Current Results From The Advanced Photovoltaic Solar Array (APSA) Program

Richard M. Kurland, TRW Space and Electronics Group, Spacecraft Technology Division, Redondo Beach, CA 90278
Paul M. Stella, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

The paper continues the. status reporting of the ultralightweight flexible, blanket, flatpack, foldout solar may testbed wing that was presented at the. previous two IECECs (Stella, 199?.; Kurland, 1991). The test bed wing as been built and subjected to a variety of critical functional tests a fter exposure 10 simulate.d launch environments. The 6 kW beginning-of-life (HOI.) wing design is capable of providing over 130 W/kg (1101.) specific power as an intermediate milestone towards NASA's far term goal of 300 W/kg at 20 kW.

The last phase of the APSA program has been in progress about one year with a number of analyst.s and panel-level tests to better ldc.fine a variety of design options, to support flight hardware experiments on host spacecraft, and to enhance. the overall operational reliability of ftcxiblc.-blanket array designs under conditions where solar cell circuits arc shadowed or contain cracked cells. Although the final results arc not yet available on all the on-going activities, the nature of the effort in progress is summarized and a description of some flight test hardware is presented.

Design Configuration

A detailed description of the Al'SA wing design is presented in the 26th IECEC technical paper (Kurland, 1991). The basic design configuration is shown in Fig. 1. The deployed and stowed size for the base.liac 5.8 kW (1101.) wing arc shown in Figs. 2 and 3. Two wings of this configuration can provide a spacecraft with 11.6 kW (BOL) and 7.8 kW end-of-life (EOL) power after 10 years in geosynchronous (GEO) orbit. The wing consists of a flat fold, multiple pane], flexible blanket on which solar cell modules arc installed and connected to printed circuit electrical harnesses that run along the outside longitudinal edges of the blanket assembly. For launch, the, accordion-folded blanket is stowed in a graphite/clmxy blanket housing assembly with a polyimide foam layer On the inner surfaces to cushion the folded blanket during launch. 'J'here is no interleaving cushioning material between the folded panels. Solar cells from adjacent panels arc in direct contact when the blanket is folded and stowed in the. blanket housing assembly under a preload pressure, of 3500 to 7000 Pa (0.5 to 1 psi). The blanket is deployed (unfolded) by extending a motor-actuated, fiberglass, continuous tri-longeron, lattice mast that uncoils from an aluminum cylindrical can ister structure., The blanket is supported by two tensioned guidewire systems attache.d to the rear fold line.s of the blanket to prevent any large out-of-plane excursions during deployment. When fully deployed, the blanket is tensioned in the longitudinal direction by a series of cons[ant-force springs at the inboard end of the blanket.

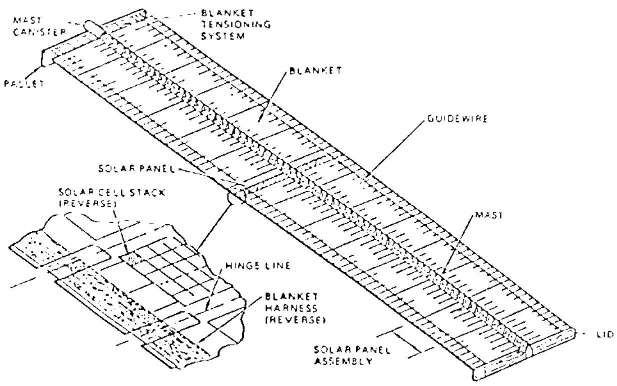

Fig. 1, Generic wing configuration.

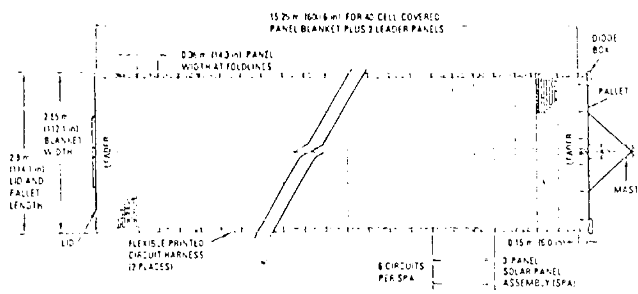

Fig 2, 5.8 kW (BOL) GEO deployed wing.

