DESCRIPTION OF AN IMMERSED PHOTOVOLTAIC CONCENTRATING
SOLAR POWER SYSTEM

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ABSTRACT

Recent advancements in photovoltaic solar cells made from Gallium Arsenide (GaAs) have shown that with concentration ratios greater than one solar constant, overall efficiencies up to 23% can be achieved. A second issue applicable to solar power systems for spacecraft is the cost driver, which requires that the efficiency/weight ratio be improved so that solar panels with high output, weighing less, will reduce payload weights, which, in turn, reduces launch costs. This has resulted in a “Figure of Merit” being introduced to grade the characteristics of solar panels for spacecraft. This Figure of Merit defines a ratio of watts/kilogram for a solar panel. Typical flat plate panels on current spacecraft, fabricated with silicon solar cells without concentration, provide Figures of Merit of 25 to 30 watts/Kg.

This paper describes a new design of a 1.9/1 solar concentrator in which conservative calculations show improvements on this Figure of Merit by a major factor (3 to 4). An alternate 2.88/1 concentrator configuration using larger GaAs cells, thereby greatly reducing the number of cells per panel, and thereby reducing the complexity of the solar panel assembly, is also presented and has been analyzed to show an equivalent Figure of Merit.

The proposed flat solar panel is a mosaic arrangement of modular 5 mm. x 5 mm. GaAs cells in a rectangular “honeycomb” type grid, which performs the triple function of:

1. Optical Concentrator
2. Basic structure for the Solar Panel, having a thickness of 1/5 of current solar panels.
3. Current carriers for the solar power generated by the cells

The cells are optically immersed in a “Cassegrainian-type” fused silica concentrator which, through the use of total internal reflection, produces no obscuration and achieves a wide field of view to ease the tracking requirements for the solar panel. (Patent Pending).

The computed “Figure of Merit for this design has been computed to be > 126 watts/Kg., or over four times the current capabilities of the best flat plate solar panels.

A second design is also presented which uses a stamped pyramidal reflective concentrator on an immersed solar cell, allowing larger cells and fewer cells per panel. This design has a computed “Figure of Merit” of 158 watts/Kg.

The panel in either design is designed for an automated assembly process necessary in order to reduce the cost. The paper describes this proposed automated fabrication assembly process, based upon current “Pick and Place” PC board assembly technology. The Van Allen radiation survivability of this design is also addressed in the paper.
DESCRIPTION OF DESIGN NO. 1
(5 mm. x 5 mm. GaAs CELLS)

Figure 1 shows the configuration of a typical concentrating element, having dimensions of 6.9 mm. x 6.9 mm. The concentration is achieved in a novel way using a folded mirror system, which, if it were operated with air or vacuum between the elements, would produce obscuration by the secondary folding mirror as in a classic “Cassegrainian” system in which a parabolic concave primary mirror converges light on a hyperbolic convex secondary mirror, which redirects the light to a focus near the center of the primary mirror. Since the secondary mirror is opaque in such a system, there will be obscuration of some rays, resulting in a loss of optical energy reaching the focal plane.

However, in an immersed system as shown in Figure 1, rays entering the optic, which, in this case, is fused silica, having a refraction index of 1.485, once the ray reflects from the silvered surface that it hits, if the ray in the fused silica reaches the front surface (unsilvered) at an angle to its normal greater than 42°, total internal reflection takes place, and the ray is directed back toward the primary surface. If a photovoltaic solar cell having a refractive index equal to or larger than 1.485 (or whatever the refractive index of the optic is) the ray will be absorbed by the cell and will generate electricity. This is true at any angle up to 90° relative to the normal to the immersion surface.

The first reflective surface, which is silvered, can take the shape of any surface (pyramid, cone, sphere, paraboloid, etc). In this case, an optimization analysis dictated that this reflective surface should be a pyramid, which provides the thinnest possible optical element, thus saving weight. Furthermore, since solar arrays are arranged in a Cartesian grid fashion, a square cross-section, rather than round was found to be preferable. There is no obscuration in this system, since rays which do not hit the silvered surface, hit the solar cell, so that there is no area of the entrance aperture that is obscured for near normal incidence rays to the entrance aperture. As the rays deviate from normal, the reflected rays from one facet of the pyramid do not exceed 42° and they therefore escape through the front aperture, and do not reach the solar cell. However, since a concentrating solar panel must track the sun to some degree, this small loss does not apply to a system which properly tracks the sun. This feature is advantageous for spacecraft which need power before the solar tracking system has locked-on to the sun. In this system the degraded power for off-axis pointing is only approximately 20%, while for conventional tracking systems the off-axis power drops to near zero.

