THIN-FILM SOLAR ARRAY EARTH ORBIT MISSION APPLICABILITY ASSESSMENT

David J. Hoffman
Thomas W. Kerslake
Aloysius F. Hepp
NASA Glenn Research Center, Cleveland, OH.

Ryne P. Raffaelle
Rochester Institute of Technology, Rochester, New York

ABSTRACT

This is a preliminary assessment of the applicability and spacecraft-level impact of using very lightweight thin-film solar arrays with relatively large deployed areas for representative Earth orbiting missions. The most and least attractive features of thin-film solar arrays are briefly discussed. A simple calculation is then presented illustrating that from a solar array alone mass perspective, larger arrays with less efficient but lighter thin-film solar cells can weigh less than smaller arrays with more efficient but heavier crystalline cells. However, a proper spacecraft-level systems assessment must take into account the additional mass associated with solar array deployed area: the propellant needed to desaturate the momentum accumulated from area-related disturbance torques and to perform aerodynamic drag makeup reboost. The results for such an assessment are presented for a representative low Earth orbit (LEO) mission, as a function of altitude and mission life, and a geostationary Earth orbit (GEO) mission. Discussion of the results includes a list of specific mission types most likely to benefit from using thin-film arrays. NASA Glenn's low-temperature approach to depositing thin-film cells on lightweight, flexible plastic substrates is also briefly discussed to provide a perspective on one approach to achieving this enabling technology. The paper concludes with a list of issues to be addressed prior to use of thin-film solar arrays in space and the observation that with their unique characteristics, very lightweight arrays using efficient, thin-film cells on flexible substrates may become the best array option for a subset of Earth orbiting missions.

BACKGROUND

Photovoltaic (PV) solar arrays using thin-film solar cell technology have much promise for future Earth-orbiting space missions. The most attractive features of thin-film solar arrays include the following:

Extremely lightweight	– enabling the highest solar array mass specific power, W/kg.
Low cost	– enabled by large scale "roll-to-roll" thin-film manufacturing processes.
Good packageability	– solar cell and blanket flexibility increase stowage options.
Radiation tolerant	– amorphous and polycrystalline thin-film cells are inherently resistant (1).

However, the projected efficiency of thin-film PV cells is currently about one-third to one-half of advanced thin-crystal silicon (Si) and multi-junction (or multi-band gap, MBG) gallium arsenide (GaAs) based cells. Consequently, for Earth orbiting missions, especially those in low Earth orbit (LEO), spacecraft-level impacts associated with the large deployed array area required for thin-film arrays can offset or even negate their lower array-level mass and cost benefits. The less attractive features of thin-film solar arrays are summarized below:

Large deployed areas	– two or three times the size of high-efficiency crystalline cell arrays. – increased propellant required for CMG desaturation and drag makeup. – possible instrument field-of-view impacts. – larger, potentially less stiff arrays may have lower first fundamental frequencies with potential attitude control system impacts and are more sensitive to propulsion system thrust levels.
Potentially less reliable	– more complicated deployment and support systems as compared to standard rigid panel arrays.

Recognizing the less attractive features of thin-film arrays, it is easy to conclude that unless dramatic gains are made in thin-film cell efficiency, these arrays will not fully replace high-efficiency cell arrays in the foreseeable future. Each type of array will support missions that take advantage of their unique characteristics. Figure 1 depicts the characteristics of solar arrays using either high-efficiency crystalline cells or thin-film cells by plotting cell efficiency and array power density (or area specific power, W/m^2) versus area density (or area specific mass, kg/m^2). Flexible planar, concentrator or inflatable arrays of moderate area density (1-2.5 kg/m^2) using either relatively heavy but very efficient multi-junction solar cells, or relatively lighter but less efficient thin silicon cells, could obtain an array-level specific power approaching 300 W/kg. To get to this level from the current state-of-the-art ~70 W/kg, new solar array substrates, support structures and deployment concepts may be needed in conjunction with improved cell technology (2)

Ultra-lightweight arrays (0.25-1.0 kg/m^2) using lightweight thin-film solar cells of moderate efficiency may enable the attainment of even greater array-level specific power. As the plot in figure 1 implies, very lightweight thin-film arrays may be the most feasible means of approaching the very high specific power necessary to enable missions with very high power requirements, such as space solar power satellites, manned Mars or lunar surface missions and some high-power solar electric propulsion (SEP) concepts (3, 4).

THIN-FILM ARRAY MASS BENEFITS

Array mass specific power, W/kg, is a key metric featured in Figure 1 and is often discussed, in many cases without full consideration of what is accounted for in its numerator and denominator. Further, the mass of the solar array alone is just one component in one subsystem of the entire spacecraft. To perform a proper systems assessment, the mass of other subsystems must be included, especially the mass of these subsystems that result from aspects of the original subsystem being assessed. This will be discussed further later. For this section, array mass alone serves as a starting point to illustrate the promise thin-film arrays.

