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MULTI-BANDGAP HIGH EFFICIENCY CONVERTER (RAINBOW)

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ABSTRACT

Many proposals have been made to increase solar array efficiency by using two or more cells with appropriately spaced bandgaps to span a greater portion of the incident spectrum. One such technique is to split the solar spectrum and focus each portion on a different cell bandgap. Each bandgap is selected to best match the input spectral portion and thus obtain maximum efficiency. This paper reports on the reexamination of the spectrally split, individually matched cell approach using modern-day optics and lightweight structures. The RAINBOW multi-bandgap system represents a unique combination of solar cells, concentrators and beam splitters. The use of separate cells offers the widest possible scope of material choices. Many different component combinations are possible. The relatively low temperature operation, due to reduced thermal input per cell, adds to the performance increase. Finally, RAINBOW is a flexible system which can readily expand as new high efficiency components are developed. Based to a large extent on data for real cells and optical components, RAINBOW is expected to convert over 40% of incident solar energy to electricity at the system level. This conclusion is based on preliminary analyses of cell and optics performances.

INTRODUCTION

Solar photovoltaic arrays are the most widely used form of energy conversion for powering all types of spacecraft. They are reliable, well understood, and adequate for most space applications. The principal drawback of solar arrays is their relatively high cost, with their relatively high mass being second. Both of these factors could be overcome if the overall array power conversion efficiency were to be significantly increased. For terrestrial applications, mass is less important, while efficiency and especially cost are more important.

State of the art solar arrays utilize only a limited portion of the incident solar spectrum, wasting the remainder. This is because a solar cell can only generate current if the wavelength of the incident light is greater than the bandgap energy of the semiconductor. The incident photons must have enough energy to promote electrons to the conduction band of the semiconductor. Furthermore, for wavelengths with energies much greater than the bandgap, the excess energy cannot be utilized. Thus even high quality cells with high quantum efficiencies, such as GaAs, exhibit relatively modest conversion efficiencies, since they cannot respond with high quantum efficiencies to more than a relatively small portion of the incident spectrum. AM0 (space) and AM1.5 (terrestrial) solar spectra are available in the literature (e. g. Green, 1992).

Many proposals have been made to increase solar array efficiency by using two or more cells with appropriately spaced bandgaps to span a greater portion of the incident spectrum. The leading candidate technique to implement this is a vertically-stacked configuration in which two dissimilar bandgap cells are stacked atop one another. This creates, in effect, a vertically stacked array. This can be used with or without optical concentration, and requires no spectral filter, since the wavelengths not usable by the top cell pass through and can be absorbed by the bottom cell. The methods have been discussed in detail in the literature and a wide variety of experimental stacked cells have been developed, primarily two-junction but also three-junction cells (Yamaguchi and Wakamatsu, 1996; Chiang et. al., 1996; and Yeh et. al., 1996). Presently, several different industry, university and national laboratory groups are pursuing the stacked-cell approach for two- and three-junction stacks. This technique is nearing in-space demonstration in the SCARLET solar array being developed by BMDO, NASA-LeRC and JPL for the New Millennium program. It has the disadvantage that it is very difficult, if not impossible, to implement more than three different bandgap cells in the stacked cell scheme.

The alternative technique is to split the solar spectrum and focus each portion on a different cell bandgap. Each bandgap is selected to best match the input spectral portion and thus obtain maximum efficiency. This technique was first conceived by Alvi et. al (1976), who proposed the use of selective mirrors to divide the incident solar spectrum into energy bands to which selected cells could respond. Further development of this concept was done by Blocker (1978), and an array based on the concept was studied and reported by Bekey and Blocker (1978). The general results at the time were that very high array efficiencies were indeed attainable, and that the reduced thermal loads produced further beneficial effects. However, these were partially offset by the large losses of the then-current optical systems to attain the spectral separation. In addition, the mass of the spectral system was such that the overall mass efficiency of the array suffered. Thus, though interesting, the advantages of the technique in terms of the ultimate measures of merit of a solar array, such as watts/m^2, watts/kg, and dollars/watt, showed significant but not revolutionary advantages relative to actual planar arrays or projections for vertically stacked arrays.

