TPV-9 World Conference
Abstract Booklet

Feria Valencia, Spain; September 9, 2010

Chairman: Mr. Jason Strauch, Sandia National Laboratories
Cochair: Dr. Lewis Fraas, JX Crystals, Inc.
Technical Chair: Dr. Christopher Murray, General Atomics

Introduction

Greetings and welcome to the Ninth World Conference on Thermophotovoltaic technology and energy systems. We have a good event organized and will have 3 sessions of five talks each. The major topic areas covered are TPV cell developments, emitter developments, and systems. TPV systems have the further categories of hydrocarbon heated (both small and mesoscale), space power and terrestrial energy. The conference is being held in Room 3g/f. Thank you all for coming and your continuing work in improving TPV devices, systems and applications.

Below are the talk authors and titles, followed by the full abstracts below that.

Session 1, 13:30-15:00, Thursday afternoon

1. JE Strauch, JG Cederberg, GR Girard, SR Lee, GA Ten Eyck, Sandia National Laboratories, Albuquerque, NM; Chris and Sue Murray, General Atomics, San Diego, CA, **Cell-System**
   Thermophotovoltaic Research and Cell Development at Sandia National Laboratories.
2. Peter Bermel, Massachusetts Institute of Technology, Cambridge, MA. **System-Hydrocarbon?**
   Design and global optimization of high-efficiency Thermophotovoltaic systems.
3. Kuanron Qiu, CANMET Ottawa Natural Resources, Canada. **System-Terrestrial-Hydrocarbon**
   TPV power generation in gas-fired heating systems.
4. Alejandro Data and Carlos Algora, Universidad Politécnica de Madrid , Spain; Ivan Celanovic, MIT, Cambridge, MA. **System-Terrestrial**
   Efficiency Limit of Planar Geometry Solar Thermophotovoltaic Systems Using Angular Selective Absorbers.
5. P. Carrington, A. Krier, K.J. Cheetham, N.B. Cook and M. Yin, Lancaster University Physics Dept., Lancaster, UK. **Cell Developments**
   Low Bandgap GaInAsSbP Pentanary Thermo-photovoltaic Cells.

Session 2, 15:15-16:45, Thursday afternoon

1. Johan van der Heide and Giovanni Flamand, IMEC, Leuven, Belgium; Kristof Dessein, UNICORE EOM, Olen, Belgium. **Cell Developments**
   TPV Cells on Germanium Substrates with a Rough Surface.
2. Richard Kaszeta, Creare, Inc, Hanover, NH; YiXiang Yeng, John Joannopouplos and Ivan Celanovic, MIT, Campbridge, MA. **Emitters**
   Advanced Radiative Emitters for Radioisotope Thermophotovoltaic Power Systems.
3. Chris Murray, General Atomics, San Diego, CA; Jason Strauch, Sandia National Laboratories, Albuquerque, NM; Richard Kaszeta, Creare, Inc, Hanover, NH. **System-Space Power**
   Development of a High Efficiency TPV Panel for Space Power.
4. David Wolford, Donald Chubb and Eric Clark, NASA Glenn Research Center, Cleveland, OH. **System-Space Power**
   High Temperature Measurement of the Spectral Emittance of Thermophotovoltaic Fabrication Materials.
5. Lew Fraas and H.X. Huang, JX Crystals, Issaquah, WA; Jason Strauch and Willie Luk, Sandia National Laboratories, Albuquerque, NM. **Emitters**
   Development of a Catalytic Matched Emitter for a Portable Propane Fired TPV Power System.

