions. Figure 9 presents life cycle cost as a function of space station basing altitude assuming $100M (constant) per STS launch for 10, 20, and 30 year missions.

The comparative results from these analyses indicate that:

a) The MCC array results in a 20 to 30 percent reduction in total life cycle costs relative to the flexible blanket array.

b) The MCC array is 20 to 30 percent lower in initial costs (i.e., fabrication and launch costs) relative to the flexible blanket array due primarily to specific BOL costs ($/W).

c) Solar array area, rather than weight, is the key life cycle cost parameter, especially at lower basing altitudes.

d) Drag makeup (hence basing altitude and atmospheric density model) and STS launch cost are the significant life cycle cost drivers.

e) Above a space station basing altitude of 210 to 240 nautical miles, less than the equivalent of one full STS flight is required to provide drag makeup propellant for a 20-year mission.

f) Solar array recurring cost and weight, and STS launch cost, are the primary life cycle cost drivers at the higher basing altitudes, or for shorter duration missions.

The studies also showed that each percentage point improvement in EOL solar cell efficiency will reduce life cycle costs by approximately 6 to 8 percent. This has particular meaning for the MCC array system since the concept is inherently adaptable to the use of advanced high efficiency solar cells as they become available. The small size of such advanced cells, and the smaller quantity of solar cell material required by the MCC array, will ease their transition from the laboratory into economical production.

Table 2. Key Manned Space Station (MSS) Solar Array Life Cycle Cost Assumptions

1. STS direct insertion of payload to 28.5-degree inclined orbit.

2. Gross STS payload capability of 79,000 pounds at 100 nmi, declining linearly to 56,000 pounds at 300 nmi.

3. Net STS payload capability of 53,600 pounds at 185 nmi, declining linearly to 42,400 pounds at 300 nmi, when considering a 7000 pound aerospace support equipment allowance and an 85 percent manifest factor.

4. Cost of STS launch ranges from $70 to $150M per flight.

5. Jacchia 1996 average and $+2\sigma$ air density model for total mission lifetime.

6. Constant MSS basing altitude ranging from 185 to 300 nmi.

7. Drag makeup propellant weight of 0.50, 0.25, 0.10, 0.04, and 0.02 pound/year/ft^2 of array area at 185, 210, 240, 270, and 300 nmi basing altitude, respectively, assuming a MSS ballistic coefficient of 18 and a propellant I_{SP} of 290 seconds (1996 average atmospheric density).

8. Drag makeup propellant weight of 0.75, 0.38, 0.15, 0.075, and 0.038 pound/year/ft^2 of array area at 185, 210, 240, 270, and 300 nmi MSS basing altitude, respectively, assuming a MSS ballistic coefficient of 18 and a propellant I_{SP} of 290 seconds (1996 $+2\sigma$ atmospheric density).

9. 75 kW (EOL) solar array for the initial launch in 1991, with an additional 75 kW (EOL) solar array installed in 1996. No replacement of the solar array over the total mission lifetime.

10. Total mission lifetimes of 10 to 30 years.

11. Flexible blanket recurring cost of $500/W (EOL), 10 years; concentrator array recurring cost of $250/W (EOL), 10 years. EOL specific cost for other mission durations proportional to array area.

12. Solar array sun-pointed during all orbit phases.

13. 75 kW (EOL) flexible blanket array weight and size of 2600 pounds per 7600 ft^2 for a 5-year mission, increasing linearly to 3000 pounds per 8800 ft^2 for a 30-year mission, using 2-mil, 10 ohm-cm BSF/BSR silicon cells (η_0 = 13 percent at 28 °C AMO) and 6-mil fused silica covers). Sizing based on 250 nmi (i = 30 degrees) orbit.

14. 75 kW (EOL) concentrator array weight and size of 6200 pounds per 5300 ft^2 for a 5-year mission, increasing linearly to 7100 pounds per 6100 ft^2 for a 30-year mission, using 10-mil nickel optics and GaAs cells (η = 20 percent at 85°C at 130 CR). Sizing based on 250 nmi (i = 30 degrees) orbit.

15. Life cycle cost in 1983 dollars.

16. No repair/maintenance cost or EVA assembly/construction cost. No NASA add-on cost. Cost for drag makeup propellant and tankage not considered. Solar array design/development cost not considered.

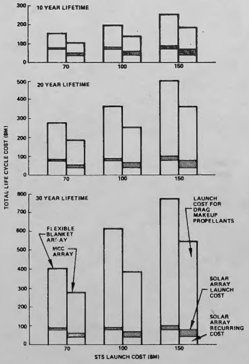


Figure 8.
150 kW (EOL) Solar Array Life Cycle Cost as a Function of STS Launch Cost and Mission Duration (185 nmi MSS Basing Altitude; 1996 Average Atmospheric Air Density Model)

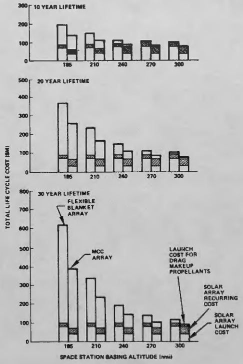


Figure 9.
150 kW (EOL) Solar Array Life Cycle Cost as a Function of Space Station Basing Altitude and Mission Duration ($100M/STS Launch; 1996 Average Atmospheric Air Density Model)

REFERENCES

1. "Study of Multikilowatt Solar Arrays for Earth Orbit Applications," final report on NASA (MSFC) Contract NAS8-32986, TRW Report 33295-6001-UT-00, September 1980.

2. R. E. Patterson, et al, "Design and Performance Trades for a Miniaturized Photovoltaic Concentrator Array," 16th IEEE Photovoltaic Specialists Conference, San Diego, CA, 27-30 September 1982.

3. R. E. Patterson, "Study of Multikilowatt Solar Arrays for Earth Orbit Applications," final report on NASA (MSFC) Contract NAS8-34131, TRW Report 38172-6001-UE-00, October 1983.

4. R. M. Kurland, "Ultralightweight Solar Array Development," 1984 Technical Plan for TRW Internal Research and Development Project Number 84353221.