Lightweight Flexible Solar Array Validation Report

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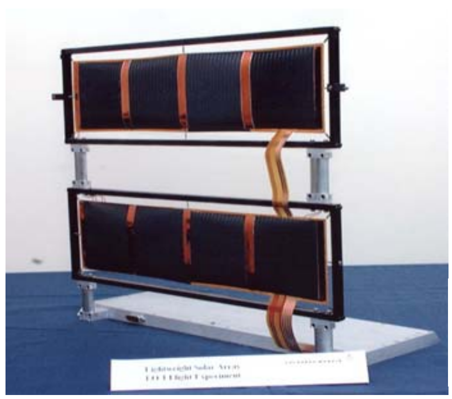
1. INTRODUCTION

Photovoltaic (PV) arrays are the primary sources of electrical power for geosynchronous and low-earth-orbiting satellites. The Lightweight Flexible Solar Array (LFSA) technology could, for some missions, provide higher power-to-weight ratios (specific energy) than conventional solar arrays, thus allowing a higher science payload mass fraction. Current solar array technologies provide specific energies in the range of 20-40 Watts/kg when the solar array deployment system and the solar array drive are considered.[1] With further developments in the efficiency of thin-film solar cells, this technology could provide specific energies greater than 175 Watts/kg.

2. TECHNOLOGY DESCRIPTION

2.1 LFSA Experiment

The LFSA technology is a lightweight PV solar array system. The unique new technology features of this solar array are the use of copper indium diselinide ($CuInSe_2$ or CIS) solar cells on a flexible substrate and the use of shape memory alloys (SMAs) for the hinge and deployment system. Figure 1 is a photograph of the LFSA EO-1 (Earth-Observing-1) flight experiment. Figure 2 is a photograph of the SMA hinges. Figure 3 is a schematic of the LFSA control circuitry. Each of the two panels is approximately 5 in. wide by 18 in. long. The hinges are deployed by heating the SMA hinges. The heaters are powered by the spacecraft 28-volt bus. The LFSA electronics also convert +28-volt power to 5 and 15 volts for the op-amps and telemetry electronics.



Each of two panels is approximately 5 in. wide by 18 in. long

Figure 1. EO-1 LFSA Experiment

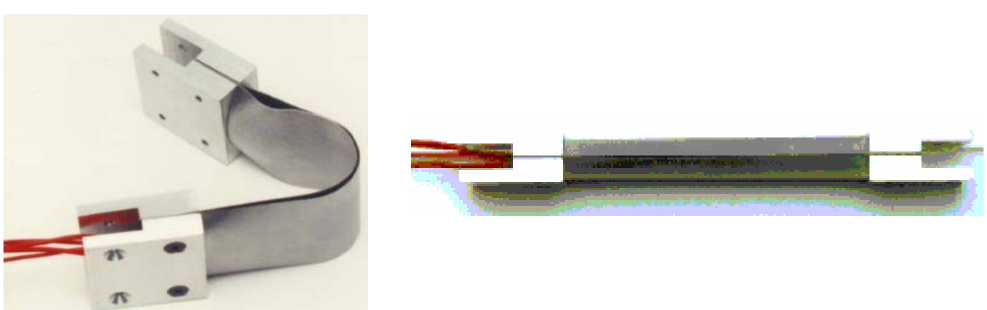


Figure 2. Shape-Memory Alloy Hinges, Stowed (Left), and Deployed (Right)