Session 3, 17:00-18:30, Thursday afternoon

1. Walker Chan and Ivan Celanovic, MIT, Cambridge, MA; **System-Hydrocarbon**
   MIT Micro-Thermophotovoltaic Generator Project.
2. Lew Fraas, Jim Avery and Leonid Minkin, JX Crystals, Issaquah, WA; Jason Strauch, Kevin Dullea and Paul Hines, Sandia National Laboratories, Albuquerque, NM. **System-Hydrocarbon**
   Thermal Modeling and Testing of a Small Propane Fired TPV Demonstrator.
3. Lew Fraas and Leonid Minkin, JX Crystals, Issaquah, WA. **System-Hydrocarbon**
   Design of a Portable Propane Fired Cylindrical TPV Battery Replacement.
4. Lew Fraas, Jim Avery and E Shifman, JX Crystal, Issaquah, WA; Jason Strauch and Gerry Girard, Sandia National Laboratories. **System-Terrestrial**
   Dual Focus Cassegrain Module Can Achieve >45% Efficiency
5. TPV-9 Attendees Round Table Panel discussion on furthering collaborative TPV research for power systems, efficiency enhancements of renewable energy systems and other topics of interest.

Abstracts

Session 1, 13:30-15:00, Thursday afternoon

JE Strauch, JG Cederberg, GR Girard, SR Lee, GA Ten Eyck, Sandia National Laboratories, Albuquerque, NM; Chris and Sue Murray, General Atomics, San Diego, CA, **Cell-System**
Thermophotovoltaic Research and Cell Development at Sandia National Laboratories.

Thermophotovoltaic (TPV) power systems have potential use in many power generating applications: waste heat recovery in high temperature industrial processes, lightweight and/or miniature electrical power generators, and solar concentrators with sunlight converted infrared radiation by a high temperature emitter. Our focus at Sandia National Laboratories has been to develop TPV device fabrication and characterization capability for use in a variety of thermal energy to electrical power conversion applications. This research and development effort includes epitaxial growth of 0.6eV InGaAs / InP, die fabrication of novel flip-chip multi-junction monolithic interconnected module (MIM) devices, packaging of devices into power systems using high temperature materials, characterization of TPV devices and systems with a variety of infrared emitters, and modeling TPV device and system capability. Each of these areas will be briefly discussed, and the capabilities of different infrared emitting materials are a primary area of discussion. Wavelength selective emitters and filters - such as photonic crystals interference filters, and spectral control filters - are essential for optimum TPV system performance. Our results showing the power generation potential of TPV systems will be presented.

Peter Bermel, Massachusetts Institute of Technology, Cambridge, MA. **System-Hydrocarbon?**
Design and global optimization of high-efficiency Thermophotovoltaic systems.

Despite their great promise, small experimental thermophotovoltaic (TPV) systems generally exhibit extremely low power conversion efficiencies (approximately 1%), mostly due to heat losses such as thermal emission of undesirable mid-wavelength infrared radiation. Photonic crystals (PhC) have the potential to strongly suppress such losses. However, PhC-based designs present a set of non-convex optimization problems requiring efficient objective function evaluation and global optimization algorithms. Both are applied to two example systems: improved micro-TPV generators and solar thermal TPV systems. Micro-TPV reactors experience up to a 27-fold increase in their efficiency and power output; solar thermal TPV systems see an even greater 45-fold increase in their efficiency (exceeding the Shockley-Quiesser limit for a single-junction photovoltaic cell).

Kuanron Qiu, S. Hayden, CANMET Ottawa Natural Resources, Canada. **System-Terrestrial**

TPV power generation in gas-fired heating systems.

Interest has grown in direct thermal-to-electric energy conversion using solid state technologies such as thermophotovoltaics (TPV). TPV devices can be integrated into gasfired residential heating systems where the TPV converts a portion of combustion heat to electricity to power the heating systems' electrical components and the remaining heat is recovered for domestic hot water and spacing heating needs. The values provided to the consumer by the integrated energy system would be both the heating system reliability and a reduction in home power consumption. In the present study, a TPV integrated gasfired boiler has been designed, constructed and tested. A commercially available boiler is used as a precursor to build the TPV integrated heating system. The aim of the present work is to generate enough electricity by the TPV cells such that the gas-fired boiler could be self-powering. Development of the self-powered heating equipment is considered as a first target. The outcome of this study may lead to the development of micro-CHP systems that export electricity to other home electrical loads.

