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14. ABSTRACT Advanced solar arrays capable of generating greater than 50 kW of total power, at power densities greater than 250 W/kg, are required for many future Air Force missions. The largest heritage systems are limited to less than 15 kW of total power, at roughly 50 W/kg. The Roll Out and Passively Deployed Array (RAPDAR) design will demonstrate the feasibility of 50 kW, 250 W/kg-class solar array systems through an innovative design that takes full advantage of the latest advances in thin-film photovoltaic and TEMBO® Elastic Memory Composite (EMC) deployment technologies. The use of solar energy to passively deploy the array further improves the overall system efficiency. The present paper addresses the development and validation of detailed designs for the RAPDAR (patent applied for) structural system. Specific focus is placed on the development and validation of the EMC longerons, which are the primary structural members for the RAPDAR system controlling packaging and deployment, and providing primary stiffness and strength to the deployed system. The paper includes results from both analysis and testing of EMC longerons that demonstrate deployment and shape-storage capacity.

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Development of a Novel, Passively Deployed Roll-Out Solar Array

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Abstract – Advanced solar arrays capable of generating greater than 50 kW of total power, at power densities greater than 250 W/kg, are required for many future Air Force missions. The largest heritage systems are limited to less than 15 kW of total power, at roughly 50 W/kg. The Roll Out and Passively Deployed Array (RAPDAR) design will demonstrate the feasibility of 50 kW, 250 W/kg-class solar array systems through an innovative design that takes full advantage of the latest advances in thin-film photovoltaic and TEMBO® Elastic Memory Composite (EMC) deployment technologies. The use of solar energy to passively deploy the array further improves the overall system efficiency. The present paper addresses the development and validation of detailed designs for the RAPDAR (patent applied for) structural system. Specific focus is placed on the development and validation of the EMC longerons, which are the primary structural members for the RAPDAR system controlling packaging and deployment, and providing primary stiffness and strength to the deployed system. The paper includes results from both analysis and testing of EMC longerons that demonstrate deployment and shape-storage capacity.

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1. INTRODUCTION

Future satellite power subsystems will be designed to achieve higher power levels, power densities (kW/kg), launch packaging densities (kW/m^3), and lower unit costs ($/kW) than can be achieved with current solar array technologies. The largest currently available commercial solar arrays provide only about 15 kW end-of-life power, with power densities of 50-70 W/kg, packaging efficiencies of 10-15 kW/m^3, and costs of about $1,000/Watt. Future large spacecraft may require up to 50 kW of power at power densities greater than 250W/kg, as well as lower costs and improved packaging density and power density. Scale-up of current technologies, such as rigid flat-panel solar arrays, is likely to be very expensive and require larger launch vehicles due to their inherent packaging limitations and low mass efficiency. Thin film photovoltaic (TFPV) solar arrays offer the potential for providing very high power levels in a lightweight configuration that can be compactly packaged for

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launch. However, the lower power-conversion efficiency of TFPV as compared to existing photovoltaic technologies means that larger deployed areas are required to provide a given total power. This limitation in TFPV technology means that TFPV systems will only be practical if more efficient deployment technologies and structural designs can be developed.

Current deployable solar array systems are based on designs that have been in existence for more than 30 years. In general, these heritage designs can be divided into two classes: 1) hinged-panel arrays, which are mechanically simple but mass inefficient, and 2) tensioned-membrane arrays, which are mechanically complex but mass efficient. Arguably, no deployable solar array designs exist that are *both* mechanically simple *and* mass efficient. To address this need, the Roll Out and Passively Deployed Solar Array (RAPDAR) combines an innovative structural concept with TEMBO® Elastic Memory Composite (EMC) technology for efficient packaging, deployment control, and post-deployed stiffness and strength. RAPDAR is being developed as an enabling technology for future ultra-large, ultra-efficient TFPV solar arrays.

TEMBO® Elastic Memory Composites

TEMBO® EMC materials exhibit many favorable qualities for deployable space structures and have piqued a broad interest within America's deployable space structures industry.[1] To date, TEMBO® EMC materials have been fabricated into a variety of components for deployable structures, including laminated plates and shells, open-grid lattices, pultruded rods, and hinges.[2] TEMBO® EMC materials, which combine a fully-cured thermoset TEMBO® shape memory polymer matrix with traditional fiber reinforcements, are characterized by an ability to "freeze" and release induced strain energy via a specific thermo-mechanical cycle.[3] Furthermore, TEMBO® EMC materials can achieve significantly higher induced packaging strains than traditional hard-resin composites without damage to the fibers or the resin,[4] which leads to TEMBO® EMC components that can be packaged more compactly than traditional designs. TEMBO® EMC materials also provide high strength and modulus, and low density, which leads to lightweight component designs. Finally, TEMBO® EMC materials provide the added advantage of much lower stored strain energy than traditional high-strain, high-stiffness materials, thus significantly reducing parasitic mass associated with launch-containment devices. These unique capabilities are currently being exploited in the development of the highly efficient RAPDAR structural system.