The arrangement of the modular cells in a two dimensional solar panel is shown in Figure 2. In this design, the square “honeycomb” grid used in most solar panels provides additional optical concentration in addition to providing the required stiffness and strength to hold the cells in a single panel, quantities of which are tied together and folded accordion style during launch against the side of the payload.

As can be seen in Figure 2, for a nominal 6.9 mm. x 6.9 mm. concentrating optic exterior dimension, the grid spacing is 7.25 mm. x 7.25 mm. This allows a 0.35 mm. grid dimension between adjacent cells and allows the two piece grid construction shown in Figure 2. The aluminum extruded “c” section is an effective “clip” which slips over the “dovetail” mounting rail of the anodized aluminum pyramidal reflector grid, and for the continuous length piece equal to the width of the solar panel (one to two meters), this “c” section also accomplishes the function of electrical power conductor for the electrical energy generated by the linear array of cells adjacent to it. In the orthogonal direction, there is no “C” section required to retain the cells, and the anodizing coating of the aluminum grid prevents shorting out the plus and minus power busses.

A GaAs cell at full load produces approximately 0.8 volts d.c. Therefore, this voltage will appear between the plus and minus bus “c section” rails. For a 1 meter wide panel, there will be 138 cells in parallel, which will have an output current capability of 2.34 amperes. Since typical solar panels are designed to produce high voltages at low currents, at a 100 volt output, 43 of these bus bar pairs will be connected in series at the edge of the solar panel, and these series combinations will be connected in parallel with other sets of 43 bus bar pairs at the edge of the
SOLAR PANEL FABRICATION PROCESS

For the nominal size of the concentrator cell shown in Figures 1 and 2, there are 19,000 cells required for a 1 meter x 1 meter solar panel. It is therefore impractical to hand assemble such a solar panel. As will be seen in the calculation of the Figure of Merit for this solar power system, the weight and Figure of Merit is directly proportional the thickness of the fuse silica concentrating optic/solar cell substrate. Therefore, to maximize the Figure of Merit, we have chosen a nominal 5 mm. x 5 mm. solar cell dimension, as shown in Figure 6. If we increase this dimension to 1.0 cm. x 1.0 cm. then the number of cells in a 1.0 meter x 1.0 meter panel reduces by 4/1 to only 4756 cells, but the Figure of Merit degrades by 2/1. Even for 4756 cells an automated assembly system is necessary.

This automated assembly system uses the technology already developed by the electronics/TV industry, in which printed circuit boards are automatically populated by components using robot driven “pick-and-place” equipment, in which components are taken by a robot arm, which has a vacuum chuck, and is placed into its prescribed location on the printed circuit board to an accuracy of ±25 μm. This technology is already highly developed for printed circuit boards of up to 30 cm. x 30 cm.

For the solar panel manufacturing process proposed for this system, similar pick and place machines will be designed. These machines will first place the fused silica optical elements (without the solar cells) into the carbon fiber epoxy grid. Then, the machine will deposit the required amount of immersion medium, (of which a suitable example is Dow Corning silicone No. 93-500, which is already approved by NASA for long term space use) on each of the optical elements. During the pot life of this silicone material, the machine will mount the cells on the wet fused silica to a precision of ±50 μm, thus achieving optical immersion. After the silicone has fully cured, the same machine will ball-bond the leads to the bus bars using currently developed techniques, thus completing the fabrication of the solar panel in a fully automated process.

DESCRIPTION OF DESIGN NO. 2 (17 mm. x 17 mm. GaAs CELLS)

A valid criticism and disadvantage of Design No. 1 described above is that 19,000 cells are required for a 1.0 x 1.0 meter solar panel. This makes the solar panel assembly process complicated, requires 38,000 ball-bonded joints to be successfully made if the full power capability of the solar panel is to be realized. Also, because of the small cell size, the positioning tolerances of the cell placement machinery must be commensurately small. Counterbalancing this disadvantage is the very thin 2.1 mm. thickness of the solar panel.

