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Thermophotovoltaic Energy Conversion for Space Applications

V.L. Teofilo[1], P. Choong[1], W. Chen[2], J. Chang[1], Y-L. Tseng[1]

[1]*Lockheed Martin Space Systems Company, Advanced Technology Center, 3251 Hanover St, Palo Alto, CA*
[2]*University of California, Material Sciences Dept., San Diego, CA*
408-743-2275, vince.teofilo@lmco.com

Abstract. Thermophotovoltaic (TPV) energy conversion cells have made steady and over the years considerable progress since first evaluated by Lockheed Martin for direct conversion using nuclear power sources in the mid 1980s. The design trades and evaluations for application to the early defensive missile satellites of the Strategic Defense Initiative found the cell technology to be immature with unacceptably low cell efficiencies comparable to thermoelectric of <10%. Rapid advances in the epitaxial growth technology for ternary compound semiconductors, novel double hetero-structure junctions, innovative monolithic integrated cell architecture, and bandpass tandem filter have, in concert, significantly improved cell efficiencies to 25% with the promise of 35% using solar cell like multi-junction approach in the near future. Recent NASA sponsored design and feasibility testing programs have demonstrated the potential for 19% system efficiency for 100 We radioisotopic power sources at an integrated specific power of ~14 We/kg. Current state of TPV cell technology however limits the operating temperature of the converter cells to < 400K due to radiator mass consideration. This limitation imposes no system mass penalty for the low power application for use with radioisotopes power sources because of the high specific power of the TPV cell converters. However, the application of TPV energy conversion for high power sources has been perceived as having a major impediment above 1 kWe due to the relative low waste heat rejection temperature. We explore this limitation and compare the integrated specific power of TPV converters with current and projected TPV cells with other advanced space power conversion technologies. We find that when the redundancy needed required for extended space exploration missions is considered, the TPV converters have a much higher range of applicability then previously understood. Furthermore, we believe that with a relatively modest modifications of the current epitaxial growth in MOCVD, an optimal cell architecture for elevated TPV operation can be found to out-perform the state-of-the-art TPV at an elevated temperature.

Keywords: Energy Conversion, Space Power, Themorphotvoltaic, TPV, Photovoltaic, Passive Energy Convertor, RTG, Space Nuclear Power.
PACS: 84.60Bk.

INTRODUCTION

TPV is an offshoot of photovoltaics in which infrared photons from a heated emitter are converted to electricity. It had been considered as a power conversion technology for converting heat from nuclear sources in the past, but limitations in efficiency kept it from being a viable choice. However, new advances in the photovoltaic and compound semiconductor wafer industries have substantially increased cell performance to give rise renewed interest in TPV as a viable passive energy conversion technology. TPV has now been used successfully in several terrestrial applications. More importantly, it has undergone serious development by DOE Naval Reactors, and will continue to be developed by them in the future.

This is very encouraging for the development of TPV, but there are two issues with the use of this technology for space applications: the efficiency and power density are highest at low operating (room) temperatures and decrease as temperature increases, and the radiation tolerance is not well characterized. These issues are just starting to

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receive attention because they are not concerns for terrestrial applications. KAPL has recently reported (DePoy, et al, 2003) measured conversion efficiencies of about 20% (radiator 950°C, diodes 22°C) for a module in a prototypic cavity test environment. These tests used InGaAsSb diodes with 0.52-eV bandgap and front surface filters for spectral control. New low bandgap compound processing techniques have substantially improved the TPV cell efficiency. However, the efficiency of the more important photon utilization is controlled by the reflectivity and absorptivity of the spectral filter, a set of coatings or photonic crystal structure external to the diode junction. In effect, filter performance in TPV systems is now dominant over diode performance, and sets the requirement on the optimum diode bandgap. A high spectral efficiency requires filters with very high reflectivity and low absorptivity for photons below the bandgap, and high transmissivities and low reflectivity for photons above it. Current cells produced by EMCORE operate at up to 25 % efficiency at 300 K with 1350 K emitter source will decrease to <10% efficiency when operating at the temperature limits of the spectral filter being used, about 415 K.