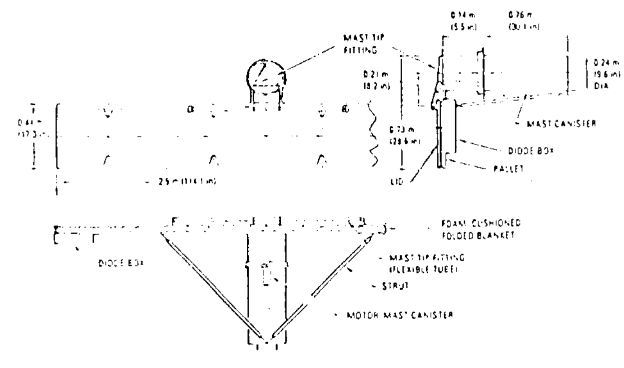

Fig. 3. 5.8 kW (BOL) GEO stowed wing.

Over the last year the baseline design has seen only minor changes as the result of ongoing analyses or component/system-level tests:

1) For ultralightweight applications, the, 50 μm (2 mil) carbon-loaded Kapton blanket substrate material was replaced by germanium-coated regular Kapton. The germanium coating has the same surface, resistivity (-108 ohms/square) as the carbon-loaded material to permit grounding of the blanket substrate, to prevent electrostatic charge buildup from orbital plasma environments. It is also very resistant to atomic oxygen degradation (Banks, 1 992), thus provides long term protection for low earth orbit (11;0) missions. It also has favorable thermophysical properties ($\alpha/\varepsilon \approx 0.5/0.8$), thereby reducing the heat loading and operating temperature of silicon solar ccl] circuits by up to 15°C from the earth's heating for 1 .EO missions.

?.) Bypass diodes arc integrated into the. solar cell circuit design to ensure reliable power performance. of the array when subjected to shadowing or as the result of cracked cells. The preliminary conservat ive requi rement to have a thin wafer d iodc bypass every eight cells (Kurland, 1991) is currently under review based on a series of cell and circuit-level tests and analyses. Final guidelines won't be available for several months. However, it is clear that thin silicon cells will require protection using shunt diodes. Analysis and tests not funded under the APSA program also show this to be true for GaAs/Ge cells on a thin blanket substràte.

3) Under TRW discretionary funding a heavier blanket construction option was developed that replaces the single Kapton layer with a gcr[~ial~illll~-coated Kapton/graphite composite laminate. While heavier, the substrate eliminates the need for shunt diodes when using GaAs/Ge cells and may reduce the number of shunt diodes required for silicon solar ccl] circuits because of its heat conduction properties, A full size 3-panel solar pane] assembly was constructed with thin large area GaAs/Ge cells and incorporated into the APSA wing, Stowed wing vibration tests successfully demonstrate.d the viability of the design concept.

I'ancl-l.eve] **Activities**

SAMPIE Panel

In support of the NASA/LeRC Solar Array Module Plasma **interaction** Experiment (SAM 1'11 :) a series of test articles were fabricated consisting of 15 x 15 cm (6x6 in.) square pane.ts each with a 12-cell, soldered, series-interconnected circuit using 2 x 4 cm, thin (-75 pm) silicon BSFR solar cells with 100 μm thick AR/UV-coated ceria-doped microsheet covers. Both germanium-coated and carbon-load Kapton substrate test article.s were constructed, all mounted on a thick aluminum plate. The SAMPIE program will investigate high voltage discharge characteristics on-board Shuttle in 1993 (Wald, 1991).

Plasma chamber testing of the coupons in preparation for the. flight test indicate acceptable behavior in that the power loss from the plasma interaction with the. weakly conducting blanket substrates is very small (Hillard,1 993).