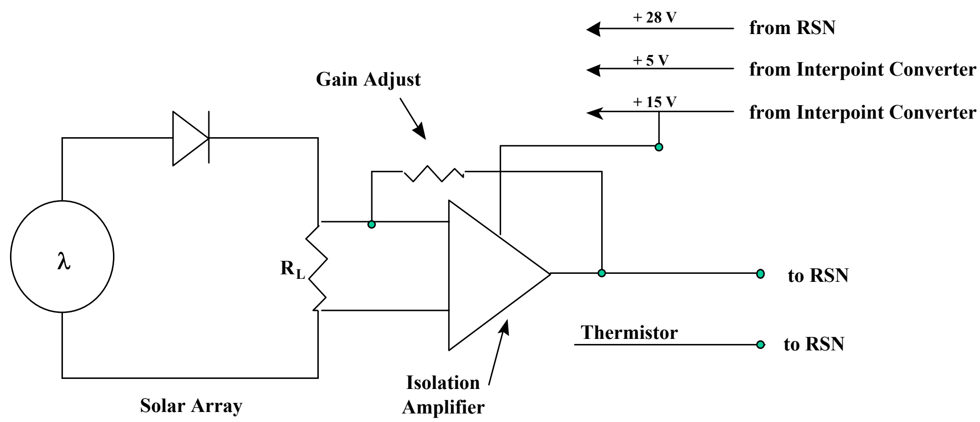


Figure 3. LFSA Control Circuit Schematic

2.2 CIS Solar Cells

Silicon (Si), gallium arsenide on germanium (GaAs/Ge), and multi-junction (MJ) solar cells are technologies that involve crystal growth on a fragile wafer. The CIS thin-film solar cell technology is based on $CuInSe_2$ being vapor deposited on a flexible substrate that is substantially lighter than cells bonded to a rigid panel. The LFSA solar cell modules are 4 in x 4 in and each consists of 15 monolithically interconnected cells in series. The Air-Mass-Zero (AM0) module efficiency achieved for this size is approximately 2%. Higher efficiencies have been achieved on smaller areas (see Figure 4)[2].

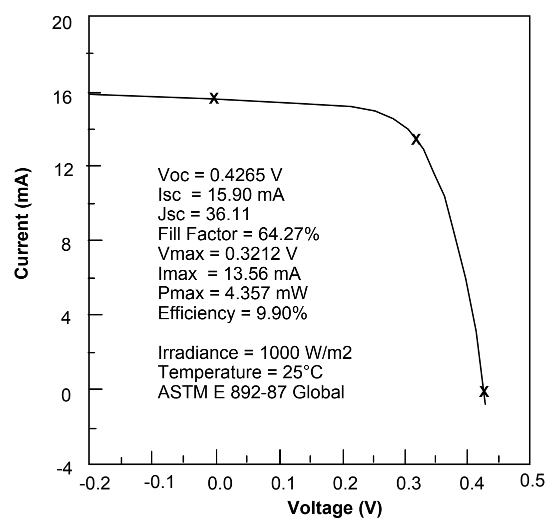


Figure 4. Air Mass 1.5 I-V Curve for a 0.5 cm^2 CIS Thin Film Solar Cell

2.3 Shape Memory Alloys

Use of SMAs provides substantial weight savings over conventional hinges, deployment systems, and solar array drives. Therefore, a combination of these technologies could provide significant improvement in power-to-weight ratios. In addition, the SMA provides a shockless deployment environment that could improve the spacecraft dynamics during deployment, and also is much safer to handle, integrate, and test than conventional pyro-based systems. Since it is also electrically resettable the same device flies that is tested. The SMA deployment/hinge devices are significantly cheaper, simpler and therefore more reliable than current technology designs.

SMAs undergo a reversible crystalline phase transformation that is the basis of the "shape memory effect." The low temperature phase is a twinned, martensitic structure that is capable of large strain deformation (in excess of 10% in some alloys) with relatively little stress (approximately 70 MPa). The high temperature phase is a cubic-based, austenitic structure with mechanical behavior more similar to conventional metals. When the martensite is deformed, and then heated, the original heat-treated shape is recovered. However, if the deformed martensite is constrained during heating, high recovery stresses evolve (>690 MPa is possible in some alloys). A combination of the two effects allows SMAs to produce mechanical work with the application of heat.

Despite their attractive capabilities, the utility of SMAs in the past has been limited due to a lack of understanding of their very interdependent force-length-temperature response and associated non-linear and hysteretic behavior as well as the effects of creep, fatigue, and material property drift that results from transformational cycling. These effects have been under study to provide the basis for effective alloy processing and "training" before incorporation in applications. Moreover, recent development of analytic modeling theory has made possible effective engineering of optimized mechanisms and devices based on experimentally derived parameters from property-stabilized SMA material.