TPV Integrated Boiler System

Alejandro Data and Carlos Algora, Universidad Politécnica de Madrid , Spain; Ivan Celanovic, MIT, Cambridge, MA. **System-Terrestrial**

Efficiency Limit of Planar Geometry Solar Thermophotovoltaic Systems Using Angular Selective Absorbers.

Solar Thermophotovolatic (STPV) generators have one of the highest limiting efficiency among the rest of solar photovoltaic concepts (85.4%) [1], however, this limit is obtained under a set of very restrictive constraints. Firstly a perfectly monochromatic radiation exchange between the emitter and the photovoltaic diode is assumed (which is assumed to have only radiative recombination losses). Secondly, the emitter must have an area much larger than the absorber (approaching infinity), to compensate the very narrow spectral range of emission (approaching zero) of the emitter. And finally an ultra high sun concentration factor system (approaching the maximum concentration on the Earth of 46,050 suns), or a special kind of directionally selective absorber is assumed to minimize the absorber radiation losses. These constraints introduce significant technological issues that make the STPV efficiency limit unachievable in practice. In this work we demonstrate how both spectral and angularly selective absorber combined with either spectral cut-off emitters (which only emit photons with energies greater than $\varepsilon_{cut\text{-}off}$) and/or black body emitters with back side reflectors (BSR) PV cells, can achieve high limiting efficiencies, exceeding 60%. The main advantages of these designs are that they can be done using a planar geometry (i.e. absorber-to-emitter area ratio of one) and an optical system with a concentration factor ranging from very low (1-10 suns) up to high (1000 suns). The modeling is based on the detailed balance theory to provide the upper bound of efficiency [2,3].

[1] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*: Wiley, 2003.

[2] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells " *Journal of Applied Physics*, vol. 32, pp. 510-519, 1961.

[3] G. L. Araújo and A. Martí, "Absolute limiting efficiencies for photovoltaic energy conversion," *Solar Energy Materials and Solar Cells*, vol. 33, pp. 213-240, 1994.

P. Carrington, A. Krier, K.J. Cheetham, N.B. Cook and M. Yin, Lancaster University Physics Dept., Lancaster, UK. **Cell Developments**

Low Bandgap GaInAsSbP Pentanary Thermo-photovoltaic Cells.

Recent interest in thermophotovoltaic (TPV) cells has been driven by applications in industrial waste heat recovery, domestic combined heat and power generation, hydrogen powered transport and silent or remote power generation. For thermal emitter temperatures in the range 1000-1500 °C the blackbody spectrum requires an optimum bandgap between 0.3-0.6 eV which is considerably lower than virtually all conventional TPV cells. In this work we report on the liquid phase epitaxial growth of GaInAsSbP alloys on GaSb and InAs substrates. Our objective is to develop these materials for use in low bandgap TPV cells that could operate with cooler thermal sources around 1000 °C.

The advantage of utilizing the pentanary alloy $Ga_{1x}In_xAs_ySb_{1-y-z}P_z$ is that the presence of the fifth element in the alloy allows an additional degree of freedom to tailor the material properties by changing the alloy chemical composition. For a given value of the band gap (or lattice constant) parameters such as the refractive index, spin-orbit valence band splitting (Δ_{so}) or thermal expansion coefficient can be independently varied. Furthermore a wider growth temperature window ~15 °C exists compared to the liquid phase epitaxial growth of similar ternary/quaternary materials enabling more reproducible growth and further material optimization[1].

Epitaxial growth of $Ga_{1-x}In_xAs_ySb_{1-y-z}P_z$ single epilayers and *p-i-n* homostructures was carried out from antimony-rich melts onto both p-type GaSb (100) and n-type InAs (100) substrates using a conventional horizontal sliding graphite boat in an ultrapure hydrogen atmosphere. Growth was implemented from supercooled melts at temperatures within the interval 585-600 °C. The resulting layers were characterized using high resolution X-ray diffraction, scanning electron microscopy and photoluminescence (PL). The *p-i-n* structures were processed into 1 mm diameter mesa-etched diodes using conventional photolithography and processing techniques.

