Thermophotovoltaics for Combined Heat and Power
Using Low NOx Gas Fired Radiant Tube Burners

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Abstract: Three new developments have now occurred, making economical TPV systems possible. The first development is the diffused junction GaSb cell that responds out to 1.8 microns producing over 1 W/cm² electric, given a blackbody IR emitter temperature of 1250 C. This high power density along with a simple diffused junction cell makes an array cost of $0.50 per Watt possible. The second development is new IR emitters and filters that put 75% of the radiant energy in the cell convertible band. The third development is a set of commercially available ceramic radiant tube burners that operate at up to 1250 C. Herein, we present near term and longer term spectral control designs leading to a 1.5 kW TPV generator / furnace incorporating these new features. This TPV generator / furnace is designed to replace the residential furnace for combined heat and power for the home.

INTRODUCTION

Solar cells can produce electric power from sunlight without burning a fuel. If very low cost solar cells can be made, a homeowner can generate his own electricity at rates below the electric utility rate. However, while this can be true during summer months, there is a problem in winter months when the sun does not shine. Low bandgap photovoltaic or “solar” cells can solve this problem. A homeowner can put solar cells on his roof for electric power in the summer months and “solar” cells in his furnace for electric power during the winter months. The idea of “solar” cells in a heating furnace is called ThermoPhotoVoltaics or ThermoPV or TPV. The idea is that a ceramic element is placed in the flame in the furnace and this element then glows like the coals in a fireplace. “Solar” cells near by then convert the glow into electricity. Using TPV, the homeowner generates electricity whenever heat is needed. Therefore, it is not necessary to burn additional fuel.

While this TPV concept is simple, the problem has been that the two types of solar cells (or more accurately photovoltaic cells) are not the same. While the solar cells on the roof convert visible light into electricity, the TPV cells in the furnace need to convert infrared radiation into electricity. JX Crystals has invented and developed the required GaSb TPV cells.

OVERVIEW OF KEY COMPONENTS

After inventing the required IR sensitive cells, JX Crystals began to develop complete TPV systems. This effort then required us to invent and integrate several key components into a practical generator that can be manufactured economically.
While the TPV idea was first proposed in 1960, three new developments have taken place in the last ten years that now make economical TPV systems possible. The first new development is the diffused junction GaSb cell [1,2,3,4]. Personnel now at JX Crystals were the first to fabricate GaSb cells in 1989. In 1991, our work was presented in a paper entitled “Fundamental Characterization Studies of GaSb Solar Cells” [1]. This new GaSb cell responds out to 1.8 microns. The process used to fabricate this cell replicates the silicon solar cell fabrication process. Diffusions are known to be much less expensive than epitaxy and, unlike in complex epi cells, no toxic gases are used in our process. JX Crystals has issued patents and licensed patents on the GaSb cell and circuits [2]. Two TPV circuits incorporating these new cells are shown in figure 1a along with a power curve in figure 1b showing 2 Watts per cell. The power density is over 100 times more than the traditional planar solar cell making cost of $0.50 per Watt possible.

FIGURE 1a. 72 GaSb cells shingle mounted on a circuit measuring 5 cm by 26 cm. Top circuit shows shingles with steps and cracks; bottom circuit is covered with planar filter covers.

FIGURE 1b. Illuminated current vs. voltage test for 72-cell circuit showing over two Watts per cell and over 1 Watt per cm².

FF = .680
Voc = 11.94 volts
Isc = 18.76 amps
Pmax = 152 watts
The second new development is new IR emitters and filters that put 75% of the radiant energy in the cell convertible band. These spectral control elements [5,6,7] along with the TPV cells and circuits have been described in more detail previously [1-7]. However, since these elements are key to the success of TPV systems, we will describe near term and longer term spectral control options in the next section.

The third new development is the commercial availability of low NOx SiC radiant-tube burners that operate at up to 1250°C. Figure 2a shows a schematic of a radiant-tube burner from WS Inc. and figure 2b shows a photograph of several of these burner tubes in operation in an industrial furnace. According to the WS Inc. literature, “In over a decade of practical experience with ceramic radiant tubes, material failure due to thermal wear has not yet occurred.”

In a subsequent section of this paper, we will describe a TPV generator / furnace built around these three key components. This unit is designed for combined heat and power (CHP) for the home.

