

Ceramic IR Emitter with Spectral Match to GaSb PV Cells for TPV

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ABSTRACT

A high temperature ceramic selective emitter for thermophotovoltaic (TPV) electric generators is described with a spectral match to GaSb IR cells. While solar cells generate electricity quietly and are lightweight, traditional solar cells are used with sunlight and only generate electricity during the day. Workers at JX Crystals invented the GaSb IR cell as a booster cell to demonstrate a solar cell conversion efficiency of 35%. JX Crystals now makes these IR cells. In TPV, these cells can potentially be used with flame heated ceramic emitters to generate electricity quietly day and night. One of the most important requirements for TPV is a good spectral match between the ceramic IR emitted and the IR PV cells. The first problem is to find, demonstrate, and integrate a doped ceramic IR emitter with a spectral match to these GaSb cells. Recently, nickel oxide and cobalt oxide doped MgO-based ceramics have been shown experimentally and theoretically to have spectral selectivity but no attempts have been made to integrate these ceramic IR emitters into a fully operational TPV generator. Herein, we review the history of TPV and note that a key to future progress will be the integration of an appropriate ceramic emitter with cells and a burner to demonstrate an operational TPV generator. Integrating TPV into a residential boiler is discussed as a potential future large volume commercial market.

INTRODUCTION

Fuel fired TPV generators have 4 very interesting features. First, they have very high power densities and this makes the PV cells affordable. For example, with an emitter temperature at 1200 C, the cell electric power density can be over 1 W/cm², 100 times higher than a traditional solar cell operating in sunlight. Second, they are very light weight. For example compared to a Li-ion battery, one TPV power system described previously is lighter, has much higher specific energy, operates longer, and is very easily refueled. Third, these generators are quiet because the burn is continuous, and finally, fourth, a large number of hydrocarbon fuels can be used. The light weight and quiet features make these units interesting to the military for lighter batteries for soldiers or for power and propulsion systems for unmanned aerial vehicles (UAVs). The high power density, quiet, and fuel adaptability features make these TPV units suitable for combined heat and power in home and industrial applications.

After a review of TPV historical developments and given GaSb TPV cells at JX Crystals (JXC), this paper will focus on integrating these IR cells with a spectrally matched IR ceramic emitter to allow commercially viable TPV systems.

TPV Historical Background

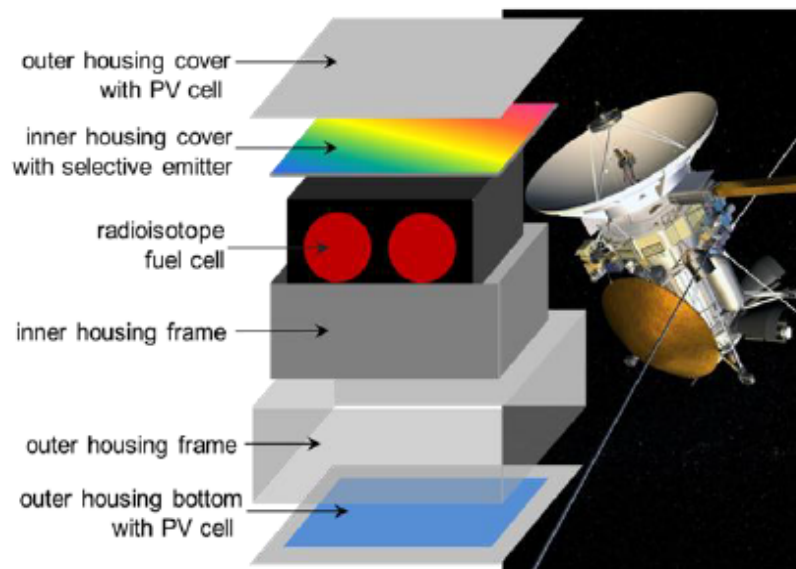
TPV was first demonstrated by HH Kolm at MIT Lincoln Labs [1] in 1956 when he placed a recently demonstrated silicon solar cell next to the mantle from a Colman lantern.

While TPV R&D funding was very sporadic, some significant advances followed. J. Werth at GM realized that while silicon might be appropriate for the spectrum from the sun at 6000 K, from Wein's Displacement Law where $\lambda_{\text{max}} T = 2898 \mu\text{m}^\circ\text{K}$, a lower bandgap photovoltaic cell would be more appropriate. Werth [2] demonstrated TPV using a propane-heated emitter and a Germanium (Ge) cell (1963). His emitter temperature (T) was 1700 K corresponding to a peak black body wavelength of 1.7 μm . However, using a blackbody IR emitter was a problem because only 25% of the radiation for a 1700 K emitter falls at wavelengths below 1.7 μm in the cell response band. The remaining 75% is wasted heat potentially just heating the TPV cell. However, then G. Guazzoni (1972) from the Army proposed using rare earth oxide IR emitters [3]. These rare earth oxide IR emitters have emission lines in the PV cell response band. Unfortunately, the Ge cell performance was still quite poor. L. Fraas et al [4,5] then invented and demonstrated the GaSb cell (1989) with near ideal performance and a spectral response out to 1.8 μm and with a bandgap energy of 0.72 eV.