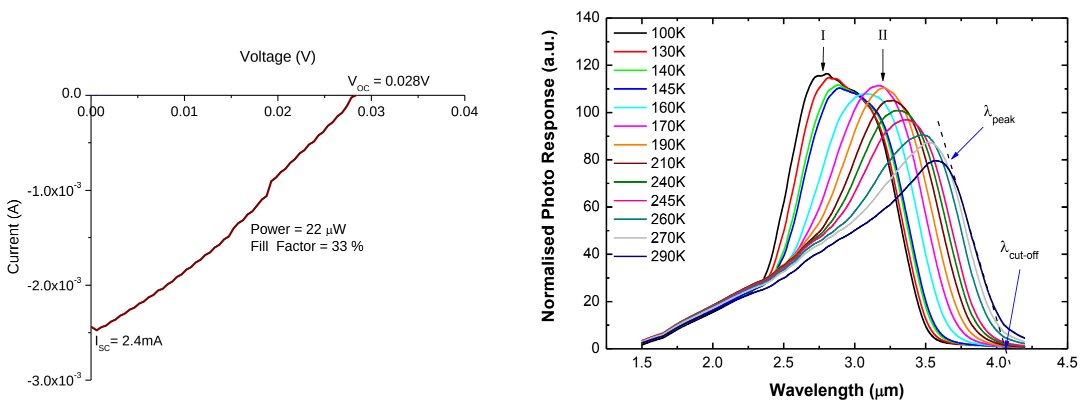


Figure 1: Temperature dependent photo-response for P-i/N InAsSbP-GaInAsSbP-InAs device.

The alloys obtained were of excellent structural quality and exhibited bright photoluminescence at 300 K covering the 3.5-4.5 µm spectral range and with superior thermal quenching behaviour compared with InAs and InAsSb alloys of similar bandgaps. Heterojunction TPV diodes were subsequently fabricated on InAs substrates by growing a wider band gap p^+ $InAs_{0.62}Sb_{0.14}P_{0.24}$ quaternary layer above the undoped pentanary GaInAsSbP layer[2]. The quaternary wide gap layer improves transmission, maximises photo-generation in the active layer and reduces surface recombination. The temperature dependent photo-response is shown in figure 1. Two peaks, labelled I and II are observed corresponding to absorption in the $InAs_{0.62}Sb_{0.14}P_{0.24}$ window layer and the pentanary $Ga_{0.04}In_{0.96}As_{0.82}Sb_{0.14}P_{0.04}$ active later material respectively. The I-V characteristic measured using using 1100 K black body illumination is shown in figure 2. An open circuit voltage of 0.028 V and a short-circuit current of 2.4 mA was obtained with 500mW/cm^2 illumination intensity, producing a maximum output power of 22 µW, with a corresponding fill factor of 33%. Further work is required to investigate intrinsic defects in these materials to improve the diode turn-on voltage and to optimise the cell architecture.

[1] Krier, Applied Physics Letters, 91, 082102 (2007)

[2] Cook et al, Applied Physics Letters, 95, 021110 (2009)

Figure 2: Expanded current-voltage (I-V) curve for P-i/N InAsSbP-GaInAsSbP-InAs diode under illumination by a halogen lamp ~500mW/cm^2, measured at 300 K.

This work was supported by the UK Technology Strategy Board (TP11/LCE/6/I/AE096F).

Session 2, 15:15-16:45, Thursday afternoon

Johan van der Heide and Giovanni Flamand, IMEC, Leuven, Belgium; Kristof Dessein, UNICORE EOM, Olen, Belgium. **Cell Developments**

TPV Cells on Germanium Substrates with a Rough Surface.

