AFRL Thin Film Solar Cell Development and Upcoming Flight Experiments

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Abstract—The many advantages of thin-film solar cells, namely flexibility, high radiation resistance, low mass, and low cost production, will go untapped until space environmental effects on them are well understood, which requires on-orbit testing. In response to the need to perform on-orbit testing of thin-film solar cells, the Space Vehicles Directorate of the Air Force Research Laboratory (AFRL) is preparing two flight experiments. The thin-film solar cell flight experiment on the AFRL Roadrunner Mission will consist of two technologies, amorphous silicon (a-Si) and Copper Indium Gallium di-Selenide (CIGS), each producing roughly 60 W of power. The flight is planned for mid-2005 and will be in Low Earth Orbit (LEO). The AFRL Deployable Structures Experiment (DSX) will host a significantly larger thin-film solar cell experiment (4.5 kW) and will fly in Medium Earth Orbit (MEO) in 2009. The main objectives of both flight experiments are to characterize on-orbit thin-film solar cell performance, enabling the creation of on-orbit performance models and successful transition to operational use.1,2

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1. INTRODUCTION

The mission of AFRL is to lead the discovery, development, and integration of affordable warfighting technologies for our air and space forces. Included in the “air and space” forces are satellites, which require power systems to provide power to operational military payloads. These power systems have certain needs that basically fall into two categories: increased capability and decreased cost.

Power system needs include increased payload mass budgets, reduced power system and launch costs, increased on-orbit available power, and extended mission lifetime. There are many solar array performance metrics that are indicators of these capabilities, including efficiency, specific power (W/kg), and stowage volume (W/m³). Stowage volume is a particularly important parameter because it is an indicator of the maximum power that can be achieved for a given launch vehicle fairing and spacecraft. On-orbit power requirements have been steadily increasing over the years in both the commercial realm and for government missions. Therefore, it is important to work toward space power solutions that meet future high power on-orbit requirements.

To meet future spacecraft power system needs while reducing cost, AFRL is investing in thin-film solar cell development of two technologies: a-Si and CIGS, both of which offer lightweight, flexible, low mass solutions to the ever-increasing satellite power needs. Each technology is currently at a Technology Readiness Level (TRL) of 3-4. Section 2 discusses AFRL’s approach to thin-film solar cell research.

To successfully transition thin-film solar cell technology to operational use, TRL must be 7 or higher. To reach TRL 7, defined as a successful solar array prototype in flight, AFRL is investing in two flight experiments. The thin-film solar cell flight experiment on the AFRL Roadrunner Mission will consist of a-Si and CIGS, each producing roughly 60 W of power (Figure 1). The flight is planned for mid-2005 and will be in LEO. The AFRL Deployable Structures Experiment (DSX) will host a significantly larger thin-film solar cell experiment (4.5 kW) and it will fly in MEO in 2009 (Figure 2). Each experiment will demonstrate a different deployment mechanism for the thin-film solar cells. Both experiments will contribute to the characterization of on-orbit thin-film solar cell performance,
enabling the creation of on-orbit performance models essential for successful transition to operational use. The flight experiments are discussed in Section 3.

2. **Thin-Film Solar Cell Research**

AFRL’s thin-film solar cell research is focused on two technologies: a-Si and CIGS. While their efficiencies are low compared to state-of-the-art crystalline solar cells, they have other unique attributes that make them very attractive for space use. These attributes include flexibility, low mass, high radiation resistance, and low cost production.

The flexibility and low mass of thin-film solar cells are particularly beneficial because they allow innovative solar array support structures and stowage schemes. With innovative support structures that are currently being developed by multiple aerospace companies, thin-film solar arrays could potentially provide much greater stowed volume (45-60 W/m³ vs. 10-15 W/m³), much greater specific power (250-500 W/kg vs. 70 W/kg), and much lower cost (~$250/W vs. ~$1000/W) than rigid flat panel solar arrays. Stowed volume is of particular interest for increasing on-orbit power availability that has been limited in the past by available launch fairing volume (>100 kW vs. ~30 kW).

