

Design, Analysis & Testing of the CellSaver Concentrator for Spacecraft Solar Arrays

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ABSTRACT

CellSaver is an on-panel reflective concentrator used to significantly reduce the cost of spacecraft multi-junction solar cell arrays. CellSaver is a unique concentrator because it can easily be retrofit on to existing solar array platforms due to its compatibility with standard large area multi-junction solar cells and standard composite solar panels and its ability to stow in very small panel gaps (<1 cm.) This paper presents CellSaver design details and space flight qualification test results. Detailed test data is given for electrical performance measurements with EMCORE and Spectrolab triple-junction cell strings, GEO thermal cycling, stowed random vibration, and electron, proton and UV radiation exposure.

CELLSAVER INTRODUCTION

Typically solar cells and cell laydown account for over 70% of the cost of a large (> 5 kW) spacecraft triple-junction solar array. Therefore, an effective way to reduce solar array cost is to reduce the quantity of solar cells required. Recently, many reflective solar concentrators [1,2,3] and refractive solar concentrators [4,5] have been developed for this purpose with varying degrees of space-flight success, operational limitations and up-front user investment required. CellSaver (US and Foreign patents granted and pending) is a concentrator designed to provide the benefits of high performance, reliability, and low costs (both recurring and initial implementation) without the disadvantages of significant solar array platform re-design or spacecraft operational changes.

As shown in Figure 1, CellSaver is an on-panel reflective concentrating element designed to reduce the cost of spacecraft solar arrays by replacing approximately half of the solar cells with relatively inexpensive reflectors. CellSavers bend to the side and nest with each other to stow neatly between panels during launch as shown in Figure 2. When the solar panels unfold in space, CellSavers self-deploy under their own spring energy creating rows of nominally 2X reflective concentrators.

CellSaver has been designed for straightforward retrofit onto existing solar array platforms through features that facilitate easy installation on graphite composite panels, its ability to stow for long durations in tight panel gaps (< 1 cm) and full compatibility with existing panel deployment systems. When the solar array panels are stowed, CellSavers fit entirely in the envelope of the existing panel stack. Additionally,

CellSaver has been optimized for use with all standard sizes of large area GaInP₂/GaAs/Ge triple-junction cells and to be fully compatible with the qualified cell-laydown and interconnect processes of the leading photovoltaic suppliers.

CellSavers are constructed from a single piece of thin (25µm), high-strength titanium foil with a space-flight compatible high reflectance coating. No organic materials are used minimizing radiation and thermal cycle induced property changes and degradation. High-strength titanium foil was selected because it can be folded to extremely tight radii between panels (< 0.5 cm) without yielding, it is extremely stable under exposure to space radiation and thermal cycling, and it is lightweight. The high reflectance coating is vapor deposited silver with a protective transparent dielectric overcoat. The glassy ceramic window prevents tarnishing of the silver due to atmospheric exposure, naturally occurring atomic oxygen erosion in LEO and xenon ion erosion caused by spacecraft ion propulsion systems. The reflective coating provides high reflectance over the entire response range of the GaInP₂/GaAs/Ge triple-junction cell (350nm to 1800nm).

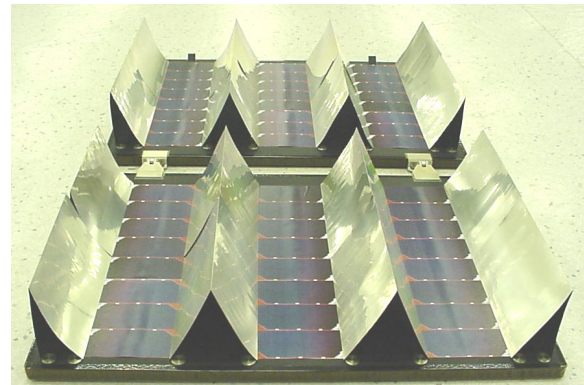


Fig. 1. CellSaver Solar Concentrator Panels.

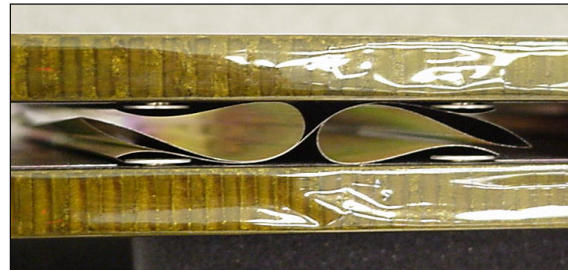


Fig. 2. Stowed CellSavers in a 1.1 cm gap.