Several integral deployment/structural hinge concepts based on SMA carpenters' hinges are being developed for application to lightweight solar array technology. A dual flexure concept was developed for integration on the EO-1/LFSA flight experiment (Figure 2). In this concept, the SMA strips are heat treated in the deployed ("hot") configuration and joined at the ends by metallic structural fittings. In the martensitic ("cold") state, the hinge is manually buckled and folded into the stowed configuration. Application of heat via internally bonded, flexible nichrome heaters transforms the SMA into the austenitic ("hot") state and causes the hinge to deploy. Once deployed, power is turned off and the SMA is allowed to cool back to the low temperature martensitic phase. Although the martensite phase is "softer" than the high temperature austenite phase, the very efficient section geometry in the deployed configuration allows the martensitic SMA hinge to support the lightweight solar array sections.[3] For the EO-1 SMA flexures, the specific alloy employed was the classic binary NiTi (50%Ni/50%Ti) that has an austenite transition temperature of 70ºC.

3. TECHNOLOGY VALIDATION

The validation objectives for the LFSA were twofold. The first objective was to demonstrate the release and controlled deployment of the CIS solar panels using the shape memory alloy release mechanism and hinges. The second objective was to monitor the PV performance of the CIS solar cells to assess their electrical output and degradation in the EO-1 orbital environment.

3.1 Ground Test Verification

The tests illustrated in Figure 5 were performed to verify the performance of the LFSA on the ground. Test levels are presented in Table 1.

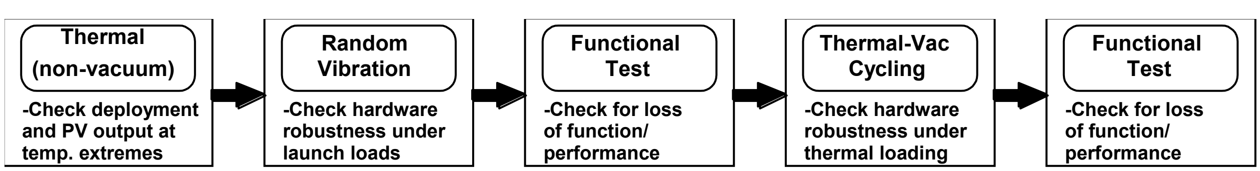


Figure 5. LFSA Ground Test Sequence

Table 1. Qualification Tests

Description	Requirement	Test
1) Vibration (gRMS) Acceptance Protoflight	 10.65 15.04	 10.64 15.04
2) Thermal Vac (°C) 24 cycles	-10 to +50	-40 to +80
3) Acoustic (OASPL*dB) Acceptance Protoflight	 138.1 141.1	 138.1 141.1
4) Functional Tests (Deployment Required)	Two (with EO-1 Spacecraft)	Six (with Flight Parts)

To verify that the LFSA was functional when integrated with the EO-1 spacecraft, the panel deployment was commanded via the spacecraft command and data handling (C&DH) system, and the panels were illuminated by tungsten lamps during execution of the current-voltage (I-V) curve sweep command.

3.2 Ground Test Results

Verification by test was employed for the EO-1 experiment. This approach assessed the performance and functional attributes of the thin-film PVs, deployment hinges, launch locks, I-V measurement electronics and structural components.

Primary testing included thermal (non-vacuum), vibration, acoustic, and thermal-vacuum cycling. Functional testing was conducted between each of these tests to verify array electrical properties and the integrity of deployment mechanisms. Vibration testing demonstrated the ability of the EO-1 experiment to endure the maximum expected environment during launch plus margin. Although testing was accomplished in the three principal orthogonal axes, the Z axis (thickness direction) was of particular interest as it placed maximum load on the thin-film PVs and suspension system. These materials did not demonstrate degradation, verifying that edge restrained array panels could survive launch environments.

Thermal cycling demonstrates the ability of the system to withstand thermal stresses associated with the on-orbit environment. Of particular interest is the adhesion of the CIS PVs to its Kapton substrate as well as the electrical properties of the hot soak temperature. Debonding and flaking of the CIS deposits were not observed. Following thermal cycling, the experiment was removed from the test chamber and an I-V curve collected at 25°C. I-V curves were found to be similar to those of the “as fabricated” modules. Ambient cell potential and current at maximum power were found not to vary more than 3% over 24 thermal cycles between –40°C and +80°C. This performance was consistent with previous data.