Thin Film Photovoltaic Cells

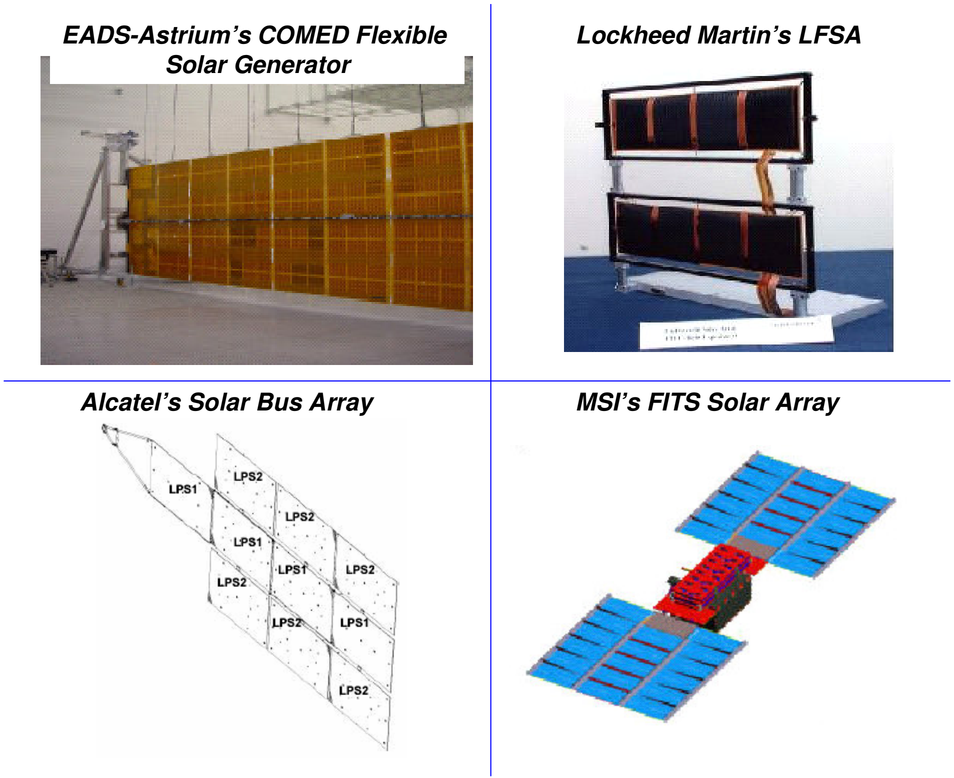
TFPV cells have become attractive for space applications due to their increased specific power (W/kg), superior radiation resistance, reduced cost, and increased flexibility as compared to traditional rigid crystalline cells.[5,6] The most common TFPV's consist of either amorphous silicon (a-Si) alloy or Copper Indium Gallium deSelinide (CIGS) cells deposited on a thin metallic or polyimide substrate resulting in very thin, highly flexible solar array material. A highly simplified, roll-to-roll processing method is utilized to produce the cells resulting in a highly scalable process with a significant cost reduction over rigid crystalline cells. Thus far, solar cell specific powers between 300-400 W/kg and efficiencies greater than 10% have been achieved.[7,8]

Next Generation of Deployable Solar Arrays

The combination of TEMBO® EMC materials with TFPV cells creates the potential of revolutionizing the design of deployable solar arrays. TEMBO® EMC materials eliminate the need for highly complex deployment mechanisms, massive launch canisters, and deployment-control systems, while TFPV arrays enable the use of simple packaging and deployment techniques. Furthermore, it is anticipated that the architectural simplicity and solid-state fabrication techniques will enable these advanced TEMBO® EMC/TFPV array systems to be built and flight qualified for roughly one-fifth the cost (per Watt of on-orbit power) of current crystalline photovoltaic systems. The shape memory and high-strain characteristics of TEMBO® EMC coupled with the flexibility of the TFPV enables a completely new class of furlable solar array structures that marks a major departure from heritage technologies.