**FIGURE 2.** (a) Schematic of a low NOx radiant tube burner as manufactured by WS Inc. (b) Photograph of several of these burners in operation in an industrial furnace.
SPECTRAL CONTROL

Given cells and circuits that work and a developed high-temperature radiant tube burner with a recuperator, the key to the success of TPV is in the spectral control. The optical path for TPV begins with the IR emitter and ends with the PV cells. The components in between such as a spectral filter or an emitter foil are designed to control the spectrum of the radiation. Ideally, the emitted spectrum would consist only of photons with wavelengths in the PV cell convertible band. However in practice, this is not achieved. Ideally, the IR filter would reflect all non-convertible photons back to the emitter and transmit all convertible photons to the PV cell array. However in practice, this is also not achieved. Here, we describe spectral control in terms of three optical elements, the IR emitter, the IR filter, and the PV cells. Two compromise solutions for spectral control are described in this section.

The two alternate spectral control systems we describe here differ primarily in the type of emitter utilized. The PV cells are common and both use dielectric filters. To qualitatively understand spectral control, it is convenient to divide the emitted spectrum into the following three wavelength ranges:

1. Short wavelength (<1.8 microns) radiation that the PV cells can convert.
2. Mid-wavelength (< 3.6 microns and >1.8 microns) radiation where a simple dielectric filter easily reflects and recycles non-useful radiation.
3. Long wavelength (> 3.6 microns) radiation which must somehow be suppressed.

As the quantum efficiency shows in figure 3, a GaSb PV cell efficiently converts short wavelength photons into electricity. Similarly, as the reflection spectra in figure 4 shows, simple dielectric filters efficiently reflect mid-wavelength photons back to the emitter. The two spectral control systems we describe here represent alternate means of suppressing the long wavelength radiant energy.

![Figure 3. GaSb cell internal quantum efficiency.](image)
Our first method of suppressing the longer wavelength radiation uses a double quartz heat shield around a SiC emitter. Since quartz absorbs longer wavelengths beyond 4 microns, the inner most quartz shield absorbs energy from the SiC emitter and re-radiates half of that energy back toward the emitter. The second heat shield does the same thing with the net result that the long wavelength emitted energy is reduced by 3 times. In effect, as is shown in figure 5(a), the emittance is reduced by 3 times at wavelengths beyond 4 microns. We first described this double quartz heat shield concept in the 2nd TPV conference in 1995 [8]. Pierce and Guazzoni presented further information on this concept in the 4th TPV conference in 1998 [9].

The higher performance longer-term option uses an antireflection-coated tungsten foil around the heated SiC tube [5,6,7]. Tungsten has a low emittance (high reflection) at long wavelengths and using the anti-reflection (AR) coating can enhance its emittance at cell-convertible shorter wavelengths. The measured emittance of AR/W is shown in figure 5(b). A patent on this emitter has been issued to JX Crystals Inc. [6]

Referring to figure 5, note that the emittance at shorter wavelength for AR/W is comparable to SiC and its emittance at longer wavelengths is lower than for the double quartz shield case yielding better spectral control. However, the negative for AR/W is that it can not operate in air. As in a light bulb, a noble gas backfill is required. Figure 6 shows the radiant power spectra arriving at the PV cells for the two spectral control cases just described.
FIGURE 6. Emitted power spectra for (a) SiC / q2 at 1200 C & (b) AR/W at 1300 C.

In figure 6(a), the emittance for SiC with two-quartz shields from figure 5(a) is convolved with a blackbody at 1200 C and the 18 layer filter spectra from figure 4(b). The 18-layer filter is used because it has reflectivity extending out to 4 microns where the quartz shields become effective at reducing the SiC emittance. In figure 6(b), the AR/W emittance is convolved with a blackbody at 1300 C and the 9-layer filter spectra.

Qualitatively, figure 6 shows that both spectral control strategies are effective. We have used TracePro to analyze the performance of each of these options and these results will be presented in the next section. First, however, we describe our proposed generator / furnace design for home combined heat and power. This design begins with a commercially available WS radiant tube burner.

1.5 KW TPV GENERATOR / FURNACE DESIGN AND PERFORMANCE

We have previously described the design, fabrication, and testing of a 500 W cylindrical TPV generator [7] in which a TPV array surrounds a custom radiant tube burner. All of the parts for this 500 W TPV generator were built at JX Crystals. We have now adapted this earlier design to use a small WS Inc radiant tube burner resulting in a detailed design of a larger 1.5 kW TPV generator / furnace. Figure 7 shows an overview of this design.

Referring to figure 7, note that there are three SiC ceramic parts. They are the large SiC radiant tube, the inner SiC recuperator, and an inner SiC tube. These parts are in the standard WS radiant tube design. However, we are incorporating five important modifications.

The first modification is a ceramic insulator stand-off at the bottom inside the outer SiC tube supporting the inner SiC tube. This stand-off both supports the inner SiC but also insulates the end of the outer tube to avoid or at least reduce heat losses at the lower end. This is unlike the standard WS design where the end glows (see figure 2b).

