REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
26-06-2006

2. REPORT TYPE
Conference Paper POSTPRINT

3. DATES COVERED *(From - To)*
2005 - 2006

4. TITLE AND SUBTITLE
Development of a Passively Deployed Roll-Out Solar Array

5a. CONTRACT NUMBER
FA9453-05-C-0049 & FA9453-05-C-0050

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
65502F

6. AUTHOR(S)
Rory Barrett, Douglas Campbell, Mark S. Lake, Larry Adams, Robert Taylor, Erik Abrahamson,
Mark R. Scherbarth,* Jeffry Welsh,* Gregg Freebury,† Neal Beidleman,† Jamie Abbot‡

5d. PROJECT NUMBER
3005

5e. TASK NUMBER
VP

5f. WORK UNIT NUMBER
MW/MX

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Composite Technology Development Inc
2600 Campus Dr
Lafayette, CO 80026

JLA Technologies‡
8111 El Extenso Ct
San Diego, CA 92119

Idea Incorporated†
PO Box 4362, Aspen, CO 81612

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory*
Space Vehicles Directorate
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/VSSV

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-VS-PS-TP-2006-1050

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (Clearance #VS06-0199)

13. SUPPLEMENTARY NOTES
Authors' final manuscript, published in the 4th International Energy Conversion and Engineering Conference, 26-29 June 2006, San Diego, CA

Government Purpose Rights

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 20 kW of total power, at roughly 80 W/kg. To meet the requirements of future Air Force missions, the Rollout And Passively Deployed ARray (RAPDAR™) has been developed. This innovative, patent-pending design takes full advantage of the latest advances in thin-film photovoltaic and TEMBO® Elastic Memory Composite (EMC) deployment technologies. A key feature of the design is the use of solar energy to passively actuate the TEMBO® EMC members and deploy the array. The present paper addresses the development and validation of detailed designs for the RAPDAR™ (patent applied for) structural system. Specific focus is placed on comparing the performance projections of RAPDAR™ with other thin-film array systems, and 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.

15. SUBJECT TERMS
Solar Arrays, RAPDAR™, Thin-Film Arrays, Photovoltaic, TEMBO®, EMC, Longerons, Stiffness, SBIR, Elastic Memory Composite, Rollout and Passively Deployed Array

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Lt Corey M. Duncan
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	Unlimited	10	505-846-5393

Development of a Passively Deployed Roll-Out Solar Array

Rory, Barrett [1], Douglas Campbell [2], Mark S. Lake[3], Larry Adams[*], Robert Taylor and Erik Abrahamson[4]
Composite Technology Development, Inc., Lafayette, CO, 80026
phone: 303-664-0394, email: rory@ctd-materials.com

Mark R. Scherbarth[5], Jeffry Welsh
Air Force Research Laboratory, Kirtland AFB, NM 87117-5776

Gregg Freebury[6] and Neal Beidleman[6]
Idea Incorporated, Aspen, CO 81612

and

Jamie Abbot [7]
JLA Technologies, San Diego, CA 92119

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 20 kW of total power, at roughly 80 W/kg. To meet the requirements of future Air Force missions, the Rollout And Passively Deployed ARray (RAPDAR™) has been developed. This innovative, patent-pending design takes full advantage of the latest advances in thin-film photovoltaic and TEMBO® Elastic Memory Composite (EMC) deployment technologies. A key feature of the design is the use of solar energy to passively actuate the TEMBO® EMC members and deploy the array. The present paper addresses the development and validation of detailed designs for the RAPDAR™ (patent applied for) structural system. Specific focus is placed on comparing the performance projections of RAPDAR™ with other thin-film array systems, and 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.