3.3 On-Orbit Test Validations and Usage Experience

The LFSA on-orbit test validation phase started shortly after launch when the LFSA was deployed. The indicator switches and the panel temperature profiles indicated that the deployment was nominal (Figure 6). The elapsed time to deploy Panel 1 was between 30 and 40 seconds, whereas the deployment time for Panel 2 was approximately one-half the time for Panel 1.

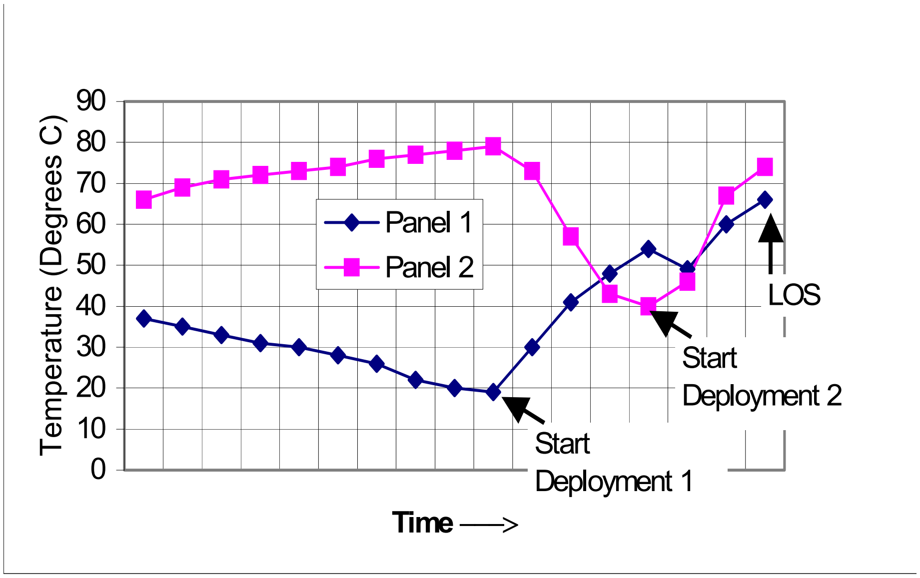


Figure 6. Panel Temperatures During Deployment

The current-voltage output was initially consistent with ground-based electrical measurements of the CIS modules. However, about one month after launch, unexpected degradation in current output appeared (Figure 7). About four months after launch, around March 30, 2001, a large step decrease in current output was observed. Array voltage did not appear to be affected in the same manner. After this degradation became evident, a rapid thermal cycling test in a nitrogen environment was performed on an engineering model of the LFSA at Lockheed Martin Astronautics. Final test results showed a similar degradation pattern that has been linked to excessive diffusion between PV contacts and the indium solder used to make the connection. Based on this. it has been concluded that the large decrease in current is due to progressive fracture of solder joints between the CIS modules and the flexible harness that carries current to the LFSA measurement electronics. During the LFSA fabrication process, copper is sputtered over the CIS material and soldered to a copper strip on the flexible harness completing interconnection. Ground test results showed gradual erosion of copper down to the absorber layer during thermal exposure. This supports the hypothesis that the copper atoms diffuse into the solder at the high end of the temperature cycle, thereby producing insufficient adhesion at the CIS junction. This lack of adequate adhesion, in turn, causes gradual failure of the entire joint. The process is likely accelerated by stresses induced from thermal cycling.

The final conclusion is that, being subjected to a rapid thermal cycling environment, the interconnection solder joints progressively failed over time to a point where a sufficient number of joints failed suddenly so as to produce the observed large step degradation in power output of the LFSA. No further current output flight data was acquired because the current had fallen to a point of being within the measurement noise level. Since this event, contact metallurgy practice for this application has been revised to include a diffusion barrier between the soldered top contact and the CIS absorber layer. This consists of titanium deposited on the CIS followed by palladium and then silver. This stack creates an ohmic contact with adequate bonding to the absorber and eliminates the mass transport processes responsible for degradation of EO-1-type electrical connections. Efficiency and large area deposition capability for CIS have dramatically improved since assembly of EO-1. It is expected that future arrays approaching 8% efficiency with improved contacts will be delivered as primary power sources in the near future. Evaluation of these arrays, in conjunction with revised contact and interconnect approaches, is being conducted to ensure survivability of future systems. These results are expected to be published late in 2002.

