RAINBOW: A NEW ULTRA-HIGH EFFICIENCY SOLAR ARRAY

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Solar arrays are the most widely used form of energy for powering spacecraft. They are reliable, well understood, and adequate for most space applications. The principal drawback of solar arrays is their high cost, with their weight and large size being second, both of which stem principally from their generally low conversion efficiency.

The principal reason for the poor efficiency of solar arrays is that they 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 incoming light photon energy is greater than that of the so-called band-gap energy of the semiconductor--that is the incident photons have enough energy to promote electrons into the conduction band of the semiconductor. This means that all longer wavelength components than those corresponding to that of the band-gap energy are not converted to electrons, and thus their energy is lost.

In addition, all incoming shorter wavelengths have photon energies higher than that of the band gap, and the excess energy of those photons is also lost. Thus even the highest quality cells will of necessity exhibit low conversion efficiencies, as they inherently cannot convert but a relatively small portion of the energy in the incident solar spectrum to electricity.

Many proposals have been made to increase the array efficiency by using two or more cells with appropriately spaced band gap energies, so as to convert a greater portion of the incident sunlight spectrum. The current leading implementation candidate is a vertically-stacked array in which two or three dissimilar band gap cells are stacked atop one another. These stacks can be used with or without concentration, and require no spectral filters as the wavelengths not usable by the top cells pass through to be converted in the lower cells. a 2 cell concentrated technique is nearing space test in the SCARLET array being developed by USAF Research Laboratories, NASA Lewis, and JPL.

This vertically stacked multiple bandgap technique is yielding efficiencies of about 30%, and is claimed to be able to go up to about 40% in a 4 cell stack by the Air Force Research Laboratories in Albuquerque. The efficiency of such vertically stacked cells could, in theory, go higher by stacking many more dissimilar bandgap cells, limited principally by the energy losses incurred in traversing upper cells before reaching lower ones.

In practice, however, two fundamental difficulties arise in vertically stacked arrays. The first is in matching the currents and voltages produced by the different types of cells, as all cell types must of necessity be the same size but each produces a different voltage so that they are difficult to connect into one charging circuit. The second is that of thermal limits due to the fact that all the heat from the incoming radiation must be dissipated by conduction to the heat sink through the lowest cell attach area. This limits the maximum concentration ratio that can effectively be used to small values. That, in turn, limits the ratio of input aperture to cell area, which results in a relatively high cost array since the expense is principally in the cells themselves.

A more promising multiple cell alternative technique is described here. It is to split the solar spectrum into a rainbow and impress different spectral regions on different cells, each cell having a band gap selected to best match its narrow input spectral region. This optimum matching is the means to obtain the maximum array conversion efficiency.

This spectrally split multiple matched band gap cell technique has a number of fundamental advantages over vertical stacking. These are: each cell converts principally only those wavelengths to which it is most sensitive, wasting little energy that cannot be converted; energy reaching a cell is not attenuated by passing through upper cells; the heat input to each cell is minimized because all other wavelength portions are sent to other cells; the mounting area for heat dissipation increases with the number of cell types, and therefore greater concentration ratios can be used without overheating the cells; and finally a larger number of lower voltage cells can be used in series strings than higher voltage cells, thus making voltage and current matching much easier and more efficient.

In theory, overall efficiencies in the 60-70% range are possible with this technique. It was first conceived in 1955 by Jackson, and reinvented in 1976 by Blocker. A system study of an array using this technique was done by Bekey, and reported by Bekey and Blocker in the AIAA journal Aeronautics and Astronautics in 1978. That system used a concentrator, a collimator, and a number of dichroic filters each with an appropriately designed passband, and a number of band-gap matched cells, one per spectral region.

The general results at the time verified that very high array efficiencies were theoretically possible, but were limited in practice far short by the large losses of the then-current concentrator and splitter optical materials used to attain the spectral separation. In addition, the weight of the many dichroic mirrors necessary and their supporting structure was such that the overall weight of the array suffered. Thus, though interesting, the advantages of the technique in terms of the ultimate measures of merit of an array--watts/sq.m., watts/kg, and $/watt, showed significant but not revolutionary advantages over either GaAs planar arrays or projections for vertically stacked multiple cell arrays.