As is true for many advanced concepts, technology advances make it appropriate and highly desirable to periodically reexamine the conclusions. This paper reports on the reexamination of the spectrally split, individually matched cell approach using modern-day optics and lightweight structures. The system concept, with the dichroic filter option, is illustrated for three different bandgaps in Fig. 1.

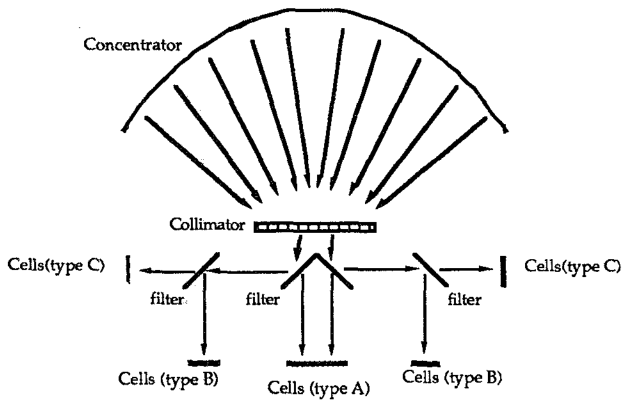

FIG. 1. SPECTRALLY SPLIT, INDIVIDUALLY MATCHED CELL CONCEPT USING DICHROIC FILTERS; ILLUSTRATED FOR 3 CELL BANDGAPS

This version uses an optical concentrator, a collimator, a number of dichroic filters, each with an appropriately designed passband, and cells which are bandgap matched to the passbands, one bandgap per spectral region. For most bandgaps, actual measurements on real cells with different bandgaps are incorporated. For bandgaps for which optical and electronic, but not solar photovoltaic data are available (such as above 2 eV), performance estimates are based on actual material data and derated as needed to account for stages of development and real materials issues. In addition, the overall system efficiencies are also projected and account for most anticipated losses. This is called the RAINBOW system concept because it can be readily extended to a larger number of cell bandgaps. In this paper, the advantages of this concept over other classes of solar photovoltaic arrays are shown.

PERFORMANCE MODELING (CELL LEVEL PROJECTIONS)

Selection of a Voltage-Matched System

In a multijunction configuration, cells of different bandgaps can be either current-matched or voltage-matched. The voltage-matched option was selected, based upon the original voltage-matching concept developed at Sandia National Laboratory (Gee, 1987). In a voltage-matched system, electrical connections are made at the module level rather than at the cell level. Cells of the same bandgap are wired into series strings. Strings of cells of different bandgaps are then wired in parallel. Each individual string provides the same output voltage. The lower bandgap cells are each physically smaller, to allow more cells in series; because their voltages are lower, they are connected into longer series strings. Finally, individual cells of different bandgaps do not have to be physically stacked. Further details of the concept are provided by Gee (1987).

Bandgap and Efficiency Calculations

The JPL computer model calculated optimum bandgaps for a system with different numbers of bandgaps. It was based upon Willson's AM0 solar spectrum (136.8 mw/cm^2 total; Willson, 1985). The spectrum was divided into 100 increments, starting at 0.205 µm and ending at 2.95 µm, covering 134.3 mw/cm^2 (98.2%) of the total. The remaining 1.8% lies at wavelengths beyond 2.95 µm. Each increment is expressed as a function of flux (mw/cm2) and integrated intensity up to that wavelength (mw/cm^2).

Each cell bandgap was assumed to cover a specific increment of the AM0 spectrum. Parallel calculations were performed for two cases: first, where each bandgap accommodated an equal number of the 100 steps in the AM0 spectrum, and second, where each bandgap accommodated an equal integrated intensity slice of the AM0 spectrum. Both cases would be straightforward to implement. The calculated efficiencies for the second case were slightly higher and are detailed below.

