PROGRESS IN DEVELOPING HIGH PERFORMANCE SOLAR BLANKETS AND ARRAYS*

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INTRODUCTION

The development of high efficiency (> 13% AMO), ultrathin (50 μm) silicon solar cells offers both opportunity and challenge. It is possible to consider 400 W/kg blanket designs by using this cell in conjunction with flexible substrates, ultrathin covers and welded interconnects. By designing array structure which is mechanically and dynamically compatible with very low mass blankets, solar arrays with a specific power approaching 200 W/kg are achievable. Further improvements in blanket performance (higher power and lower mass per unit area), which could come from the implementation of higher efficiency cells operating at lower temperatures (silicon or GaAs), and the use of encapsulants, would result in the development of 300 W/kg solar arrays. There is a trend toward higher power.

There is a tred toward higher power and longer operating life in nearly every future mission being planned, whether for NASA, defense or commercial application. It is also becoming apparent that the Shuttle launch capability will not grow as rapidly as had been orginally anticipated. Thus there is a need for the development of low mass solar arrays.

APPROACH

Figure 1 is a plot of beginning of life (BOL) array specific power as a function of array structure mass per unit area. It is possible to develop an optimum strategy for providing a high performance array by analyzing the relationship between array performance and the figures of merit for the blanket and structure components. It is apparent that increasing the specific power of the array blanket will provide much greater initial improvements in array specific power.

However as the blanket specific power increases (lower mass per unit area) for a fixed structure mass, the dynamics of the array begin to change. Thus it becomes necessary to modify the structure to bring the array into conformance with such requirements as stiffness and natural frequency. Even excluding array dynamics from consideration, lowering the structure mass becomes an attractive and even necessary option if array specific power is to exceed 150 W/kg BOL. Therefore once a relatively high performance blanket (> 250 W/kg) is achieved, efforts to develop a low mass structure become the more effective method of increasing the array's specific power.

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BLANKET DEVELOPMENT

Simple calculations show that the present SEP blanket (105 W/kg), which represents current state of the art, would be improved to nearly 150 W/kg by replacing the baseline cells and covers with ultrathin versions. Thus there is a strong incentive to develop a cost effective and scaleable approach to fabricating ultrathin solar cell blankets. The prospect that ultrathin GaAs solar cells will be available within this decade is another strong argument for pursuing this effort.

Manufacturing Methods

NASA-JPL is presently sponsoring three contracts aimed at devising a method for assembling ultrathin components. One effort seeks to retain as many conventional manufacturing processes as possible and concentrate on modifying only those that are proven to be incompatible. The rationale for this philosophy is that based on current projections for array demand and the fact that ultrathin cell blankets will not capture the near-term market, the expense to recapitalize for this new technology cannot be justified.

Substantial progress in producing ultrathin cell modules has been made using this approach, and a prototype module has been subjected to over 6000 thermal cycles (+80 to -80°C) without any significant electrical or mechanical degradation. The baseline process uses a kapton substrate, conventional DC 93-500 adhesive for substrate and cover bonding, welded silver-plated invar interconnects, 62 μm cells and 50 μm glass covers (ref. 1).

A second effort seeks to reduce the difficulty in handling these parts by investigating the use of automated machinery to interconnect the cell strings. In this approach ultrasonic welding of silver mesh is employed. Results to date indicate that weld joints with acceptable pull strength (200 gms in shear) and less than one percent electrical degradation can be achieved with this technique. Methods for bonding covers have also been developed.

A third parallel activity has developed special tooling, based on concepts proven effective for terrestrial module fabrication, to minimize the amount of handling operations the ultrathin cells and covers receive during assemby. The initial trial run using this cell-interconnect-registrationtool (CIRT) showed a dramatic improvement in yield as compared to conventional handling processes. Further work is now underway to make improvements in the tool design. Although parallel-gap resistance welded interconnects were used for the proof test, a substantial effort will be made in this phase to investigate the possibility of laser welding as a joining method.

Ultrathin Solar Cells

The NASA-JPL pilot line program demonstrated that ultrathin silicon solar cells could be produced in quantity (ref. 2). Cells from this program, along with versions supplied by two space qualified sources, to a specification, are being used for the blanket development work. The newer versions incorporate such technology improvements as back surface reflectors, multiple antireflection coatings and an alternate back surface field technique. This recent procurement resulted in the delivery of cells with an average 28°C AMO efficiency of 12.5 percent, some cells exceeding 13 percent.

JPL also procured an improved version of the ultrathin cell from the original supplier. The device employs a gridded back contact to reduce cell mass, and cells exceeding 13 percent AMO were provided (ref. 3). This second generation ultrathin cell is an important milestone for achieving even higher levels of blanket specific power. It offers the potential of reducing cell bowing, since the amount of contact metal is the same on both sides, reducing cell mass and lowering cell operating temperature because most of the back surface is free of metal.