CELLSAVER ARRAY CHARACTERISTICS

Key features of CellSaver solar arrays, determined from several previous analyses and tests [6,7], are summarized in Table 1. As shown, the resulting CellSaver solar array has many desirable features that are a direct result of the following factors:

- CellSavers cost approximately only 25% of the cells and laydown that they replace.
- CellSaver mass (0.31 kg/m²) is only 26% of the cells, coverglass and adhesive (1.18 kg/m²) they replace.
- CellSaver follows a strict design and test philosophy mandating easy retrofit into existing solar array platforms and test flows.

It is believed that the unique characteristics of CellSaver make it one of the best near-term options for reducing the cost of existing qualified solar arrays.

Table 1. CellSaver array characteristics.

Characteristic	Basis*	Key Feature
Cost (\$/W)	A	Typical array system cost savings of 25% compared to planar array
Areal Power (W/m ²)	A & T	Approximately 12% less power per unit area than planar array with same cell type (EOL 15 year GEO)
Mass (W/kg)	A	Array level mass savings of 2% to 20% compared to planar array depending on application
Sun Pointing	T	Power follows cosine law for $\alpha = \pm 10^\circ$, $\beta = \pm 25^\circ$
Thermal	A	Solar cells typically operate only about 25°C hotter than planar array in all orbits
Electrostatic Discharge	T	All metal CellSaver design is redundantly grounded to substrate and isolated from solar cells
Electrical Testing	T	Standard LAPSS test verifies performance
Mechanical Testing	T	Full end-to-end deployment test on standard off-loader
CellSaver Stowing	T	Simple ground support equipment enables rapid stowing
CellSaver or Cell Repair & Replacement	T	Mounting system allows easy CellSaver removal and re-installation. Excellent access for cell repair or replacement when adjacent CellSaver is removed.
Required Array Modifications	A & T	None. Uses standard 3J cells, laydown, interconnects, panels, panel gaps and deployment mechanisms

* A = Analysis, T = Tested

CELLSAVER SPACE QUALIFICATION TESTING

A space-flight qualification program for CellSaver, including ground, launch and on-orbit environmental testing, is successfully nearing completion. The CellSaver qualification test program is similar in scope to that performed for solar cells by solar cell manufacturers. A summary of the CellSaver qualification tests, environments, test hardware and key results are given in Table 2. More detailed descriptions and results for the electrical performance tests, stowed random vibration tests, GEO thermal cycle tests and the radiation tests are discussed in the following sections. Thus far, CellSaver has passed all environmental tests.

Table 2. Space Qualification Testing Summary.

Test	Environment	Test Article	Key Results
Electrical	AM0 Large Area Pulsed Solar Simulator (LAPSS)	Multiple CellSaver designs with EMCORE, TECSTAR and Spectrolab multi-junction cell strings	Excellent optical efficiency and off-pointing performance measured
Random Vibration	x, y & z axes at 52grms, 45grms & 87grms respectively	CellSaver panel pair with four 176 mm long CellSavers and a 4-cell string of TEC3i	No measurable shape change or reduction in power output
GEO Thermal Cycling	-175° to 120°C 2,000 cycles	Two CellSaver panels, one with 4-cell string of TECSTAR TEC3i	Power reduction less than 1% after 2000 cycles (= 20+ years)
LEO Thermal-Vacuum Cycling	-115°C to 135°C 1x10 ⁻⁵ Torr 12 cycles	CellSaver panel with 8 CellSavers & three 10-cell strings of TECSTAR TEC3i (8 cm x 4cm)	No measurable power degradation in any string
LEO Thermal-Vacuum Cycling	-115°C to 135°C 1x10 ⁻⁵ Torr 12 cycles	CellSaver panel with 8 CellSavers & 3 10-cell strings of EMCORE 28% ATJ (7.61cm x 3.72cm)	No measurable power degradation in any string
Long Term Stowage	Stowed in 11mm gap at ambient for 3 years	CellSaver panel pair with four 176 mm long CellSavers	No significant shape change or power reduction after 4 months
Small Panel Gap	Down to 5 mm panel spacing for 1 minute	CellSaver panel pair with four 176 mm long CellSavers	Stowed in 5 mm panel gap without optical or shape degradation
Deployment Cycling	50 stow and deploy cycles	CellSaver panel pair with four 176 mm long CellSavers	No measurable shape change or reduction in power output
Deployed Strength	130 g static load applied in x, y & z axes	CellSaver panel pair with four 152 mm long CellSavers	Deployed CellSaver undamaged by 130g static loading in all three axes
Xenon Plume Resistance	Xenon ion plume at multiple energies & angles	Reflector material (50mm x 89mm)	Erosion rate of protective coating successfully measured
LEO Thermal Cycling	-100°C to 120°C 80,000 cycles	CellSaver panel with eight CellSavers & three 10-cell strings TECSTAR TEC3i	Testing started, to be completed by 11/02
LEO Thermal Cycling	-100°C to 120°C 80,000 cycles	CellSaver panel with eight CellSavers & three 10-cell strings of EMCORE Advanced 3J	Testing started, to be completed by 11/02
Humidity	90% RH at 22°C for 60 days	Three CellSaver panels each with two 176 mm CellSavers	No visual defects. P _{mp} degradation approximately 1%
Electrons & Protons	15 year GEO dose per AE8 and AP8	Reflector material (25mm x 76mm)	No coating degradation after 3 year equivalent GEO exposure. Test On-going.
UV Radiation	10,000+ Equivalent Sun Hours	Reflector material (25mm x 76mm)	No coating degradation after 1300 ESH. Test On-going.