A spectrum splitter provides increments of the AM0 spectrum to cells of different bandgap, so that each cell is selectively illuminated with a narrow energy band. Hence, the power conversion efficiencies of each individual cell in a spectral splitter system are much higher than they would be under a full AM0 spectrum. The highest literature cell efficiency reported under selective illumination is 59% for an $Al_{0.23}Ga_{0.77}As$/GaAs heterojunction cell, at laser input intensities up to 54 W/cm^2 at 826 nm (D'Amato et. al., 1992). The second-highest literature efficiency under such conditions is 50% to 55% for a GaAs cell, under AlGaAs laser diode illumination, linked via an optical waveguide, at input intensities of 1 W/cm^2 (Iles, 1990).

In the JPL model, these were taken as the highest practical efficiencies for individual cells under bandpass illumination. Lower cell efficiencies, ranging from 25% to 40%, were assumed for cells at less advanced stages of development or with fundamental barriers to high efficiency. Efficiencies of multicell systems, with individual cell efficiencies ranging from 59% to 25% under bandpass illumination, were calculated. The results for individual cell efficiencies of 59%

and 50% are presented in Fig. 2. The composite efficiency, for the 59% cells, ranged from 56% (25 bandgaps) down to 33% (2 bandgaps). Similarly, the composite efficiency for the 50% cells ranged from 48% (25 bandgaps) down to 33% (2 bandgaps). The calculations assumed that the efficiency at a single wavelength applied to the entire band. This is reflected in the results, where the calculated composite efficiency rises as the number of bandgaps is increased. This is as expected.

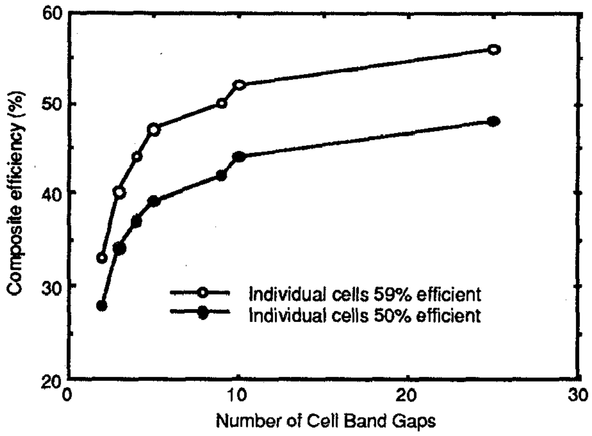

FIG. 2. CALCULATED COMPOSITE EFFICIENCIES FOR A LARGE NUMBER OF CELL BANDGAPS UNDER SELECTIVE ILLUMINATION

The trade between projected performance and practicality yielded an optimum 9 cell system whose composite efficiency was 50% (for the 59% efficient cells) or 42% (for the 50% efficient cells). The calculated performance improvement for a larger number of bandgaps was only a few percentage points, and outweighed by the greater complexity of such a system. The 10 cell system, although calculated to be of higher efficiency than the 9 cell system, included two bandgaps for non-practical materials and was thus derated.

The calculated bandgaps for this 9 cell system ranged from 3.06 eV down to 0.60 eV. Seven of these nine bandgaps were found to correspond closely to practical materials which have been investigated for either photovoltaics (PV), or thermophotovoltaics (TPV). The highest bandgap materials (SiC and GaN) have been appreciably developed for optoelectronic and microwave applications, but not yet for PV applications. Although solar cell device structures for SiC or GaN would certainly need to be developed and optimized, fundamentally new materials development would not be required. These nine materials were:

- 6H-SiC (2.9 eV) or GaN (3.44 eV, on a 6H-SiC substrate)
- 3C-SiC (2.3 eV)
- $Ga_{0.53}In_{0.47}P$ (1.95 eV, slightly mismatched to a GaAs substrate)
- $Al_{0.20}Ga_{0.80}As$ (1.71 eV, lattice matched to a GaAs substrate)
- GaAs (1.43 eV)
- $Ga_{0.87}In_{0.13}As$ (1.25 eV, slightly mismatched to a GaAs substrate)
- Si (1.11 eV)
- $Ga_{0.48}In_{0.52}As$ (0.75 eV, slightly mismatched to an InP substrate), and
- $Ga_{0.36}In_{0.64}As$ (0.60 eV, mismatched to an InP substrate).