It is expected that further modifications will be made to the ultrathin solar cell to improve operating efficiency and handling properties. The feedback received from the blanket development program will be used to write a specification for an optimized ultrathin solar cell compatible with whatever blanket fabrication process is developed.

Ultrathin Covers

Many mission orbits require only minimal shielding, but until the development of the ultrathin cell, the thinnest covers available were ∿100 μm. Prototype ultrathin blankets used 50 to 75 μm microsheet glass which would not be acceptable for space use. Currently the blanket development programs are using 50 μm textured fused silica, but these covers do not have uv-rejection filters. Another alternative is to use ceria-doped microsheet. Sample quantities of 50 μm material have been obtained and will be used in the program.

Perhaps the most exciting candidate now being evaluated is a transparent polyimide polymer which was originally developed for commercial applications. Preliminary testing, which has been very encouraging, has been performed. Details of this evaluation are provided in another paper published in this volume (ref. 4).

A space qualified encapsulant is necessary in order to achieve a blanket specific power approaching 500 W/kg. By using an encapsulant, even thinner protective layers (< 25 μm) could be considered, and no adhesive would be necessary, thus saving additional mass. Encapsulation would also provide major benefits for blanket fabrication with respect to labor cost and yield.

Substrate

The baseline blanket design employs very thin (25 μm) kapton sheets. This may not be practical for two reasons. Thin, flexible substrates offer very little protection from the effects of the omnidirectional space radiation environment. For low earth orbital applications this is of little consequence, but for high earth or geosynchronous applications, where radiation levels are at least 6×10^{13} equivalent 1 MeV electrons/cm^2 annually, a thicker substrate may be necessary to protect the cells from backside radiation degradation. Trade-offs to determine the optimum substrate thickness for end of life array specific power will need to be done. Work is planned to determine the effects of space radiation on cells that have relatively little backside protection.

A second concern which has to transferring extremely thin substrates which have cell assembly (cell plus cover) circuits bonded to them. Although it is relatively easy to fabricate modules with thin substrates, it is much more difficult to join these modules into panels and ultimately integrate the panels into an array. Thus the present design will probably employ thicker (50 μm) composite, laminated or fiber reinforced substrates.

Adhesive

Processes to provide extremely thin ($\leq$ 25 μm) adhesive bondlines for coverglass and circuit bonding have not been reduced to practice. Presently 50 m bondlines are a realistic estimate for the blanket design. In the case of the coverglass, the implementation of an encapsultant such as the polyimide polymer now being evaluated, would eliminate adhesive. For substrate-circuit attachment, it may be necessary to consider "spot" bonding, wherein only certain areas of each cell are bonded to the substrate. This may cause the cell to run hotter, thus reducing power output. Therefore at some point it may be necessary to test this concept in order to obtain sufficient data to allow a trade-off to be made to determine the best approach to optimize end-of-life array specific power.

Interconnects

It is assumed that welding will be used for interconnecting. Currently three interconnect materials are being employed; silver, silver plated molybdenum and silver plated invar. The present practical lower limit of thickness for the base material is approximately 25 μm and in the latter two cases the amount of silver necessary to assure proper interconnect conductivity and weld suitability is in the order of 20 μm.

Ideally it would be better to either reduce the thickness of the interconnect base material or consider a low mass, highly conducting material such as aluminum. The prospect for securing thinner interconnects is not good unless funding is provided to develop the necessary etching and rolling technology. Based on the current situation, it is more likely that attempting to develop lower mass interconnect materials is the better approach.

However the mass advantages may be compromised by the substantial mismatch in thermal coefficient of expansion between the solar cell (silicon or GaAs) and an interconnect such as aluminum. Work will be undertaken in the future to investigate the possibility of using aluminum as an interconnect material, once the main problems associated with fabricating a space qualified ultrathin solar cell blanket are resolved.

Harness

In many analyses of blanket specific power, the mass of the harness or bus is not taken into consideration. Realistically the bus must be taken into account. The present harness material is copper and because of the low operating voltage of the array (30-40 volts), the harness mass is roughly 0.20 kg/m^2 for the current baseline design. As the mass of the other blanket components is reduced, the impact of the harness will act to constrain blanket performance. By increasing the operating voltage of the array to perhaps 120 volts and substituting aluminum for copper, the mass of the harness could be reduced to approximately .025 kg/m^2.

STRUCTURE DEVELOPMENT

NASA-JPL sponsored an effort to develop array structure design concepts that would have low mass and be dynamically compatible with very low mass blankets (0.25 to 0.65 kg/m^2). Three concepts were evaluated; the Astromast used for the SEP array, a modified version of the extendible support structure used on the Seasat spacecraft, and the stacking triangular articulated compact beam (STACBEAM), which was finally chosen for further development.