Nuclear power, be it the radioisotope or the fission reactor type, are characterized by compactness, long-life and high temperature. The TPV conversion technology is a good match with the thermal output of a radioisotope heat source or a nuclear reactor to provide electrical power for long-life interplanetary space missions where solar arrays are ineffective, at conversion efficiencies many times that of competitive radioisotope thermoelectric generators (RTG). The combination of nuclear power and TPV will give rise to an innovative electric power system that would enable many space missions and applications that were previously thought of as impossible or impractical. This has been studied recently and reported in 2003 by Lockheed Martin-KAPL (Brown, et al., 2003), which extended the 1994 Teledyne study of a radioisotope TPV generation (Schock, et al., 1994) by the use of a tandem spectral filter and up-to-date measured efficiency data for GaSb diodes. The result was a design value of 12.12 We/kg for space applications.

Just like other heat engines, the thermal efficiency of TPV energy conversion systems is sensitive to the heat source temperature at the hot end and the converter (diode) temperature at the cold end. Recent technology advances and system innovations have raised the expectation on the achievable TPV system efficiency to a new level, making it very competitive with the best of the dynamic systems. Each of the new technologies or architectures, by itself or in combination, can improve the TPV performance substantially. Despite the spectacular TPV performance achieved so far, there are still the following two major roadblocks to its adoption in space applications: (1) The relative low-power density, which is very sensitive to the hot-end temperature; and (2) The severe performance degradation due to elevated cell temperature required for manageable heat rejection systems in space. The first roadblock is fundamentally an engineering and cost issue. The solution is in sight by the combination of raising the heat source temperature using better refractory metal and heat source fuel material, and using nano-engineered emitter surfaces. The second roadblock is more physical, because the performance degradation is mostly the result of inherent dark current from semiconductor junctions. Recent advances that improve the performance at high-operating temperature are discussed in the following paragraphs.

THERMOPHOTOVOLTAIC CELLS

Thermophotovoltaics is a class of photonic-based electrical-generation devices. Heat is converted to electricity by using a heated surface (the emitter) that radiates infrared (IR) photons to an adjacent low bandgap photovoltaic cell (typically made with binary, ternary, or quaternary semiconductors such as InGaAs, GaSb, InAs, or InGaAsSb), which converts these IR photons to electricity. Solid-state TPV energy conversion uses photovoltaic devices in the form of a p-n diode to convert radiant thermal photons directly into electricity. TPV is an outgrowth of photovoltaic solar cell technology. The source of photon radiation from the sun, now is replaced by a heat source with much longer wavelength photon radiation as shown schematically in Figure 1.

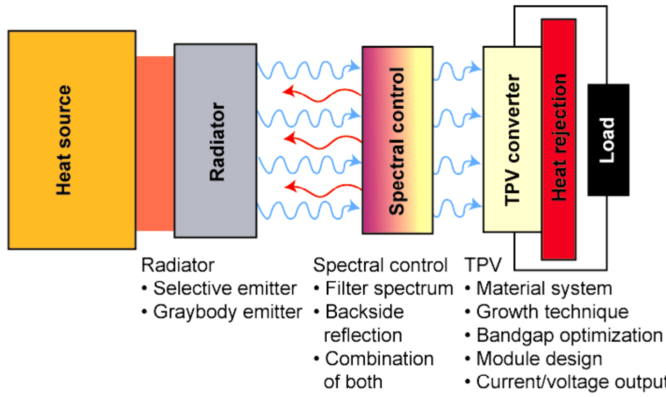


FIGURE 1. Basic Elements of Thermophotovoltaic Conversion.