ELECTRICAL PERFORMANCE TEST DATA

Excellent electrical performance has been measured for CellSavers with EMCORE Advanced Triple Junction (ATJ) cells, Spectrolab Improved Triple-Junction (ITJ) cells and TECSTAR TEC3i cells. ABLE LAPSS test results for the EMCORE and Spectrolab cells are shown in Figures 3, 4 and summarized in Table 3. The LAPSS data shows good light collection efficiency with cell string power increasing from 94% to 96% of the concentration ratio. The power ratios are slightly higher than the current ratios due to the well-known phenomenon of increased cell voltage under concentration [6]. Measured CellSaver performance with 4cm x 8cm TECSTAR TEC3i cells was similar to the Spectrolab and EMCORE cell data as previously reported [7,8].

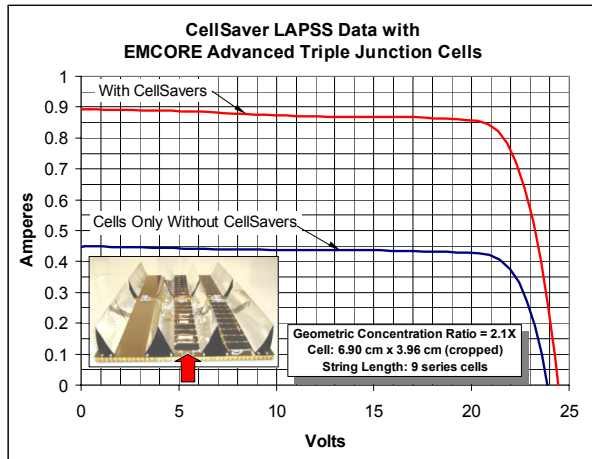


Fig. 3. Electrical performance with EMCORE ATJ.

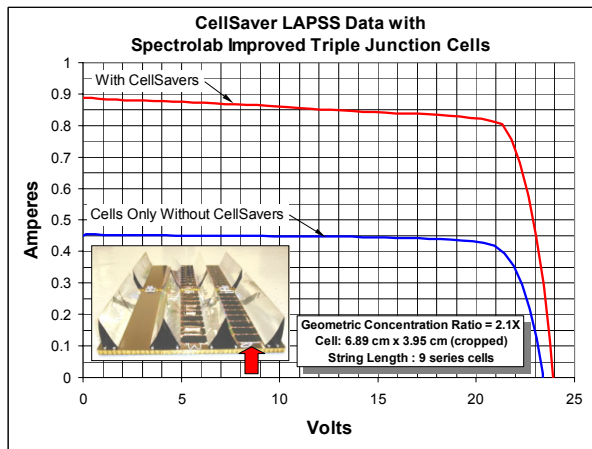


Fig. 4. Electrical Performance with Spectrolab ITJ.