2. A SURVEY OF TFPV SOLAR ARRAY CONCEPTS

A recent literature search revealed several flight development programs for TVPV arrays within both the United States and European space markets. Most of these systems have specific power targets greater than 100W/kg. Both EADS-Astrium's COMED Flexible Solar Generator and Microsat System Inc.'s Foldable, Integrated, Thin-film Stiffened array (FITS) feature folded panels of TFPV that are deployed using elastic hinge elements.[9,10] Alcatel's SOLARBUS array and Lockheed Martin's Lightweight Flexible Solar Array (LFSA) take a similar, panel-folded


EADS-Astrium's COMED Flexible Solar Generator

Lockheed Martin's LFSA

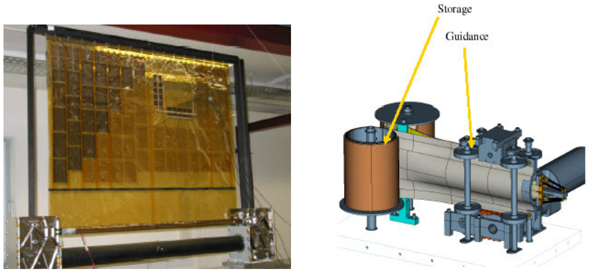
Alcatel's Solar Bus Array

MSI's FITS Solar Array

Figure 1. Various TFPV Solar Array Systems[9,10,11,12]

design and combine shape memory deployment through the use of shape memory alloy (SMA) torsion and hinge actuators respectively.[11,12] Figure 1 presents photographs and illustrations of these four, flat-panel concepts.

Hoch Technoligie Systeme (HTS) takes a substantially different approach with their Flexible Solar Generator by using a continuously spooled concept that suspends the TFPV cells between two primary longerons (see Figure 2(a)). Deployment is accomplished by using a motor and driving mechanism to unspool the system. Furthermore, the two primary longerons are constructed of two face-to-face carpenter tape booms that are bonded in-orbit during deployment resulting in a lenticular cross-section (see Figure 2(b)).



(a) Realized Structure (b) In-orbit boom bonding

Figure 2. HTS's Flexible Solar Generator[13]

With the exception of HTS's Flexible Solar Generator, these concepts do not demonstrate a significant departure from heritage deployment technologies and as a result are inherently limited in the total power and packaging efficiencies that can be achieved. HTS's concept while being a significant departure from heritage deployment technologies involves significant mechanical complexity and structural performance uncertainty associated with the in-orbit boom bonding step. All of these concepts share the same limitation in that they are difficult to scale to large (i.e., > 15kW total power) sizes while maintaining a reasonable deployed frequency (i.e., ≥0.2 Hz) due to their lack of structural depth. As a result, none of these concepts could be practically considered for future missions, which require a very high power.

3. RAPDAR SYSTEM OVERVIEW

The overall layout of the RAPDAR array system is shown in Figure 3. The design is scalable to between 1 and 50 kW size, and is applicable to a variety of future large commercial and government solar arrays. The RAPDAR system features two TEMBO® EMC primary longerons that are flattened and rolled for stowage and regain their original cross-section during deployment. The primary longerons are connected by a series of battens, forming a central panel. Wing panels attach to the outsides of both primary longerons, and stow by folding across the center panel. As the center panel unrolls, the wings open and are held at a slight angle to the center panel by tensioned diagonals running from the tip of one wing to the tip of the other. TFPV blankets span the length and width of the deployed structure.

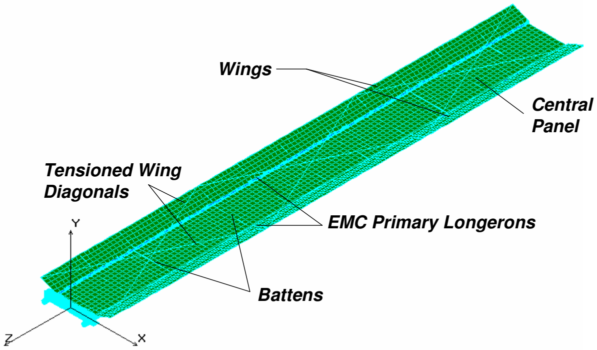
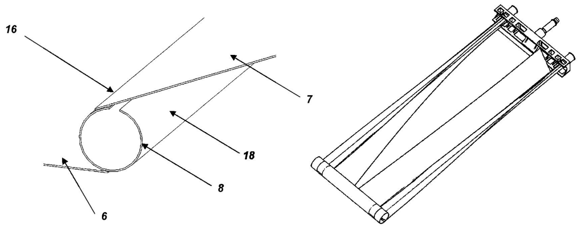


Figure 3. RAPDAR solar array system.