From a solar array alone mass perspective, larger arrays with less efficient but lighter thin-film solar cells can weigh less than smaller arrays with more efficient but heavier crystalline cells. Array mass specific power can be obtained by dividing the area specific power (W/m^2) by the array's area density (kg/m^2). Area specific power is a function of the cell efficiency and array packing factor, which is the ratio of solar cell area to total array area. Area density is a function of the cell material density and thickness and the array substrate, wiring, support structure and mechanisms. To a first order, the cell efficiency required to match the specific power of an array of a given type but using different cells can be estimated with the following equation,

$$\eta_{TF} = \eta_2 \left(\frac{PF_2}{PF_{TF}} \right) \left(\frac{Array + Cell_{TF}}{Array + Cell_2} \right) \qquad \text{(Eq. 1)}$$

where η is the cell efficiency, *PF* is the array packing factor, *Array* is the area density (kg/m^2) of the array, including its wiring, substrate, support structure and mechanisms, and *Cell* is the cell area density. While the array area density is held constant in this first order approximation, in actuality, it would decrease with the use of lighter cell technology.

Figure 2 shows the approximate thin-film cell efficiency required to match the specific power of a high efficiency cell array using equation 1. Cell material densities, including the coverglass, of 0.50 kg/m^2 for the Si cell, 1.0 kg/m^2 for the multi-junction GaAs cells, and 0.2 kg/m^2 for the thin-film cells are assumed in figure 2. In practice, the actual cell efficiency required to match array specific mass will also depend on the cell operating temperature and degradation of the cell efficiency from environmental effects over the mission life. Nevertheless, figure 2 can be used to discern trends. For example, the figure shows that for very lightweight arrays (area densities from 0.25 to 0.75 kg/m^2), only moderate thin-film cell efficiencies are required to match the specific power of arrays using much higher efficiency, but heavier cells. Improvements in thin-film cell efficiencies may still be necessary in order to reduce the size of thin-film arrays in order to minimize attitude control system impacts and to reduce array stowed volume and deployment complexity for missions with these concerns.

While the potential array mass benefit is evident for thin-film arrays, it is mitigated, in some cases more than others, when spacecraft-level mass impacts are included.

PAST SYSTEMS STUDIES

A number of past studies have assessed the spacecraft-systems level impacts of solar cell and array technologies for Earth orbiting missions. In 1999, Eugene Ralph performed system trades for crystalline and thin-film cells on rigid, flexible and concentrator arrays in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) (5, 6). Ralph's results in reference 5 indicate that GEO arrays using high efficiency MBG GaAs-based cells have mass and cost advantages over alternatives, especially when the area penalty (increased attitude control fuel) of arrays using the less efficient thin-film cells is included. With Ralph's assumptions, thin-film cell efficiency needs to be at least 12.6% to be competitive in GEO. For LEO, Ralph concluded that while the most efficient multi-junction cell array has the lowest mass, arrays with 9% to 12.6% efficient thin-film cells have competitive area-adjusted costs.

The paper by Bell outlines a model developed by the Aerospace Corporation to "determine optimal power subsystem suites as a function of spacecraft design and total system cost" (7). Example model results are reported for a 100 satellite high-power (15kW) LEO constellation and a small, single-mission 1 kW LEO satellite. Study results for both cases favored high efficiency cell solar arrays. Because satellites in the LEO constellation were delivered to a low parking orbit and then transferred to the final 1852 km orbit, the large area of the 8%-10% efficient thin-film arrays led to significant attitude control system impacts, and ultimately higher mission costs. For the single-mission low power LEO case, the Aerospace model favored mature, low nonrecurring cost array technologies using 16% efficient Si and 21.5% efficient GaAs cells.

Each of the studies reviewed above looked at near-term thin-film cell technology on flexible, but not necessarily lightweight arrays for Earth orbiting applications. Only when the cell efficiency of a thin-film array was greater than 10% did they compare favorably with crystalline cell arrays for some of the missions studied.

EARTH ORBITING MISSIONS SYSTEMS ASSESSMENT

The objective of the present assessment is to perform a spacecraft-systems level assessment similar to the ones just reviewed, but assuming higher-performing cell and array technology in order to determine the "crossover" points in terms of systems mass. While small-area thin-film cells developed in the laboratory have exceeded 17% AM1.5 efficiency, thin-film cell efficiency of 10% (AM0) can be considered state-of-art for this technology. In this study, the performance of very lightweight thin-film arrays with assumed cell efficiencies of 10% and 15% (AM0, 28° C) sized for a representative LEO mission over a range of altitudes and mission lifetimes is evaluated. In addition, the spacecraft-level mass impacts of array size for a representative GEO mission is also assessed.