First Systems Applications

By 1990, the stage was set to start to look for applications for TPV. The US government funding opportunities focused on space and military applications. Both NASA and the Navy proposed using TPV with nuclear heat sources. NASA proposed TPV with radioisotope heat sources [6] for potential missions to the outer planets as shown in figure 1. However, for safety reasons, the upper limit IR emitter temperature for a nuclear source is 1200 K requiring a TPV cell with a bandgap energy of about 0.55 eV. So, D.Wilt et al [7] from NASA Glenn in 1994 proposed and demonstrated an InGaAs/InP PV cell. Subsequently, by adjusting the In to Ga ratio, they along with researchers from the Navy, were able to demonstrate a more complex cell with a bandgap energy of 0.6 eV responding out to 2.1 μm .

Figure 1: NASA concept for Radioisotope TPV Power System for deep space and Mars missions Uses PuO_2 fuel. (Figure from I. Celanovic, TPV-10, Frankfurt, 2012)



Meanwhile, the Army was interested in a quiet TPV battery charger using a hydrocarbon burner as the heat source where a higher IR emitter temperature of 1500 K would be feasible. However, they required the use of JP8, a liquid logistic fuel and this complicated the development of a simpler TPV demonstrator. Nevertheless, JX Crystals teaming with Tecogen as a subcontractor under a Army Small Business Innovative Research contract succeeded in

delivering the 200 W TPV generator shown in figure 2. However, the primary interest at JX Crystals was in the potential commercial TPV market for combined heat and power.

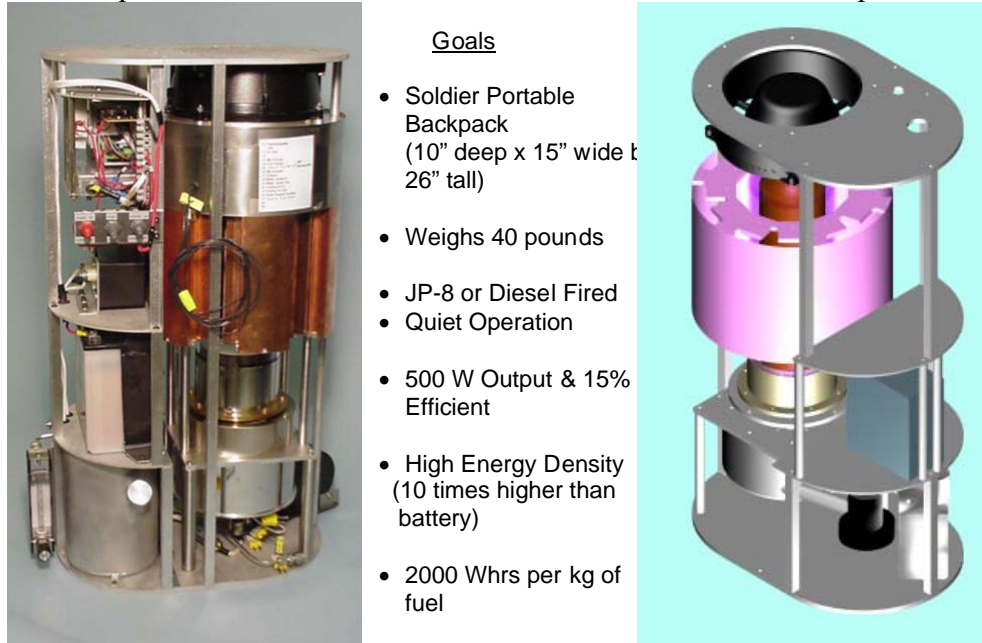


Figure 2: JX Crystals ThermoPhotoVoltaic Battery Recharge Unit for Army delivered in 2000.

As a starting point for the potential TPV commercial market and using internal R&D funds, JX Crystals (JXC) developed the Midnight Sun™ TPV Stove [8] shown in figure 3 for off-grid cabins.

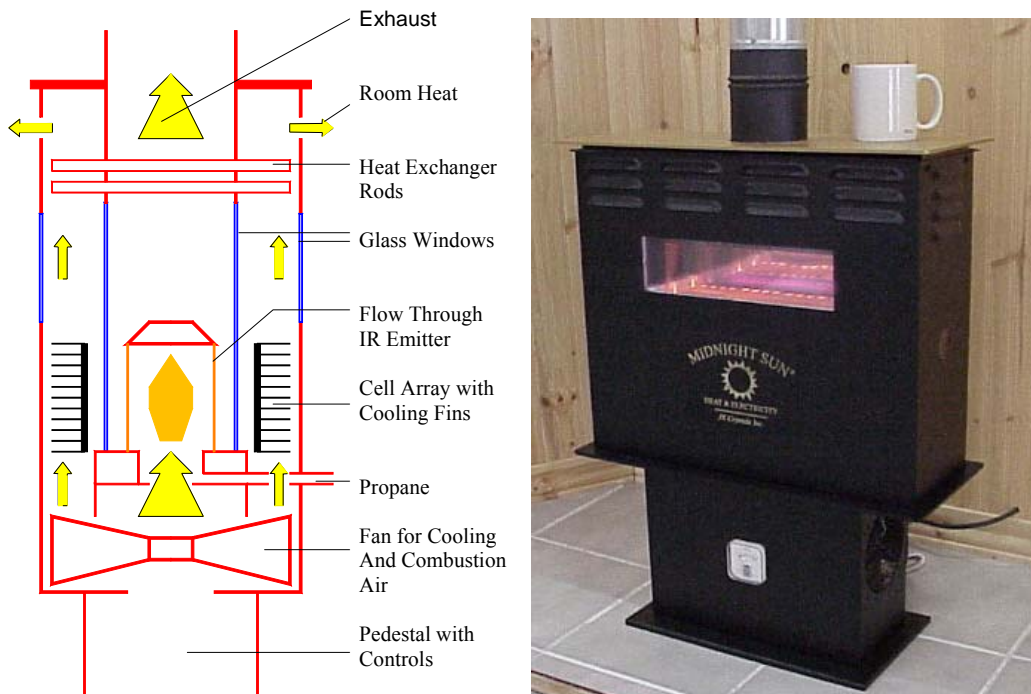


Figure 3: JXC Midnight Sun™ TPV Stove co-generates 25,000 BTU per hour (7.25 kW) of heat and 100 W of electricity