Additional features used to identify these practical materials included:

- Actual or estimated cell or materials cost.
- Ease of high quality materials growth.
- Knowledge and applicability of device processing technology.
- Availability of high quality substrates, either exactly or closely lattice-matched.
- Capability of substrate to be made thin, if not already lightweight.
- Availability of literature data.
- Feasibility of a conventional p-n or p-i-n junction cell structure.

The model calculations under bandpass illumination were repeated for a set of three real cells (GaInP, 1.90 eV; GaAs, 1.43 eV; Ge, 0.67 eV) being pursued by industry for monolithic stacks. This was done to verify the overall integrity of the model. Calculated composite efficiencies were 37% (for 59% efficient cells), 31% (for 50% efficient cells), 25% (for 40% efficient cells) and 20% (for 33% efficient cells). These composites are in accord with general industry projections.

String Length Calculations

Voltage matching was performed at V_{max} (the voltage at a cell's maximum power point) to determine optimum string lengths for power processing. This was done for an operating temperature of 28°C. In the 9 cell system, the number of cells per string was calculated for each bandgap. The goal was 28 V per string, the present NASA/JPL spacecraft bus standard. However, the calculation can be readily extended to higher voltage systems. A diagram of how the nine strings would be connected to form a single electrical output is shown in Fig. 3. The overall diagram is not to scale, but the relative cell sizes are approximately to scale. The number of cells per string ranged from 20 (for 6H-SiC) up to 185 (for $Ga_{0.36}In_{0.64}As$).

Temperature effects have the potential to affect voltage matching. The cell short circuit current (J_{sc}) increases slightly as a function of temperature, whereas V_{oc}, V_{max} and fill factor all decrease as a function of temperature. The dominant variation is that of voltage, and the change with temperature is largest for low bandgap cells. For high temperature operation, the strings of low bandgap cells would need to be lengthened. Conversely, for low temperature operation, the strings of high bandgap cells would need to be lengthened. If there is significant temperature variation during the mission, the strings may move in and out of voltage matching. For such a mission, the power processing system would need to be designed to address this issue.

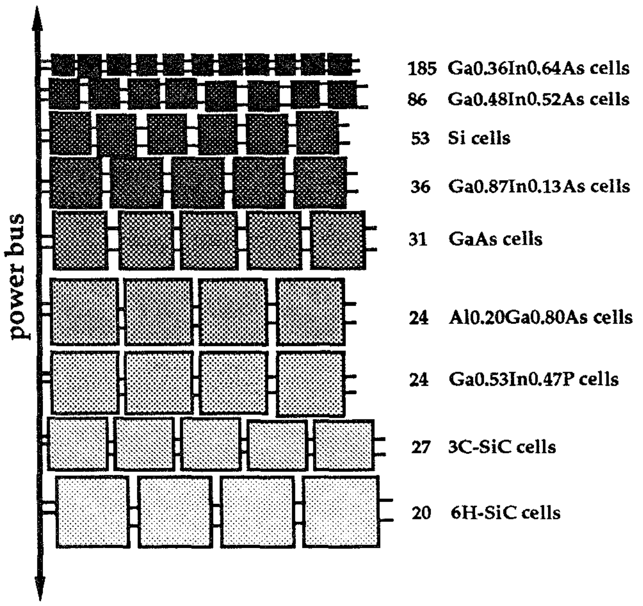

FIG. 3. VOLTAGE MATCHING SCHEME FOR THE CELL STRINGS IN THE 9 BANDGAP SYSTEM (NOT TO SCALE)

RAINBOW SYSTEM DESIGN

Concentrator Optics Issues

Losses due to packing factors and concentrator optics included three derating factors:

- 95% cell packing factor for a single-collector system,
- 95% optics packing factor for a multiple collector system (relative to single-collector), and
- 90% overall efficiency for concentrator optics (includes reflection and transmission losses).