The NASA Glenn Array Design Assessment Model (ADAM) was used to perform the assessments. ADAM was developed at Glenn to support evaluation of array design alternatives (8). ADAM includes several integrated array design modules, databases to manage input set alternatives for running the design modules, and a user interface with input forms and model outputs. Outputs include over 100 items representing solar array, power system and spacecraft characteristics and performance. The spacecraft characteristics include estimates of the propellant required for reboost (drag makeup) and to desaturate CMGs or reaction wheels as a result of environmental disturbance torques (due to aerodynamic drag, gravity gradient, solar radiation pressure and magnetic moments).

For both LEO and GEO assessments, the baseline to which all mass results are normalized is an array using 30% GaAs-based multi-band gap (MBG) high-efficiency solar cells on rigid panels. While 30% MBG cells are not yet widely available commercially, high-efficiency MBG cells on rigid panels are a commonly used type of array for NASA Earth-orbiting missions. The first alternative array design assumes use of the same MBG cells but now on a flexible array substrate with a deployable coilable lattice boom, similar to the design of the International Space Station solar arrays. The next two alternatives are flexible thin-film cell array designs: one assumes 10% efficient thin-film cells and the other assumes 15% efficient cells. Both thin-film PV blanket area densities are 0.23 kg/m^2, which can be obtained if the thin-film cells are deposited on a plastic substrate or a very thin metal foil. All flexible array coilable lattice deployment booms are sized for $\geq$ 0.25 Hz minimum first fundamental frequency. For both LEO and GEO missions, the spacecraft is assumed to be Earth nadir-pointing with two single axis sun-tracking solar arrays. Average atmospheric density is assumed throughout the mission life.

Specific assumptions for the representative LEO and GEO cases are summarized in the following table:

LEO Mission Assumptions	GEO Misson Assumptions
400 km to 1200 km altitude; 5 year life	10 kW EOL Bus Power
0.25 to 5 year life at 500 km altitude	10 year mission life
2 kW EOL Bus Power	Constant maximum value of secular components of solar array radiation pressure torques
2500 kg Spacecraft Dry Mass	

RESULTS

LEO Mission Altitude Study –

Figure 3 shows mass as a function of altitude for the three alternative solar array designs alone as well as including the propellant mass required for impacts directly associated with solar array area - momentum wheel desaturation and drag makeup performed by hydrazine thrusters. In each case, the mass is normalized to the 30% efficient MBG cell rigid array, either alone or including its associated propellant mass.

The plot indicates that the mass of each type of solar array is constant over the range of altitudes. The flexible 30% MBG cell array is half the mass of the same cells on a rigid array. The 10% thin-film cell array has slightly greater mass, 0.57 of the baseline, while the 15% thin-film cell array has the least mass at 0.45 of the rigid baseline.

When including the propellant mass required as a result of array area, figure 3 shows that for the assumptions in this study the total mass increases rapidly below 700 km. At 600 km, the mass of the 10% thin-film cell array and its associated propellant equals the mass of the baseline rigid array and its associated propellant. This occurs at approximately 550 km for the 15% thin-film cell array. The reason for this is that the aerodynamic torque rapidly increases as the atmospheric density increases as altitude decreases.

Beyond 800 km, gravity gradient and solar pressure become the dominant disturbance torques, but are much less severe than the aerodynamic torques experienced at lower altitudes. At these higher altitudes, the propellant mass associated with solar array area is much less and approaches a negligible addition to the array mass alone.

LEO Mission Life Study –

The LEO altitude study clearly shows the severe impact of large array areas on propellant mass for lower LEO altitudes for a five-year mission duration. It also showed that flexible arrays using either 10% to 15% thin-film cells, or 30% MBG cells for that matter, offer a significant mass advantage (~50%) when considering the array alone. This implies that there will be a mission duration for which the alternative thin-film arrays should be competitive even when their associated propellant mass is included.

Figure 4 shows the mass of array plus propellant for the three flexible array options as compared to the rigid baseline for mission durations of three months to five years at an altitude of 500 km. For missions under three years, the 15% thin-film cell array and its propellant mass is less the 30% MBG cell rigid array baseline. Mission durations for the 10% thin-film cell array must be less than 1.5 years to preclude a mass penalty over the rigid array baseline when including propellant.

GEO Mission Study –

In GEO, the dominant environmental disturbance torque is a result of solar radiation pressure. The magnitude of this torque is directly related to the size of the solar arrays and the offset of the center-of-pressure that this force acts through and the spacecraft’s center of mass. While radiation pressure is predominantly a cyclic torque for a nadir-pointing spacecraft, there are non-zero (secular) components that result in the need for momentum storage and subsequent desaturation via thrusters.

Figure 5 shows the mass breakdown of solar arrays sized to provide 10 kW to the spacecraft bus over a 10-year mission. Also included is a “worst case” estimate of the propellant needed to desaturate the momentum wheels as a result of solar pressure torques. The 30% MBG cell arrays have a significant portion of their mass in the cell and cover glass masses. The dominant mass for the 30% MBG cell rigid array is the rigid panels.