DISCUSSION

Figure 3 shows the basic TPV concept. In a TPV unit, a fuel such as propane or methane is burned in a heater or furnace and a ceramic element is located in the flame. The ceramic element emits intense infrared radiation and a photovoltaic array surrounding this emitter converts this infrared energy into electric power. Thus, a TPV unit co-generates heat and electricity. Over the past several years, JXC has demonstrated that GaSb cells enable a large number of TPV applications ranging from a battery charger for the Army (figure 2) to a home heating-stove (figure 3) to a home furnace-generator [9].

Spectral Control – Key Performance Problem and Solutions

While the TPV product concept shown in figure 3 is very exciting, its commercialization has run into a technical problem. The technical problem is the TPV electrical conversion efficiency and that problem relates to the development of a ceramic IR emitter with a spectral match to the GaSb IR cell. As we argue in this paper, the development of a spectral-selective ceramic IR emitter and its integration will be a key for future TPV commercialization. Specifically in the following, the present performance of the system in figure 3 is described followed by a recipe for improvement using a new ceramic IR emitter with a spectrum matched to the GaSb cell.

The intrinsic TPV electrical conversion efficiency can be defined as the product of the cell in-band conversion efficiency, the spectral efficiency, and the view factor. The spectral efficiency is the fraction of the IR emitter radiant energy in the cell conversion band. In the TPV stove in figure 3, a SiC blackbody emitter was used along with a dielectric filter for spectral control. Inserting actual numbers for the TPV stove shown in figure 3, the GaSb cell in-band conversion efficiency has been measured at 30% [10] and given a blackbody emitter temperature of 1500 °K as explained previously from Wien's Displacement Law, the spectral efficiency is only 25%. Because the cell array and the emitter are the same size and well separated, the view factor is only 0.5. Multiplying these 3 numbers gives a TPV efficiency of 4%. A dielectric filter was used in the TPV stove to reflect IR radiation in the 2 to 5 micron wavelength band back toward the blackbody emitter. However, in retrospect, it was not very effective because of the view-factor problem. Only about 50% of the energy hitting the filter is in the reflection band and only 50% of that is returned to the emitter. So the filter improves the TPV efficiency to $1.25 \times 4\% = 5\%$.

This TPV efficiency can theoretically be substantially improved by using the NiO-doped ceramic material proposed by Fraas and Ferguson in 1997 [11] and developed further in 2001 by Ferguson and Dogan [12]. Fraas and Ferguson noted that the problem for rare earth oxide emitters is that the f-level transition element IR emission lines are very narrow so that little actual energy is contained within the narrow lines. They suggested using the d-level transition elements [11]. The emissivity data for NiO-doped magnesia [12] is shown in figure 4. In fact, the IR emission band centered at 1.4 μm is now much broader. Because the emissivity is suppressed in the 2 to 6 micron wavelength band but high in the cell conversion band, the spectral efficiency can now be substantially improved to 61%. Furthermore, now the view factor from the emitter to the cell array can be increased to 0.75 by making the cell array bigger than the emitter. This does not work when a filter at the cell plane is used because the filter return rate to the emitter is then very small. Anyway, with the larger spectral efficiency and larger view-

factor, the projected TPV efficiency now becomes $0.3 \times 0.61 \times 0.75 = 14\%$. This is a potential improvement by a factor of 2.75.