PASP-APEX Panel

In 1993, the Photovoltaic Array Space Power - Advanced PV and Electronics Experiment (PASP-APEX) will be launched for a 3 year elliptical near polar orbit **mission** (350 x 1850 km, 70 degree inclination) to measure high voltage discharge arid radiation effects on advanced power designs (Burger, 1991). A small panel was fabricated consisting of germanium coated Kapton with a 12-cell, soldered, series-interconnected circuit using 2..6 x 5.1 cm thin (~65 μm) silicon BSFR solar cells with 50pm thick AR/U V coated ceria-doped microsheet covers. The blanket section is supported in an aluminum frame.

Thin **Film GaAs Solar Cell Thermal Cycle Panel**

The development of the peeled-film (also referred to as CLEFT) GaAs CCII by Kopin Corporation has the potential to improve the specific. power and power density performance of the APSA array design by almost 40 percent, because the cell stack (cover-integrated cell) combines a mass less than a thin silicon cell stack with a photovoltaic conversion efficiency slightly greater than conventional thick GaAs/Ge cells. A 2 x 4 cm cell, 5 to 10pm thick, when combined with a **50** to 100pm coverglass weighs from 170 to 270 mg and has a 28°C Ah40 efficiency of 18 to 19 percent, compared to 13.8 percent for a thin 290 to 390 mg silicon ccl] stack.

Two 12-cell solder-intcrconrmcted circuit panels using a SO μm germanium coated Kapton substrate (Fig. 4) were fabricated to evaluate the producibility of interconnected circuits and to evaluate long term thermal cycle. performance. The thermal cycle tests, beginning in mi - 1993, wilt be similar to those successfully performed on thin silicon cell panels (Scheiman, 1990), and will simulate 30 year GEO (-70 to 60°C)and 10 year LEO (-1 00 to 100°C) conditions.

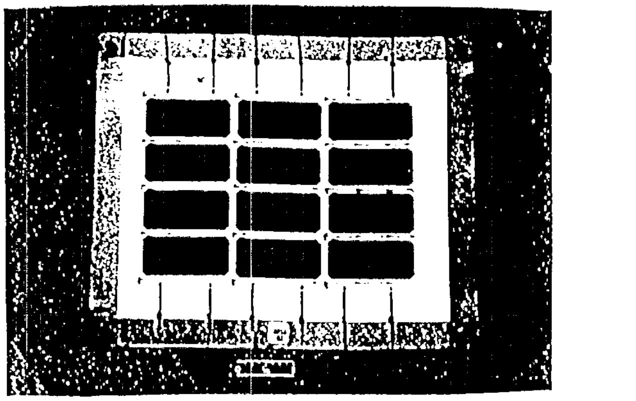

Fig. 4. Kopin peeled-film GaAs solar ccl] the.rmal cycle panel.

Several techniques were investigated to attach an interconnector to the thin gold contact pads that are supported by the DC93500 silicone adhesive layer that bonds the cover to the ultra-thin peeled-film cell. Thermosonic and ultrasonic bonding of gold ribbon/wire or aluminum wire, were attempted using micro-electronic wiring production techniques normally used for large-scale integrated circuits. The results were unsuccessful because the soft DC93500 adhesive support layer did not provide sufficient rigidity to permit intermetallic joining of the ribbon/wire to the contact pact. Other attempts were very successful when a rigid epoxy adhesive was substituted for the space-qualified silicone adhesive. However, since the epoxy adhesive is not space-qualified for solar cell stack applications, it was not used in the test panels. Instead a special inplane relief loop, silver-coated, Invar interconnector was developed and successfully joined to the gold contact pads with a tiny preform of low-temperature (143°C) indium-silver solder. A special electrode, slightly larger than the contact area, was used with low pressure (<200 mg) to minimize deformation of the contact pact or the chevron-shaped thermal relief fingers that connect the contact pad to the cell body (Fig. 5).