An alternate configuration of this design uses much larger 17 mm. x 17 mm. GaAs cells in a 2.88/1 pyramidal concentrator, and reduces the number of cells per 1 m² panel to only 1076 cells, thereby reducing the solar panel assembly complexity by a factor of almost 20/1.

In this configuration, in order to reduce the thickness of the fused silica immersion element, it does not act as a concentrating optic, and functions only as a structural substrate for the GaAs cell as well as a window and radiation shield. The optical concentration is achieved in this design by the pyramidal reflective structural grid. As can be seen in Figures 3, 4, and 5, the assembly technique is closely similar to that of Design No. 1, except the concentrating grid is made of an aluminum thin wall structure fabricated by stamping, pressure-forming, or investment casting.

There are three advantages applicable to this method of construction:

1. The stamping or pressure forming method can be made very low cost in quantity production.
2. If aluminum or magnesium sheet metal is used, in these processes, it can be polished before forming, and can be clear anodized after forming to produce a high emissivity surface on the reflector to facilitate heat immersion.
dissipation of the solar cells into the forward hemisphere.

3. The 10 mm. thickness of the waffle grid makes it extremely rigid as compared to current solar panels.

If an investment casting process is used, the mold must have an adequately high polish so as to produce specular reflection for the pyramidal concentrator.

The assembly technique for this design is shown in Figure 4. The completed solar panel is composed of four components, assembled in the following order:

1. The “honeycomb” pyramidal aluminum or magnesium grid structure
2. The solar cell fused silica substrates
3. The solar cells
4. The power bus/cell retainers

Ideally, the grid structure would be formed in 1 meter x 1 meter sections, or smaller sections could be precisely welded together to form these sections.

The “Pick and Place” automated assembler would first mount the fused silica substrates into their appropriate places on the grid, leaving a small space between them for thermal “breathing”.

The one meter long power bus/cell retainers are precoated with bonding cement at the joining surfaces shown in Figure 3, and manually mounted on the grid.

Using the “Pick and Place” equipment, the GaAs solar cells, pre-coated with the silicone adhesive, would then be mounted and immersed on the rear surface of the fused silica substrates.

The final step in the assembly is the ball bonding of the two gold leads of each cell to the gold-plated aluminum/magnesium bus bar/cell retainers, and the connection of the positive and negative bus bars in series/parallel grids to achieve the high voltage/current configuration of the completed solar panel.

CALCULATION OF THE FIGURE OF MERIT FOR BOTH DESIGNS

DESIGN NO. 1

For the GaAs solar cell having dimensions of 5.0 mm. x 5.0 mm. the entrance aperture is 0.563 cm². The 0.137 w/cm² solar irradiance entering this aperture is 0.077 watt. By anti-reflection coating the front surface of the fused silica optic, >98% passes through, so that 0.075 watt reaches either the solar cell directly, or reflects from the silvered surfaces.

The power reaching the cell directly = 0.0343 watt

The aperture area having one reflection amounts to 0.17 cm². With a silver reflectance of 0.95 the power reaching the cell after one reflection is 0.023 watt. The remaining power reaches the cell after two reflections and has an aperture area of 0.056 cm² has a reflectance of 0.9. This dual reflected power is 0.0069 watt.

The total power reaching the cell is therefore 0.0343 + 0.023 + 0.0069 = 0.0642 watt.

Conservatively assuming a 20% efficiency for the GaAs cell the electrical energy generated is 0.0128 watt.

The weight of the assembly shown in Figure 2 is comprised of:

Fused silica optic (density 2.2 gm/cc) + mass of GaAs cells = 0.0297 + 0.011 + 0.019 gram = 0.0594 gram

The grid assembly (density 3 gms/cc) weighs 0.0417 gram for each element

The total mass per element is therefore: 0.0594 + 0.0417 = 0.101 gram

FIGURE OF MERIT = 0.0128/0.101 = 0.1267 watt/gram = 126.7 watts/Kg.

In this configuration, the stiffness of the solar panel is maintained by the grid structure, which is equivalent to a “honeycomb” construction, used extensively in the Aerospace Industry.
because of its very high stiffness-to-weight ratio. The solar cell/optic assemblies are not part of this structure, since they simply "nest" inside this honeycomb structure.