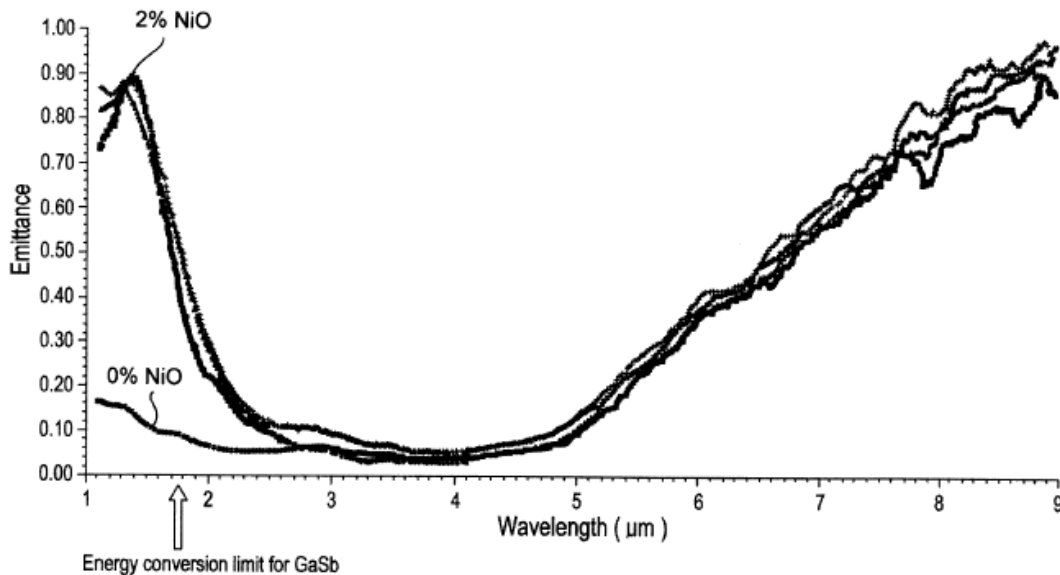


Figure 4: Spectral emittance measurements [12] for a 2 wt.% NiO-doped MgO tape cast ribbon at 1268 and 1404°C. The emissivity of the 2 wt.% NiO-doped MgO emitter appears nearly constant within this temperature range. The emittance of an ‘undoped’ MgO ribbon is also included for comparison. The emissivity of the NiO-doped MgO is much greater than it is for the ‘undoped’ MgO at wavelengths less than about 1.9 μm where radiant energy is efficiently converted by photovoltaic cells, but NiO doping has little effect on the emittance at longer wavelengths.

There is one more item as technical background. The overall system fuel to electrical conversion efficiency includes one more term. The TPV efficiency above describes the conversion of radiant energy into electrical energy but the overall efficiency needs to include the fuel chemical to radiation conversion efficiency. In the stove in figure 3, the flame temperature is 2200 °K and the emitter temperature is 1500 °K. This means that only approximately $700/2200 = 32\%$ of the fuel energy has been converted to radiant energy. So, the overall stove electrical conversion efficiency for the figure 3 example is about $0.32 \times 5 = 1.6\%$. This calculation is roughly consistent with the specification numbers given in the figure 3 caption ($100/7250 = 1.4\%$). With the new NiO-doped matched emitter configuration, this efficiency might be improved to 4.4%. This also means that the electric power output for our Midnight Sun™ TPV Stove could potentially be increased as well. Hence, a ceramic IR emitter with a spectral output matched to the GaSb TPV cell is a key for further TPV system development.

There are also other approaches to improving spectral efficiency for TPV. Note that a problem for ceramic IR emitters still remains for wavelengths longer than 6 μm . There are atomic vibration modes for all materials potentially creating long wavelength IR emission. However, Fraas has noted that the plasma from the electron cloud in metals will suppress this long wavelength emission and that if a refractory metal like tungsten or tantalum is coated with a dielectric layer like Hafnia as an antireflection layer with a wavelength centered at 1.5 μm , a TPV IR emitter can be produced [13] as shown in figure 5. In combination with a dielectric filter to suppress the mid-wavelength radiation between 1.8 and 3.6 μm , the TPV spectral

efficiency can then in theory be increased to 74%. A problem is that a vacuum or an inert gas is then required.



**7.5 cm diameter &
28 cm long**

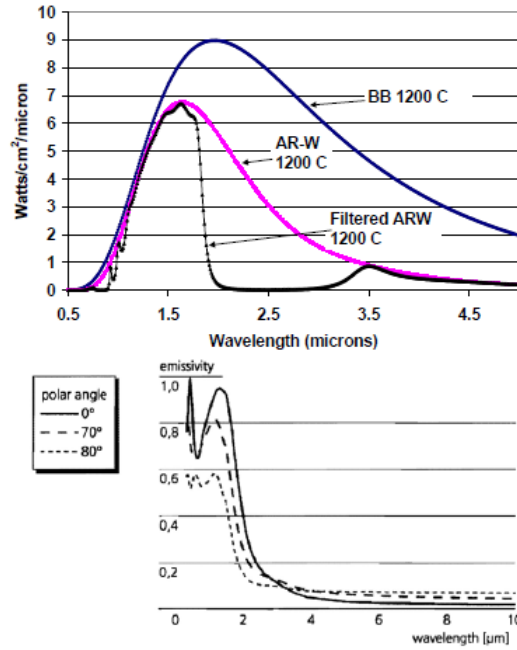


Figure 5: An antireflection (HfO₂) coated tungsten emitter is shown. In combination with a dielectric filter, a high TPV spectral efficiency is possible.

Sai et al [14] and more recently Celanovic et al at MIT [15, 16] have proposed a more elegant but also more complex method of obtaining a high TPV spectral efficiency by creating the 2D Photonic Crystal (PhC) as shown in figure 6. The PhC consists of an array of patterning holes in a tantalum or tungsten foil on a micron scale. The exact scale is tailored for the desired spectral emission band. This approach also requires a vacuum or inert gas enclosure. Another problem for this approach is the high temperature stability of the microscopic pattern.

The PhC approach may well be suited for the NASA space application (figure 1) as vacuum is automatic in space and the upper T limit for the radioisotope may be compatible with the pattern stability requirement. However, for terrestrial applications as shown in figure 2, vacuum will be more challenging. For example, the TPV unit built on the left in figure 2 was designed to use the AR coated tungsten emitter shown in figure 5. However, the required vacuum could not be maintained and so the delivered unit used a platinum foil emitter instead.

The TPV IR emitter options discussed here are summarized in table 1.