Packaging and Deployment Concept

As shown in Figure 4, the TEMBO® EMC primary longeron is a slit-tube design. This allows the tube to be flattened and rolled. The battens and wing-edge longerons are made of an elastic material and have open cross-sections to allow them to be flattened during packaging. The TEMBO® EMC primary longeron also functions as the wing hinge during packaging and deployment. The wings are folded onto the central panel while flattening the primary longeron, which puts the three-panel assembly into a single plane configuration that can be rolled into a cylindrical package.



Close-up of Longeron Partially Deployed System

Figure 4. RAPDAR TEMBO® EMC primary longeron.

The deploying force is primarily derived from the strain energy stored in the rolled TEMBO® EMC primary longerons. Additional strain energy is stored in the other frame elements, which are flattened and rolled into the stowed configuration. Most importantly, the TEMBO® EMC primary longerons are designed to "freeze" all of the stored strain energy in their cold state, and release this energy in a controlled fashion when heated passively by the sun (as will be discussed in the next section).

While the TEMBO® EMC primary longerons are unrolling, the wings are being deployed due to their integral nature (Figure 5). The depth established by the deploying wings minimizes the ability for the partially unrolled array to roll back on itself like a yo-yo. When deployment is complete, the wing-to-wing diagonal cables are tensioned to stabilize and stiffen the structure. Figure 5 shows four stages of deployment overlaid on one another.

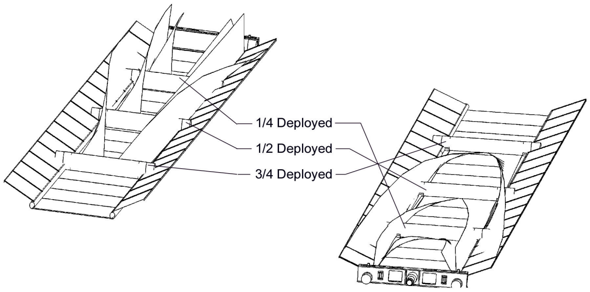


Figure 5. Stages of deployment.

System Scalability

As previously stated, the array system is scalable to between 1 and 50kW size. This is a key system feature that differentiates it from other TFPV flight development programs. By incorporating the wings, the RAPDAR system achieves deployed stability and structural depth, which is a feature key to maintaining reasonable deployed frequencies at larger sizes. Furthermore, the spooled packaging method takes full advantage of the TFPV's flexibility resulting in a highly efficient array system with projected power densities several factors greater than other TFPV solar array concepts.

For example, analyses have shown that a 50kW version of the RAPDAR solar array system would be approximately 6m wide by 60m in length, possess a total mass of approximately 140 kg, and exhibit a fundamental frequency of 0.23 Hz. This frequency is relatively high for the size and mass of the system, a key performance metric that will moderate demands on actuation and control systems. Note, the projected power density for the system would be over 350 W/kg, which is significantly higher than the 200 W/kg threshold identified as a market requirement.

4. RAPDAR PASSIVE DEPLOYMENT

Deploying a TEMBO® EMC structure requires the presence of heat since both packaging and deployment must be accomplished above the polymer's glass transition temperature, T_g. Historically, TEMBO® EMC components have incorporated surface-bonded heaters for packaging and deployment control. A unique aspect of the RAPDAR solar array is the use of solar energy to control deployment. Referred to as passive deployment, the concept of exploiting the solar thermal environment to enable deployment significantly reduces the system's complexity and eliminates the need for on-board power during deployment, thus improving the system's overall efficiency. The feasibility of passive deployment has been demonstrated through thermal analyses and ground testing, as described in the following subsections.

Analysis

Preliminary thermal analyses based on a geosynchronous orbit (GEO) were performed to determine estimates for the peak temperatures, temperature distributions, and heating rates that would be experienced in the TEMBO® EMC primary longerons due to passive solar heating. These analyses considered only heating from the solar flux (i.e., no heating from the Earth's albedo was considered). The analyses assumed optical properties (i.e., absorbtance and emmittance) of bare graphite epoxy on the inside surface of the TEMBO® EMC primary longerons, and either bare or white-coated optical properties on the outside surface. Finally, steady-state and transient analyses were performed.

