Validation Report
for the
EO-1 Lightweight Flexible Solar Array Experiment

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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 100 Watts/Kg.

2. Technology Description

2.1 LFSA Experiment

The LFSA technology is a lightweight photovoltaic solar array system. The unique features of this solar array are the use of copper indium diselinide ($CuInSe_2$ or CIS) solar cells and shape memory alloys (SMA) for the hinge and deployment system. Figure 1 is a photograph of the LFSA EO-1 flight experiment. Figure 2 is a photograph of the SMA hinges. Figure 3 is a schematic of the LFSA control circuitry. The hinges are deployed by means of heaters 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.

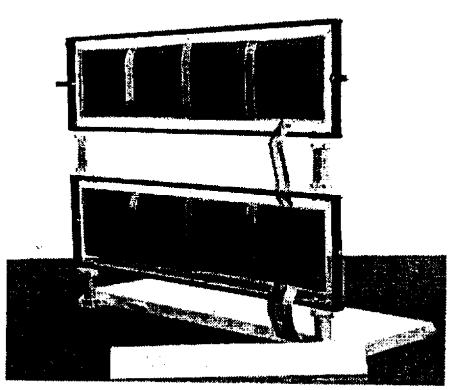


Figure 1. EO-1 LFSA Experiment.

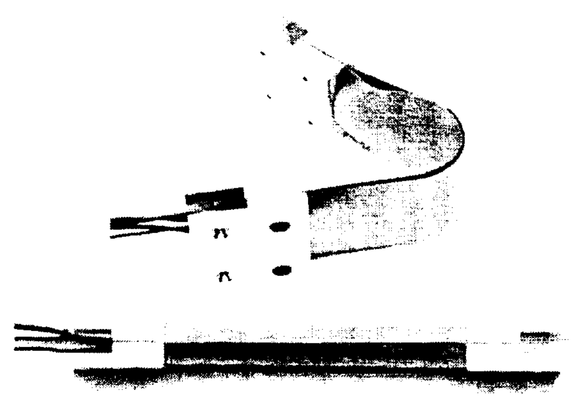


Figure 2. Shape-Memory Alloy Hinges, Stowed (Top), and Deployed (Bottom).

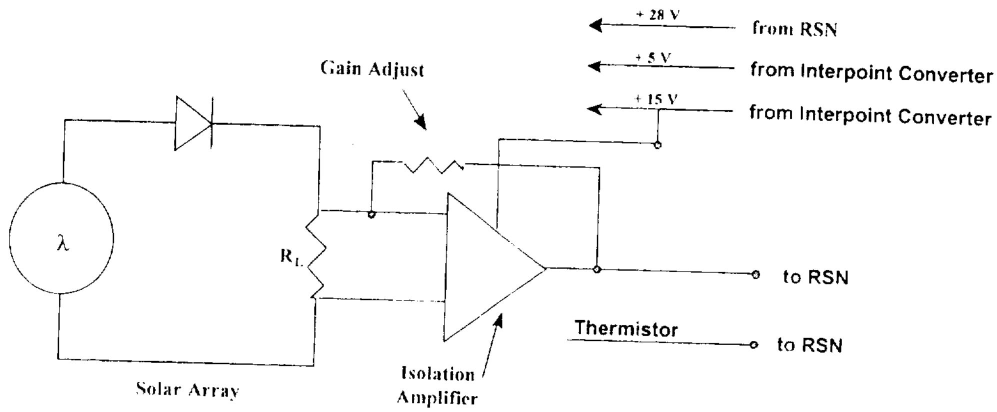


Figure 3. LFSA Schematic.

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 vapor deposited on a flexible substrate which is substantially lighter than cells bonded to a rigid panel. The LFSA solar cell modules are 4" x 4" and each consist of 15 monolithically-interconnected cells in series. The Air-Mass-Zero (AM0) module efficiency achieved for this size was approximately 2%. Higher efficiencies have been achieved on smaller areas (See Figure 4.)[2].

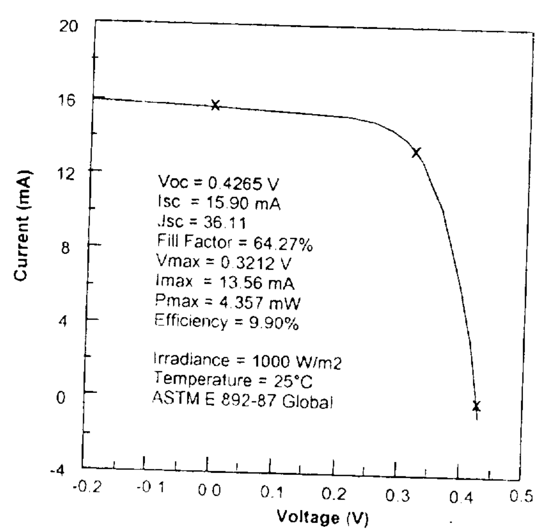


Figure 4. Air-Mass 1.5 I-V Curve for a 0.5 cm2 CIS Thin Film Solar Cell.