The results suggest that more development work is needed at the cell-level and at the circuit production level before cells of this type can be considered a viable cost-effective or weight-effective option to current production "bulk" silicon or GaAs/Ge cells. However, this initial effort indicates the potential for future very high specific performance blanket designs.

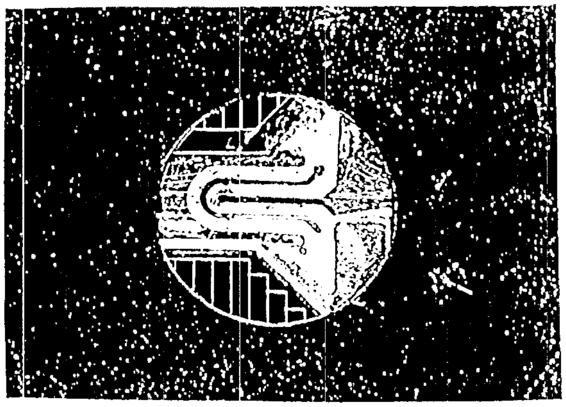

Fig. 5 Interconnection detail, Kopin peeled-film GaAs solar cell (viewed from cutout in panel substrate).

Solar Cell and Circuit Reverse Bias Testing

A comprehensive coupon-level testing and analysis effort is in progress to determine weight- and cost-effective measures to ensure electrical integrity of the solar cell circuits against hot spots resulting from shadowing or cell breakage that can more readily occur for flexible blanket arrays. This activity represents a more indepth effort than the 1991 effort which conservatively concluded thin wafer diodes would be needed for every eight thin silicon solar cells.

Reverse bias characteristics and failure modes were measured on 200 thin BSFR silicon flight production cells from two domestic suppliers. Testing was done as a function of temperature, short circuit current level, repetitively pulsed reverse bias conditions, long duration reverse bias conditions, and charged particle irradiation conditions. Figs. 6 and 7 illustrate the wide variation in reverse breakdown voltage at ambient temperature. There were distinctive differences in the results from the two suppliers, one having a large spread in characteristics, with breakdown occurring from 10 to 65 volts at a current density level ~1 x I_{SC}; and the other characterized by a narrower spread with high voltage (45 to 65 V) and low current density (~0.2 x I_{SC}). The difference in behavior is thought to be due to the methods used in producing the back surface field (boron diffusion doping versus ion-implantation). The effects of temperature level, pulsed or long duration reverse bias conditions or radiation on the reverse bias characteristics were small. Failure modes for both type of cells were either by shunting or shorting; open failures did not occur. Failure modes were observed via infrared thermography, with follow-up evaluation using scanning electron microscope and energy dispersive X-ray analyses on failure sites.

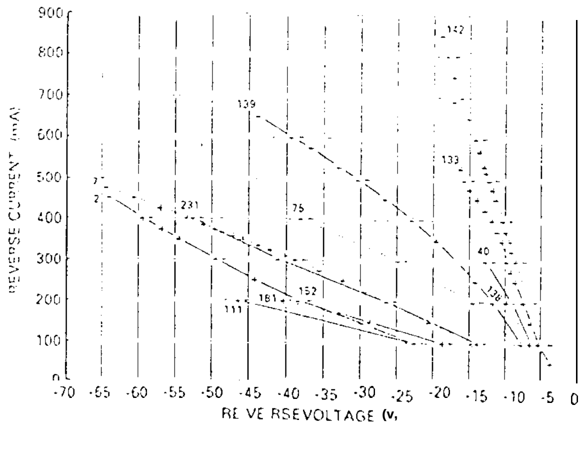

Fig. 6. Reverse bias characterization of boron diffusion thin BSFR silicon solar cells.

As part of the solar cell characterization activities, large area (0.5 x 2.4 cm), 380μm thick wafer diodes were obtained from a domestic supplier and characterized under forward and reverse conditions, at temperature, under long duration conditions and after charged particle irradiation. Thinner (~100 μm) wafer diodes were not readily available from domestic sources, but are being developed in limited quantity in Japan. These diodes, however, were not available for the APSA program.

