MASS PROPERTIES SURVEY OF SOLAR ARRAY TECHNOLOGIES

Robert Kraus
W.J. Schafer Associates
Arlington, VA 22209

INTRODUCTION

An overview of the technologies, electrical performance, and mass characteristics of many of the presently available and the more advanced developmental space solar array technologies is presented. Qualitative trends and quantitative mass estimates as total array output power is increased from 1 kW to 5 kW at EOL from a single wing are shown.

The array technologies are part of a database supporting an ongoing solar power subsystem model development for top level subsystem and technology analyses. The model is used to estimate the overall electrical and thermal performance of the complete subsystem, and then calculate the mass and volume of the array, batteries, power management, and thermal control elements as an initial sizing. Technology tradeoffs and advantages can then be quantified within a consistent, system-level framework.

The array types considered here include planar rigid panel designs, flexible and rigid fold-out planar arrays, and two concentrator designs, one with one critical axis and the other with two critical axes. Solar cell technologies of silicon, gallium arsenide, and indium phosphide were included in the analyses.

Comparisons were made at the array level; hinges, booms, harnesses, support structures, power transfer, and launch retention mountings were included. It is important to note that the results presented here are approximations, and in some cases revised or modified performance and mass estimates of specific designs; this was necessary to fit the objective of this paper - an apples to apples comparison of array technologies.

SOLAR ARRAY TECHNOLOGIES

Planar rigid panel arrays have been the most commonly used design to date. The substrate used here comprises 10 mil graphite epoxy facesheets over an 0.75 inch aluminum honeycomb. Graphite epoxy facesheets provide more strength than aluminum facesheets at approximately two-thirds the mass density. Additional components are an insulation layer, adhesives, harness, and thermal control paint. The areal mass density of the substrate components was 1.6 kg/m2, including a 10% contingency. This represents an equivalent fused silica shield thickness of approximately 29 mils; 30 mils was used for degradation calculations. The packing factor of the cells was 0.90.

Solar cells of silicon (Si) and gallium arsenide on germanium (GaAs/Ge) were considered for GEO applications. Indium Phosphide (InP) was considered for an orbit closer to the radiation belts. Cell parameters are given in Table 1.

Three conceptually similar lightweight fold-out blanket designs of varying technical maturity were considered. The solar cells are mounted to thin blankets of kapton or lightweight metal that are a few mils thick. Electrical harnesses run along the outside longitudinal edges of the blanket. For launch, the blankets are folded and sandwiched in a foam housing. The arrays are then deployed using a continuously coiled lattice mast. Once deployed, the blanket is tensioned by a hanger/spring assembly.

The fold-out arrays considered were the Advanced Photovoltaic Solar Array (APSA) under development by NASA and JPL [1], another lightweight array of silicon on kapton under development at Lockheed [2], and the recently completed design of the SDIO planar Survivable Power Subsystem (SUPER) array [3]. The APSA array uses small (2 x 4 cm) thin (2.2 mil) silicon cells (13.8 % efficient BOL) on a kapton blanket. The blanket housing, mast, and deployment structures for the APSA array are very light. The Lockheed array under development has larger, thicker silicon cells (7.1 x 7.1 cm, 4 mils) on a kapton blanket with a lower packing factor than the APSA array. The SDIO planar SUPER design has large gallium arsenide on germanium cells (5.9 x 5.9 cm, 3.5 mils, 18% efficient) on a beryllium substrate. Because of the similarity in the designs, the fold out SUPER structures (boom, mast, etc) were used for the Lockheed Si on kapton array.

ORBIT ENVIRONMENT AND DESIGN DRIVERS

A geosynchronous (GEO) orbit of 35760 km, 0 deg inclination was selected for the flexible and rigid fold-out blanket designs, as it is the designed application. EOL performance was determined after 10 years. For the analyses here of both flexible blanket designs, the kapton blanket provided 3 mils of equivalent fused silica shielding on the back side of the solar cell. The planar SUPER substrate provided 12 mils of shielding, including the germanium cell substrate. The APSA array has 2 mil coverglasses, the lightweight silicon on kapton and the planar SUPER arrays have 3 mil coverglasses. Mass characteristics of rigid panels with 3 mils of coverglass in this environment were also determined and were compared to the lightweight blankets.