2.3 Shape Memory Alloys

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

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 (approx. 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 which 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. The dual flexure concept was developed for integration on the EO-1/LFSA flight experiment (See 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 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]

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

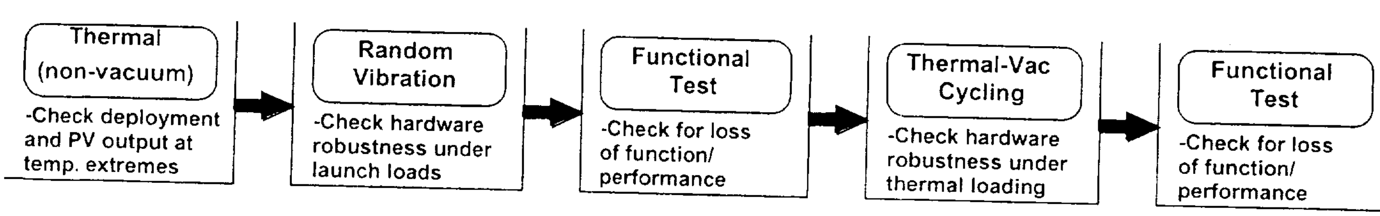


Figure 5. LFSA Ground Test Sequence.

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

3.1 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 photovoltaics, deployment hinges, launch locks, I-V measurement electronics and structural components.

Primary testing included thermal cycling within vacuum, vibration loading and acoustic exposure. 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 places maximum load on the thin film photovoltaics and suspension system. These materials did not demonstrate degradation, verifying that edge restrained array panels could survive launch environments.

Table 1. Qualification Tests.

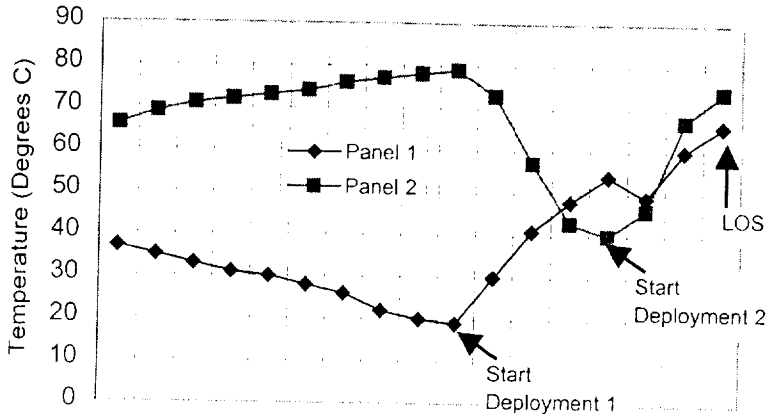
Description	Requirement	Test
1) Vibration (gRMS)		
Acceptance	10.65	10.64
Protoflight	15.04	15.04
2) Thermal Vac (°C)	-10 to +50	-40 to +80
3) Acoustic (OASPL*dB)		
Acceptance	138.1	138.1
Protoflight	141.1	141.1
4) Functional Tests (Deployment Required	Two (with EO-1 Spacecraft)	Six (with Flight Parts)

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 photovoltaics 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 consistent with previous data.