The flexible arrays offer significant mass savings over the rigid array, even when propellant mass is included. For the thin-film cell arrays, the major mass contribution comes from the flexible blanket substrate and the addition of the propellant mass. However, for the significantly higher power level of this GEO mission as compared the LEO mission in this assessment, the mass advantage of the 15% thin-film cell flexible solar array is so significant (its mass is about 1/4th of the rigid array) that its additional propellant mass burden does not yield its mass advantage even to the flexible 30% MBG cell array.

DISCUSSION

It is recognized that different assumptions for any number of the parameters assumed in the above analysis could lead to a different threshold (e.g. altitude or mission life) for which one array option results in a lower total system mass as compared with another. In other words, while the results above are meant to be representative to realistic classes of Earth-orbiting missions, results for actual, individual missions will no doubt vary.

That said, it is felt that the input assumptions and model fidelity is good enough to indicate more specifically the Earth-orbiting mission types which could make best use of the mass advantages thin-film solar arrays without mitigation from the spacecraft-level mass impacts associated with larger deployed areas.

Attractive Earth-orbiting applications for thin-film arrays include:

- LEO missions above 500 km to 800 km
- LEO missions of short duration, especially at lower altitudes
- LEO sun-syncronous missions with array normal perpendicular to velocity vector
- LEO-to-GEO transfer missions: good radiation tolerance.
- GEO missions, given thin-film cell efficiency $\geq$10%
- Very small micro/nanosat missions

While some of the types of missions in the preceding list were not addressed in this study, the benefits of thin-film solar arrays for these missions are at least intuitively obvious, and have been quantitatively explored in other studies (see reference 4 for SEP transfer missions).

THIN-FILM CELL DEVELOPMENT AT NASA GLENN

Among the desirable attributes in any space-bound component, subsystem or system are high specific power, radiation tolerance and high reliability, without sacrificing performance. NASA Glenn is currently developing space-bound technologies in thin film chalcopyrite solar cells and thin-film lithium polymer batteries (9). The thin-film solar cell efforts at Glenn are summarized below.

The key to achieving high specific power solar arrays is the development of a high-efficiency, thin-film solar cell that can be fabricated directly on a flexible, lightweight, space-qualified durable substrate. Such substrates include Kapton™ (DuPont) or other polyimides or suitable polymer films. While the results of the present study indicate that lightweight thin-film cells with moderate efficiency on lightweight substrates can compete on a mass basis, higher cell efficiencies will be required to mitigate impacts associated with large array area. Current thin-film cell fabrication approaches are limited by either (A) the ultimate efficiency that can be achieved with the device material and structure, or (B) the requirement for high-temperature deposition processes that are incompatible with all presently known flexible polymides, or other polymer substrate materials.

At Glenn, a chemically based approach is enabling the development of a process that will produce high-efficiency cells at temperatures below 400 °C. Such low temperatures minimize the problems associated with the difference between the coefficients of thermal expansion of the substrate and thin-film solar cell and/or decomposition of the substrate.

Polymer substrates can be used in low temperatures processes. As such, thin-film solar cell materials can be deposited onto molybdenum-coated Kapton, or other suitable substrates, via a chemical spray process using advanced single-source precursors. A single-source precursor containing all the required chemically-coordinated atoms such as copper, indium, sulfur and others, will enable the use of low deposition temperatures that are compatible with the substrate of choice (10).

A combination of low-temperature chemical vapor deposition and chemical bath deposition has been used to produce $ZnO/CdS/CuInSe_2$ thin-film photovoltaic solar cells on lightweight flexible plastic substrates, depicted in figure 6 (11)

CONCLUSION

Until thin-film PV is further developed, future Earth-orbiting missions will most likely keep using high efficiency silicon or MBG cell rigid planar arrays, and perhaps an occasional flexible MBG cell array or a concentrator array. In order for thin-film solar arrays to be more seriously considered, a number of issues need to be further addressed:

1. Thin-film *cell efficiencies* **increase** and/or *substrate mass* **decreases**.
   Need economical large-scale production of large-area (e.g. >10-cm^2) thin-film cells with stable efficiencies > 10% to 15% (1-Sun AM0) on low-mass substrates (1-mil metallic, 5-mil pre-preg composite ply, 2-mil polymer, open-weave polymer).

2. Thin-film *cell* **space qualification is completed**.
   Need to demonstrate tolerance to radiation, thermal cycling (delamination), mechanical strain (packaging and blanket tensioning) and (for amorphous silicon) light-induced instability.

3. Thin-film *solar arrays* are **designed** and **space qualified**.
   Need packaging, deployment systems and support structures tailored to thin-films.