The goals of AFRL’s thin-film solar cell research are to increase conversion efficiency, increase cell level specific
power, establish space survivability, and develop monolithic integration. Each goal is a means toward either increasing on-orbit power capability or reducing power system cost.

In contrast to crystalline wafer solar cells that were developed initially for space and eventually adapted to terrestrial applications, the thrust behind the development of thin-film solar cells has come from the terrestrial market, primarily because of the potential for lower production costs. As a result, some commonly used thin-film substrates and materials are unsuitable for space applications. For example, CIGS modules with Air Mass 1.5 efficiencies of 12% are commercially available with 3.2 mm-thick glass substrates. Less fragile and lower mass substrates such as metal foils and Kapton films are more suitable for space. EVA and other polymeric encapsulants have been developed to protect thin-film cells from the effects of weather, but are likely insufficient for shielding arrays from the space environment.

AFRL-funded cell development programs are intended to make changes in cell technology geared to space application by increasing cell specific power via tilting performance/cost tradeoffs toward higher efficiencies and supporting the development of cell production processes with lightweight substrates such as metal foils and polyimide.

For a-Si, the more mature technology of the two, the challenges have been to increase efficiencies above the 10% threshold, to integrate cells into modules, and to use lightweight substrates. United Solar Ovonic (USO) has increased the efficiency of their product to 9.8% Air Mass Zero (AM0) (all efficiencies in this paper are measured with increased the efficiency of their product to 9.8% Air Mass light-weight substrates. United Solar Ovonic (USO) has threshold, to integrate cells into modules, and to use polyimide.

Polyimide or an insulating layer on a metal foil. Large-scale pinhole-free coatings on metal foils at low cost have been problematic in the past, but AFRL programs are making headway. Monolithically integrated a-Si is currently being mass-produced on 2-mil polyimide at Iowa Thin Film Technologies (ITFT), and ITFT has recently demonstrated monolithically integrated cells on 1-mil thick polyimide. ITFT sub-modules have AM0 efficiencies of 4.5% for 0.93-m² (10 ft²) areas [4]. Under an AFRL-funded program, ITFT is developing a higher efficiency product with a target goal of 9%. The development of high temperature polymers also promises to enable monolithic integration for CIGS cells on flexible substrates.

Array blanket development programs are continuing under Dual Use Science and Technology (DUS&T) programs. Two multi-year programs with Lockheed Martin Space Systems and Boeing Satellite Systems involve 50-50% cost sharing between industry and government and are focusing on the design and development of thin-film solar cell modules for space. The modules are being designed to meet specifications imposed by innovative, mass efficient solar arrays.

The Lockheed Martin DUS&T program is working to optimize cells for space, and has generated specifications for module strength and structural support requirements. The effort has resulted in the technology to construct a 3-m² (32-ft²) module comprised of 30 USO a-Si solar cells. Smaller 3-cell modules have also been fabricated. A 3-cell module and individual cells have been thermal cycled from -175°C to +120°C for 100 cycles and 1100 cycles, respectively. Cell efficiencies after thermal cycling were within 97% of pre-test values [4].
The Boeing DUS&T program has identified 1kW, 20 kW, and 50 kW arrays suitable for thin-film blankets. The Boeing program is also developing modules, their electrical architectures, and structural support requirements. Subcontractors on the Boeing program are USO, ITN Energy Systems, and MicroSat Systems. The program has produced a comprehensive requirements document covering all aspects of the thin-film blanket, array and interconnect design [4].

3. UPCOMING THIN-FILM SOLAR CELL FLIGHT EXPERIMENTS

The many advantages of thin-film solar cells will go untapped until space environmental effects on them are well understood. Ground testing of thin-film solar cells subjected to various space environmental conditions such as space radiation, UV exposure, micrometeorite impacts, and space plasma interactions is a necessary step to utilizing thin-film solar cells in an operational system. However, the majority of this testing is performed sequentially, with only one space environmental condition present at a time. While this sequential testing will go a long way toward predicting device performance on orbit, its predictive capability assumes that the effects of the various space environmental phenomena on thin-film solar cells are not synergistic (interdependent). For example, ground testing can be performed for thin-film solar cells subjected to single energy charged particles at accelerated dosage rates in a sequential fashion, but experimental facilities that can perform concurrent testing with a full spectrum of charged particle energies at near the actual dosage rate, while the sample is being illuminated with an AM0 solar spectrum and held at operational temperature under vacuum, are nonexistent and believed to be cost prohibitive to construct. A space experiment with thin-film solar cells, coupled with ground testing, is therefore needed to provide the data to determine the interdependency of the space environmental influences.