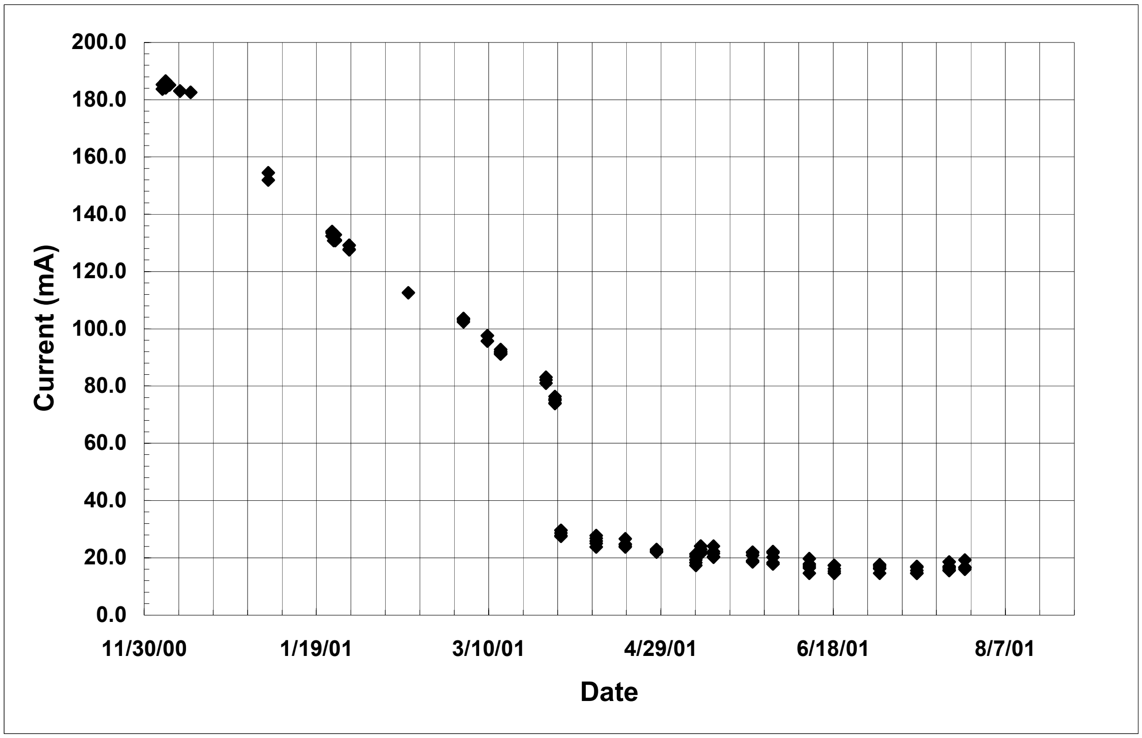


Figure 7. LFSA Current at 2 Volts vs. Time

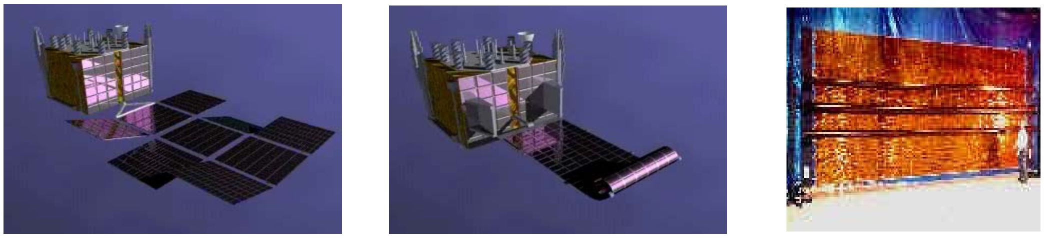
4. NEW APPLICATIONS POSSIBILITIES

The LFSA concept has the potential to produce high specific power (W/kg) if the efficiency of thin-film solar cells improves to 10% or better. At present, large-area CIS does not approach this minimum when deposited on flexible substrates. Amorphous silicon modules, however, have been fabricated on flexible substrates with an AM0 efficiency of approximately 8-9%[4]. Such modules have flown as experiments on the MIR space station[5].