4. *Appropriate missions* are **identified…**
   …that would benefit from thin-film array attributes (high specific power, good packageability, radiation tolerance, low cost) and whose benefits are not mitigated by spacecraft-level operations issues associated with larger area, low-mass arrays (see the "Discussion" section for a list of Earth-orbiting mission candidates.)

Once available and space qualified, moderate to relatively high efficiency thin-film cells on lightweight flexible substrates will offer significant mass and cost benefits. This approach may even enable ultra-lightweight solar arrays to attain the very high specific mass required for future high-power missions and applications. Further, as thin-film cell efficiency improves, the packaging, deployment and attitude/control impacts of the larger array area will diminish. With these characteristics, very lightweight arrays using efficient, thin-film cells on flexible substrates may become a leading alternative for a large subset of Earth-orbiting missions.

REFERENCES

1. Woodyard, J., Landis, G., "Radiation Resistance of Thin Film Solar Cells", *Solar Cells*, Vol. 31, No. 4, pp. 297-329, 1991 (also NASA Technical Memorandum TM-103715).
2. Jones, P.A., White, Stephen F., Harvey, T.J., "A High Specific Power Solar Array for Low to Mid-Power Spacecraft", Proceedings of the Space Photovoltaic Research and Technology Conference (SPRAT XII), 1992, NASA CP-3210, pp. 177-187.
3. Landis, G., Hepp, A., "Applications of Thin-Film PV for Space", Proceedings of the 26th Intersociety Energy Conversion Engineering Conference, Vol. 2, pp. 256-261, Aug. 1991.
4. Kerslake, Thomas W., Gefert, Leon P., "Solar Power System Analyses for Electric Propulsion Missions", NASA/TM-1999-209289, SAE 99-01-2449, 34th IECEC, August 1999.
5. Ralph, E.L., Woike, T.W., "Solar Cell Array System Trades – Present and Future", AIAA, 1999.
6. Ralph, E.L., "High Efficiency Solar Cell Arrays System Trade-Offs", IEEE, 1994.
7. Bell, Kevin D., Marvin, Dean C., "Power Generation and Storage Technology Selection for an Optimal Spacecraft System Design", IECEC 1999-01-2531.
8. Hoffman, David J., Kerslake, Thomas W., Hepp, Aloysius F., Jacobs, Mark K., Ponnusamy, Deva, "Thin-Film Photovoltaic Solar Array Parametric Assessment", 35th Intersociety Energy Conversion Engineering Conference, Las Vegas, NV, July 24-28, 2000. "Thin-Film PV Solar Array Assessment for Satellites, Final Review Report," contract number NAS3-26565, Task Order 31.
9. Raffaelle, R.P., Harris, J.D., Rybicki, G.C., Scheiman, D.A., Hepp, A.F., "A Facile Route to Thin-Film Solid State Lithium Microelectric Batteries", *J. of Power Sources*, in press, 2000.

10. Hollingsworth, J.A., Hepp, A.F., and Buhro, W.E., ‘Spray CVD of Copper Indium Sulfide films: Control of Microstructure and Crystallographic Orientation”, *Chemical Vapor Deposition*, Vol.3, pp. 105-108, 1999.
11. J.D. Harris, D.G. Hehemann, J.E. Cowen, A.F. Hepp, R.P. Raffaelle, J.A. Hollingsworth, “Using Single Source Precursors and Spray Chemical Vapor Deposition to Grow Thin Film $CuInS_2$,” *28th Photovoltaic Specialists Conference*, September 17-22, pp. 563-566, 2000.

Figure 1 - Lightweight solar array technology thrusts.