The second important recommended change relates to the inner SiC tube. In the standard WS design, all three SiC tubes are made using Si bonded SiC. This material has an upper temperature limit of 1350 C. Here, we recommend using a higher quality SiC for the inner tube with a higher temperature capability.

The third important change is the addition of the fold-back section in the outer SiC tube. This allows the addition of the secondary stainless steel recuperator coaxial with the first higher temperature SiC recuperator.
In the longer term, the fourth important feature in our design is the use of the AR coated refractory metal foil IR emitter wrapped around the outer SiC tube as a means of controlling the IR spectra for maximum conversion efficiency. There are also refractory metal foil heat shield wrappings.

In the longer term, the fifth and final important feature in our design is the use of o-ring seals at the top and bottom PCA flanges. These seals are required so that the space between the PCA and the radiant tube can be evacuated and back filled with a noble gas such as krypton. This is done for two reasons. First, it is necessary to protect the emitter foil against oxidation and second, krypton is used to reduce heat transfer losses to the PV array via thermal conduction through the gas. This noble gas fill feature appears daunting but is really no different than the conventional incandescent tungsten filament light bulb.

We have projected the performance of this TPV generator design based on data from WS Inc. and our own experience with burners and based on modeling of the emitter and PV array performance using TracePro. TracePro is a Monte Carlo based software package by Lambda Research that has been used for TPV modeling by Richard Thomas at Bechtel Bettis [10]. Table 1 summarizes the resultant predicted system performance for a near term design using SiC with a double quartz shield and a longer term design using an AR/W foil emitter with a hermetic seal.
As Table 1 shows, TracePro calculation indicates that our TPV generator / furnace should be capable of producing 1.5 kW of electricity for a burn rate of 12.2 kW with an overall electrical conversion efficiency of 12.3% for the AR/W emitter case. Similarly, our TPV generator / furnace should be capable of producing 1.1 kW of electricity for a burn rate of 14 kW with an overall electrical conversion efficiency of 8% for the SiC emitter case with a double quartz shield.

Note that the unit that we are describing is designed to produce both power and heat. Therefore, the cells are operated at 50°C in the Table 1 calculation. This higher cell temperature operation reduces the electrical efficiency relative to room temperature operation but allows for hot water and space heating for the home. In a combined heat and power (CHP) system, the waste exhaust heat can also be used. The CHP efficiency can then be over 90%.

TPV TEST STATION

A TPV test station using a WS SiC radiant tube burner is being assembled at the Alberta Research Council in Canada. Figure 8 shows photographs of this system. Experimental data from this test station will be used to verify model calculations and to evolve the TPV key components.

ECONOMICS

From the point of view of the homeowner and the country, our strategy is to conserve fuel and save money by combining an energy efficient TPV furnace (winter) with a renewable energy source, solar cells (summer). While the TPV furnace does burn fuel, it utilizes the fuel energy with over 90% efficiency (referred to the fuel lower heating value, 100% efficiency is possible). Our distributed combined heat and power residential system saves on the need for additional central power plants and additional transmission
lines. While fuel energy utilization efficiency in a central power plant might be 40%, the other 60% will be thrown away as waste heat. Co-generating electricity and heat in the home with TPV avoids burning fuel in the central power plant.

A very interesting advantage for our TPV generator / furnace is that it is both a generator and a furnace. Therefore, for a new home purchase, one gets a credit for the furnace. In other words, a new homeowner can chose to buy a furnace for $2700 for example or a TPV generator / furnace for $2700+$1500 = $4200.

Figure 8: TPV experimental test station with glowing WS SiC radiant-tube burner (left) and water cooled filter array (right).

CONCLUSIONS

From the point of view of technical design and market potential for this technology, the conclusions in this paper are very positive. We present a design capable of producing 1.5 kW electric with an array efficiency of 15.4%, a burner / recuperator efficiency of 80%, an overall electrical efficiency of 12.3% and a combined heat and power efficiency of over 90%. The cost analysis of this design suggests a total cost of approximately $3200. JX Crystals’ analysis for the US market suggests an installed cost to a homeowner of $4200. Given a furnace credit of $2700 (for heating), this corresponds to a cost for the electric generator of $1500/1.5kW or $1000/kW. This corresponds to an energy payback time of approximately 4 years at 10 cents per kWh.
REFERENCES

2. US Patents #5,217,539, #5,389,158, #6,057,507, #6,232,545 B1, and PCTs assigned to JX Crystals Inc.
6. US Patent # 6,177,628 and PCT assigned to JX Crystals Inc.