I. 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 22 kW end-of-life power, with power densities of 50-80 W/kg, packaging efficiencies of 10 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 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. RAPDAR™ 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 launch. However, the lower power-conversion efficiency of TFPV as compared to existing photovoltaic technologies means that larger deployed areas are required

---

[1] Senior Program Manager, 2600 Campus Drive, Member AIAA.
[2] Senior Engineer, 2600 Campus Drive, Member AIAA.
[3] Chief Engineer, 2600 Campus Drive, Associate Fellow AIAA.
[4] Engineer, 2600 Campus Drive, Member AIAA.
[5] Captain USAF, 3550 Aberdeen Ave SE.
[6] Consultant, PO Box 4362.
[7] Consultant, 8111 El Extenso Ct.

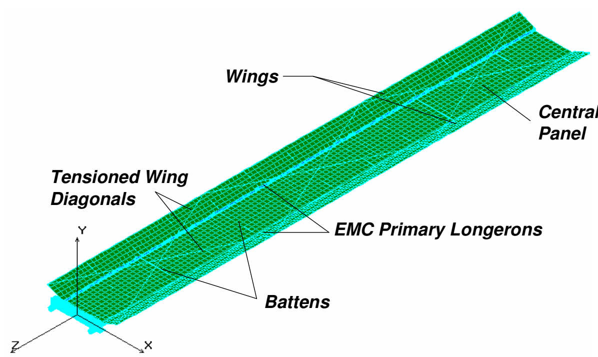
to provide a given total power. This limitation in TFPV technology means that TFPV systems will only be practical if more efficient deployment technologies and structural designs can be developed.

A. TFPV Cell Technology

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.[1,2] The most common TFPV cells 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 greater than 1200 W/kg and efficiencies greater of 10% at AM0 have been reported.[2,3,4]

B. Advantages of TEMBO® EMC Material for TFPV Solar Arrays

TEMBO® Elastic Memory Composite (EMC) materials exhibit many favorable qualities that lead to very innovative designs for deployable TFPV solar arrays.[5] In particular, TEMBO® EMC materials, which combine a fully-cured thermoset TEMBO® shape memory polymer matrix with traditional fiber reinforcements, have the ability to "freeze" and release induced strain energy via a specific thermo-mechanical cycle.[6] Furthermore, TEMBO® EMC materials can achieve significantly higher induced packaging strains than traditional hard-resin composites without damage to the fibers or the resin,[7] which leads to TEMBO® EMC components that can be packaged more compactly than traditional 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. 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, so many possible EMC structural-component designs could be considered.[8]



(a) Schematic of key components.

(b) Engineering test model.

Figure 1 - RAPDAR™ solar array system (patent pending).

The combination of TEMBO® EMC structural components with TFPV cells creates the potential of revolutionizing the design of deployable solar arrays. TEMBO® EMC structural components could 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.

II. RAPDAR™ System Overview

The overall layout of the RAPDAR™ array system is shown in Figure 1. The patent-pending 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.

A. Packaging and Deployment Concept

As shown in Figure 2, 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-

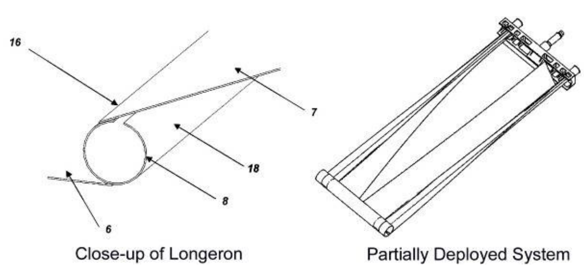


Figure 2 - RAPDAR™ TEMBO® EMC primary longeron.

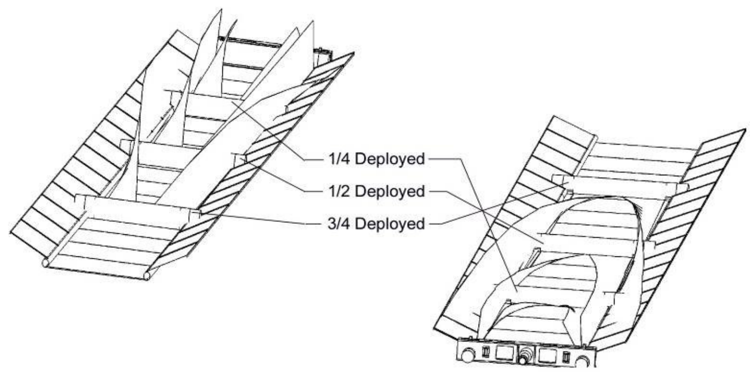


Figure 3 - Stages of deployment.