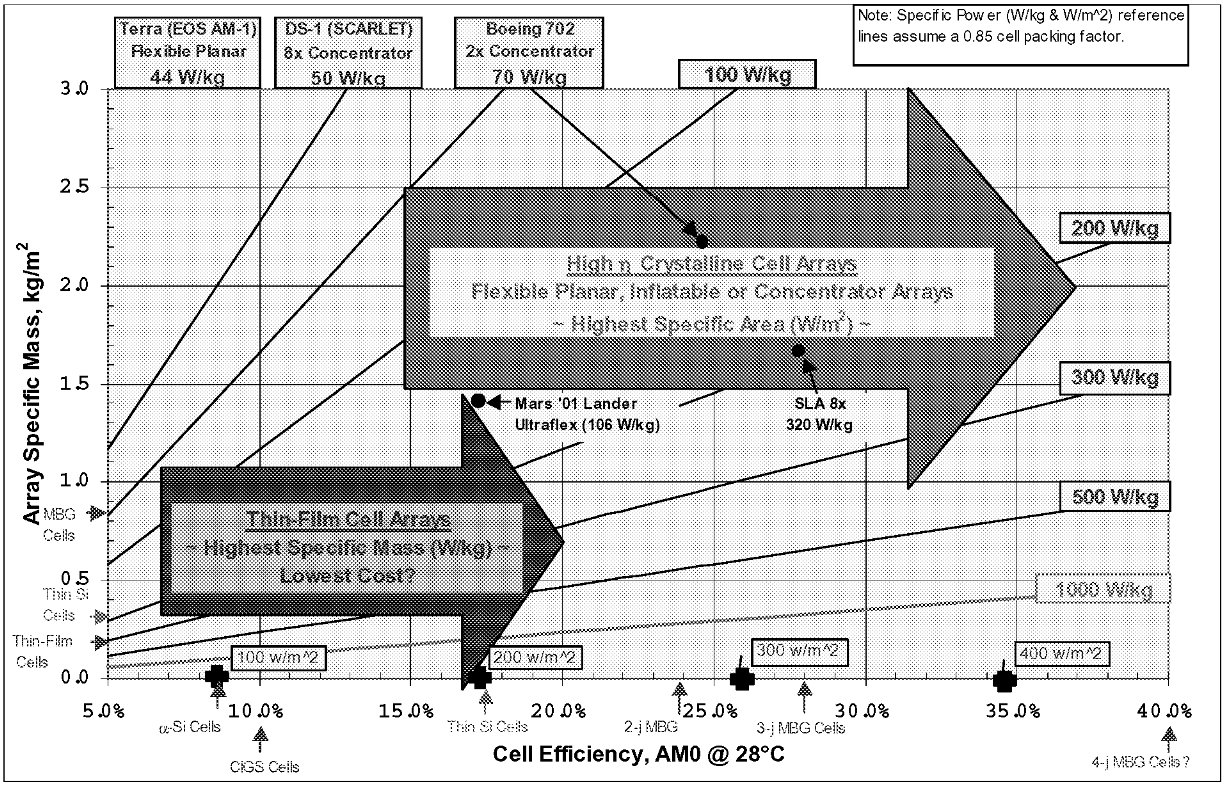


Figure 2 - Approximate thin-film cell efficiency required to match high efficiency cell array mass.

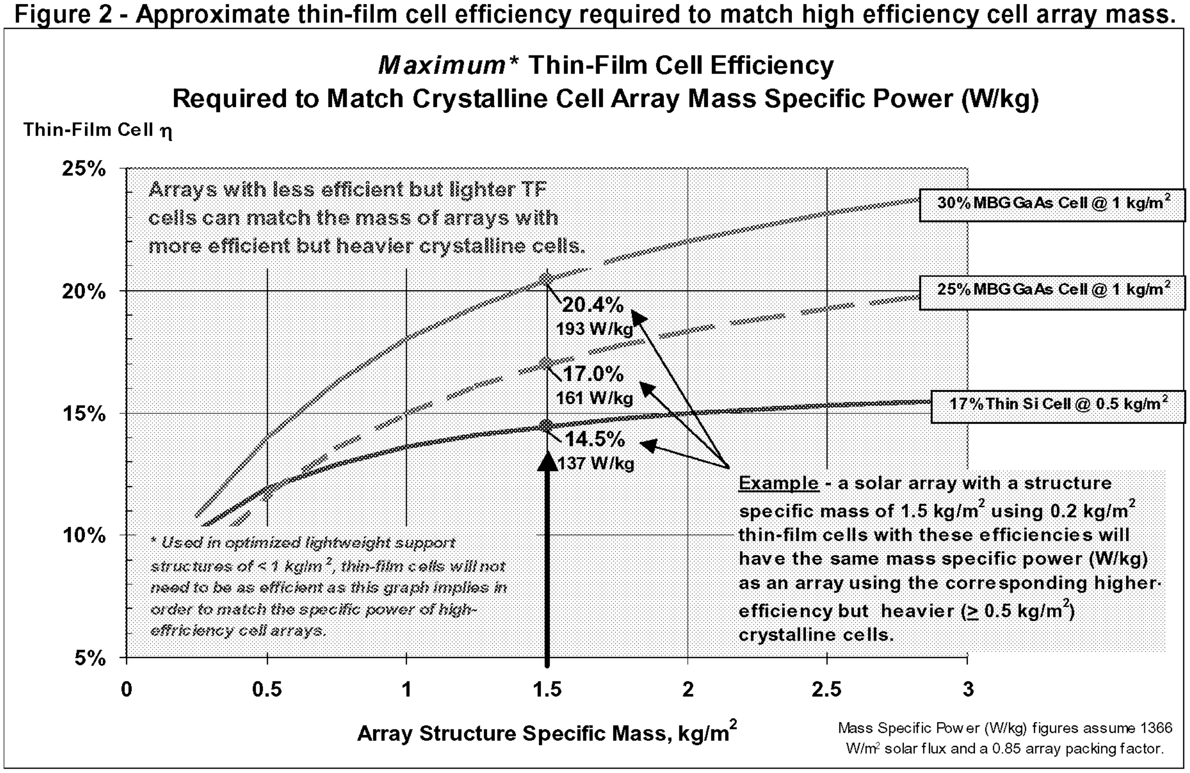


Figure 3 – Larger LEO arrays require in additional propellant.