Figure 6 presents steady-state thermal analysis results where the inside of the roll is solar pointing. The temperature contours indicate a temperature variation of over 200°C between the top and bottom of the roll. The maximum realized temperature exceeds 100°C and occurs throughout the transition region of the slit-tube longeron. This is key since recovering induced strains in the transition region enables longeron deployment. It should be noted that the glass transition temperatures and hence, deployment temperatures, of the TEMBO® EMC shape memory polymer matrix systems considered for RAPDAR are between 60 and 80°C. Therefore, this steady-state analysis indicates the feasibility of using in-orbit solar energy to achieve laminate temperatures that exceed the matrix's glass temperature thus enabling longeron deployment.

A preliminary transient thermal analysis was performed to determine an estimate for the heating rate of the TEMBO® EMC longeron, and hence, the passive deployment rate of the RAPDAR system. These analyses assumed that a white coating is applied to the longeron's outer surface to aid in cooling the deployed longeron thus stiffening the EMC longerons once they achieve full cross-section (i.e., deployment). The transient thermal analysis was based on the single-longeron model shown in Figure 7, and assumed that the longeron rotates relative to the sun to mimic the unrolling motion that occurs during deployment.

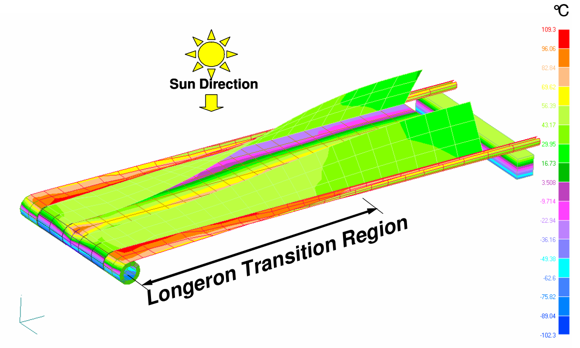


Figure 6. Steady-state RAPDAR thermal analysis.

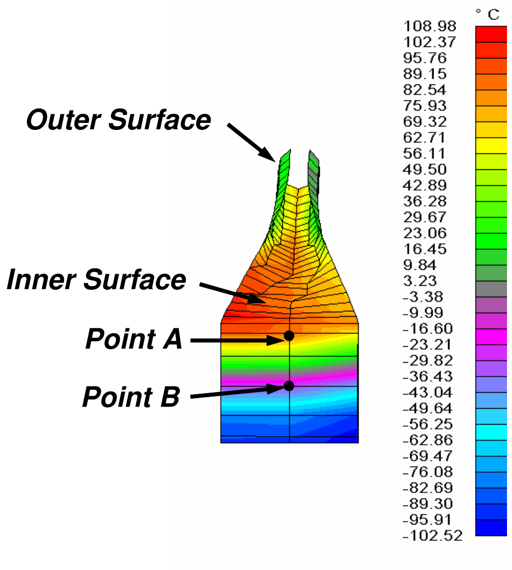


Figure 7. Transient longeron thermal analysis with white coating applied on the outside surface.

The key temperature results plotted in Figure 7 are the temperatures at Points A and B, which are 90 degrees away from each other on the packaged-longeron roll. These minimum and maximum temperatures are plotted in Figure 8 as a function of rotation rate of the packaged longeron (relative to the sun). The results indicate that as the rotation rate increases, the maximum and minimum roll temperatures converge. Figure 8 indicates that a longeron deployment rate of 0.1 revolutions-per-minute (RPM) could be achieved with a TEMBO® EMC material that deploys at a temperature of 60°C. This is equivalent to a linear deployment rate of 7.2 m/hr based on assumed packaged geometry. This deployment rate enables complete deployment of the 50kW, 60m long array system in just over 8 hours. Therefore, the analysis results demonstrate the feasibility of achieving full deployment of the RAPDAR 50kW array within a single geosynchronous orbit which is a key requirement for the solar array system. Furthermore, a key conclusion of the thermal analyses is that the RAPDAR structure is deployment-rate limited due to the longeron heat-up time and viscoelastic properties inherent in the TEMBO® EMC longeron material. This is a significant advantage over traditional, elastically-strained deployable structures where energy containment during deployment is a major concern which impacts the overall system design.