In response to the need to perform on-orbit experimentation on thin-film solar cells, the Space Vehicles Directorate of the Air Force Research Laboratory is preparing two flight experiments. The first will be on the AFRL Roadrunner Mission (Experimental Solar Array) and the second will be on the AFRL Deployable Structures Experiment (Thin-Film Photovoltaics Experiment). These thin-film solar cell flight experiments are a critical step in transitioning thin-film solar cells to operational use.

The thin-film solar cell flight experiment on the AFRL Roadrunner Mission (Figure 1) will consist of two technologies: amorphous silicon (manufactured by United Solar Ovonic) and CIGS (manufactured by Global Solar Electric). Two wings are planned, one for each technology, that produce roughly 60 W each and deploy using an innovative deployment scheme developed by MicroSat Systems called FITS (Foldable Integrated Stiffening). The flight is planned for mid-2005 and will be in LEO. The objectives of this thin-film solar cell flight experiment on the Roadrunner Mission include: (1) obtain flight heritage for FITS solar array deployment system; (2) obtain flight heritage in LEO for thin-film solar cells; (3) enhance Roadrunner Mission with “extra” power; and (4) obtain full current/voltage characterization of thin-film solar cells on-orbit and characterize their degradation with time.

The AFRL Deployable Structures Experiment (DSX) will host a significantly larger thin-film solar cell experiment than will be flown on the AFRL Roadrunner Mission (Figure 2) and will fly in MEO in 2009. The objective configuration includes five thin-film solar cell technologies of significant power levels: amorphous silicon from United Solar Ovonic (3 kW, 100 V), CIGS from Global Solar Electric (1 kW, 280 V), amorphous silicon from Iowa Thin Film Technologies (300 W), CIGS from DayStar International, and CIGS from International Solar Electric Technology (100 W). A thin coating is also being developed through AFRL research to protect the thin-film solar cells from the space environment while maintaining the low mass and flexibility afforded by this technology. The structure will employ a lightweight polymer substrate with lightweight composites for stiffness. The structure and solar array, called the PowerSail, will deploy using a rollout technique [5]. While this configuration is the current objective, the actual flight configuration is yet to be established and may consist of lower power levels with additional solar cell technologies (such as amorphous silicon on polyimide from United Solar Ovonic).

There are four main objectives for this flight experiment: (1) obtain flight heritage for the PowerSail rollout solar array deployment system; (2) obtain flight heritage in MEO for thin-film solar cells; (3) create predictive capability for on-orbit performance that will enable thin-film solar cell technology transition; and (4) increase TRL for thin-film solar cells at the cell-level and at the integrated array-level (from TRL 3-4 to TRL 7). Four on-orbit experiments are planned to achieve these goals: (1) full current/voltage characterization of each solar cell technology will be coupled with on-orbit Space Weather measurements to determine degradation in the MEO environment; (2) small sections of each solar cell technology will be intentionally annealed to measure performance recovery; (3) a coating degradation experiment will be conducted to decouple any solar cell performance loss due to a decrease in coating transmission; and (4) one solar cell technology will run at high voltage and all arcing events will be recorded. In preparation for this flight experiment, AFRL is undertaking the most extensive ground testing and characterization program for space qualification of thin-film solar cell technologies to date. Real time on-orbit space weather measurements will be correlated to on-orbit solar cell
performance and compared with ground-based testing to develop/validate an on-orbit predictive model (Figure 3).