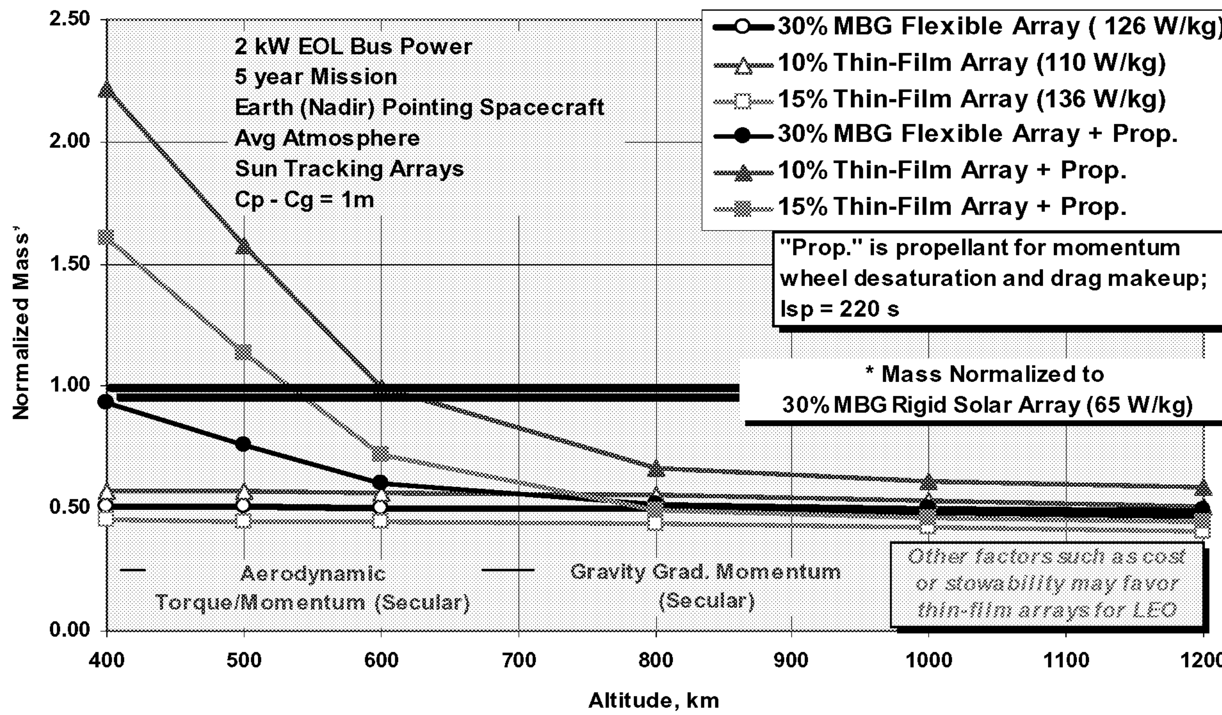
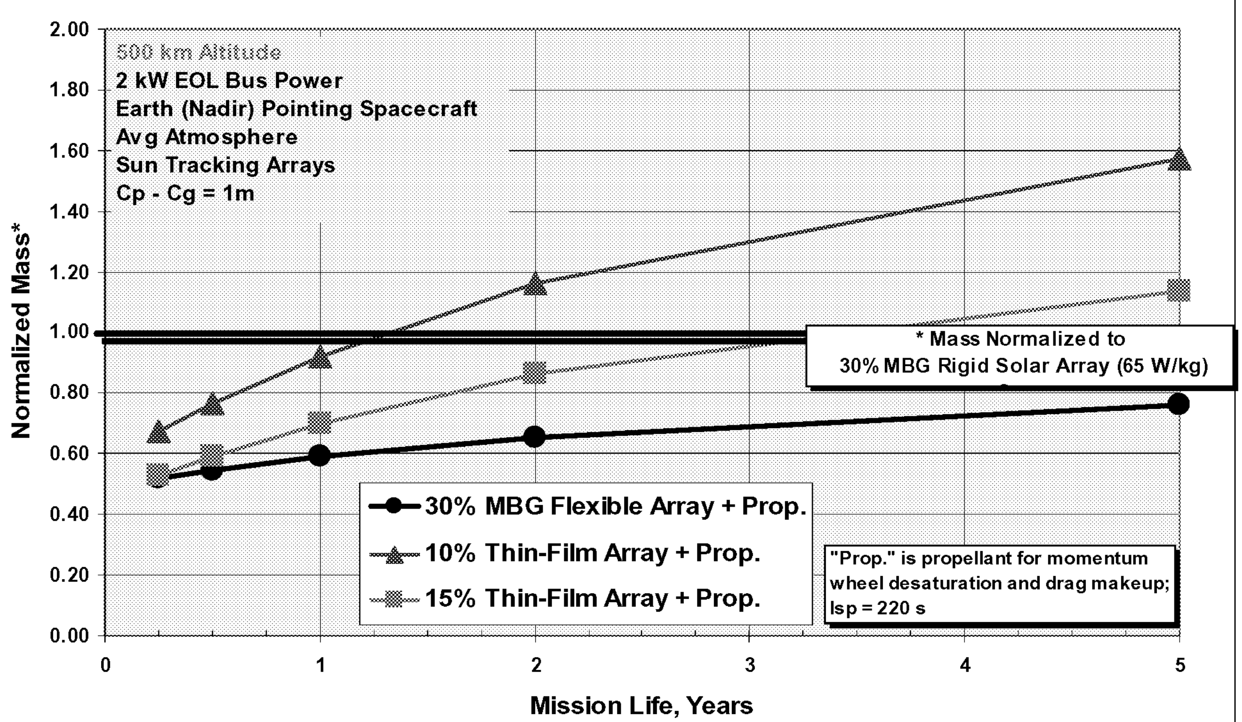