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.

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 3). When deployment is complete, the wing-to-wing diagonal cables are tensioned to stabilize and stiffen the structure. Figure 3 shows four stages of deployment overlaid on one another.

B. 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 deployable solar array concepts. By incorporating the wings, the RAPDAR™ system achieves deployed stability and structural depth, which are 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 8m 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 250 W/kg threshold identified as a market requirement.

C. Comparison with Advanced Crystalline Solar Cell Array Systems

A study was performed to identify the potential performance of RAPDAR™ thin-film array systems, and to contrast that with crystalline cell platforms to project when and where RAPDAR™ thin-film arrays will be desirable. Representative power levels and system level requirements for Geostationary Orbit (GEO), interplanetary

(IP) and 50 kW mission applications were assumed and a number of array configurations were considered. This study compares various array options against real mission requirements at end of life (EOL) using consistency in regard to loss factors, thermal effects, mass margins, radiation degradation, and other analyses. Comparisons of resulting performance metrics such as W/kg, W/m^2, W/m^3, and available power are given with commentary on design particulars, risks, and technology readiness. Data for the Rigid Panel and Ultraflex arrays has been taken from D. M. Murphy et al. "Thin Film and Crystalline Solar Cell Array System Performance Comparisons"9.

The arrays studied range in power level from 10 to 50 kW at end-of-life (EOL). This broad range makes applicable a variety of array configurations. Types studied include flexible blanket and rigid panel designs. The arrays considered (See Figure 4- Figure 5) are briefly introduced next.

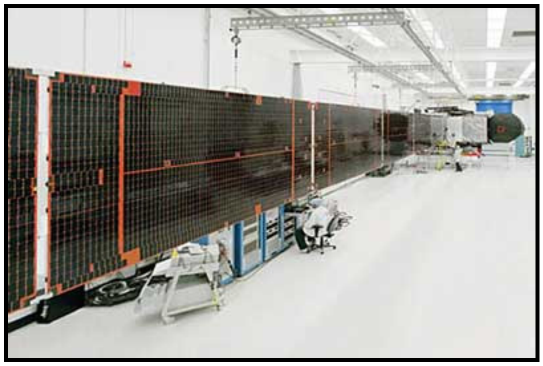


Figure 4 – Rigid Panel Array

Figure 5 – UltraFlex Array (Courtesy AEC-Able)

A typical – yet high performance – folding rigid panel planar array is considered to provide a baseline that represents only modest advancement over current state-of-the-practice. The UltraFlex[10] array, which is a circular blanket array supported like an umbrella, is considered as it provides a competitive advanced-concept alternative to RAPDAR™. UltraFlex has an improved power density (kW/kg) compared to a rigid panel array. However, UltraFlex, which stows by fan-folding, is limited in the amount of area that can be deployed.

Cell-Performance Assumptions: Today's state-of-the-art crystalline (triple-junction III-V devices) or multi-junction (MJ) cells are produced by at least two vendors and capable of greater than 26.5% AM0 min lot average efficiencies. Each mission/ array configuration is sized for a range of efficiency assumptions, from 25 to 35% BOL (28°C, AM0). 140 mm thick cells with 3-mil (min) covers are assumed.