1. Introduction

In order to further reduce the cost of thermophotovoltaic (TPV) cells; at imec research is ongoing where TPV cells are fabricated on germanium substrates with a rough surface finishing. In the past, TPV cells were always fabricated on substrates with mirror-polished front surfaces which are needed for the epi-growth of the TPV cell, but our cell processing does not require such an excellent front surface finishing. In this paper results are presented of the fabrication of TPV cells on a germanium substrate with a rough front and rear surface.

2. Fabrication and results

The cells were created using imec's innovative TPV cell fabrication process [1]. In this process an emitter is realized by diffusion from a spin-on dopant source containing phosphorous and both sides are passivated with hydrogen-rich amorphous silicon. Front contact is realized by diffusion of palladium through the a-Si passivation layer and rear contact between the aluminium layer and base of the cell is created by application of laser fired contact. The substrate used was a lowly doped (2Ω.cm) 500µm thick germanium substrate, with a rough surface.

[1] J. van der Heide et al. "Cost-efficient thermophotovoltaic cells based on germanium substrates", Solar Energy Materials & Solar Cells 93 (2009) 1810-1816.

The obtained cell results (IV and EQE) are shown in Figure 1. The results of IV measurements under 1 and 5 suns illumination, and EQE at short wavelengths are comparable to that of cells fabricated on wafers with a polished surface. When the EQE results of the rough substrates (triangles) and the polished substrates (dots, squares) are compared in the relevant wavelength range, it can be seen that the rough wafer performs remarkably better. This can be explained by an improved optical confinement due to the rough surface. Using thicker substrates also shows a higher EQE as a result of an improved absorbance.

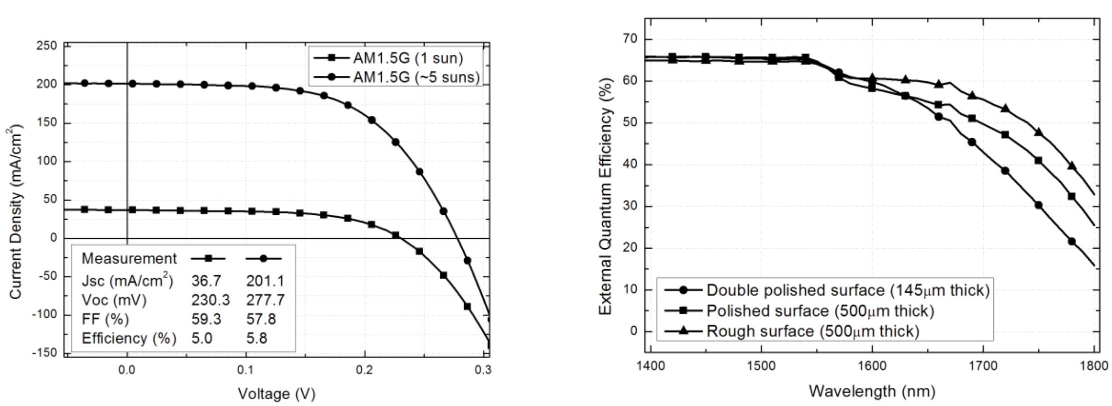


Figure 1: IV measurement results (under 1 and 5 suns) and external quantum efficiency of a TPV cell fabricated on a germanium wafers with a rough surface (no ARC). In the EQE measurement cells with a polished surface are added for comparison.

3. Conclusion and outlook

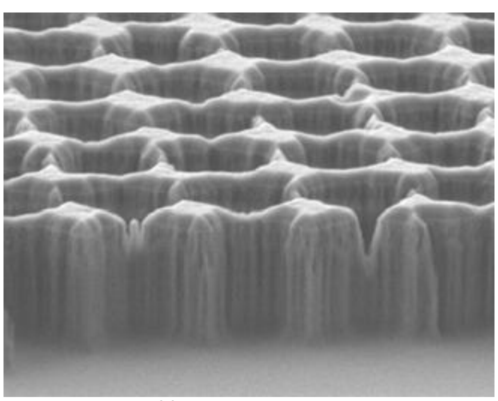
TPV cells have been realized on substrates with a rough surface, giving the same performance as cells made on substrates with a polished surface. The associated cost reduction of the cells is an important aspect for the application of these germanium receiver cells in TPV applications.