Table 1 IR Emitter Options for spectral control for TPV

<u>Option</u>	<u>Comment</u>
F-band ceramic oxide	Emission lines very narrow
AR hafnia coated refractory metal	Proven but reacts with air; Simple & large sizes possible
2D photonic crystal refractory metal	Proven but reacts with air; Complex fab & size limited
D-band ceramic oxide	Proven & exciting but more development required

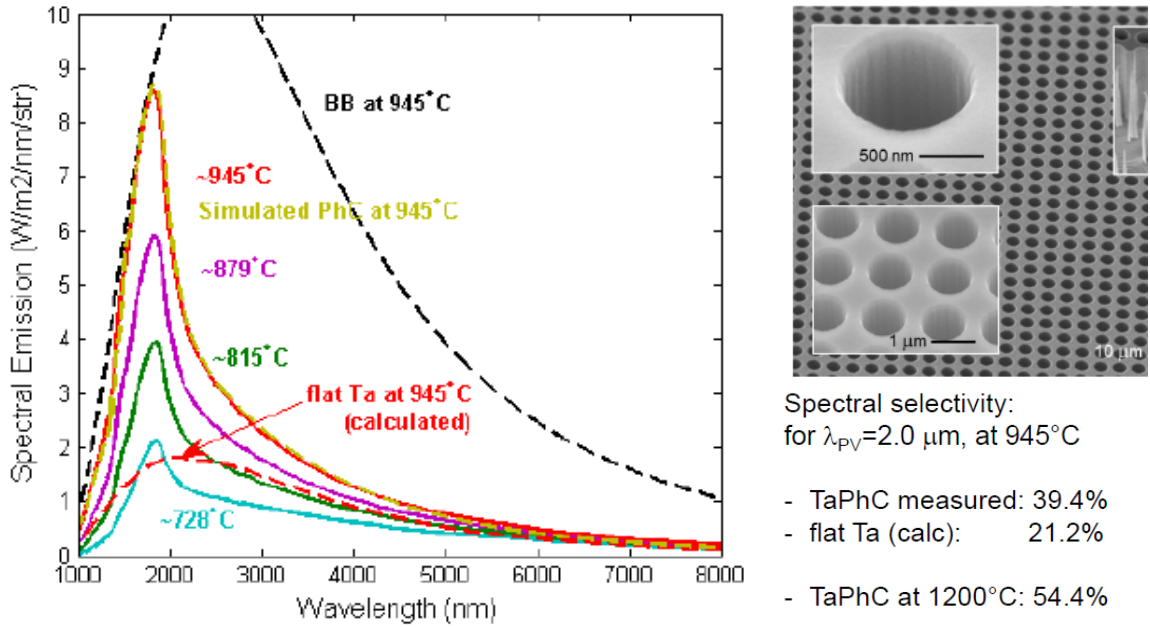


Figure 6: Measured emission [15, 16] of Ta PhC at high T.

PATH FORWARD FOR TPV

Near Term – Small TPV Systems

Figures 7 and 8 show concepts for small TPV demonstrators.

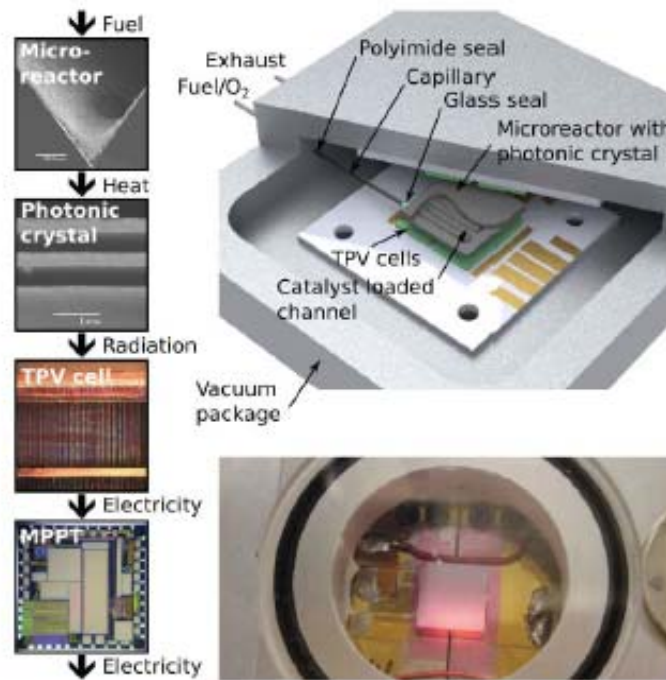


Figure 7: MIT experimental demonstrator of Micro-TPV [16, 17].
350 mW of electrical power has already been demonstrated.

Both JX Crystals and MIT agree that the simplest TPV systems development path will be for small systems where experiments can be conducted rapidly with the lowest development costs.

Figure 7 shows a micro-TPV demonstrator [16, 17] under development at MIT. This unit uses 0.6 eV TPV cells along with a PhC IR emitter both in vacuum. It could be instructive for various applications including the development of components and systems of interest to NASA.

Figure 8(a) shows a light weight cylindrical TPV battery replacement design by JXC. A butane fired 20 W size TPV unit has been described previously [18]. As noted in figure 8(b), this unit can be scaled to 50 W cylinders two of which are shown hypothetically on the wings of an unmanned aerial vehicle. Of most interest here as shown in figure 8(c), the emitter assembly will consist of a picket fence NiO/MgO IR emitter assembly thereby proving that TPV spectral control technology.