The concentrator optics factor included losses for cell alignment with optics, chromatic aberration, nonuniform illumination over the cell plane, cell location with respect to the lens focal length, pointing angle tolerances, and lens defects. The most probable concentrator lens, a Fresnel configuration, is particularly tolerant of defects. Because the factors are multiplicative, the net effect would be to reduce the system efficiency by a factor of 0.812.

Under high concentration, cell efficiencies rise, and cell waste heat losses are reduced. This is partially countered by a "greenhouse effect" limiting frontside radiative cooling through the concentrator lenses. Overall, however, preliminary calculations indicate that a modest cell operating temperature reduction can be achieved. Pointing requirements are also much stricter for high concentration. Hence, the minimum concentration compatible with power output requirements would generally be recommended.

Spectrum Splitter Overview

The spectrum splitter is a key part of the system because it provides each cell with a narrow region of the incident solar spectrum which is at or just above the cell bandgap energy. The options initially considered were:

- Dichroic beamsplitters, which can provide efficient band isolation. Dielectric-stack coating technology has improved substantially in recent years, particularly in power handling and durability.
- Efficient and highly capable single-order diffractive optics, which have been designed and fabricated at JPL. A thin film dispersive device with prism-like properties (each wavelength goes into a single order) may be feasible for a multi-order system.
- Prisms can provide minimal reflective losses.
- "Flat prisms" have the advantages of low mass and small focal length.
- Total reflection devices.

The two leading candidates at this writing are dichroic beamsplitters and prisms. Most of the effort to date has focused on the beamsplitter filter option. Typical filters can withstand a maximum of about 10X or perhaps 20X optical concentration, which is acceptable for RAINBOW. The availability of vendors' data on maximum feasible optical concentration, has been limited. Anticipated optical losses due to the filters are being quantified, as is the sensitivity of a filter-based system to offpointing or misalignment. The filter option is described further in section C, below. In parallel, preliminary computer modeling of a prism-based system (John Grievenkamp, University of Arizona) is in progress. There is concern that it will be difficult to sufficiently avoid spectral order overlap with a practicable prism system. The prism-based optics also appear to be relatively massive; significant mass reduction will be required for it to be a viable option.

RAINBOW System Level Efficiency Calculations

Initial system level efficiency calculations assumed a linear Fresnel optical concentrator and dichroic filter beamsplitters. Key system trades included: number of cells and their bandgaps, the most effective way to split up the input spectrum, the concentration ratio, mass and cost. Each dichroic filter was assumed to have a reflectance of 100 % above the corresponding cell bandgap, a reflectance of 0% below the bandgap, and a transition region (0 to 100% reflectance) spanning about 20 nm. These are ideal values used for the initial calculations; state of the art is probably closer to about 90% reflectance above bandgap and 10% below bandgap. The center of the transition region was located at the bandgap. Vendor data indicated that the filters could accept up to about 20 suns (20X) input illumination. Because each cell sees only a portion of the input AM0 spectrum, the cell operating temperature will be reduced relative to a system without a spectrum splitter. For example, up to 5X concentration provides the same thermal input as a conventional cell under unsplit 1X AM0. This acts to further increase the cell efficiency and is particularly pronounced for lower bandgap cells.

The calculations also assumed a Fresnel linear trough concentrator, similar to that currently being used by AEC-ABLE for their SCARLET linear trough optical concentrator system. Efficiencies of 95% were assumed for the concentrator, and 99.9% for each dichroic filter. The 95% number accommodates realistic losses. For these initial calculations, the 99.9% number is an ideal one. The general system concept, not to scale, was illustrated in Fig. 1. A collimator may or may not be needed in the final system design. Individual cell data were based on state of the art solar cells, when available, and on the results of single junction cell laser measurements (D'Amato et. al., 1992; Iles, 1990). Cell data for materials such as GaN and SiC, where solar cells have not yet been fabricated, were estimated. Projected high bandgap performance was based on real data for comparable lower bandgap materials, but significantly derated to account for their lesser stages of development and their anticipated lower efficiencies.