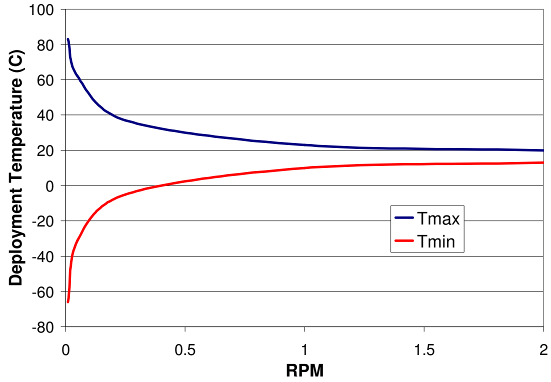


Figure 8. Relationship between longeron deployment rate and deployment temperature.

Ground Testing

The feasibility of passive deployment was further explored through ground testing that consisted of deploying TEMBO® EMC longerons using radiant heaters. Figure 9 presents a photograph of the test setup for the dual-longeron deployment where each longeron is packaged around a cylindrical mandrel, which is used to sequence the longerons during deployment. Both single- and dual-longeron deployments were performed. Testing was performed both horizontally and vertically, the latter of which was done with gravity off-loaded. The radiant heaters were adjusted such that the resulting peak temperatures of the TEMBO® EMC longerons were consistent with the previously discussed thermal analyses. The longerons were fabricated using a three-ply laminate architecture. Laminate constituents were IM-7 carbon fiber and a thermoset epoxy TEMBO® EMC matrix with a glass transition temperature of 77°C (details to be discussed in the next section).

Figure 10 presents a thermal image taken during deployment testing of a single, horizontally deployed longeron where the maximum achieved temperature was in the 80-90°C range. Laminate temperature was monitored using a hand-held infrared thermometer and a wide-field thermal-imaging system. Deployment initiated at 60°C for a single longeron and 80°C for sequenced, dual-longerons. It is presumed that friction and/or resistance associated with the sequencer was responsible for the difference in deployment-initiation temperatures.

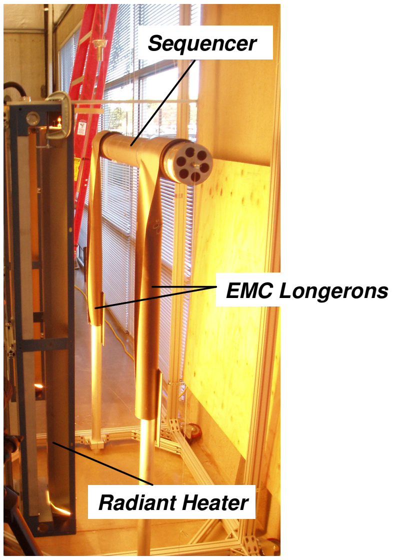


Figure 9. Dual-longeron deployment test.

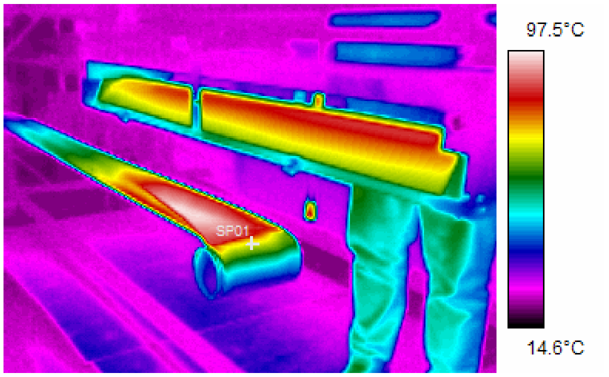


Figure 10. Thermal image of a single longeron.

Figure 11 presents the results for two separate dual-longeron vertical deployments. Deployment, which is defined as the percent of the longeron deployed relative to the original longeron length, is presented as a function of time. The results for the two tests are nearly identical indicating excellent repeatability. Both tests produced full deployment of the 3m-long TEMBO® EMC longerons in approximately 28 minutes. It should be noted that thermal losses associated with the in-orbit deployment would likely reduce the deployment rate. However it is also likely that an increased deployment rate can be realized by reducing the deployment temperature (i.e., the glass transition temperature of the EMC matrix). Based on these tests and the previously described on-orbit thermal analyses, it is reasonable to conclude that the passively deploying the full 50kW RAPDAR array is feasible.