Both planned experiments will contribute to technology transition of thin-film solar cells to operational space use in two areas: on-orbit performance predictive modeling and increase in Technology Readiness Level. The on-orbit performance predictive capability will be created through validation/development of radiation, annealing, and plasma interaction models. The increase in Technology Readiness Level will be achieved at the thin-film cell level and the integrated array level through both extensive ground testing and on-orbit demonstration.

4. CONCLUSION

Thin-film solar cells have many beneficial attributes for space power systems, namely flexibility, high radiation resistance, low mass, and low cost production. The present AFRL program in thin-film solar cell development and the corresponding flight experiments is expected to result in their future, operational use in space.

REFERENCES


**BIOGRAPHY**

**Dr. Jennifer Granata** specializes in the characterization, analysis, and qualification of photovoltaics for space. She is a member of the Aerospace Corp. and supports the AFRL Space Vehicles Directorate Advanced Space Power Generation group at Kirtland AFB. Dr. Granata is responsible for qualification and characterization of thin-film solar cell technologies to be used on Deployable Structures Experiment (DSX). She is also responsible for customer support. Prior to joining Aerospace Corp. in 2003, Dr. Granata worked for Spectrolab, Inc. where she focused on the characterization and space qualification of crystalline multijunction solar cell technologies. Dr. Granata received her PhD in Physics from Colorado State University in 1999.

**Dr. Paul Hausgen** is a key member of the Advanced Space Power Generation group at AFRL. He is responsible for the development of lightweight thin-film solar arrays for the Roadrunner and DSX (Deployable Structures Experiment) flight experiments. Dr. Hausgen also directs lightweight solar module development programs with Lockheed Martin Astronautics and Boeing Satellite Systems. In addition, he directs lightweight solar array support structure efforts with Boeing Satellite Systems (in cooperation with NASA Glenn) and Microsat Systems. He also directed efforts on the improvement of thin-film solar cell efficiency. Dr. Hausgen received his Ph.D. from Georgia Institute of Technology in Mechanical Engineering in 2000. He has previously conducted research in thermal-to-electric conversion systems and the application of nano-molecular structures for solar spectrum alteration. Dr. Hausgen holds one U.S. patent.

**Dr. Donna Senft** is Chief of the Advanced Space Power Generation group at the Air Force Research Laboratory Space Vehicles Directorate at Kirtland AFB, New Mexico. She is responsible for the development of space solar cell and array technology for the Air Force and oversees a broad portfolio of efforts ranging from the development of multijunction solar cells to thin-film photovoltaics to long-range studies on the impact of nanotechnology on power generation. Dr. Senft received her Ph.D. in Materials Science and Engineering from the University of Illinois at Urbana-Champaign in 1994 and also holds degrees in Physics and Engineering Science. Dr. Senft has previously been employed by Sandia National Laboratories and has participated in a small start-up business venture. She is the holder of 3 US patents and has published a number of papers in photovoltaics and the fundamentals of the nucleation and growth of device materials.

**Dr. Pawel Tlomak** has managed R&D programs as a member of the Advanced Space Power Generation group at AFRL since 2000. His work focuses on development and fabrication of multifunctional protective coatings systems for thin-film photovoltaics, requirements for their space qualification and space flight components development. Dr. Tlomak joined the Air Force Research Laboratory in 1992, conducting work on fast densification of composites for space application, thermal management systems, materials for nuclear propulsion, and synergistic effects of space environment on materials performance. He co-developed on-ground micro-meteorites impact testing technology using laser-driven hypervelocity flyers. Dr. Tlomak received his Ph.D. in Materials Science and Engineering from Southern Illinois University in 1988. His work at the Materials Technology Center concentrated on space materials and involved development of oxidation protection systems for carbon-carbon and ceramic composites, chemical vapor deposition, friction, wear and dynamic properties testing.

**Mr. John Merrill** is Deputy Program Manager for the Advanced Power Generation Group in the Space Vehicles Directorate, Air Force Research Laboratory. His responsibilities are a mix of program management and research projects primarily in the development of photovoltaics for space. Mr. Merrill previously was involved in development of next generation thermal-to-electric conversion technologies and has also investigated embrittlement behavior in Ni-based single crystal superalloys. He holds a B.S. and M.S. in Materials Engineering from Auburn University.