A series of bench top circuit tests under ambient conditions were also performed to simulate diode-bypassed cell modules containing each of the cell types with varying number of series cells. External cell circuits for higher voltage levels were simulated by a voltage supply.

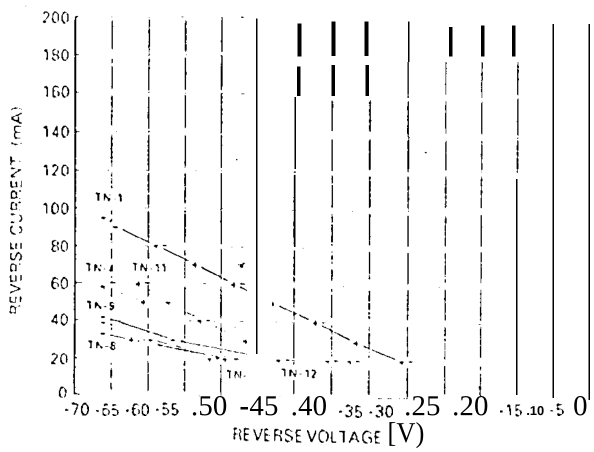

Fig. 7 Reverse bias characteristics of boron ion-implanted thin silicon BSFR solar calls

Fig. **8** illustrates the test setup. Test results (Figs. 9 and 10) show a substantial difference in the diode/cell current sharing, for the two ccl] type.s as a function of shadow condition or simulated cell cracking condition. The boron ion-implanted BSFR silicon cell carries current essenti ally proportional to its illuminated area (i.e., a 100 percent shadowed cell results in all current bypassing the cell via the diode circuit). Whereas, for the. boron diffusion BSFR silicon cell, the current sharing is sensitive to the actual reverse characteristics of the shadowed cell and the number of cells within the diode-bypassed circuit, Current sharing by the cell of 50to65 percent, respectively, was observed for a 100 percent shadowed cell when 8 and 11 series cells were diode-by passed.

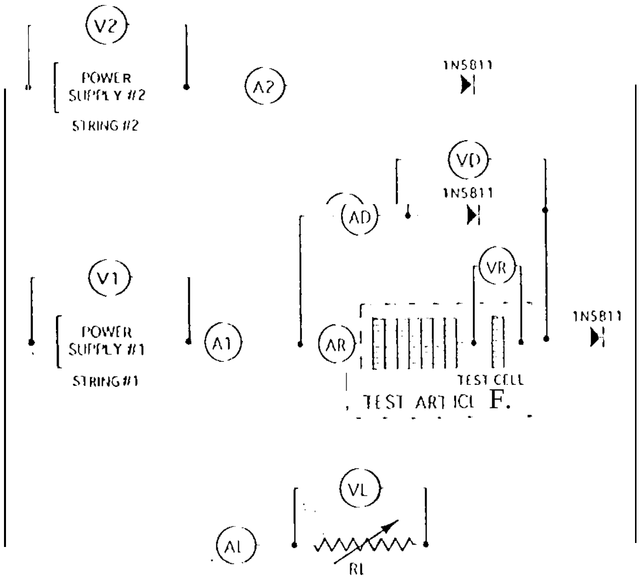

Fig. 8. Bypass circuit Test Set-Up

The circuit test results correlate well with prior analyses done. in 1991 and give confide.ncc that the modeling of conditions beyond those tested will yield useful data for bypass circuit design. These test results, in conjunction with the solar ccl] and diode tests, arc now being analyzed to develop guidelines for weight- and cost-effective circuit protection designs. This is being done as a function of solar cell rc.verse bias features, bus voltage level, heat conduction properties of the, blanket substrate, and the degree of cell cracking or nature of cell/circuit shadowing.