The STACBEAM design has many attractive features including low mass, sequential deployment, high stiffness and the capacity for growth (ref. 5). Preliminary design work has begun and a working model of the beam, consisting of 8 bays or segments, has been built using graphite-epoxy. A breadboard model of the deployment mechanism has been constructed, and in the next phase a more accurate or "high fidelity" version will be constructed. Based on the progress to date, it appears that the STACBEAM will provide the low mass array structure that is necessary to achieve solar arrays with specific power in excess of 150 W/kg.

DISCUSSION

Table 1 represents the best estimate of the current status of high performance solar cell blankets and arrays. It is based on the present progress of the various NASA-JPL programs supporting this effort. In order to present the most realistic assessment, contingency factors have been applied to the cell performance at array operating temperature. This approach has borrowed heavily from the SEP array development program. For example, the cell output has been derated to account for fabrication losses, cell mismatch, diode losses, array packing factor and temperature. Although substantial progress has been made in the development of the STACBEAM array structure, enough work remains so that it is not realistic to state that it is ready at present for space flight operation. Whether the present SEP array structure would prove compatible with current blanket mass per unit area is still not settled, but in an optimistic analysis, it is assumed suitable.

Table 2 reflects the potential of the NASA-JPL programs now being pursued. As stated previously, a number of issues such as the thermal penalty associated with adhesive "spot" bonding and the practicality of aluminum interconnects remain to be resolved. Of even greater importance is the question of silicon solar cell efficiency at array operating temperature and the use of an encapsulation approach to replace conventional coverglass. It is expected that these will be major factors in determining the ultimate specific power of silicon solar cell blankets. A higher degree of confidence is attached to the efforts underway to develop a new, low mass array structure.

The utility of employing GaAs solar cells has not been addressed because sufficient information on the technology is still unavailable. However comments must address certain aspects of thin GaAs cells. Recently there have been published reports concerning the potential of ultrathin ($\lesssim 50\ \mu m$) GaAs devices (ref. 6, 7 and 8). Much work remains before any of this technology can be realistically considered for space applications. If it were optimistically assumed that 10 μm GaAs solar cells with an AMO conversion efficiency, at operating temperature, approaching 18 percent could be achieved in a manner lending itself to a cost effective and practical approach to incorporation into space solar arrays, then space solar arrays with specific power at beginning-of-life exceeding 300 W/kg could be forecasted.

CONCLUSIONS

Encouraging progress towards achieving solar cell arrays capable of 300 W/kg (BOL) specific power has been made. Present technology involving advanced ultrathin silicon solar cells, welding and flexible substrates indicate that a solar array could be built, using current technology, that would be sixty percent better than the present state-of-the-art. Significant improvements will occur in the near future, provided the current programs continue. It is not unrealistic to consider attaining 300 W/kg (BOL) silicon solar array technology based on current progress.

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TABLE 1.

Present Blanket and Array Status

COMPONENT	DESCRIPTION	kg/m^2	NOTES
Substrate	Kapton/50 μm	.070	handling, radiation
Adhesive (substrate)	DC-93-500/50 μm	.055	bondline limitations
Solar Cell	Silicon/62 μm	.117	11% at op.temp.
Cell Contacts	Silver/4 μm	.005	gridded back, welding
Adhesive (cover)	DC-93-500/50 μm	.044	bondline limitations
Cover	CMS/50 μm	.100	thinnest available
Interconnect	Mo, Invar, Silver/25 μm	.018	thinnest available
Plating (IC)	Silver/20 μm	.017	needed for Mo, Invar
Padding, etc.	-	.011	based on SEP
Harness	Copper	.046	based on SEP
TOTAL BLANKET		.483	80% packing factor
Array Structure		.581	SEP
TOTAL ARRAY		1.064	

Blanket Specific Power	231 W/kg	(based on 112 W/m^2)
Array Specific Power	105 W/kg	

TABLE 2.

Anticipated Blanket and Array Performance

COMPONENT	DESCRIPTION	kg/m^2	NOTES
Substrate	Composite/50 μm	.070	handling, radiation
Adhesive (substrate)	DC-93-500/50 μm	.006	spot bonding
Solar Cell	Silicon/50 μm	.095	14% at op.temp.
Cell Contacts	Silver/4 μm	.005	gridded back, welding
Adhesive (cover)		-0-	none required
Cover	Encapsulant/25 μm	.034	shielding
Interconnect	Aluminum/30 μm	.007	conductivity
Plating (IC)	Silver/20 μm	.002	spot plating
Padding, etc.	-	.011	based on SEP
Harness	Aluminum	.025	advanced SEP concept
TOTAL BLANKET		.255	80% packing factor
Array Structure		.321	STACBEAM I
TOTAL ARRAY		.576	

Blanket Specific Power	557 W/kg	(based on 142 W/m^2)
Array Specific Power	247 W/kg	

FIGURE 1

ARRAY SPECIFIC POWER vs STRUCTURE MASS