An orbit of 1111 km (600 nmi) at 80 degrees inclination was used for concentrator and InP technologies that are more resistant to the moderate natural radiation levels of this environment. In GEO, most of the damage to solar cells is due to electrons, whereas at 1111 km the damage is due primarily to protons. The equivalent 1 MeV fluence at 1111 km is approximately twice that at GEO.

The SUPER concentrator array is under development by SDIO to survive nuclear and laser threats.[4] The design provides a great deal of shielding to the 21.5% efficiency GaAs solar cells (at least 60 mils with infinite backshielding). It is also designed for a heavy lift launch vehicle, so extra structural mass for strength is included. Another novel concentrator using fresnel domes and very high efficiency (30%) GaAs on gallium antimidide is under development by Boeing after earlier development by NASA and Entech through an SDIO SBIR. The reference design used here is based on a Space Station design and has an aluminum concentrator structure.[5] For this study 9 mils front, and 12 mils equivalent back shielding were used.

The optical efficiency of the SUPER concentrator given in Table 3 includes the product of geometric off-pointing factors and mirror contamination. The fresnel concentrator optical efficiency is the product of lens absorption and darkening.

Degradation for the solar cells was determined using the technique outlined in reference [6]. The 1 Mev equivalent flux was determined from reference [6], and degradation factors specified in reference [7] were used for Si and GaAs/Ge cells. InP degradation was determined from unpublished Naval Research Laboratory documents.

Power from the array is calculated assuming full perpendicular solar insolation of 1350 W/m2. Cell power output is adjusted for operating temperature and environment degradation. An additional 4% loss due to micrometeorites, uv darkening, and harness line loss is also factored into the calculations. The electrical characteristics of the fold-out and concentrator arrays is summarized in Tables 2 and 3.

ARRAY SCALING AND ALGORITHM DEVELOPMENT

In order to make a more complete and consistent comparison between technologies, a total single wing array concept design consisting of solar cells, panel substrate, deployment, power transfer and harness, and support and launch retention structures was developed for each of the array designs.

An earlier rigid planar array study assumed boom and mechanisms to be 30% of cell-covered panel mass for 5 kW designs.[8] More detailed weight statements recently obtained for arrays indicated multipliers that were much larger for multi-kilowatt arrays; scaling parameters became even more difficult to determine because of the uniqueness of each reference design. Some estimates were made, however, such as limiting the area of individual panels, and using spring hinges between panels. A solar array drive motor, hinge, boom, and launch support mass were constant for all power levels. The power harness and power transfer slip ring mass were calculated as a ratio of the power output. When incorporated into the scaling algorithms and recalculated, the mass of the additional hardware represented 80% of the panel-only mass at 5 kW, and 170% of the panel mass at 1 kW.

For each of the fold-out array designs, mass properties information was available for a specific point design of 3000 to 4000 W array power at EOL. Blanket housing, mast canister, mast motor, array/spacecraft hinge, support tube, and support structure mass remained constant as power output was increased for each design. A diode box was not included. The APSA program does not include some of the components listed above, so an averaged value based on the other designs was used. As output power was increased, blanket panels and mast mass were added. Power transfer and harness masses were added as a ratio of array power.

These ratios were based on a range of design points. After setting the scaling parameters, the recalculated mass for each array was within a few per cent of its reference design point.

At 1111 km, only power producing panels are considered due to the variations of the technologies. The SUPER concentrator design is based on modularity; panels are available in full (~6 m2) or half (~3 m2) sizes. The fresnel concentrator design was converted to a W/kg ratio to determine mass at each power level. A major mass driver for this design is the fresnel dome. Two domes were considered, a high mass dome that has been demonstrated, and a low mass version under development. Due to the developmental nature of the design, a 15% contingency was added to the estimates. The InP panels were calculated using the same procedure as the GEO Si and GaAs/Ge panels.

Although the scaling approach described above may not represent the "best" array configuration, and may provide insufficient or extra mechanical support especially at the extremes (1000 and 5000 W), it does provide a consistant approach and seemed reasonable within the scope and limits of the study.