4.1 Future Opportunities

Next generation spacecraft are demanding increased power to accommodate advanced science instrumentation, housekeeping, communication, and attitude subsystems. Combined with the need to reduce spacecraft size, it is apparent that dramatic improvements in solar array technology are required to advance the current state of practice. The EO-1 experiment has demonstrated advanced technologies that have the potential to satisfy the specific system power goal of greater than 175 W/kg if the efficiency of thin-film solar cells improves to 10% or better. Figure 8 represents several solar array approaches planned for development and flight qualification. Two Air Force Research Laboratory-sponsored programs with Aeroastro, Inc. are currently in place to demonstrate these approaches. These two programs are the Lightweight Solar Array (LSA) program, which considers ultra lightweight deployment mechanisms, launch retention devices, and composite structures, and the Air Force Dual Use Science Technology (DUST) program, which is based on fabrication of high efficiency thin-film PVs. Both of these programs will be employed to build primary power systems for two near term spacecraft applications. Deliveries are expected to occur late 2002.

Fold-Out Array | **Roll-Out Array** | **Inflatable Array**



to 1 kW
> 100 W/kg

2 to 8 kW
> 175 W/kg

8 to 20 kW
> 200 W/kg

Figure 8. Future Solar Array System Designs

5. FUTURE MISSIONS INFUSION OPPORTUNITIES

Aeroastro, Inc. missions, the Sport orbital transfer vehicle and Encounter spacecraft, will employ LFSA technology as primary power systems. System specifications and array requirements are currently being generated. Sport will use flexible thin film attached to its aerobrake similar to the rollout array design. Encounter requires six 1 m x 0.5 m PV panels of 350 watts similar to that shown for the foldout array design.

6. LESSONS LEARNED

LFSA structural and deployment components are sufficiently mature to be baselined in future solar array designs. Performance for these systems has been verified through qualification testing and on-orbit missions.

Efficiency of thin-film PVs, aperture area, and the mass of the substrate remain key issues. Large area (36 cm x 4 cm) amorphous silicon cells with sufficient efficiency (approximately 9%) have been produced on thin metallic substrates.[6] CIS cells require additional development to attain the present maturity of amorphous silicon. Although efficiency as high as 8% has been documented,[7] the CIS cell size is only 5 cm^2. Since assembly of the EO-1, efficiency and large area deposition capability for CIS cells on a flexible substrate have dramatically improved. It is expected that future arrays approaching 8% efficiency with improved contacts will be delivered as primary power sources in the near future. Development programs such as DUST will emphasize large area deposition of CIGS (Copper Indium Gallium Diselinide) PV on thin metallic substrates with improved efficiency.

Thin-film PV power source continues to be an evolving technology. Process sensitivity and scalability tend to limit device efficiency. Efficiency is improved through the use of high temperature processes but these have forced the use of metallic substrates vs. polyimide as used on EO-1.

Flight opportunities are necessary to move the technology forward. They provide the means of total system verification as well as verifying on-orbit performance.

Interconnect technology needs to be advanced. It is not sufficient to have high performance PV material and rely on traditional methods of creating electrical connections. As the result of the problem experienced on the EO-1, interconnect technology for CIS thin-film cells on a flexible substrate has been advanced by adding a diffusion barrier between the soldered contact and the CIS absorber layer.

7. SUMMARY AND CONCLUSIONS

The EO-1 LFSA experiment has demonstrated advanced technologies that have the potential to satisfy the specific system power goal of greater than 175 W/kg if the efficiency of thin-film solar cells improves to 10% or better. At present, large-area CIS does not approach this minimum when deposited on flexible substrates. Efficiency of thin-film PVs, aperture area, and the mass of the substrate remain key issues.

In conclusion, the ability to conduct a controlled deployment of the LFSA experiment using the shape memory alloy release and deployment system has been validated but work remains to be done in increasing the efficiency of CIS thin-film solar cells. Even though the PV performance of the CIS solar array assembly experienced a failure, the failure mechanism was identified and an advanced interconnect process has been developed for future use.

8. CONTACT INFORMATION

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