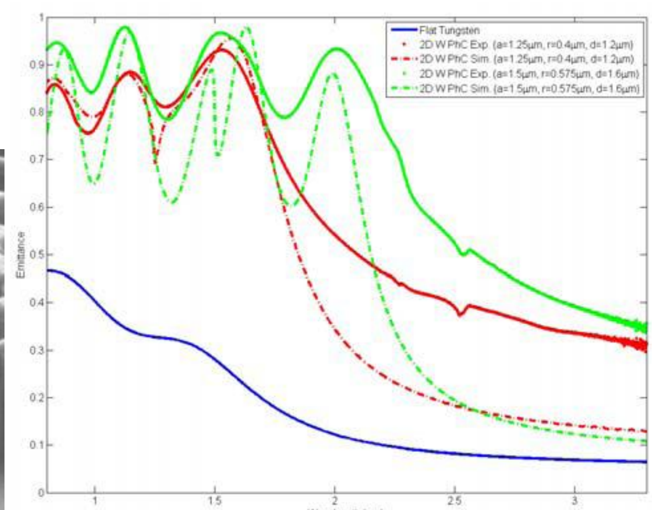
[1] J. van der Heide et al. "Cost-efficient thermophotovoltaic cells based on germanium substrates", Solar Energy Materials & Solar Cells 93 (2009) 1810-1816.

Richard Kaszeta, Creare, Inc, Hanover, NH; YiXiang Yeng, Michael Ghebrebrhan John Joannopouplos, Marin Soljacic and Ivan Celanovic, MIT, Campbridge, MA. **Emitters**

Advanced Radiative Emitters for Radioisotope Thermophotovoltaic Power Systems.

Radioisotope power systems (RPS) are critical for future flagship exploration missions in space and on planetary surfaces. Small improvements in the RPS performance, weight, size, and/or reliability can have a dramatic effect on the scientific capability of the vehicle and the overall mission costs. Radioisotope thermophotovoltaic (RTPV) energy converters are a particular type of RPS that directly converts the heat produced by a general purpose heat source (GPHS) to electrical power using a specialized photovoltaic (PV) cell. A key element in an RTPV system is the radiative emitter that converts GPHS thermal energy to radiative energy that illuminates the PV cell. Creare and the Massachusetts Institute of Technology (MIT) have developed and demonstrated an advanced two-dimensional (2-D) photonic crystal (PhC) radiative emitter that is optimized for RTPV systems. Micrographs of one sample emitter are shown in Figure 1(a). As shown in Figure 1(b), the emitter provides high emittance in the bandgap of the PV cell (wavelengths under 2.0 µm) with low emittance elsewhere that, when coupled with advanced PV cell filter technology, will provide simultaneously high TPV power density and efficiency. We have also developed prototype concepts for fabricating these crystal topographies on larger substrate surfaces.





SEM image of fabricated 2D tungsten photonic crystal emitter, with hole diameter of 1,150 nm, depth of 1,600 nm, and periodicity of 1,500 nm.
Spectral Emittance of 2-D Photonic Crystals for two PhC Geometries (simulation and measurement results) as well as for flat tungsten substrate.

Figure 1. Photonic Crystal Optimized for RTPV Applications

Chris Murray, General Atomics, San Diego, CA; Jason Strauch, Sandia National Laboratories, Albuquerque, NM; Richard Kaszeta, Creare, Inc, Hanover, NH. **System-Space Power**
Development of a High Efficiency TPV Panel for Space Power.