As described previously, TFPV cells are subdivided into two categories: Cu(In,Ga)Se2 (CIGS) cells and amorphous silicon (a-Si) cells. Space-compatible CIGS cells demonstrated efficiencies above 15% (AM0), however these cells have a high thermal coefficient (-0.6 %/C), and so it is critical to maintain a reasonable operating temperature. Amorphous silicon cells are a more mature product with high space radiation resistance, but the efficiency potential is lower (~10%). This study assumes a beginning-of-life efficiency of 8.5% for a-Si and 11.5% for CIGS with a realistic knockdown for end-of-life efficiency. The TFPV arrays are assumed to have an areal mass of 0.075 kg/m^2, representing TFPV cells on 1-mil Kapton with appropriate optical and radiation coatings.

Discussion of Findings: Detailed array sizing calculations and performance results are presented in Figure 6. Power level and other metrics are reported for a 2-wing RAPDAR™ system, except where otherwise indicated. Figure 7 presents a plot of specific-power performance for the three designs. Clearly RAPDAR™ provides substantially higher specific-power capability than either crystalline-cell-array design. Figure 8 presents a plot of packaging performance (measured by kW/m^3 of packaged volume) for the three array systems. For low-power designs, all three designs provide comparable packaging performance, but RAPDAR™ provides scalability to higher-power designs that is not readily achievable with either crystalline-cell design. Finally, Figure 9 presents a comparison of the deployed power density (measured in kW/m^2) of the three designs. Clearly, RAPDAR™ requires significantly larger deployed areas due to the use of less-efficient TFPV cells. However, as shown in Figure 7, this greater deployed area is achieved with significantly lower total system mass.

In summary, this set of analyses shows that RAPDAR™ arrays using TFPV cells, which produce 8.5 – 11.5% efficiency for an assumed blanket areal density of 0.075kg/m^2 can provide significant increases in specific power over crystalline-cell arrays. The projected specific power (W/kg) of RAPDAR™ is 200-300% higher than an advanced rigid panel array with MJ cells for 10-20 kW applications, and 50% to 120% higher than projections for the Ultraflex design. These gains combined with a significant expected cost reduction from ~$1000/ Watt to ~$500/ Watt and scalability to 100kW make RAPDAR™ very attractive for many future missions.

