Development of Terrestrial Concentrator Modules Using High-Efficiency Multi-Junction Solar Cells

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ABSTRACT

Since February 2001, ENTECH has been working under subcontract to NREL on the development of a new high-efficiency concentrator module using multi-junction (MJ) cells, as part of the DOE/NCPV High Performance Photovoltaics Initiative. ENTECH's new module builds upon ENTECH's successful heritage of concentrator modules and systems developed over the past two decades. Indeed, the basic concept behind the new module is to have it be a "plug and play" replacement for ENTECH's current silicon-cell-based modules, which are used in small *SunLine* arrays (Fig. 1), and large *SolarRow* arrays (Fig. 2). This brief paper summarizes progress to date on the development of the new concentrator module, with emphasis on mini-concentrator module measurements being conducted to better understand the combined performance of color-mixing lenses and multi-junction cells under terrestrial sunlight.

1. Introduction and Background

ENTECH has been involved in photovoltaic concentrator technology for terrestrial applications for the past 23 years [1-5]. ENTECH's existing terrestrial concentrator module uses a large (85 cm wide aperture) acrylic lens to focus sunlight at 21X concentration onto air-cooled silicon photovoltaic cells. The performance of these ENTECH concentrators has been excellent, as shown by the long-term performance measurements for all leading photovoltaic technologies by the independent PVUSA project [6]. ENTECH's concentrator has been the performance leader.

Fig. 3 - Deep Space One Probe Launched October 1998

Fig. 1 - ENTECH *SunLine* Array

Fig. 2 – Four ENTECH *SolarRow* Arrays

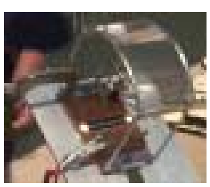
ENTECH has been involved in photovoltaic concentrator technology for space applications for the past 16 years [7-8]. ENTECH's latest space concentrator module uses a small (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiation-cooled triple-junction photovoltaic cells. These space concentrators provide outstanding performance and reliability. Launched in 1998, the *SCARLET* (solar concentrator array using refractive linear element technology) array powers both the spacecraft and the ion engine on the NASA/JPL Deep Space One probe (Fig. 3). Deep Space One is currently about 140 million miles from earth, and has visited an asteroid and a comet on its long and successful journey through deep space. The *SCARLET* array has performed flawlessly [9].

Over the past three years, ENTECH has developed a new space concentrator array technology, called the stretched lens array (SLA) [10-12]. This new SLA provides higher performance at dramatically reduced mass. Recent SLA prototype tests in space simulators have confirmed over 27% net panel-level efficiency at room temperature under space sunlight (AM0) [11-12]. As part of this new space array development, several prototype mini-concentrator modules have been tested under terrestrial sunlight by ENTECH in Keller, Texas, and by NREL in Golden, Colorado. These units have provided outstanding performance, although the triple-junction cells were optimized for the space solar spectrum, which is much different from the terrestrial solar spectrum. The following paragraphs highlight these terrestrial performance results.

2. Stretched Lens Mini-Module Performance Testing

Fig. 4 shows three stretched lens mini-concentrator modules with cells from three different suppliers. The lens is a stretched membrane Fresnel lens made from a space-qualified silicone (DC 93-500). The arched lens has an aperture width of 8.5 cm, and a focal length of 9.2 cm measured from the top of the arch. The line-focus lens is smooth on the outer convex surface, and has microscopic prisms on its inner surface. The solar cells at the focus of the three lenses in Fig. 4 are multi-junction cells from Spectrolab, EMCORE, and JX Crystals/TECSTAR, respectively. The Spectrolab and JX cells are equipped with an ENTECH prism cover to minimize gridline shadowing losses. All three of these mini-concentrator modules have been routinely measured at greater than 27% net operational module efficiency in outdoor testing at ENTECH. Indeed, many of the module efficiency values have been above 28%. The cells in each of these modules are air-cooled and have been well above the normal cell performance rating temperature of 25C.

> 27% Net Operational Module Efficiency Using Spectrolab Monolithic Triple-Junction GaInP/GaAs/Ge Cell - NREL Confirmed World Record



> 27% Net Operational Module Efficiency Using EMCORE Monolithic Triple-Junction GaInP/GaAs/Ge Cell

> 27% Net Operational Module Efficiency Using JX Crystals/TECSTAR Triple-Junction GaInP/GaAs Cell Stacked Over GaSb Cell

Mini-Concentrator Measurements Using Three Cell Types

Fig. 4 - Mini-Concentrator Measurements Using Space-Optimized Multi-Junction Cells

NREL has confirmed the world-record-level 27% $\pm$ 1.5% mini-concentrator module efficiency in tests at NREL for the leftmost unit in Fig. 4 [13]. For this unit, the mini-concentrator module efficiency has been measured under a variety of weather conditions, varying from cold winter days to hot summer days, and from Keller, Texas, to Golden, Colorado. Surprisingly, the net module operational efficiency has typically been 27% $\pm$ 2% under all of these conditions. The lens optical efficiency has been consistently measured at 92%, thereby implying an operational cell efficiency of 29% $\pm$ 2%. However, when the quantum efficiency curves of typical space cells are integrated with the standard AM1.5D spectrum, the results show a 38% higher current for the middle junction (GaAs) than for the top junction (GaInP). This large current mismatch is inconsistent with the observed cell efficiencies. Indeed, the most optimistic calculations of cell efficiency under AM1.5D are in the 26-28% range. These results fully support the recommendation by Keith Emery [14] that the reference spectrum for terrestrial multi-junction concentrator cells needs to be changed to a more realistic spectrum.

3. ENTECH's New Concentrator Module Development

To cost-effectively utilize multi-junction cells in the terrestrial marketplace, ENTECH is developing 20X secondary optics to combine with its 20X primary optics to provide an overall concentration ratio of 400X. Both primary and secondary optics will use ENTECH's proven, patented, color-mixing lens technology [5] to preclude chromatic aberration losses in the cells. Development of a robust, manufacturable 27%-efficient 400X concentrator module is the key objective of the program.

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