Table 3. CellSaver electrical test data summary

CellSaver Performance with EMCORE Advanced Junction Solar Cells						
Cell Dimensions: 6.896 cm (width) x 3.955 cm (length), 9-Cell String						
CellSaver Aperture (Peak-to-Peak Spacing) = 14.38 cm						
Geometric Concentration Ratio (GCR) = Cell Width / CellSaver Aperture = 2.085						
	Isc	Voc	Imp	Vmp	Pmp	FF
Without CellSavers	0.449	23.90	0.421	20.91	8.795	0.819
With CellSavers	0.894	24.43	0.845	20.82	17.589	0.805
Ratio (With/Without)	1.990	1.022	2.009	0.995	2.000	0.983
Efficiency = Ratio/GCR	0.955		0.964		0.959	

CellSaver Performance with Spectrolab Improved Triple Junction Solar Cells						
Cell Dimensions: 6.89 cm (width) x 3.95 cm (length), 9-Cell String						
CellSaver Aperture (Peak-to-Peak Spacing) = 14.37 cm						
Geometric Concentration Ratio (GCR) = Cell Width / CellSaver Aperture = 2.086						
	Isc	Voc	Imp	Vmp	Pmp	FF
Without CellSavers	0.454	23.41	0.417	20.91	8.726	0.822
With CellSavers	0.887	23.92	0.804	21.31	17.129	0.807
Ratio (With/Without)	1.956	1.022	1.926	1.019	1.963	0.982
Efficiency = Ratio/GCR	0.938		0.924		0.941	

RANDOM VIBRATION TEST RESULTS

Two M55J graphite/cyanate ester composite honeycomb panels each containing two 17.6 cm long CellSavers were random vibration tested in the stowed for launch position with a 1.1 cm panel gap as shown in Fig. 5. One panel had an electrically active string of four TECSTAR TEC3i 3J solar cells (4 cm x 8 cm) bonded in place. Its mating panel contained no permanently bonded solar cells. The peak test levels were 52 g_{rms}, 45 g_{rms} and 87 g_{rms} for the x, y and z axes, respectively. These test levels were chosen because they are representative of the high vibration levels at the center of a large solar panel during launch. The duration of vibration at each peak level was 1 minute and the total vibration time for all conditions at or near the peak-levels exceeded 5 minutes, which is significantly longer than the 1 minute (approximate) of vibration during an actual launch.

The electrical performance of both panels was measured before and after vibration testing. The panel without permanently bonded cells was electrically tested using a removable string of three EMCORE 2J cells. The average change in power as a result of the high-level random vibration exposure for the two panels was a 0.25% reduction, as shown in Table 4, which is less than the measurement accuracy and repeatability of the LAPSS. Post vibration inspection of the CellSavers revealed minor scuffing of the coating due to rubbing during vibration but no measurable shape change of the reflectors or damage to the solar cells. CellSavers-to-panel electrical grounding and the electrical isolation of the solar cell string from the panel and the CellSavers was measured before and after the test and was not affected by vibration exposure.

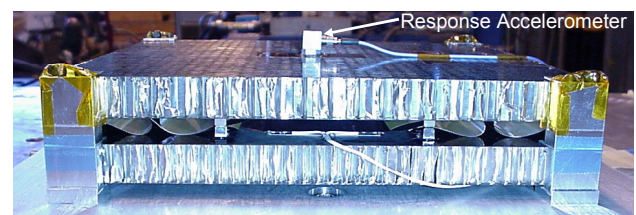


Fig. 5. CellSaver Random Vibration Test.

Table 4. Random Vibration LAPSS Test Results

Panel 8207N0500 SN1						
4-Cell String of TECSTAR TEC3i Bonded to and Vibrated with Panel						
Condition	Isc	Imp	Voc	Vmp	Pmax	FF
Pre Vibration	0.9125	0.860	10.690	9.300	8.005	0.821
Post Vibration	0.9083	0.854	10.690	9.330	7.962	0.820
Normalized (Post / Pre)	0.995	0.993	1.000	1.003	0.995	0.999

Panel 8207N0510 SN1						
Removable 3-Cell EMCORE 2J String (Not Vibrated) Used to test CellSavers						
Condition	Isc	Imp	Voc	Vmp	Pmax	FF
Pre Vibration	0.8216	0.751	7.300	6.540	4.914	0.820
Post Vibration	0.8189	0.751	7.300	6.550	4.915	0.822
Normalized (Post / Pre)	0.997	1.000	1.000	1.002	1.000	1.003