Efficiency of TPV Cells

The overall system efficiency of a TPV system is the product of factors attributable to the TPV cell efficiency, the spectral filter, and the cell module factor which includes effects of parasitic photon absorption in the non-active diode area and is defined as the total photonic energy absorbed in active diode area divided by the total photonic energy absorption. The TPV cell efficiency is the product of four diode-physics processes, as given in the following equation:

$$\eta_{cell} = QE * F_o * \frac{V_{oc}}{E_g} * FF. \tag{1}$$

QE is the quantum efficiency, which depends on diffusion length and surface recombination velocity. Achieving diffusion lengths many times that of the diode thickness will give high-quantum efficiencies, and QE's near one have been attained. F_o is the photon over excitation factor, which is limited by irreversible losses associated with excited carrier relaxation. This factor is defined as the fraction of absorbed above bandgap usable photon energy. The over-excitation is a proportional to bandgap, E_g. Typical values for the over-excitation factor with E_g less than 1eV are 6 to 8. V_{oc} is the open circuit voltage, defined by the temperature of the cell and as a ratio of short circuit current to dark current.

$$V_{oc} = kT \ln(\frac{J_{sc}}{J_r} + 1). \tag{2}$$

J_{sc} is the short circuit current and J_r is the dark current. If we substitute approximate diode equations for the currents and assume that $J_{sc}/J_r >> 1$, we can get the following equation, which better illustrates the dependence of open circuit voltage on temperature:

$$\frac{V_{oc}}{E_g} = 1 - \frac{T_c}{T_h} + \frac{kT}{E_g} \ln\left[\frac{T_h}{T_c}\right]. \tag{3}$$

T_c and T_h are the temperature of the cold side and hot side temperature, respectively. Note the drop in V_{oc}/E_g as the temperature of the cold side rises relative to that of the hot side. As discussed later, this relation will become a major roadblock for TPV in space application. FF is the fill factor and quantifies the ability of the TPV diode to deliver power to the load.

Status of TPV Cell Technology

Present state-of-the-art TPV conversion makes use of planar low bandgap semiconductor devices containing p-n junctions. Infrared radiation from the heat source enters the device and produces electron-hole pairs. The built-in voltage of the p-n junction then separates electrons from holes, making them available to do work in an external circuit. The area of the planar p/n junction limits the thermal efficiency of current compound semiconductor (typically made with binary, ternary, or quaternary semiconductors such as InGaAs, GaSb, InAs, or InGaAsSb) TPV devices to slightly over 20%.

TPV Cell Efficiency Vs. Temperature

TPV cell conversion efficiency is strongly dependent on both emitter and cell temperatures. Figure 2 shows the negative impact of dark current on cell efficiency. This degradation in TPV efficiency occurs as temperature increases regardless of emitter, material, or cell architecture, because dark current is strongly proportional to increasing temperature. The proposed highest efficiency cells on this figure include the proposed dot junction device in which the p/n junction does not cover the entire device, but is composed of a multitude of very small, equally spaced islands or dots over the face of the device. This takes advantage of cells output voltage varying inversely with the area of the p/n junction as has been demonstrated by SunPower's silicon dot-junction solar cells. However, this has not proven to be applicable to the bandgap relevant to TPV cells. However, the realization of quantum dots may offer the greatest potential to drastically improve photonic device performance through increasing photocurrent generation and collection, without increasing dark current. The presence of an ordered array of semi-conducting quantum dots within the junction of the cell results in the existence of an energy band or bands within what in an ordinary semiconductor constitutes its bandgap. These so-called "minibands" will allow for harvesting of lower energy (longer wavelength) photons, which would normally be unable to provide electron-hole pairs for cell. Application to TPV cells awaits the progress that is currently proceeding for PV cells.