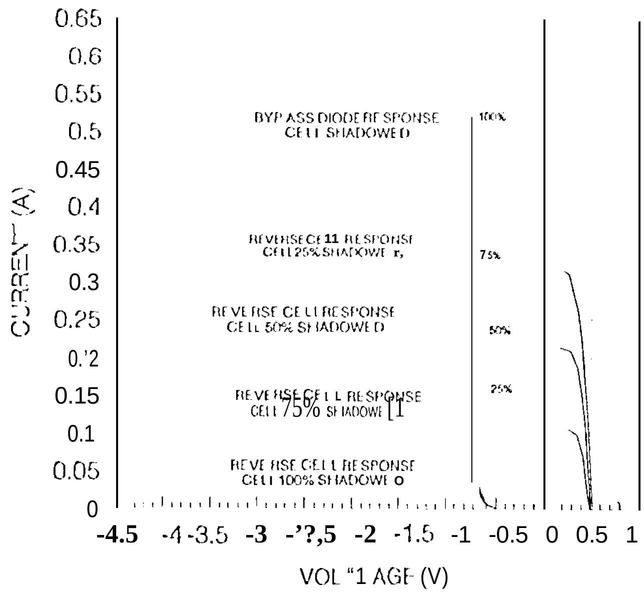

Fig. 9. Current sharing between cell and bypass circuit for a 7-cell module of boron ion-implanted thin silicon cells as a function of one cell being shaded.

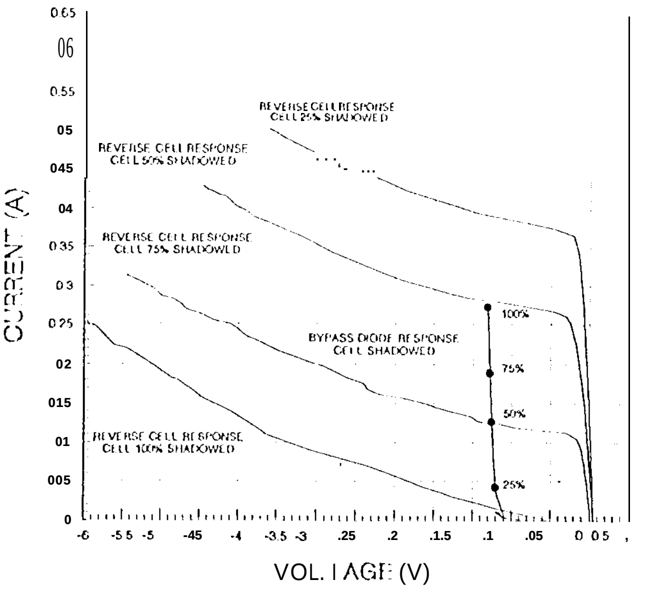

Fig. 10. Current sharing between cell and bypass circuit for a 8-cell module of boron diffusion thin silicon cells as a function of one cell being shaded.

Prototype Wing Hardware Activities

Fig. 11 shows the 8-panel initial version of the deployed prototype wing. The prototype wing is representative of the 5.8 kW (BOL) wing except in six respects: (1) it is truncated in length, consisting of an 8-panel blanket assembly (~3 m long), with two 3-panel units and two 1-panel leader panels, instead of a total of 42 panels; (2) the blanket substrate is 50 μm carbon-loaded Kapton; (3) the blanket panels incorporate 1440 2 x 4 cm (instead of 2 x 5.7 cm) live thin silicon solar cell stacks (55 μm cells, 50 μm covers) solder-interconnected to obtain a series of high voltage circuits ranging from 50 to 150 V (120 to 360 cells in series), with the rest of the panel area covered with mass-simulating aluminum blanks; (4) the live solar cell stacks are representations of flight-quality cells/covers (covers are uncoated ceria-doped glass rather than being AR/UV-coated and the cells are electrically active, although they do not necessarily possess high electrical performance characteristics); (5) there are no bypass diodes included in the solar cell circuits; and (6) construction is being done to standards consistent with the prototype nature of the hardware rather than to flight-quality standards.