RESULTS AND SUMMARY

A graph of the Si and GaAs/Ge rigid panel mass as a function of increasing array output power is shown in Figure 1. The solid lines represent the mass of only the cell covered panels. The Si panels provide approximately 43 W/kg, the GaAs/Ge 54 W/kg. The lines would pass through the origin if the power was extended to 0 W. The dashed lines of Fig. 1 represent the estimates of the total array mass. The mass of the additional hardware is 80% of the panel-only mass at 5 kW, and 170% of the panel mass at 1 kW. The uncertainty is higher at 1 and 5 kW; the mass may be overestimated at 1 kW and underestimated at 5 kW.

The mass of the lightweight blanket mass as a function of increasing array output power is shown in Figure 2. The slope of the mass growth is much less than that for the rigid panel designs, because the blanket provides 110-190 W/kg, depending on the array technologies. This design concept clearly accommodates power growth with a lower weight penalty than rigid planar designs. Substantial structural mass is still required, however.

If the two design types are compared for a 3000 W array, the lightweight silicon on kapton is 16% lighter than the rigid silicon array. The lightweight silicon on kapton array has a 40% larger array, however, because of its much lower packing factor and greater degradation. The planar SUPER provides the same power for the same mass as the lightweight silicon on kapton, but is 12% smaller than the rigid silicon. The APSA array is yet another 30% lighter, even with the additional hardware added for this study.

A comparison of the concentrator and InP panels is shown in Fig. 3. The 'staircase' nature of the SUPER half panels is evident. The envelope of the fresnel concentrators ("Lo" mass and "Hi" mass domes) indicates a very light weight concentrator array is possible. The baseline design used here was intended for a LEO orbit. The InP panel mass is very close to the high mass fresnel panel due to its inherent resistance to natural space radiation. With a very small amount of extra shielding near the cells, EOL performance of concentrators could be improved for high radiation environments with a very small mass penalty. The InP panels would also require much more structural support than the concentrator here, however, because the InP array has a 50% larger area.

It is important to note that the SUPER concentrator has only one critical axis for sun tracking; a cosine loss (and a slight shadowing loss) occurs in the other axis similar to planar designs. The fresnel concentrator requires the mass of an additional gimbal for close tolerance tracking in the other axis as well.

Solar cell efficiency improvements and novel array designs continue to dramatically reduce solar array mass. Mass of the structures to support the array and mechanisms to transfer power also are a large fraction of total array mass. Technology or design improvements in these areas will also contribute to reducing weight of satellites.

REFERENCES

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Table 1. Rigid Panel Solar Cell Technologies

Cell Technology	Size (cm)	Thickness (mils)	BOL Eff'y	Degradation
Si	4.4 x 4.4	4	13.7	0.76
GaAs/Ge	4 x 4	3.5	18.0	0.83
InP	4 x 4	10	18.0	0.95

Table 2. Fold-Out Array Parameters

Design	Cell	BOL Eff'y	Packing	Degradation
APSA	Si	13.8	0.76	0.63
Si on Kap	Si	13.7	0.67	0.72
Planar SUPER	GaAs/Ge	18.0	0.77	0.81

Table 3. Concentrator Parameters

Design	Cell	BOL Eff'y	Temp (deg C)	Optics Eff'y	Degradation
SUPER	GaAs	21.5	130	0.87	0.93
Fresnel	GaAs+GaSb	30.0	80	0.87	0.80