In 1981, InGaAs/InP heterophotodiodes were introduced, where the depletion region of an InGaAs diode was placed in a material of higher bandgap, InP, creating a heterostructure (Pearsall, 1981). The effect of the heterostructure is to reduce the dark current by suppressing the generation and recombination of carriers in the depletion regions (because of the higher bandgap) and by raising the barrier to impede the flow of the diffusion current. This idea has been extended to solar cells through molecular beam epitaxy growth (Ragay, 1994). An AlGaAs p-i-n junction is placed in a GaAs solar cell. For this structure, the ideality factor for the dark current increases with Al concentration resulting in a reduction of recombination current and an increase of importance of the diffusion current into the GaAs regions. These solar cells have lower dark current, higher open voltage, and higher efficiency than their homojunction counterparts. However, the increase of potential barriers also limits the collection probability of photocurrent, resulting in a reduction of short circuit current. Since it has been effective for solar cells, heterostructures can be extended to thermophotovoltaics. EMCORE has produced and tested InPAs/InGaAs/InPAs/InP TPV cells (Murray, et al., 2003) with data shown in Figure 3, demonstrating efficiencies as high as 26% at 25°C with reactor temperature of 1,227°C at a bandgap of 0.65 eV. For higher cell temperatures (130°C), the efficiency drops to 17%.

Individual TPV cells typically have an open-circuit voltage on the order of 0.5 volts. An innovative fabricating technique was developed at Glenn Research Center in the mid-90s to connect many individual cells on a single substrate in series, monolithically, to produce a high-voltage, low-current output. Individual pencil-like cells can be as small as a fraction of a millimeter by about 5 mm. Thirty to 60 cells can be grown monolithically on a centimeter-squared of a semi-insulating InP substrate producing 12-30 Vdc. This is known as Monlithic Intergated Modules (MIM). The technology has been transferred by GRC to the commercial industry and is being widely adopted in TPV development. Additionally, the use of a semi-insulating substrate, such as InP, facilitates incorporation of an extremely efficient back surface reflector (BSR) as a spectral control device for waste energy recuperation. Therefore, this single solid-state device incorporates two essential elements of a TPV system. It limits IR power losses by reducing the current while increasing the voltage, and it returns sub bandgap photons to the heat source very efficiently. EMCORE has produced 30-junction 2x2-cm MIM cells with a V_{oc} of 11.6 V, producing 1.4 W (Murray, et al., 2003).Figure 4 shows a cross-section and finished product with 19 MIM cells on a single 3-in. wafer.