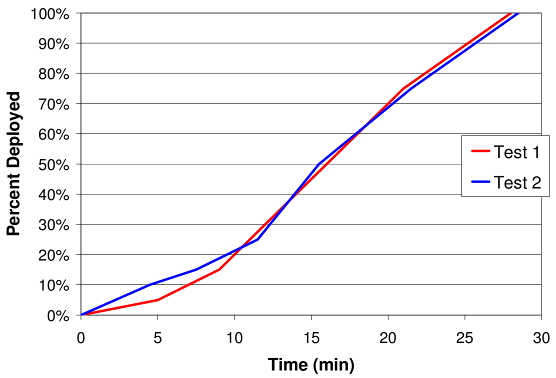


Figure 11. Dual-longeron deployment results.

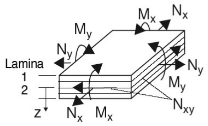
5. TEMBO® EMC LONGERON DESIGN

Certainly, the key and enabling element in the RAPDAR structural system is the TEMBO® EMC primary longeron. As described in Section 3, TEMBO® EMC longeron addresses several requirements in the packaged-, deploying-, and deployed-system design. Section 4 discussed how EMC resin material is selected based on consideration of the passive solar heating and deployment performance of the longerons. Although not explicitly discussed herein, the TEMBO® EMC longerons are the primary structural elements, providing stiffness, strength, and dimensional stability to the system. So, these considerations heavily influence the design of the EMC laminate, as well as the longeron cross-sectional diameter, and the selection of optical surface coatings.

A key requirement for the packaged system that further influences the design of the longerons is the need for the longerons to contain the strain energy of the elastically strained elements (e.g., wing-edge longerons, battens, TFPV blankets, etc.). To address this requirement in the design of the EMC laminate, an analysis method was developed that predicts the energy-storage capacity of the EMC longeron. The analysis considers variations in laminate architecture, constituent-materials, and longeron geometry. Energy-storage capacity is essentially the amount of strain energy that an EMC longeron can contain while "frozen" in its packaged configuration.

The analysis of energy-storage capacity first considers the strain energy that is "frozen" within the EMC longeron during packaging at elevated temperature (i.e., $T > T_g$), and subsequent cooling back below T_g while maintaining the packaged geometry through mechanical constraints. Next, the response of the longeron upon removal of the constraint is determined, and the amount of shape change, or relaxation, of the longeron from its packaged shape is used to quantify the energy-storage capacity. For this effort, the energy-storage capacity is quantified by the ratio of the packaged radius to the relaxed (i.e., unconstrained) radius. A longeron having poor energy-storage capacity would fully deploy upon removal of the constraint and exhibit an energy-stowage capacity of zero. Conversely, a longeron with perfect energy-storage capacity of one, would remain unchanged in the packaged configuration upon removal of the constraint.

The analysis developed and utilized for this effort combines elements of Classical Laminate Theory (CLT) and shell mechanics by comparing the strain energy densities of the individual laminas to predict the longeron's packaged shape (i.e., diameter). The expressions used to perform these calculations are shown in Figure 12 and include bending strain energy, stretching strain energy (i.e., for asymmetric laminates that exhibit extension at the neutral-strain surface), and coupling strain energy for asymmetric laminates where bending and extension are coupled.[14]



$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon \\ \kappa \end{Bmatrix}$$

Bending

$$U_b = \frac{1}{2}\{\kappa_x \quad \kappa_y \quad \kappa_{xy}\}[D]\begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

Stretching

$$U_S = \frac{1}{2}\{\varepsilon_x \quad \varepsilon_y \quad \varepsilon_{xy}\}[A]\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix}$$

Coupling

$$U_c = \{\kappa_x \quad \kappa_y \quad \kappa_{xy}\}[B]\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix}$$

Figure 12. Expressions for calculating strain energy densities.[14]

To assess the performance of the EMC longeron in containing its own strain energy *plus* the elastic strain energy from the rest of the system, strain-energy densities for both the EMC longeron and the elastic elements are calculated individually and summed. The plot in Figure 13 presents typical results for a test sample, which included an EMC layer and a non-EMC layer to mimic the elastic elements in the rest of the RAPDAR system. The strain energy is plotted as a function of packaged curvature where the sum of the two (i.e., EMC and elastic) strain energies exhibits a minima, corresponding to the equilibrium state that the assembly should achieve when the packaging constraint is removed. Specifically, the test specimen was packaged to a 5.7cm initial diameter and predicted to assume a minimum energy radius of 8.5cm upon removal of the packaging constraint, which corresponds to an energy-storage capacity of 0.675.