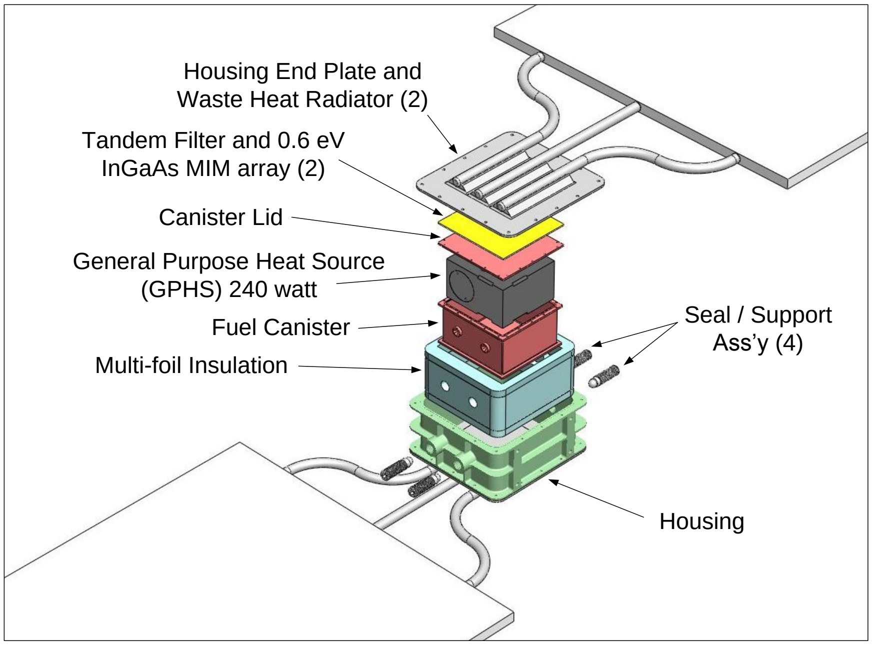
David Wolford, Donald Chubb and Eric Clark, NASA Glenn Research Center, Cleveland, OH; Dave Scheiman, Ohio Aerospace Institute, Brook Park, OH; Patrick Magari and Richard Kaszeta, Creare, Inc., Hanover, NH **System-Space Power**

Overview and Status of Radioisotope Thermophotovoltaic (RTPV) Power System Development for Space Exploration Missions.

A program overview and status report is presented for Radioisotope Thermophotovoltaic (RTPV) energy conversion technology being developed at NASA Glenn Research Center. Several characteristic properties make RTPV attractive as a potential future power source for space exploration. Characteristics include small size, low mass and the absence of moving parts. The power system in development is to have a 250 watt thermal input. Performance objectives are to achieve 15% system conversion efficiency and 7 watts per kilogram mass specific power. RTPV power systems must operate reliably for fifteen years in order to be adapted by mission planners.

TPV converters are analogous to solar photovoltaics (PV). However, instead of converting sunlight radiated at a temperature of 5777 K from 150,000,000 km away, the light source is 1300 K at a distance of 1.5 mm. A thermal power source is used to heat an emitting surface (emitter). The emitter is the "sun" of the TPV converter. High TPV efficiency requires effective spectral control. Only photons greater than or equal to the bandgap energy (E_g) of the PV array can be converted to electricity. Spectral control is used to recuperate (reuse) non-convertible photons less than E_g. The recuperated energy maintains a high emitter temperature and reduces waste heat radiator requirements. Essentially "PV in a box," RTPV would be useful when sunlight is too dim or too intermittent for solar PV.

Recent and near term optical cavity testing will be discussed. Photovoltaic (PV) modules for current test activity will be described. Future program objectives will be outlined.



Exploded view of a 250 Watt (thermal) RTPV energy converter for space exploration (concept)

Lew Fraas and H.X. Huang, JX Crystals, Issaquah, WA; Jason Strauch, Rob Ellis and Willie Luk, Sandia National Laboratories, Albuquerque, NM. **Emitters**

Development of a Catalytic Matched Emitter for a Portable Propane Fired TPV Power System.

Session 3, 17:00-18:30, Thursday afternoon

Walker Chan and Ivan Celanovic, MIT, Cambridge, MA; **System-Hydrocarbon**

A high-efficiency millimeter-scale thermophotovoltaic generator.