The results of the system calculations, including measured loss factors, for several different three, four and five cell systems are presented in Fig. 4. The optimum systems include four real cells: GaN or 6H-SiC, GaInP, GaAs and Ge. The projected system-level efficiencies are 40.04 % with GaN and 40.30 % with 6H-SiC. The overall power densities are 54.74 mw/cm^2 with GaN and 55.09 mw/cm^2 with 6H-SiC. These small differences are due only to the different band edge energies for GaN and 6H-SiC. It is notable that when system-level effects are taken into account, there is only minimal advantage to further increasing the number of bandgaps. However, as individual cell performances continue to improve, particularly at the highest and lowest bandgaps, this situation may change, and there may be a more significant advantage to the use of more than 4 bandgaps.

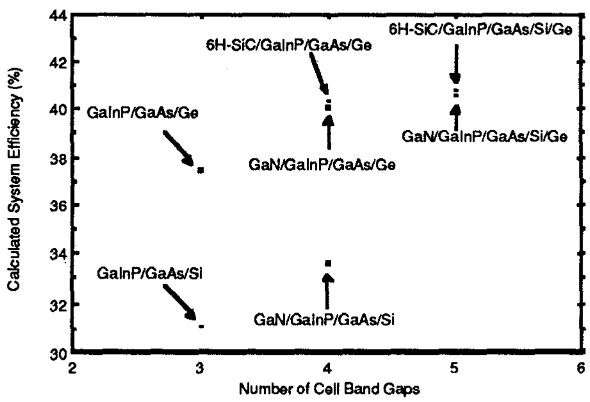

FIG. 4. CALCULATED SYSTEM LEVEL EFFICIENCIES FOR RAINBOW DESIGNS WITH 3 TO 5 CELL BANDGAPS

RAINBOW System Cost Estimate and Measures of Merit

The optical concentrator reduces the overall cost impact of the relatively expensive cells and beam splitters. A preliminary JPL cost estimate was made for a three cell case, including GaInP, GaAs, and Si cells. The cost estimate assumed the total cost of the three component cells to be 1.2 X the cost of an industry stacked multi-bandgap cell. The estimated cost of the beam splitters was taken as 20% of the cost of the industry stacked multi-bandgap cell. However, the estimated efficiency of the 3 cell RAINBOW is about 1.3 times that of an industry three junction stacked system, and the estimated area about 25% less than SCARLET's. The net effect is that the cost and mass of a RAINBOW system with three bandgaps are comparable to those of industry's SCARLET stacked-cell concentrator system. RAINBOW, however, can be expanded to a larger number of bandgaps.

A more detailed cost estimate for a four (or five) cell RAINBOW system assumed 4 (or 5) cells per concentrator element; cell efficiencies of 50% under spectrally selective illumination; a total of 36 concentrators, each with 90% transmission; each concentrator area 22 in^2, for a total of 800 in^2; an optical concentration ratio of 20 X, and a total output power of 360 W. The total system cost, including the concentrator optics, cells, cell-interconnect-coverglass assembly costs, circuit laydown, dichroics, integration, structural elements and aluminum mirrors, was $87.4 K, or $ 250/W, not including environmental testing (e. g. acoustic, vibrational, thermal). Overall, this cost represents a significant improvement relative to comparable costs for state of the art one-sun and concentrator space solar arrays. The cost estimate process is continuing to be refined. Finally, the RAINBOW four cell system (as described in Fig. 4, with GaN or 6H-SiC, GaInP, GaAs and Ge cells) was compared to state of the art alternatives (Table 1). Measures of merit were dollars per watt ($/w), watts per kilogram (w/kg) and watts per square meter (w/m2). The state of the art arrays were Si planar, GaAs planar and SCARLET linear concentrator with GaInP/GaAs cells. This general overview indicates that RAINBOW could potentially provide significant increases in measures of merit, relative to conventional photovoltaic arrays.