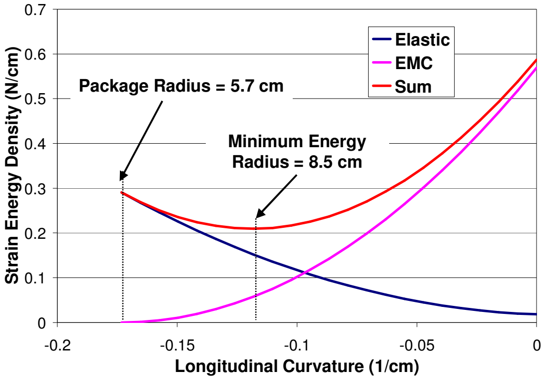


Figure 13. Plot of EMC and elastic strain energy densities that define energy-storage capacity.

Figure 14 presents two photographs of a test laminate built to correlate the analysis results presented in Figure 13. A photograph of the induced packaged shape is shown along with the relaxed (i.e., constraint-free) shape. In this test the laminate assumed a packaged radius of just over 7.6cm upon removal of the constraint after being packaged to a radius of 5.7cm. This result corresponds to an energy-storage capacity of 0.75 as compared to the predicted value of 0.675, indicating reasonable correlation.

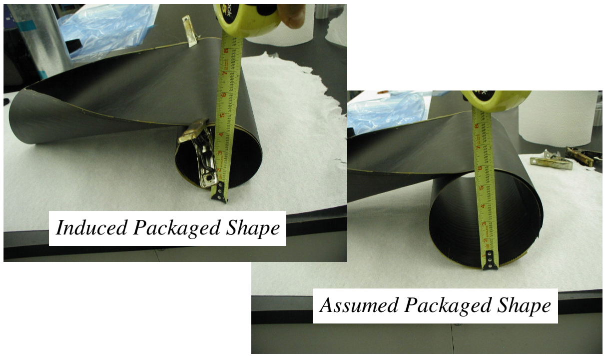


Figure 14. Photographs of a packaged EMC longeron.

6. SUMMARY

Future satellite missions will require ultra large and ultra efficient solar arrays that provide higher power levels, power densities (W/kg), launch packaging densities (kW/m^3), and lower unit costs ($/kW) than can be achieved with current solar array technologies. Scale-up of current technologies is not considered to be a viable option. The Roll-Out and Passively Deployed Array (RAPDAR) system is being developed to address these needs. RAPDAR combines both TEMBO® Elastic Memory Composite (EMC) deployment technology and Thin-Film Photovoltaic (TFPV) solar cell technology to produce a highly efficient array that is scalable to between 1 and 50kW. The key element of the RAPDAR solar array structure is a pair of TEMBO® EMC primary longerons that provide primary stiffness and strength to the deployed structure, while also controlling the deployment of the system and containing the strain energy of the system in its packaged configuration. A unique and potentially revolutionary aspect of the RAPDAR system is the use of solar energy to provide the necessary thermal energy to actuate the TEMBO® EMC longerons and hence, passively deploy the RAPDAR solar array.

The present paper provides an overview of the RAPDAR system including key design features and a comparison to other TFPV solar array systems. Furthermore, the present paper presents analyses and testing that are used to design and validate key aspects of the RAPDAR system. Specifically, the feasibility of using in-orbit solar energy to control deployment or, passive deployment, as well as the ability of the EMC longerons to contain induced strain energy and hence, the structure's packaged configuration, are investigated through analyses and demonstrated in ground testing. The key conclusions of these efforts are as follows:

- Thermal analyses and ground testing combine to demonstrate the feasibility of passively deploying a full-scale, 50kW RAPDAR solar array within a single geosynchronous orbit (GEO).
- EMC material and hence, the RAPDAR solar array, is inherently rate limited. Thus, concerns of excessive deployment energy and deployment shock typically associated with elastically-strained deployable structures are mitigated.
- EMC longerons can be designed to contain induced strain energy associated with elastically-strained elements (i.e., battens, blankets, etc.). Therefore, RAPDAR should require little or no containment devices to constrain the packaged structure during launch.

These aspects are together being exploited in the design and demonstration of the RAPDAR solar array which shows a clear departure from traditional technologies and demonstrates the potential for revolutionizing the solar array market.

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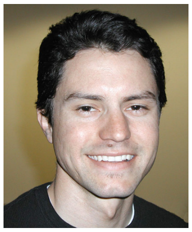
BIOGRAPHY



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