	Array Size	10 kW EOL						GEO 20 kW EOL					GEO 100 kW	
	Array Type	Ultra Flex	Ultra Flex	RAPDAR	RAPDAR	RAPDAR	Rigid Panel	Ultra Flex	RAPDAR	RAPDAR	RAPDAR	Rigid Panel	RAPDAR	RAPDAR
	Cell Type	TFPV	MJ	TFPV	TFPV	MJ	MJ	MJ	TFPV	TFPV	MJ	MJ	TFPV	TFPV
	Efficiency	11.5%	25%	8.5%	11.5%	25%	25%	25%	8.5%	11.5%	25%	25%	8.5%	11.5%
Array Power	BOL Power (kW)	10.2	11.1	12.7	11.7	10.9	11.90	26.5	25.5	23.0	24.9	25.0	127.7	115.69
	EOL Power (kW)	9.5	9.9	10.0	10.2	9.8	10.50	20.2	20.1	20.0	20.3	20.2	100.7	100.69
	BOL Specific Power (W/ kg)	161	204	352.31	380	185	95	219	382	420	185	106	469	528
	EOL Specific Power (W/kg)	150	182	278	331	166	84	167	301	365	151	86	370	459
	% Improvement on Rigid Panel	79%	117%	231%	293%	98%	0%	94%	250%	325%	76%	0%	N/A	N/A
Areal Power	Wing Aspect Ratio	1.1	1.1	3.2	2.6	1.1	1.7	1.1	3.6	2.6	1.1	3.3	16.0	16
	Array Area	103	34	109	74	33	40	79	218	145	75	80	1089	729
	BOL Areal Power (W/m^2)	99	324	117	159	331	297	337	117	106	331	311	117	158.7
	EOL Areal Power (W/m^2)	92	290	92	138	298	263	257	92	92	270	252	92	92.46
	% Improvement on Rigid Panel	-65%	10%	-65%	-48%	13%	0%	2%	-63%	-63%	7%	0%	N/A	N/A
Mass/ m^2	Areal Mass(Kg/m^2)	0.80	1.59	0.33	0.42	1.79	3.12	1.53	0.31	0.38	1.79	2.94	0.25	0.30
	% Improvement on Rigid Panel	-74%	-49%	-89%	-87%	-42%	0%	-48%	-90%	-87%	-39%	0%	N/A	N/A
Packaging	Array Stowed Volume (m^3)	0.48	0.16	0.22	0.19	0.11	1.06	0.37	0.56	0.51	0.59	2.30	1.18	0.89
	BOL Packaging (kW/m^3)	21	70	57	61	102	11	73	46	45	42	11	109	130
	EOL Packaging (kW/m^3)	20	62	45	53	92	10	55	36	39	34	9	86	113
	% Improvement on R/ MJ	97%	520%	350%	432%	818%	0%	511%	300%	338%	280%	0%	850%	1158%
	Structure Packaging (m^2/m^3)	214	212.5	486	386	308	37.7358	213.514	390	286	126	35	925	820
	% Improvement on Rigid Panel	466%	463%	1189%	922%	716%	0%	514%	1020%	722%	264%	0%	N/A	N/A
Array-Wing Properties	Deployed 1st Frequency (Hz)	0.4	0.4	0.25	>0.25		0.41	0.12	0.25	>0.25		0.1	0.23	0.23
	Stowed 1st Freq (Hz)	45	40	>35	>35		43	35	>35	>35		43	>35	>35
	PV Assembly (kg)	11.7	18	4.2	2.8	16.8	21	44	8.4	5.6	38.3	45.0	36.9	24.67
	Harness Mass (kg)	2.1	1.6	0.3	0.3	0.6	2.7	3.2	0.5	0.4	1.7	7.2	3.5	2.89
	Structure (kg)	13.3	4.8	9.9	8.6	9.2	26.1	10.1	19.0	16.0	20.7	52.1	82.2	68.40
	Mechanisms (kg)	0.6	0.6	0.0	0.0	0.0	1	0.6	0.0	0.0	0.0	1.7	0.0	0
	Yoke & Root Assy (kg)	1.9	1.4	2.8	2.8	2.8	6.5	1.9	4.6	4.6	4.6	6.5	12.0	12.01
	Tie Downs (kg)	0.8	0.6	0.8	0.8	0.8	4.8	0.8	0.8	0.8	0.8	4.8	1.6	1.6
	Wing Mass (kg)	30	27	18	15	30	62.1	60.6	33	27	66	117	136	109.575
	% Improvement on Rigid Panel	-51%	-57%	-71%	-75%	-51%	0%	-48%	-72%	-77%	-44%	0%	N/A	N/A