	Si Array	GaAs/Ge Array	GaInP/GaAs Array (SCARLET)	**RAINBOW 4 Cell Array**
$/w (Note 1)	1	1.2	1	**1**
w/kg (Note 2)	40	40	45	**60 (est'd)**
w/m^2 (Note 3)	145	190	190	**300 (at 40% system efficiency)**

Note 1: Relative costs for BOL, including recurring costs.

Note 2: For rigid panels, not including solar array drive mechanisms, at beginning of life (BOL)

Note 3: At operating temperature in geosynchronous orbit (GEO)

TABLE 1. COMPARISON OF THE RAINBOW FOUR CELL SYSTEM TO STATE OF THE ART ALTERNATIVES

In these measures of merit, it should be noted that the cost data, in particular, is highly mission specific. It involves the power level of the array, cell laydown complexity, acceptance testing requirements, and related factors. The data in Table 1 also assume mature technologies. End of life (EOL) costs per watt will favor cell systems with reduced degradation rates, in general increasing the cost of Si arrays with respect to other designs. Concentrator systems are expected to have the least cost growth for EOL conditions. Also, comparisons of this type are not absolute indicators of a particular cell systems' value. More accurate comparisons need to include highly mission specific requirements, such as radiation environment, lifetime, cell laydown complexity (shadowing, keep out zones, etc.), acceptance test requirements, and related factors.

The measures of merit included here are for BOL (beginning of life) values, and do not include factors particular to any specific mission. Geosynchronous altitude is assumed for these comparisons, with BOL power levels are assumed to be in the range of 2-5 kW. Rigid substrate array technology is assumed for all designs. Flexible substrate deployable systems are not included, even though they can achieve very high specific performance (w/kg), on the order of 80-100 w/kg, with planar designs. Such lightweight systems tend to have higher radiation degradation than the rigid substrate designs, thereby making BOL comparisons inaccurate. It is expected that concentrator/ rigid substrate designs will satisfy different mission requirements than flexible lightweight designs. The importance of the BOL/EOL discrepancies can be also seen in cost estimates. For example, silicon solar arrays are in general, significantly less costly ($/w) than GaAs arrays. Yet, when actual mission requirements and degradations are included, the GaAs design proves more cost effective. This is evidenced in the recent emphasis on GaAs cell production by the cell manufacturers.

RAINBOW Demonstration Hardware

The first set of bench top demonstration hardware for the RAINBOW concept has been designed. Fabrication is in progress at this writing. The hardware will include linear concentrator optics and several different cell bandgaps. It will be fabricated for JPL by NASA-LeRC and Entech Corporation. The second set of demonstration hardware will add a spectrum splitter and include 3 to 4 cell bandgaps. The results will be reported at the Conference.

SUMMARY

The RAINBOW multi-bandgap system represents a unique combination of solar cells, concentrators and beam splitters. The use of separate cells offers the widest possible scope of material choices. Many different component combinations are possible. The relatively low temperature operation, due to reduced thermal input per cell, adds to the performance increase. Finally, RAINBOW is a flexible system which can readily expand as new high efficiency components are developed. Based to a large extent on data for real cells and optical components, RAINBOW is expected to convert over 40% of incident solar energy to electricity at the system level. This conclusion is based on preliminary analyses of cell and optics performances. These calculations indicate that system performance is very sensitive to component parameters. At this stage, it has been necessary to assume many of these parameters based on manufacturers data, and estimates of near term technology improvements. The initial assumptions will be reviewed in the coming months, and breadboard model hardware will be used to obtain quantitative performance measurements that can be used to "calibrate" the system performance model. Fabrication of the first breadboard model hardware is in progress at this writing and results will be reported at the Conference.

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