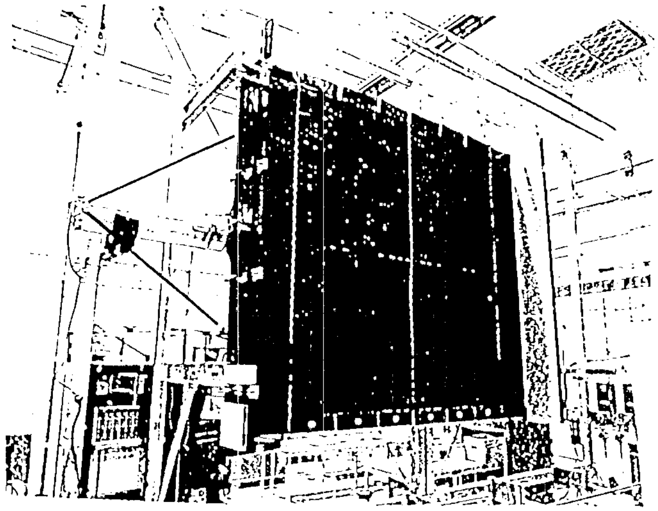

Fig. 11. Deployed 8-panel prototype wing.

The 8-panel version of the wing was subjected to a series of system-level tests whereby the stowed wing was exposed to acoustic and vibration conditions simulating the envelope of Shuttle and Atlas launch environments (Kurland, 1991). Stowed wing first mode natural frequency was about 34 Hz. in local areas of the blanket housing structure the vibration response g-loads reached 25 g's under a 10-g sine dwell base shake test. There was negligible change in the 5200 Pa (0.75 psi) stowed blanket preload pressure. Deployment testing of the wing after exposure to these environments indicated that the preload/release mechanism operated smoothly and the blanket deployed in a controlled accordion-like fashion. Inspection of the primary structure revealed no damage.

After the two acoustic tests and eight vibration tests, about one percent of the live cells were cracked. All cell cracks were considered minor. Electrical continuity was maintained in all solar cell strings.

The wing was then modified under TRW discretionary funding to incorporate a full size germanium-coated, laminated Kapton/ composite substrate in place of the inboard 3-panel unit, along with a blank inboard leader panel (Fig. 12). The 3-panel unit included about 190 2 x 4 cm, 140 μm thin GaAs/Ge cells and 180 4 x 4 cm, 90 μm thin GaAs/Ge cells, all with 150 μm ceria-doped microsheet covers. The wing was subjected to simulated 10 g launch vibration testing and subsequent deployments. Only one additional silicon cell was cracked and about one percent of the GaAs/Ge cells cracked. All cell cracks were minor with no loss in electrical continuity. The use of edge-etched coverglass reduced the amount of coverglass damage.

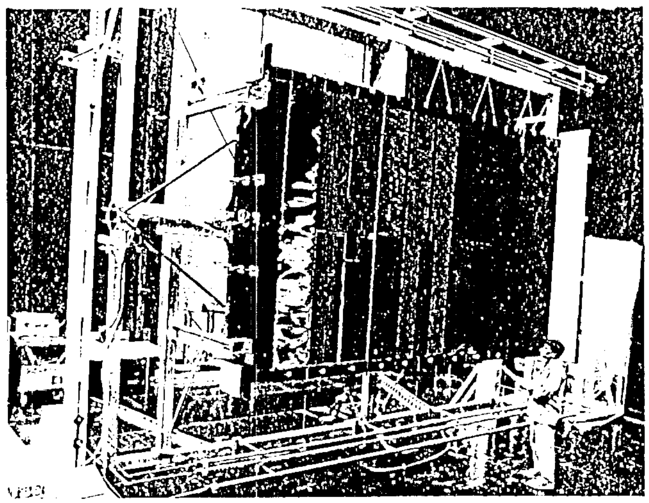

Fig. 12. Deployed 12-panel prototype wing

In conjunction with this latest version of the wing, a thermal cycle test panel was fabricated under TRW discretionary funding, consisting of the laminated substrate with thin (90 to 114 μm) 2x4 and 4x4 cm GaAs/Ge cells and two printed circuit harness segments representative of the blanket assembly harness. Thermal cycle testing representative of a LEO mission was initiated (-115 to +100°C). After about 25 percent of the planned 40,000 cycles, the power output has changed less than one percent. There was some cosmetic bowing in the substrate and wrinkling of the printed circuit harness segments.