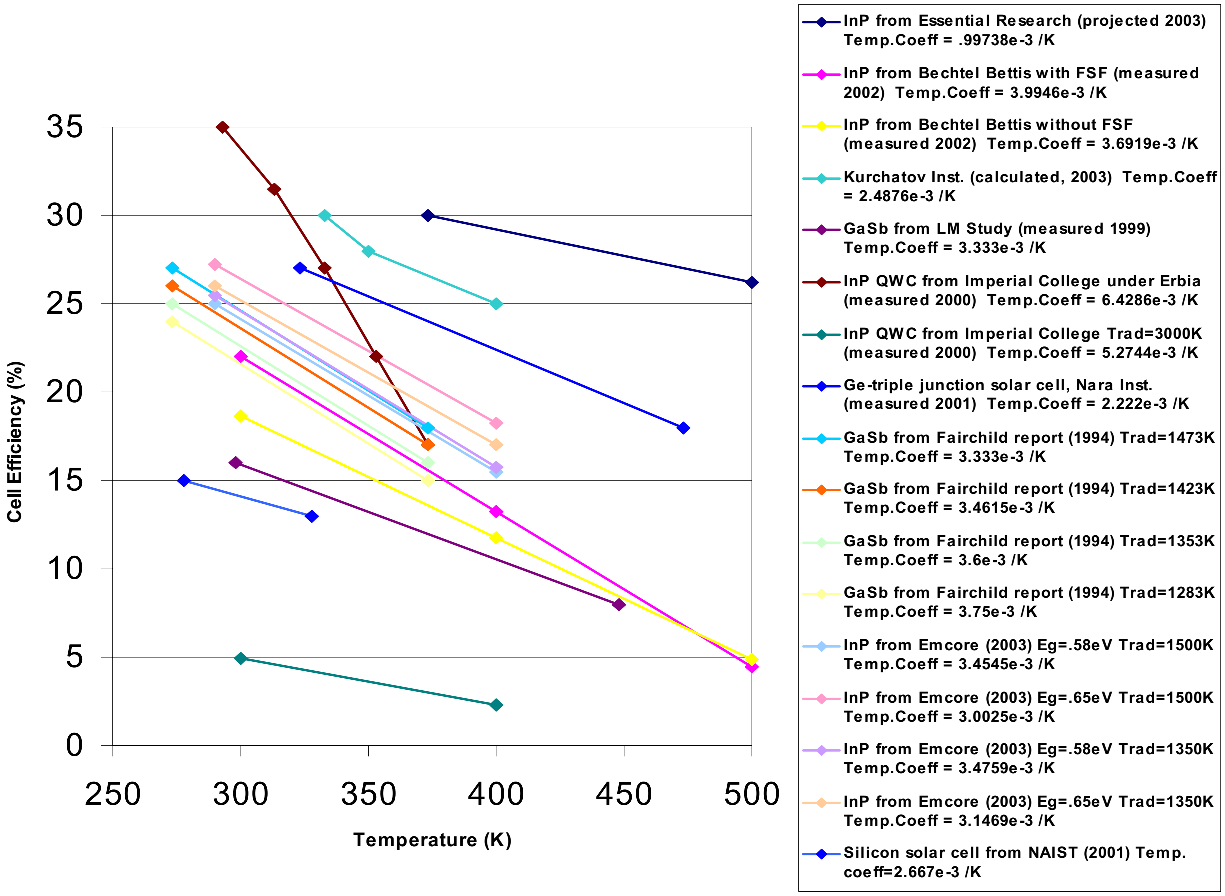


FIGURE 2. Cell Efficiency vs Cell Temperature.

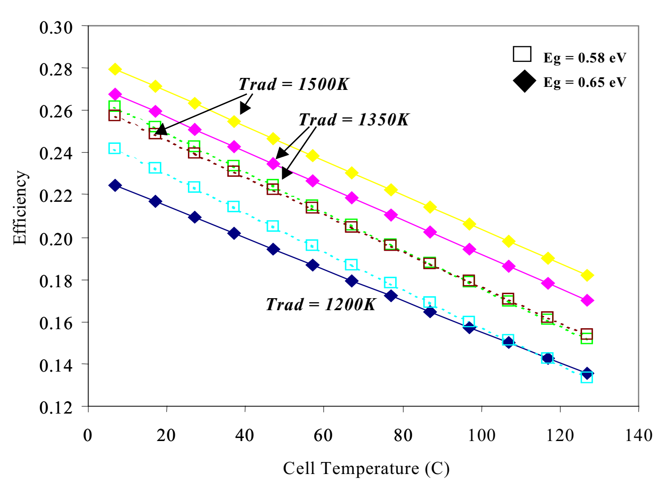
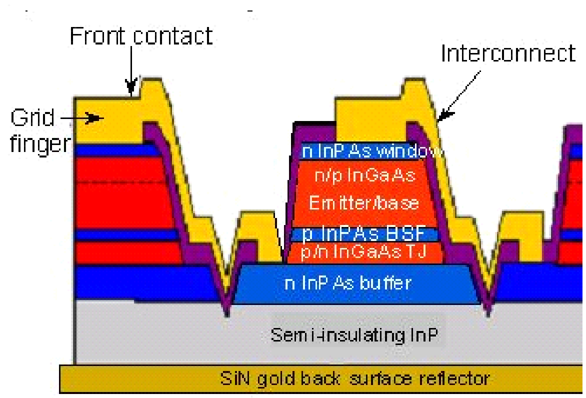
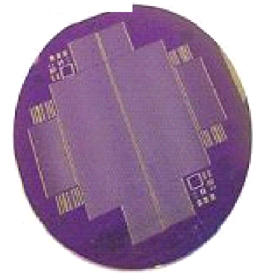


FIGURE 3. Cell Efficiency vs. Cell and Radiator Temperature of TPV Devices at Two Bandgaps (Murray, et al., 2003).