As is true for many advanced concepts, technology advances make it appropriate and highly desirable to periodically reexamine prior conclusions. A detailed study and experimental verification at JPL over the past three years has yielded much improved performance for the spectrally split technique using a dispersive spectrum splitter approach rather than dichroic filters. This system was dubbed the "RAINBOW" concept for obvious reasons.

This analysis treated all significant aspects of system optimization, including selection of optimum ban-gap energies for an arbitrary number of spectral regions, voltage and current matching string techniques, varying concentration ratios and thermal dissipation means, and varying basic cell conversion efficiencies. The analysis was repeated using real cells of varying composition, and their best placement in the rainbow determined. An analytical optimization was done for 3, 4, 5, 6, and 9 cell types.

Experimental techniques were then used to find the optimum placement of the cells in the rainbow, and to make measurements of the overall efficiencies for a real system. A six cell spectrally split system was assembled from existing laboratory equipment. This consisted of an accurate spectrum flashlamp, a prism made of low quality glass with only 70% transmittance, and six available run-of-the-mill non-optimized cells. These cells were GaP, AlGaAs, InGaP,GaAs,InGaAs, and InGaAs (differently doped), without electrical leads or cover glass. The flashlamp power was adjusted to deliver an intensity equal to 7 Suns of concentration.

Measurements were conducted initially only on four of these cells, namely the GaP, GaInP, GaAs, and InGaAs. Corrections were applied for the poor quality prism and the non-optimum location of the subset of 4 cells in the prism's spectrum. The corrected overall efficiency of that system was 52%. This efficiency is remarkably close to the theoretical efficiency of a four cell system, which is about 60%, given that little optimization was attempted. Measurements of the full 6 cell system are not yet complete, but its projected efficiency is well over 60% at 10 Suns concentration, using a high quality glass prism and with optimum cell placement in the spectral rainbow.

It must be pointed out that all the cell types discussed and measured are real cells that are readily available, not hypothetical laboratory curiosities, although some types do not have the large production history of Si or GaAs. The different required band gaps are attained by proper substrate and dopant selection as well as controlled doping ratios. As an alternative, the required different band gap cells can be constructed by ion implantation of silicon. Such cells would be considerably cheaper, though their efficiency would be slightly lower.

These experiments, though relatively crude to save money, nonetheless proved that overall solar power system efficiencies over 50% are actually attainable, and leave little doubt that they can be realized in practice. However, efficiency is not the final parameter to consider where the rubber meets the road. Ultimately what matters most in spacecraft design is the weight, cost, and surface area required to generate a given power level on a spacecraft.

The early experiments conducted at JPL were on a brassboard using laboratory rather than flight weight optics, structures, cell supports, and thermal rejection means in order to save cost. However very preliminary weight and cost analyses of flight weight and construction systems were made at JPL based on an earlier concept which used dichroic filters rather than a prism, and only 3 different cells. The cost, weight, and area of this concept was compared with a planar Si array and the SCARLET concentrated vertically stacked array.

The weight efficiency was calculated to be 60 W/Kg compared to 40 for the planar array and 45 for the SCARLET. The power per unit area was calculated to be 300 W/sq.m., compared to 145 for planar array and 190 for the SCARLET. The overall cost in $/W was assumed to be the same for all three systems because the added efficiency advantage was assumed eroded by the greater complexity and parts count. Under these conditions, the overall figure of merit , measured in $/Kg/W/sq.m. was calculated to be 3 times greater than a planar array, and twice as great as that of the SCARLET array.

While that is good, it is estimated that a properly designed and constructed 6 cell system using the simpler prism technique will have a figure of merit 4 times greater than that of a planar Si array, and 3 timer better than a SCARLET array.

Most new concepts tend to be heavier and more expensive than predicted when actually constructed in full scale and qualified for flight. Thus the final figure of merit numbers for this spectrally split, concentrated, multiple matched band-gap cell technique system are not yet in. Nonetheless the attainable efficiencies are confirmed to be extremely high, based on measurements of real systems.

Thus, while much engineering development must be done before the RAINBOW solar array is ready for use on spacecraft it is clear that this solar array concept is extremely promising, offering a far greater efficiency and figure of merit than any solar array technique yet identified.

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