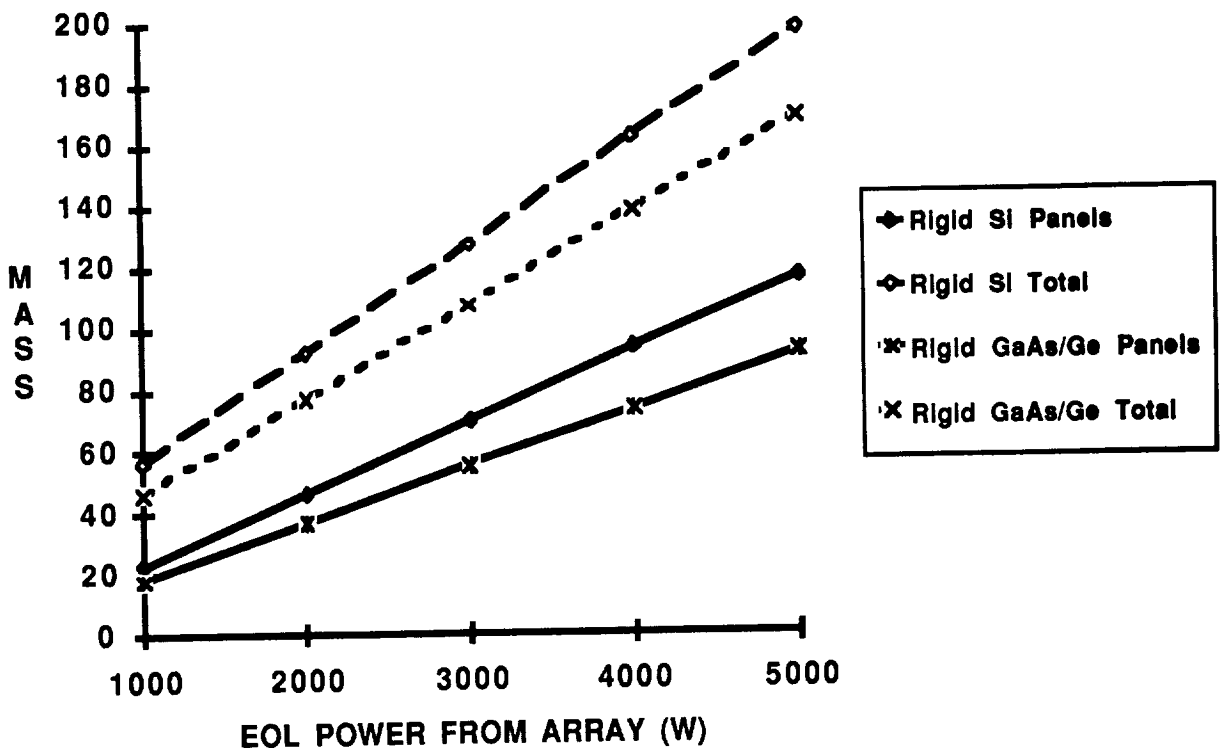

Figure 1. Rigid planar array mass

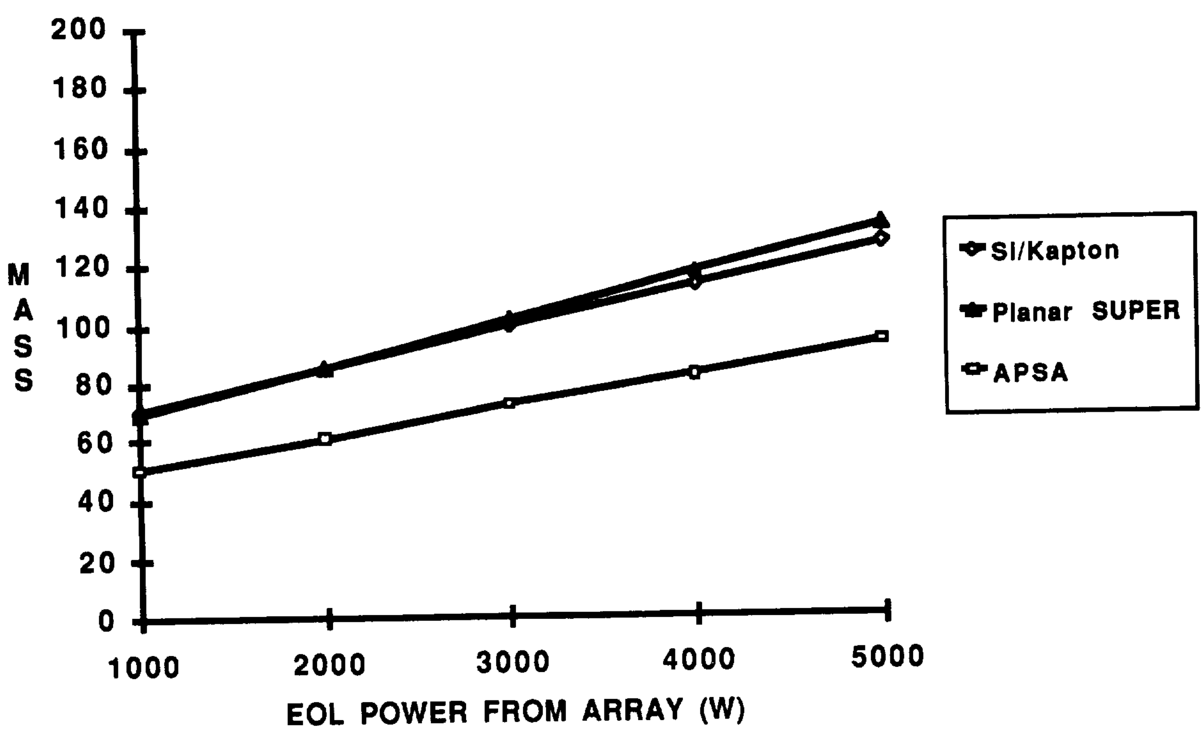