Figure 6 - Array System Designs vs. Mission and Array

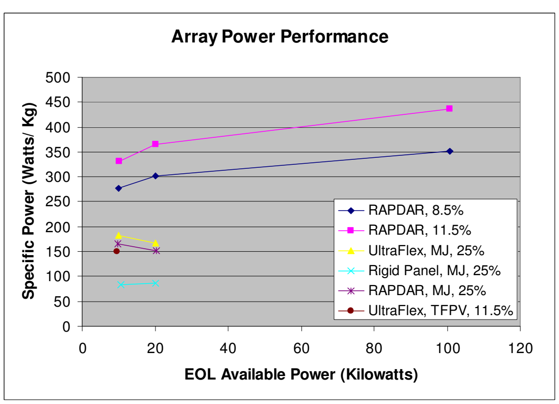


Figure 7- Array Power Performance

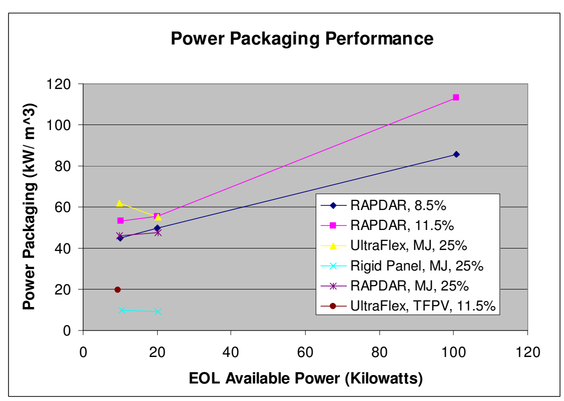


Figure 8 – Power Packaging Performance

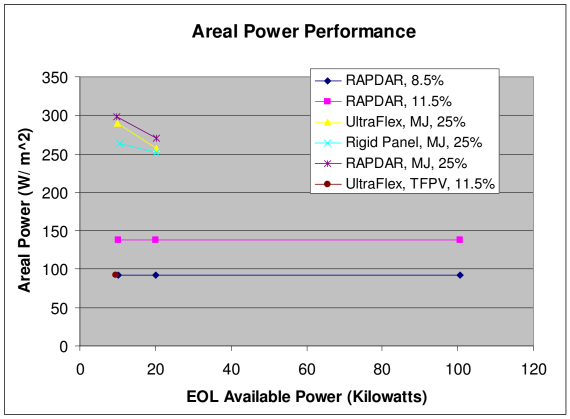


Figure 9- Areal Power Performance

III. RAPDAR™ Passive Deployment Design

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 key aspect of the RAPDAR™ solar array design 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.

A. Analysis

Preliminary thermal analyses of a 50kW RAPDAR™ array in a geosynchronous orbit (GEO) were performed to determine estimates for the peak temperatures, temperature distributions, and heating rates 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., absorptance and emittance) 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.

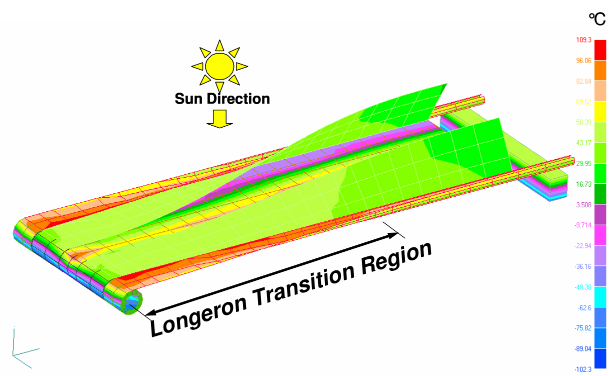


Figure 10 - Steady-state RAPDAR™ thermal analysis.

Figure 10 presents results from steady-state thermal analysis where the inside of the roll is solar pointing. The temperature contours indicate a variation of approximately -100°C to 100°C within the packaged array. The maximum temperature is just over 100°C and occurs throughout the transition region of the slit-tube TEMBO® EMC longeron. These results define the temperature range in which induced packaging strains in the TEMBO® EMC longeron must be recovered to enable 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°C 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 set of preliminary transient thermal analyses were 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 analyses

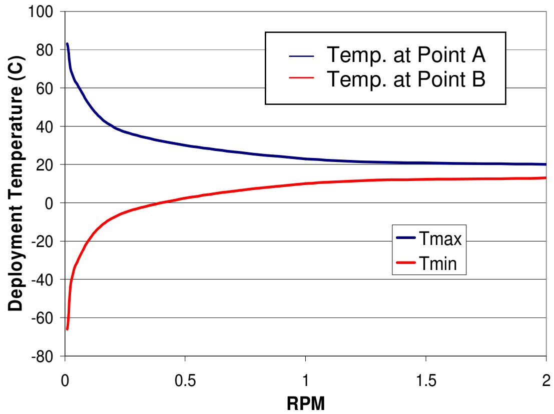


Figure 11 - Relationship between longeron deployment rate and deployment temperature.