There is also a recuperator in the cylindrical TPV generator design shown in figure 8(a) that will demonstrate improved TPV system overall efficiency. A recuperator is used to preheat the combustion air while simultaneously extracting energy from the combustion exhaust. Referring to the discussion of the TPV system efficiency components earlier, if the flame T is 2200 K and the exhoast T is reduced to 550 K, the chemical to radiation efficiency term can be increased to $1650/2200 = 75\%$ and the TPV system efficiency can then be $0.3 \times 0.61 \times 0.75 \times 75\% = 10.3\%$.

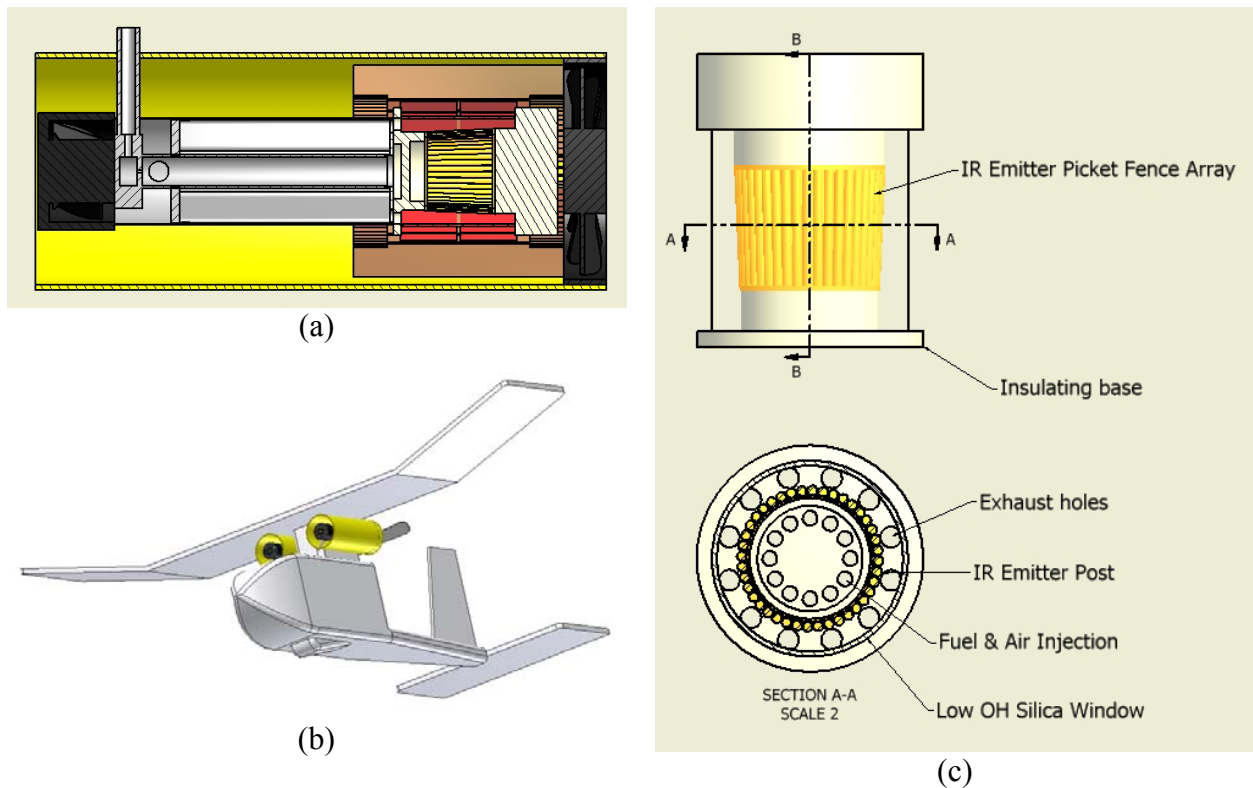


Figure 8: JXC butane fired cylindrical TPV generator design using a picket fence matched IR emitter for spectral control.

COMMERCIAL TPV APPLICATIONS

The key point here is that the development of the spectrally matched IR emitter in combination with the GaSb TPV cell will provide a path to commercial combined heat and power applications for TPV. Figure 9 shows the details of the TPV insert assembly for the Midnight Sun™ TPV stove now including a NiO/MgO picket fence IR emitter for spectral control.