GEO THERMAL CYCLE TEST RESULTS

Two CellSaver panels (identical to the vibration test panels described above) were thermal cycled 2000 times between -175°C and $+120^{\circ}\text{C}$ in ambient pressure dry nitrogen to measure the effect of GEO thermal cycling. The temperature limits were determined by a detailed thermal analysis of a CellSaver panel in GEO. The first thermal cycle test panel has a string of four TECSTAR TEC3i solar cells permanently bonded in place to test the interaction between the cells and the CellSavers during thermal cycling. The second panel, which was vibration tested prior to thermal cycling, as described above, had no cells installed during thermal cycling and thus, CellSaver degradation (including the effects previous vibration exposure) were measured independently of cell degradation.

The effect of 15 years of GEO thermal cycling (1380 cycles at 92 cycles/year) on CellSaver electrical performance is less than 1% as shown in Fig. 6. Inspection of the CellSavers at each thermal cycle break point detected no changes to the coating or reflector shape, no damage to the solar cells, no loss of CellSaver-to-panel electrical grounding and no breach of electrical isolation between the solar cells and the panel or the CellSavers.

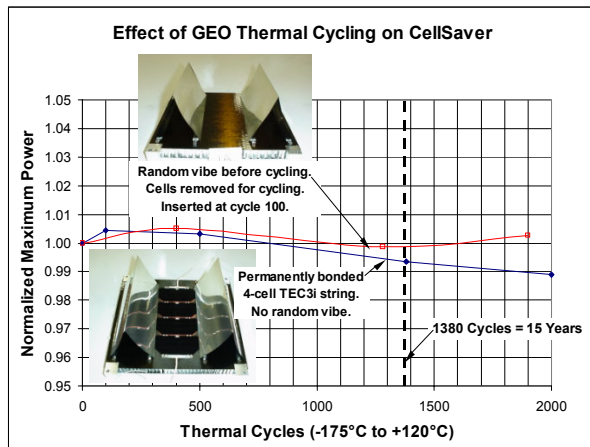


Fig 6. GEO thermal cycle test results

COMBINED RADIATION TESTING RESULTS

Combined radiation testing of the CellSaver reflector material is being performed at NASA Marshall Space Flight Center. In the tests, the reflective coating is simultaneously radiated with electrons, protons and Vacuum Ultra Violet (VUV) light. The quantity and energy levels of the electrons and protons for the test have been calculated by MSFC using a dose depth profile of the reflector for the GEO radiation environment. The National Space Science Data Center (NSSDC) models for electrons (AE8) and protons (AP8) are used to define the GEO radiation environment. Presently three years of GEO simulation has been completed and no measurable degradation has been observed as shown in Fig. 7.

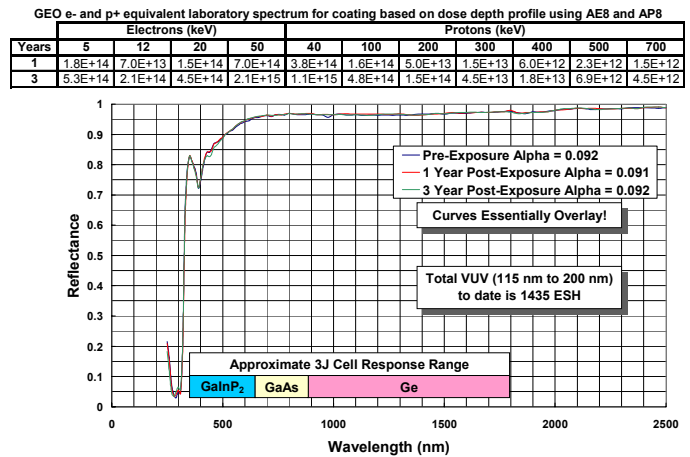
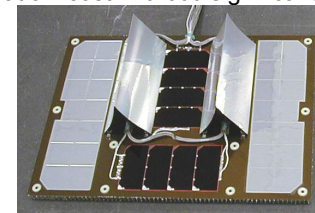


Fig 7. Combined e-, p+ and VUV effect on reflector

SUMMARY

CellSaver is a promising near-term method to reduce spacecraft power generation cost without significant array redesign or qualification.

Completed and ongoing CellSaver analyses and tests are demonstrating general feasibility. A flight experiment (shown here) scheduled for a late 2002 launch on a commercial GEO satellite will verify on-orbit performance [9].



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