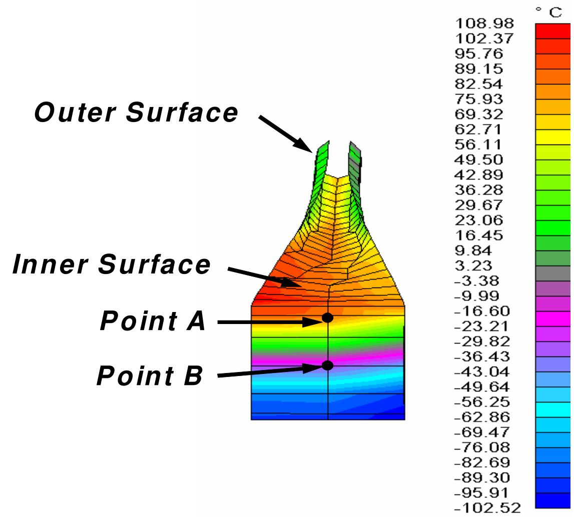


Figure 12 - Transient longeron thermal analysis with white coating applied on the outside surface.

were based on the single-longeron model shown in Figure 12, and assumed that the longeron rotates relative to the sun to mimic the unrolling motion that occurs during deployment.

The key results plotted in Figure 11 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 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 11 further indicates that a longeron deployment rate of 0.05 revolutions-per-minute (RPM) would allow the TEMBO® EMC material to heat passively to above 60°C at Point A, which is sufficient to allow the material to deploy. This equates to a linear deployment rate of 7.2 m/hr for the 50kW geometry, and complete deployment of that 60m-long array in just over 8 hours. These analysis results indicate that the RAPDAR™ 50kW array can feasibly be deployed within a single geosynchronous orbit, which is a key requirement for that particular solar array application.

B. Ground Testing

The feasibility of passive deployment was verified through ground testing that consisted of deploying TEMBO® EMC longerons using radiant heaters in air. Both single- and dual-longeron deployments were performed. Figure 13 presents a photograph of the test setup for a dual-longeron deployment where both longerons are packaged around a cylindrical mandrel that synchronizes their deployment. 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 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 77oC (details to be discussed in the next section).

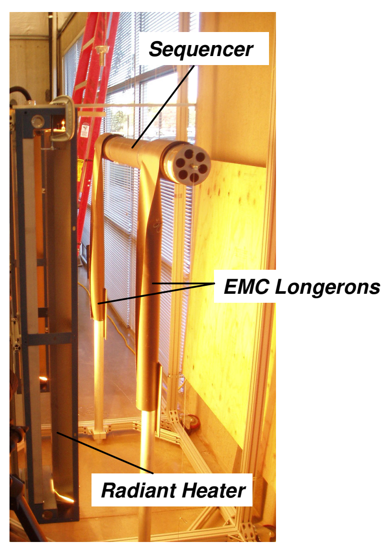


Figure 13 - Dual-longeron deployment test

Figure 14 presents a thermal image taken during deployment testing of a single, horizontally deployed longeron where the maximum achieved temperature was in the range of 80-90°C. Laminate temperature was monitored using a hand-held infrared thermometer and a wide-field thermal-imaging system.

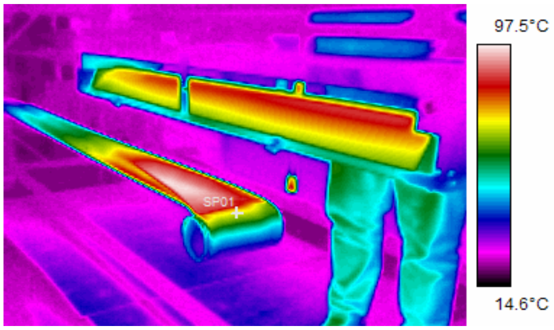


Figure 14 - Thermal image of a single longeron

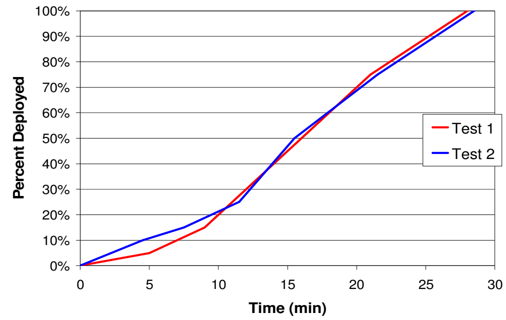


Figure 15 - Dual-longeron deployment results.