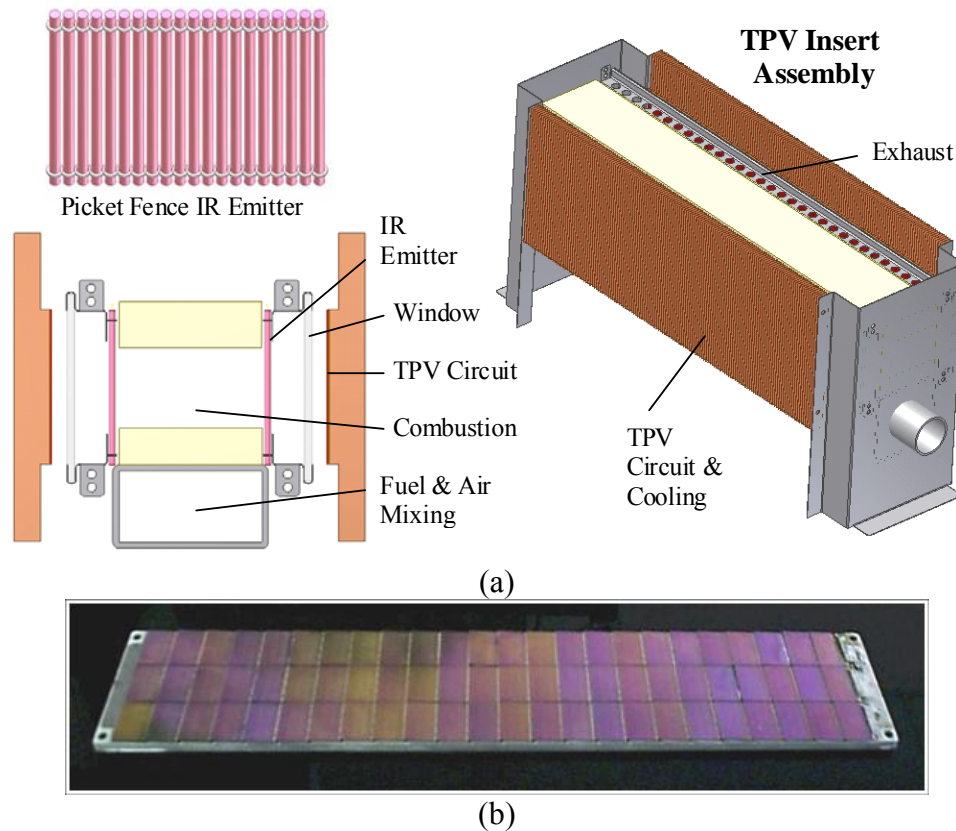


Figure 9: (a) TPV insert assembly for the Midnight Sun™ TPV Stove including a NiO/MgO picket fence IR emitter for spectral control. (b) JXC GaSb TPV circuit used in Midnight Sun™ TPV Stove.

In figure 9(a), notice that the picket fence matched IR emitter consists of an array of ceramic rods simply tied together with Nichrome wire at top and bottom. This design allows for thermal gradients and rapid thermal cycles without breakage. It is also a very flexible design allowing for both cylindrical and planar large and small emitter designs. Notice that this picket fence concept was also used in the figure 8 TPV generator design.

Referring next to figure 10, notice that this TPV insert is also potentially adaptable to residential boilers. Workers at CANMET have noted that instead of using air cooled TPV circuits as in the Midnight Sun™ TPV Stove, the TPV circuits can be water cooled. Furthermore, as noted in table 2, the TPV circuits and emitter sizes can be simply scaled up for either a self-powered TPV residential boiler or a TPV residential combined heat & power (CHP) unit.

TPV Insert Assembly

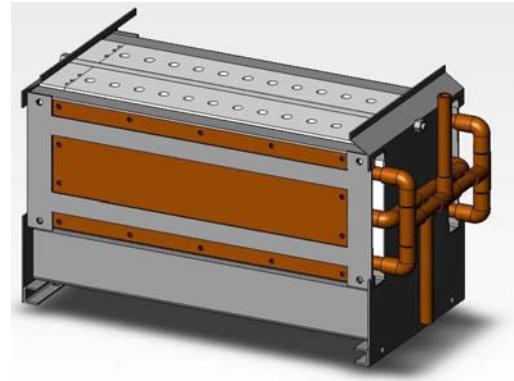
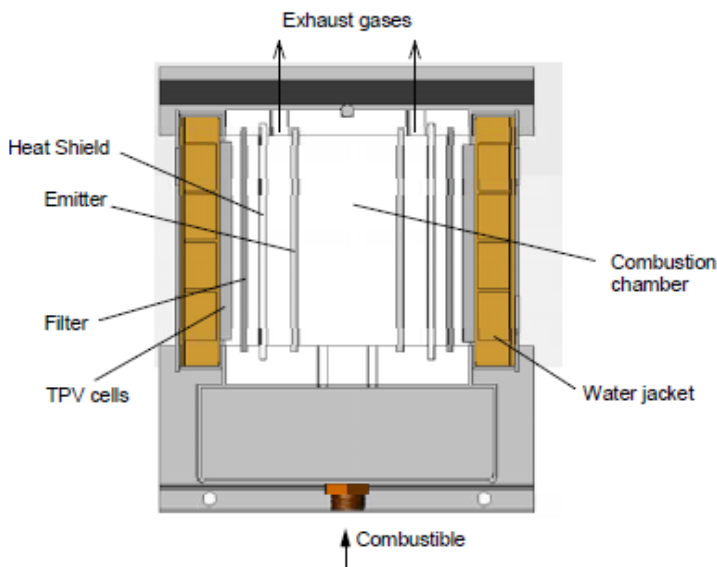


Figure 10: TPV insert modification and residential boiler to be modified.

Table 2: JXC Midnight Sun™ TPV Stove Scale-Up to TPV Self Powered Boiler & then TPV

TPV Performance Projections

TPV System	Variable	Spectral Efficiency	TPV Circuit Area	View Factor	Electric System * Efficiency	Fuel Thermal Burn Rate	TPV Electric Power
TPV Stove	SiC emitter	28% 1250 C	250 cm ²	0.5	1.4% **	8.8 kW	122 W
TPV Stove	Matched emitter	61% 1250 C	250 cm ²	0.5	2.8%	4.4 kW	122 W
TPV Boiler	Matched emitter	61% 1250 C	500 cm ²	0.7	3.9%	8.8 kW	342 W
TPV CHP	Matched emitter	61% 1250 C	1000 cm ²	0.8	4.5%	15.4 kW	695 W
TPV CHP	Matched emitter	61% 1400 C	1000 cm ²	0.8	5%	26 kW***	1.3 kW

* In all cases, cell efficiency = 30%; Fuel Chemical to Radiation Efficiency = 33%

** Example: $0.28 \times 0.5 \times 0.3 \times 0.33 = 1.4\%$

*** 26 kW thermal = 89,000 BTU/hr

CONCLUSIONS

There are now multiple possible TPV applications. These applications are dividing into military and space applications and potential commercial combined heat and power applications. For the military and space applications, cost is not an important criterion. The PhC and InGaAs/InP epitaxy cells operating in vacuum represent a complex and more expensive solutions for the military and space applications.