PROPOSED CONCEPTS FOR SPACE NUCLEAR APPLICATIONS

The pioneering study for the application of TPV to nuclear power conversion (Brown, et al., 2003) reinvestigated by Lockheed Martin-KAPL (DePoy, et al., 2003) has recently been verified in proof-of-concept tests by both Creare





(a) MIM Fabrication Layout. **(b)** MIM Cells on Wafer.

FIGURE 4. EMCORE MM Cell and Fabricated Wafer (Murray, et al., 2003).

(Crowley, et al., 2005) and Edtek (*Thermaophotovoltaic (TPV) Technology Development*). The Creare tests used InGaAs TPV cells at 0.60 eV band-gap with a simulated 1350 K emitter temperature with tandem plasma/interference filters. The Edtek tests used GaSb TPV cells with 0.7 eV bandgap cells and a gridded bandpass filter with a higher emitter temperature of 1400 K. The TPV cells were maintained at 298 K in both tests and estimates of system conversion efficiency of 17-19% were obtained. The Creare analysis of the test results confirmed a 12 We/kg specific power for this small system comparable to the estimates in (DePoy, et al., 2003) and (Brown, et al., 2003).

The first study of applying TPV power conversion to a nuclear reactor was performed by Lockheed Martin Space Power Systems as part of a Task Study in the final SP-100 contract (*Thermaophotovoltaic (TPV) Technology Development)*. This study evaluated the radioisotope TPV conversion similar to the (Brown, et al., 2003) with a range of specific powers dependent upon cell and radiator performance. They carried the study further by evaluating its application to nuclear reactors and comparing its estimated performance with thermoelectric and Brayton conversion at 20 to 50 kWe. We have performed the first conceptual design integrating the TPV converter cells with a nuclear reactor in a module similar to the power conversion assembly (PCA) design developed for thermoelectrics during the SP-100 project (Josloff and Mondt, 1997). The PCA acts as a compact heat exchanger between the hot coolant from the reactor and the cold coolant from the radiator with the TPV energy conversion device in the middle. Using packaging fractions for PCA components used with thermoelectrics, an estimate of the PCA mass and power using TPV cells described above has been made and is shown in Table 1. As can be seen from this estimate, using MIM TPV units has a distinct advantage. Integrated system efficiency is reduced by losses and the cell efficiency is reduced due to dark current at the high operating temperature. An excess beginning of life (BOL) power level has been included to accommodate these losses and any degradation due to space radiation. The specific power of the module with mass contingency is ~300 W/kg. The corresponding mass of the PCA with Si-Ge thermoelectric (TE) units is 70 kg corresponding to a specific power of < 150 W/kg. A conceptual design was also performed for implementing the TPV converter strings directly on the radiator as proposed in an early SP-100 thermoelectric converter configuration. However, preliminary mass estimates indicated significant increases in mass over the PCA converter concept resulting in ~ 150 We/kg module. When the radiator mass is included in the analysis for various cell designs as a function of cell temperature with constant emitter temperature of 1350 K as shown in Fig. 5, we note with the EMCORE cells the optimum temperature of 400K maximizes the specific power to 50 W /kg including a two sided radiator at 4 kg/m^2. This is comparable to the specific power of the PCA using TE rejecting heat at 650 K. The quantum TPV cell module/radiator would have a specific power > 100 W/kg due to its projected higher efficiency and mitigation of efficiency degradation due to dark current by 60 %.