Figure 4 – Shorter mission life mitigates mass impact of larger solar arrays in LEO.



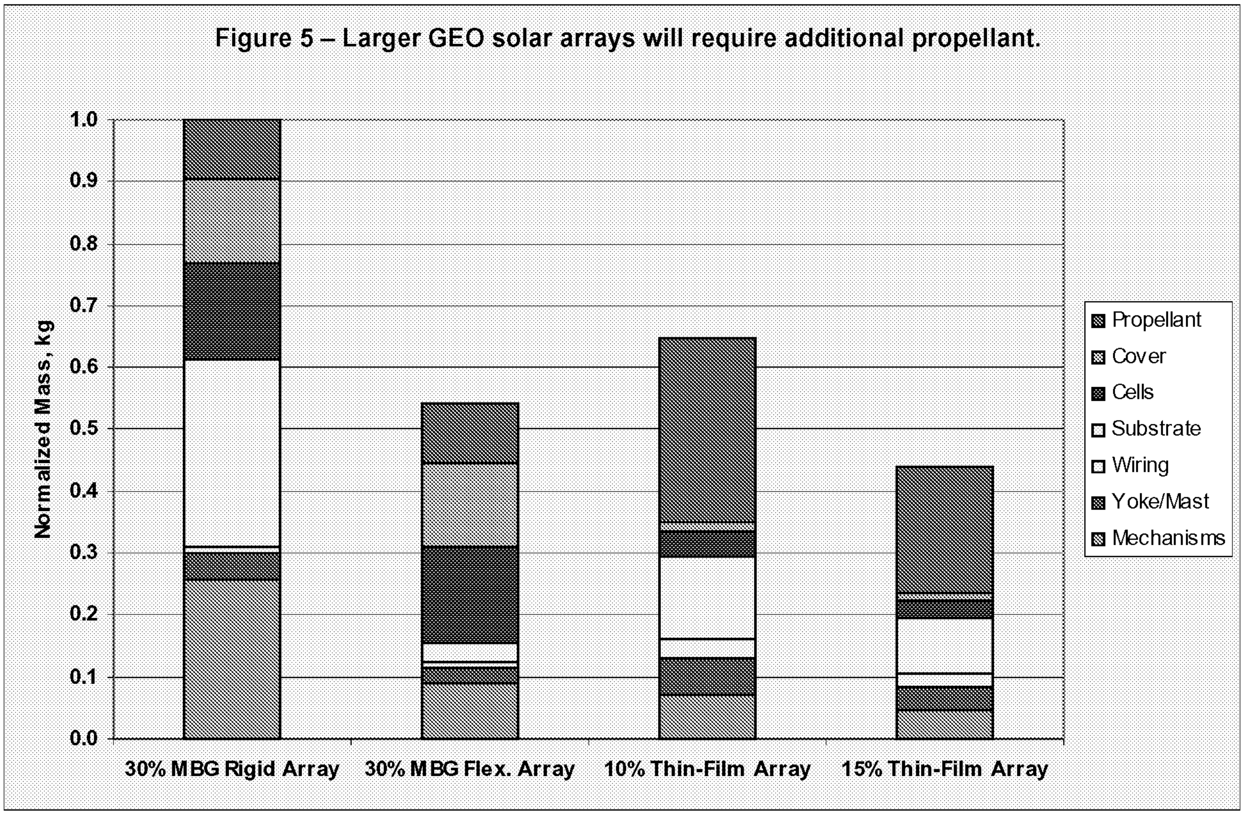


Figure 6 - NASA GRC thin-film cell approach.