3.2 On-Orbit Test Validation and Usage Experience

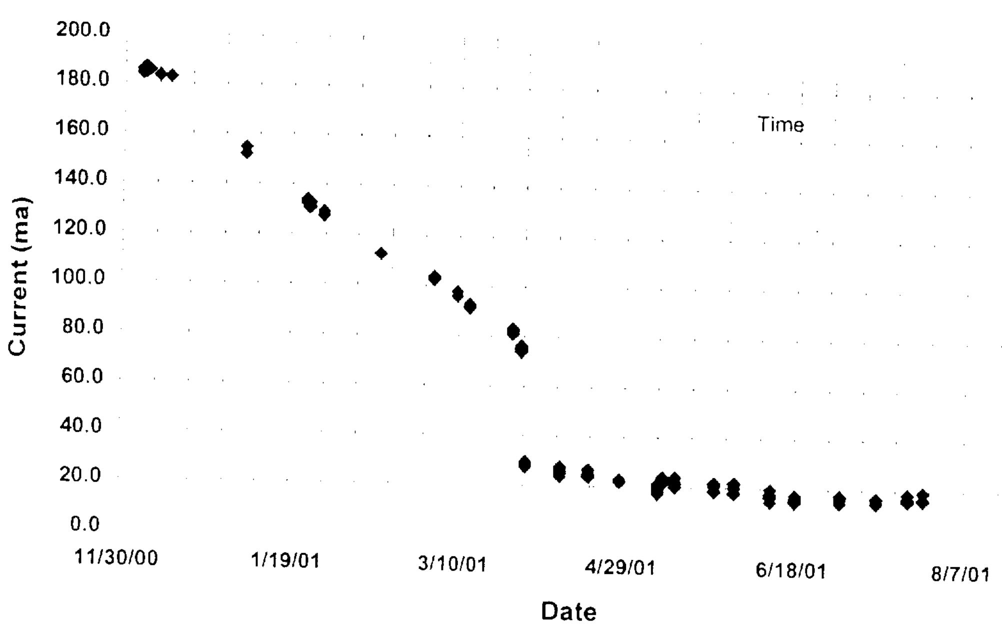
The LFSA was deployed shortly after launch. The indicator switches and the panel temperature profiles (See Figure 6.) indicated that the deployment was nominal.

Figure 6. Panel Temperatures During Deployment.



The current-voltage output was initially consistent with ground-based electrical measurements of the CIS modules. However, over time unexpected degradation in current output appeared (See Figure 7.). Around March 30, 2001, a large step decrease in current output appeared. The array voltage did not appear to be affected in the same manner. After this degradation became evident, rapid thermal cycling on an engineering model of the LFSA was done at Lockheed Martin. Early results indicate that similar degradation is beginning. The degradation appears to be due to failures of the solder joints between the CIS midules and the flexible harness that carries current to the LFSA measurement electronics. Copper was deposited over the CIS material and soldered to a copper strip on the flex harness to achieve the interconnection. One hypothesis is that the copper atoms are diffusing into the CIS at the high end of the temperature cycle. This would change the thermal expansion charactersitcs of the solder joint and could lead to failure of the joint.

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 Air-Mass-Zero (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 demonstrates advanced technologies required to satisfy the specific system power goal of greater than 175 W/kg. Figure 6 represents several solar array approaches planned for development and flight qualification. Two AFRL sponsored programs are currently in place to accomplish this. 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 photovoltaics. 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.

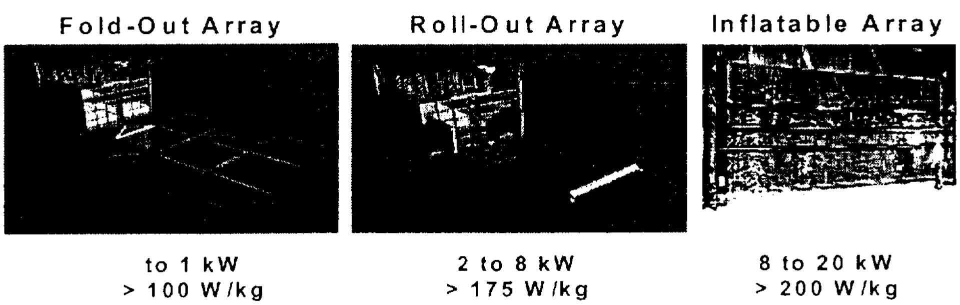


Figure 8. Future Solar Array System Designs

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 1m X 0.5 m photovoltaic panels or 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 photovoltaics, 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. CIS cells require additional development to attain the present maturity of amorphous silicon. Although efficiency as high as 8% have been documented, CIS cell size is only 5 cm^2. Development programs such as DUST will emphasize large area deposition of CIGS photovoltaic on thin metallic substrates with improved efficiency.

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8. Summary and Conclusions

The controlled deployment of the LFSA experiment using the shape memory alloy release and deployment system has been demonstrated. Work remains to be done in increasing the efficiency of CIS thin-film solar cells and in techniques for soldering the CIS terminations to the flexible harness that carries current from the array to the I-V measurement electronics.

9. Technical References

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4. M. Kagan, V. Nadorov, S. Guha, J. Yang, and A. Banerjee, "Space Qualification of Amorphous Silicon Alloy Lightweight Modules," Proceedings of the Twenty-Eighth IEEE Photovoltaic Specialists Conference, pp. 1261-1264, Anchorage, AK, September 15-22, 2000.

5. J. Tringe, J. Merrill, and K. Reinhart, "Developments in Thin-Film Photovoltaics for Space," Proceedings of the Twenty-Eighth IEEE Photovoltaic Specialists Conference, pp. 1242-1245, Anchorage, AK, September 15-22, 2000.