HIGH POWER CONVERTORS FOR SPACE NUCLEAR POWER

Stirling convertors have a significantly lower specific power then TPV convertors when applied to small radioisotope applications (Qiu, Peterson, and Augenblick., 2005) in the range of 12 We/kg for a 100 We unit but they dramatically improve to ~ 140 We/kg at 10 kWe assuming a 30% efficiency with a > 500 K rejection temperature (Schmitz1, Schreiber, and Penswick, 2005). With a heat-pipe radiator mass included, the Stirling approaches ~ 100 We/kg corresponding to the projected value for the Quantum TPV cell module operated at 400 K which is twice the specific energy of the module using the current EMCORE TPV cells. The use of Closed Brayton Cycle (CBC) turbine generators at 10 kWe is prohibitive since they are ~ 30 We/kg (Zagarola1, et al., 2005) and these small turbines when integrated with a radiator have specific powers ~ 20 We/kg. As noted by the JIMO studies, they become much more applicable for > 100 kWe applications when the unit module is ~ 40-50 kWe. For the 25 -50 kWe range for future near earth and lunar base applications the current choice will be Stirling with a possible significant improvements in specific power through use of the pulsed tube or thermo-acoustic Stirling engine design which when operated in reverse, have been developed and flown as cryocoolers for IR payload refrigeration in the last 10 years.

TABLE 1. 10-kWe TPV Power Conversion Assembly Mass Sizing.

TVP technology	BBE-SJD (1)	BBE-ISC-MIM (2)	Quantum-dot-MIM
Parameters			
Cell performance			
• Overall efficiency (%)	14	17	37
• Power density (W/cm^2)	0.4	0.665	1.5
Temperature requirements			
• Source temp (K)	1,400	1,350	1,100
• Reject temp (K)	350	400	500
Cell string for +/-135 V	4x77x5 parallel	12x4x4	15x4x4
Module area (cm^2)	1,540	568	960
Module power (W)	610	377.72	1,440
Module—cell mass (kg)	3.08	0.2304	0.312
Total module mass for 10 kWe (kg)	67.6	14.412	4.496
Power BOL (kWe)	12.2	11.3316	11.52
Total mass (kg)	88.1	27.412	10.296

Notes: 1) Blackbody emitter; ARC reflector; single junction diode; BSR KAPL
2) Blackbody emitter; integrated spectral control coatings, multi-junction module (MIM) EMCORE

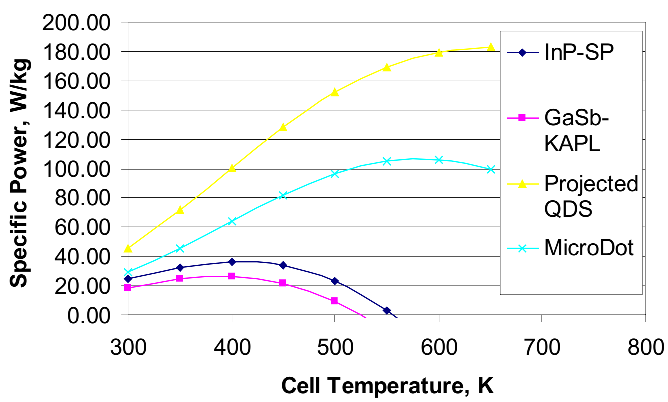


FIGURE 5. TPV Convertor Module Specific Power with Radiator.

CONCLUSION

The significant advantage of the TPV convertor compared to Stirling convertors for long-life space missions is its passive nature and the fact that just as with PV solar array blankets, redundancy is implemented at the string level. The analysis represented in Table 1 and Figure 5 used string redundancy as well as 10 % over sizing for radiation degradation from the most severe space environments envisioned for a 10 year Jupiter mission. The analysis is over-designed for Lunar and near earth applications. At the same time the Stirling or other dynamic convertors will require redundancy at the smallest convertor unit level thereby lowering the net specific power when integrated into a space system. For example a 20 kWe power systems require three 10 kWe Stirling units thereby reducing the effective specific power by 33%.

The current TPV cell technology is approaching 30% cell efficiency at 300K due steady improvement in MOCVD manufacturing process . Through the use of dual junction cells to convert below bandgap photons, further improvements in the cell efficiency are expected to take place over the next few years with expectations of approaching 40%. Finally, the potential of reducing dark current growth by 50-60% to reduce efficiency degradation with temperature through the use of impoved cell growth process or nao-structured super lattice material in the junction of these cells will allow these cells to operate at up to 500 K and surpass the expected performance of any dynamic conversion system in the foreseeable future for low power reactor applications.

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