The Figure of Merit varies inversely with the linear dimension of the solar cell. This is true because if we double the linear cell dimension to 1.0 cm, the received power is increased by 4/1 but the volume and weight of the elemental assembly increases by 8/1 because of the required doubling of the thickness of all components (except the solar cell), so that the Figure of Merit degrades by 2/1.

DESIGN NO. 2

For the GaAs solar cell having dimensions of 1.7 cm x 1.7 cm, the entrance aperture is 2.9 cm². The 0.137 w/cm² solar irradiance entering this aperture is 0.398 watt. By anti-reflection coating the front surface of the fused silica optic, >98% passes through, so that 0.390 watt reaches the solar cell directly.

The aperture area having one reflection amounts to 3.68 cm². With an aluminum reflectance of 0.95 the power reaching the cell after one reflection is 0.494 watt.

The total power reaching the cell is therefore 0.390 + 0.494 = 0.884 watt.

Conservatively assuming a 20% efficiency for the GaAs cell the electrical energy generated is 0.177 watt.

The weight of the assembly shown in Figure 2 is comprised of:

Fused silica substrate (density 2.2 gm/cc) + mass of GaAs cells = 0.32 + 0.17 + 0.019 gram = 0.51 gram

The grid assembly (density 3 gms/cc) weighs 0.454 gram for each element

The electrical bus/cell retainer (density 3 gms/cc) weighs 0.468 gram for each element.

The total mass per element is therefore: 0.51 + 0.454 0.468 = 1.433 grams

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\text{FIGURE OF MERIT} = \frac{0.177}{1.433} = 0.1235 \text{ watt/gram}
\]

\[
= 123.5 \text{ watts/Kg.}
\]

If magnesium is used for the reflector and the electrical busses, the weight of these elements reduces by 1/3 and:

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\text{FIGURE OF MERIT} = \frac{0.177/1.118}{0.1582 \text{ watt/gram}} = 0.1582 \text{ watt/gram} = 158.2 \text{ watts/Kg}
\]

SURVIVABILITY OF THESE DESIGNS IN THE SPACE ENVIRONMENT

Even though the temperature coefficient of expansion of the aluminum grid structure is much larger than that of the fused silica optical elements, this is not a significant problem because there is no physical bonding of the cells to the aluminum grid structure. The cells are only clamped in by the retainer/bus bars and are free to thermally "breathe" in the presence of grid dimensional changes due to temperature. The gold electrical leads see very little stress, since the cells "ride" with the substrate during temperature changes, and the small dimensional changes over the 17 mm dimension of the cell substrate are well within the flexural capabilities of the gold ribbon leads. Therefore in the large temperature swings applicable to solar panels when the sun sets behind the earth, minimum stress should be applied to these optical elements and their solar cells. Because of the small dimensions of the solar cells and the resilient nature of the silicone immersion medium, minimum temperature stress will be applied to the immersion interface.

The survivability of the solar cells to ionizing Van Allen radiation in space should be greatly improved with this system because the immersion optic replaces the cover glass used in present solar cells, but is 4 to 5 times thicker, thus reducing the degradation to the cells commensurately. The rear surface of the cells is protected by the germanium substrate presently used for the GaAs cells. Additional shielding is also provided by the grid structure.
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The writer wishes to acknowledge the valuable insights given by Mr. Zack Pishnov into Design No. 2 above, which allows the use of much fewer cells per panel, while still achieving a high watt/Kg. Figure of Merit as well as a high watt/Dollar Figure of Merit achievable due to its expected low fabrication cost.
FIGURE 1 MODULAR IMMERSED CONCENTRATING SOLAR CELL
FIGURE 2 IMMERSED SOLAR POWER SYSTEM SHOWING MOUNTING GRID AND POWER LEADS
FIGURE 3  SECTION VIEW OF DESIGN NO. 2
CURRENT BUS

GaAs SOLAR CELL

FIGURE 4 REAR VIEW OF DESIGN NO. 2
FIGURE 5 FRONT ISOMETRIC VIEW OF DESIGN NO. 2
FIGURE 6 CONFIGURATION OF THE GaAs SOLAR CELL WITH LEADS (DESIGN NO. 1)
(5 x 5 mm. DIMENSIONS FOR DESIGN NO. 1, AND 17 x 17 mm. FOR DESIGN NO. 2)