Microcogeneration Concepts Using Thermophotovoltaics

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ABSTRACT

The energy efficiency benefits of microcogeneration are attracting technical attention and several different technical approaches are currenty under development. The authors are currently involved with several different project using thermophotovoltaics (TPV) for microcogeneration. The specific approach involves non-selective emitters in combination with high performance optical filters and GaSb cells. Work in progress on a 500 watt, liquid fuel-fired system for portable power applications, and a solar/gas-fired TPV system are described. The authors are also currently developing concepts for integration of TPV with warm air furnaces for residential cogeneration.

Introduction

The local cogeneration of electric power and heat in residential and commercial building applications offers large gains in energy efficiency relative to conventional, heat-only equipment. Thermophotovoltaics (TPV) is an emerging cogeneration technology which may be ideally suited for this application.

TPV is an approach to convert thermal energy from a hot body, released in the form of infrared radiation to electric energy using photocells. In the subject application the hot body is produced by combustion of fuel. For the TPV system to achieve reasonable conversion efficiency, it is necessary to control the spectrum incident on the photovoltaic cells. For example, photons with energies lower than the band gap of the PV cell cannot generate electricity but become waste heat that has to be rejected from the cells. Two basic approaches have been taken to control the spectrum. The first involves selective emitters. A selective radiator, made using oxides of rare earth elements such as ytterbium has a high emissivity in a relatively narrow band of wavelengths. The region of high emissivity from the radiators is matched with the bandgap of the photovoltaic cells. The second approach involves the combination of a non-selective or broadband emitter (e.g. gray body) and an optical filter that passes only a selected part of the spectrum. To obtain high conversion efficiencies, these filters should have high reflectance for the out-of-band radiation and thus "recycle" unusable radiation to the emitter. For additional background on TPV see Schubnell, Gabler, and Bronam 1997; and Coutts and Fitzgerald 1998.

Description of the Technology

TPV is an old technology that has recently become viable due to the development of low-bandgap, infrared sensitive photovoltaic cells and unique spectral control techniques. Figure 1 illustrates the basic thermophotovoltaic conversion process. From left to right in Figure 1, energy from a heat source is absorbed by a thermal absorber/emitter which is heated to incandescence.

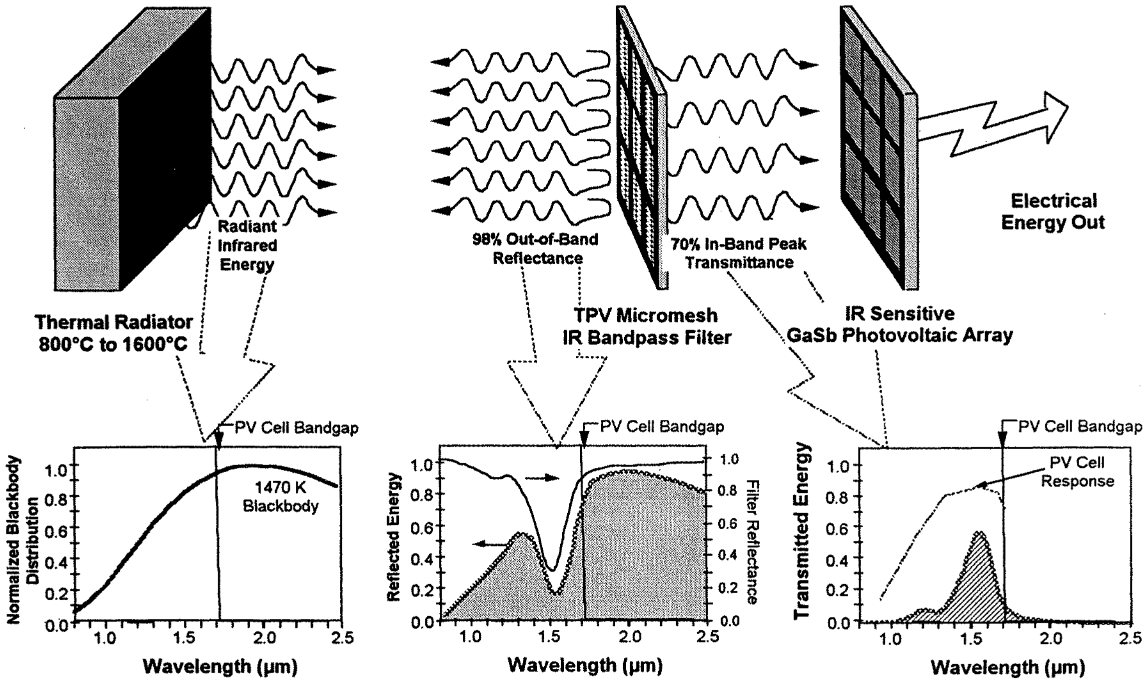


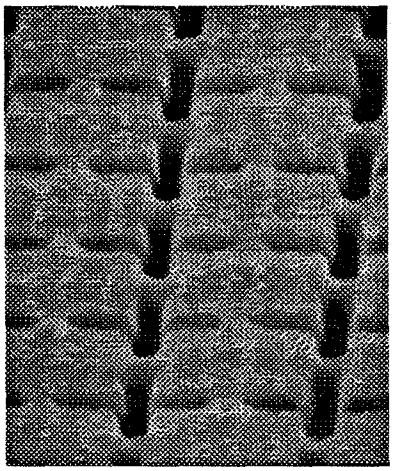
Figure 1. Illustration of Basic TPV Conversion Process