Deployment initiated when the temperature at Point A (Figure 12) reached 60oC for a single longeron and 80oC for synchronized, dual-longerons. It is presumed that mismatch associated with the synchronized deployment or offloading bias was responsible for the difference in deployment-initiation temperatures.

Figure 15 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 about 28 minutes.

Passive deployment of a single TEMBO® EMC longeron in a thermal vacuum chamber using solar-equivalent radiative heating has also been demonstrated. These tests indicated that MLI blanketing on the longerons is necessary to provide sufficient margin for achieving deployment temperatures. Full analysis and data reduction of the thermal vacuum deployments is ongoing.

IV. Summary

Future Air Force satellites 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 Rollout 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 results from analyses and tests that are being 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, is 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 wing within a single geosynchronous orbit (GEO).
- The RAPDAR™ will provide a 200-300% increase in specific power (W/ Kg) over existing rigid panel arrays and 50-120% increase over the Ultraflex array.-

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.

Acknowledgments

The authors would like to acknowledge the Space Vehicles Directorate of the Air Force Research Laboratory for their technical guidance and support of the present work under Phase II SBIR Contracts No. FA9453-05-C-0049 and FA9453-05-C-0050.

References

[1] Samson, P., “First Thin Film Festival”, 7th European Space Power Conference, Stresa, Italy, May 9-13, 2005.
[2] Beernink, K.J., et al, “High Specific Power Amorphous Silicon Alloy Photovoltaic Modules”, 29th IEEE PVSC, New Orleans, LA, May 20-24, 2002, Paper No. 3P2.14.
[3] Beernink, K.J., et al, “Ultralight Amorphous Silicon Alloy Photovoltaic Modules for Space Applications”, Presented at the Materials Research Society Spring Meeting, San Francisco, CA, April 4, 2002.
[4] Neisser, A., et al, “Flexible Solar Cells for Space: A New Development Based on Chalcopyrite Thin Films”, 7th European Space Power Conference, Stresa, Italy, May 9-13, 2005.
[5] Tupper, M. L., et al., “Developments in Elastic Memory Composite Materials for Deployable Spacecraft Structures,” Presented at the 2001 IEEE Aerospace Conference, March 10-17, 2001, Big Sky, MT, IEEE Paper No. 3673.
[6] Abrahamson, E. R., Lake, M. S., Munshi, N. A., and Gall, K., “Shape Memory Mechanics of an Elastic Memory Composite Resin,” *J. of Intel. Mat. Sys. and Struct.*, Vol. 14., October 2003, pp 623-632.
7 Murphey, T.W., Meink, T., and Mikulas, M.M., “Some Micromechanical Considerations in the Folding of Rigidizable Composite Materials,” Presented at the 42nd AIAA/ASME/ASCE/AHS/ASC SDM Conference, Seattle, WA, April 16-19, 2001, AIAA Paper No. 2001-1418.
8 Lake, M. S., and Campbell, D., “The Fundamentals of Designing Deployable Structures with Elastic Memory Composites,” Presented at the 2004 IEEE Aerospace Conference, March 6-13, 2004, Big Sky, MT, IEEE Paper No. 1134.
[9] D. M. Murphy, M. I. Eskenazi, S. F. White, and B. R. Spence, “Thin Film and Crystalline Solar Cell Array System Performance Comparisons”, Presented at the *29th IEEE PVS,* New Orleans, LA, May 20-24, 2002.
10 P. Alan Jones, Stephen F. White, & T. Jeffery Harvey, “A High Specific Power Solar Array for Low to Mid-Power Spacecraft,” Presented at Space Photovoltaic Research and Technology conference, 1992.