About 300 GaAs/Ge cells were tested for reverse bias characteristics. The results indicated that shunt diodes would not be required for GaAs/Ge cells when incorporated into the laminated blanket substrate design, but probably would be required for a thin Kapton blanket design.

Performance Estimates

Using thin BSFR silicon cells with a wafer diode every eight cells, the BOL sped'ic power anct power density arc 138 W/kg and 140 W/m^2, respectively, for a 5.8 kW BOL wing. EOL values (at 3.9 kW) arc 92 W/kg and 94 W/m^2, respectivel y, for a 1 O year GEO mission. The use of 18 percent efficient, thin (-1 15 μm) GaAs/Ge cells provide about the same specific power trends as the less costly thin silicon cells over the range of 5 to 20 kW, even though the wing length would be reduced about 30 percent for comparable power levels. This is bc-cause the increased efficiency of the GaAs/Ge cell is offset by its density which is over twice that of silicon, The usc of advanced thin film cells (a-Si, CIS), once their production maturity has been demonstrated, may improve. specific. power performance by 50 to 100 percent such that 200 W/kg (EOL) might be achievable within the next 10 years.

In progress arc circuit analyses, based on the reported reverse bias testing, to ensure that electrical integrity of silicon solar cell blankets arc maintained as the result of hot spots generated from cracked or shadowed cells. While the current design and performance estimates include an allocation for a wafer diode every eight cells, the recent cell and module tests indicate that design approach (i.e., the number of bypassed cells pcr diode) may be 100 conservative. Circuit protection guide.]incs may really depend on several factors, including: the nature of the cell reverse bias characteristics, the. circuit voltage level, the. nature of shadowing or the type/amount of cracked cells assumed. ~'bus, it is anticipated that the current APSA design and performance estimates will change to reflect updated circuit protection guidelines.

APSA Applications

'J 'he transition of APSA from a testbed program to a flight hardware program has finally been achieved. A derivative of the APSA design was selected for the NASA/GSFC EOS-AM solar array operating in a LEO polar mission. This one wing 5 kW (EOL) design will utilize 2.4 x 4.0 cm x 140 pm, 18 percent GaAs/Ge cells mounted on a german ium -coated Kapton/graphite laminated blanket. The blanket size will be about 5 m wide by 9 m long and consi st of 24 cell-covered panels and onc blank leader panel at each end. The total blanket assembly includes about 36480 cells with each 127 volt string having 1 90 series cells, without the need for shunt diodes. The blanket box structure and mechanism and mast system for EOS-AM will be a direct scale-up of the APSA design. Delivery of the first EOS-AM wing is scheduled for early 1996. Trade studies indicate the equivalent power level design using thin silicon cells would have resulted in a wing 50 percent larger in area at a cost about 10 percent more than the GaAs/Ge ccl] design.

Under near normal sun insolation the EOS-AM wing will have an estimated specific power performance of about 50 W/kg when considering the impact of mission-specific stiffness requirements and mechanical/electrical interfaces, plus the. fact that the. blanket housing assembly, mast system and harnesses arc being sized to include a power growth potential of 2.0 percent. Also, the wing is being designed to incorporate/support about 60 kg of additional components not considered under the generic APSA design. Nevertheless, the EOS-AM wing specific power performance is relatively high because of the pathfinder work done under the APSA program.

Acknowledgment

Except for specific work identified as being developed under TRW discretionary funding, all work described in this paper presents the results of research carried out by TRW Space and Electronics Group for the Jet Propulsion Laboratory, California Institute of Technology, under' contract with the National Aeronautics and Space Administration.

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