A millimeter-scale thermophotovoltaic generator was built and characterized. The generator consists of a MEMS microreactor with integrated 1D photonic crystal, four 0.52 eV InGaAsSb cells, and a maximum power point tracker. The microreactor is a 1 cm square of silicon with a serpentine channel etched through it. The channel is loaded with a platinum catalyst that supports combustion of propane in oxygen. A silicon/silicon dioxide stack deposited directly on the microreactor enhances above-bandgap thermal emission and suppresses below-bandgap emission. The maximum power point tracker steps up the voltage from InGaAsSb array to 3.3 volts while providing on-the-fly impedance matching between the cells and the load to ensure the cells are always operating at their maximum power point. With a fuel input of 10 Watts, the microreactor reaches approximately 800 C. At this operating point, the system has demonstrated fuel to electricity efficiencies of over 2% and delivers 220 mW to the load. With several simple improvements to the system, efficiencies of 3-4% should be achievable at similar operating conditions.

Lew Fraas, Jim Avery and Leonid Minkin, JX Crystals, Issaquah, WA; Jason Strauch, Kevin Dullea and Paul Hines, Sandia National Laboratories, Albuquerque, NM. **System-Hydrocarbon**

Thermal Modeling and Testing of a Small Propane Fired TPV Demonstrator.

A novel portable fuel fired cylindrical thermophotovoltaic battery charger is described. It uses an array of GaSb TPV cells along with a novel Omega recuperator design and a novel IR emitter design. Computational fluid dynamic (CFD) calculations are presented for this TPV cylinder design showing the potential for an overall fuel to electricity conversion efficiency of 10.9%. The estimated weight of the TPV cylinder is 200 gm and its volume is 900 cc. Fuel volume is arbitrary, but a comparable 900 cc of fuel will weigh 540 gm. The specific energy in a hydrocarbon fuel is 12,900 W-hr/kg, resulting in 6970 W-hr of energy in the 900 cc tank. The weight of the TPV cylinder and the fuel cylinder combined is thus 740 gm. Given a TPV conversion efficiency of 10%, the converted energy available from the fuel will be 697 W-hr. The specific energy for this TPV system will then be 697 W-hr/0.74 kg = 942 W-hr/kg. The lithium ion rechargeable battery in use by the Army Land Warrior has specific energy of 145 W-hr/kg, weighing 1.1 kg. The TPV power system described here is lighter, has 6.5 times higher specific energy, operates 7 times longer, and is easily refueled.

Lew Fraas and Leonid Minkin, JX Crystals, Issaquah, WA. **System-Hydrocarbon**

Design of a Portable Propane Fired Cylindrical TPV Battery Replacement.

Lew Fraas, Jim Avery and E Shifman, JX Crystal, Issaquah, WA; Jason Strauch and Gerry Girard, Sandia National Laboratories. **System-Terrestrial**

Dual Focus Cassegrain Module Can Achieve >45% Efficiency

Utility scale electricity production can benefit the most from the highest efficiency solar conversion possible. JX Crystals Inc has demonstrated a novel Dual-Focus Cassegrain (DFC) solar photovoltaic module with an outdoor measured solar conversion efficiency of 31%. This DFC module can now use a 40% multi-junction solar cell with a thermo-photovoltaic cell to achieve >45% efficiency. Due to the cells being separate, the heat load is distributed, allowing for greater real world system efficiency. The proposed work plans to integrate a combination of cells from JX Crystals, Sandia National Labs (SNL) and other suppliers with optimized optical components to achieve 40% outdoor measured efficiency. Key technological developments to enable this transformational conversion efficiency are the optical filters, thermal control and electrical performance matching. This research effort will result in world record concentrated solar power conversion efficiency and lay the groundwork for utility scale implementation of the technology.

TPV-9 Conference closing

TPV-9 Attendees Round Table Panel discussion on furthering collaborative TPV research for power systems, efficiency enhancements of renewable energy systems and other topics of interest