Figure 2. Foldout array mass

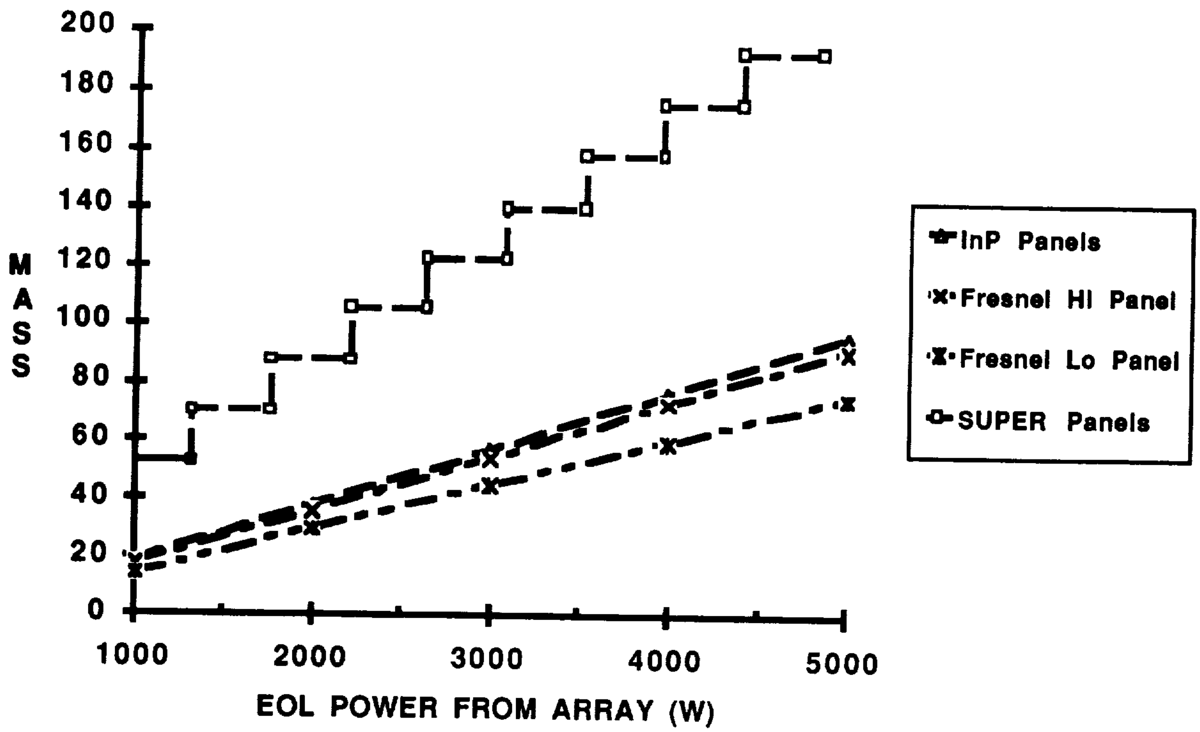

Figure 3. Concentrator and InP array mass