The GaSb diffused junction cell and the picket fence IR emitter operating in air are less expensive and less costly solutions for the commercial applications. Figure 11 and table 3 show the differences in the cell choices.

TPV for combined heat and electric power offers a path for using natural gas in distributed residential and commercial systems with over 90% CHP energy conversion efficiency. In the recent hurricane Sandy power outages on the US east coast, it would have been more desirable to generate heat and electricity indoors with TPV CHP using natural gas than to generate just electricity with outdoor internal combustion generators burning gasoline. Furthermore, many of the east coast residents would have found the additional heat quite comforting in the snow storm that followed hurricane Sandy.

Table 3: TPV Cell Cost Trades

TPV Cell	GaSb	InGaAs/InP
Fabricated Using Toxic Gases	No	Yes
Crystal Growth	Standard CZ	High Pressure CZ
Wafer Polish Before Epitaxy	No	Yes
Projected Cost In Production	\$0.8 / cm ² Similar to Si	\$5 / cm ² Similar to TJ

Complex InGaAs/InP Cell made Using Toxic Gases

Si ₃ N ₄ Anti-Reflection Coating
n InPAs Contact/Window
n+ InGaAs Emitter
p InGaAs Base
p InPAs Back Surface Field
p++ InGaAs Tunnel Junction
n++ InGaAs Tunnel Junction
n+ InPAs Lateral Conduction/Buffer
Semi-insulating InP Substrate
Si ₃ N ₄ Reflector
Gold Back Surface Reflector

Simple Diffused Junction GaSb Cell – No Toxic Gases

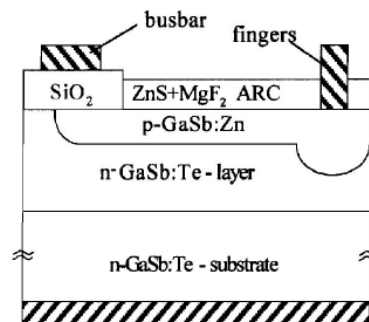


Figure 11: The InGaAs/InP TPV cell on the left is much more complex and expensive than the simpler GaSb diffused junction cell on the right.

REFERENCES

1. H.H. Kohm, Quarterly Progress Report, Solid State Research, Group 35, MIT-Lincoln Laboratory, Lexington, MA, May 1, 1956, 13.
2. J. Werth, Proc. 3rd PV Specialist Conf. Vol. II, (1963) A-6-1.
3. G.E. Guazzoni, Appl. Spectrosc, 26, (1972) 60.
4. L.M. Fraas, GR Girard, JE Avery, BA Arau, V.S. Sundaram, A.G. Thompson, J.M. Gee, J. Appl. Phys. 66, (1989) 3866.
5. L.M. Fraas, J.E. Avery, P.E. Gruenbaum, et al, Proc. 22nd PV Specialist Conf. (1991) 80.
6. A Schock and V. Kumar, Proc. 1st TPV Conf., AIP 321 (1994) 139.
7. D.W. Wilt et al, Proc. 1st TPV Conf., AIP 321 (1994) 210.
8. L. M. Fraas, R Ballantyne, S Hui, SZ Ye, et al, Proc. 4th TPV Conf., AIP 460 (1999) 480.
9. L M Fraas et al Semicond. Sci. Technol. 18 (2003) S165 & s245.
10. L. Fraas and L. Minkin, Proc. 7th TPV Conf., AIP 890 (2006) 17.
11. L. Ferguson and L. Fraas, Proc. 3rd TPV Conf., AIP 401 (1997) 169.
12. L. Ferguson and F. Dogan, Materials Science and Engineering B83 (2001) 35.
13. L. Fraas, J. Samaras, J. Avery, & L. Minkin, Proc. 28th PV Specialist Conf. (2000) 1020.
14. H. Sai, Y. Kanamori, & H. Yugami, Proc. 5th TPV Conf., AIP 653 (2002) 155.
15. V. Rinnerbauer, Y.X. Yeng, W. R. Chan, J. J. Senkevich, J. D. Joannopoulos, M. Soljačić, I. Celanovic, 27th EU PVSEC Parallel Events, TPV10 (2012).
16. Y.X. Yeng, M. Gherbrebran, P. Bermel, W. R. Chan. J. Joannopoulos, M. Soljagic, I. Celanovic, "Enabling High Temperature Nanophotonics for Energy Applications," PNAS, vol.109, No.7, p. 2280, 2012.
17. V. Rinnerbauer, S. Ndao, Y. X. Yeng, W. R. Chan, P. Bermel, J. Senkevich, J. D. Joannopoulos, M. Soljagic, I. Celanovic, "Recent developments in high-temperature photonic crystals" Energy Environ. Sci. , 5 (10), pp. 8815 - 8823, 2012.
18. L. Fraas, J. Avery, H. Huang, & L. Minkin, Proc. 37th PV Spec. Conf. (2011) 2050.