After being heated to incandescence, the absorber/emitter then radiates infrared energy. The spectral distribution of this radiated energy is shown by the shaded area in the graph below the radiator. The blackbody radiation impinges onto a bandpass filter located between the emitter/absorber and a low-bandgap PV cell. The bandpass filter transmits the radiant infrared energy that is in-band to the PV cell and reflects the remaining out-of-band energy back to the absorber/emitter which re-absorbs it. The spectral distribution of energy reflected back to the radiator is shown by the shaded area in the graph below the filter. The spectral distribution of the energy transmitted to the PV cell is shown by the shaded area in the right hand graph. By limiting the energy absorbed in the PV cell to a relatively narrow wavelength range which is centered about the PV cell's peak response wavelength, the cell can convert the transmitted energy with a theoretical efficiency up to ~48%. Thus, by limiting the transmitted energy to the cell's most efficient wavelength regime and "recycling" the energy which the cell cannot convert back to the absorber emitter, the thermophotovoltaic (TPV) can achieve high overall system efficiencies on the order of 30%.

The concept of TPV conversion has been studied for years. EDTEK personnel have participated in four testbed demonstrations of TPV conversion. The first demonstration was a solar TPV generator intended for space power applications (Horne and Thompson 1986). This solar demonstration was based on non-optimized silicon photovoltaic cells. An overall efficiency of 13.8% was demonstrated using these un-optimized parts. The main drawback observed was that silicon cells required emitter temperatures in excess of 1800°C which presented materials problems for long term space applications. Therefore, an effort was undertaken to develop a low bandgap GaSb photovoltaic cell to lower the emitter temperature requirements. Concurrently, a unique resonant metal mesh infrared bandpass filter was developed for use with the GaSb photovoltaic cell. A preliminary testbed experiment was conducted to assess the feasibility of these new components (Horne et. al. 1993). In this preliminary experiment, an array conversion efficiency of 13.3% was demonstrated using the first GaSb PV cells and un-optimized filters that were then available. Analytical models of both experiments indicated that the TPV conversion process behaved exactly as predicted and that, with optimized components, efficiencies on the order of 30% could be obtained with solar or radioisotope heat sources which do not suffer parasitic losses from exhaust gases and efficiencies up to 20% could be obtained with fossil fuel sources which do have parasitic heat losses in their exhaust gases. Thus, all of these past studies concluded that the TPV concept had lots of potential; however, lack of appropriate technology precluded the realization of that potential. EDTEK has developed two key technologies that enable efficient and practical TPV conversion. These two key TPV technologies, i. e., GaSb PV cells and resonant micromesh IR bandpass filters (Horne, Morgan and Sundaram 1995; Morgan et. as. 1996) are discussed below. Using these newly available technologies, EDTEK has recently fabricated and tested a solar concentrator fueled TPV testbed and a diesel fueled TPV testbed.

The most novel feature of this approach to implementation of TPV is a resonant micromesh infrared bandpass filter located on the surface of the thermal cavity facing the radiant emitter. This filter is the real key to efficient TPV conversion. It enables the reflection of out-of-band radiant energy back to the absorber/emitter. Failure to return unusable energy to the absorber emitter results in parasitic losses in the system which rapidly lowers overall conversion efficiency. This unique filter reflects greater than 98% of the out-of-band energy back to the emitter and is unequaled by any other technology for efficient TPV conversion. The filter's high out-of-band reflectance limits system parasitic losses to take advantage of the GaSb PV cell's inherent ~48% theoretical conversion efficiency to yield overall system fuel-to-electric efficiencies of 25% to 30% for solar energy and 17.5% to 20% for fossil fuels.

These filters are formed by etching submicron slot antenna elements into a gold film. Figure 2 illustrates these elements. To understand how these filters work one must think of electromagnetic wave theory rather than optics. The slots are simply submicron slot antennae that resonate at the desired transmission frequency. They can be modeled by antenna theory scaled to the optical wavelength regime. Oscillating electric currents induced in the gold film by the absorption of radiant energy normally result in the light being reradiated (or reflected as it is more commonly referred to) from the surface of the metal film. However, in the case of the slotted film, the currents flowing parallel to the slots set up magnetic fields parallel to the slots and electric fields across the slots. The magnetic fields couple inductively while the electric fields couple capacitively in the surrounding dielectric medium. These inductive and capacitive interactions cause a resonance at a frequency where the oscillating current wavelength corresponds roughly to the length or geometry of the slots. At this resonant frequency, the energy is coupled through to the opposite surface of the film where it is reradiated, or transmitted, from that surface. At nonresonant frequencies the light is reflected from the front surface as it would be if the slots were not present. This behavior has been characterized experimentally. Peak transmission for in-band radiation is 80%. Reflectance of out-of-band radiation is over 95%. Due to their high out-of-band reflectivity the power level in the system can be raised and lowered over an order of magnitude (by varying the emitter temperature through reduced fuel combustion) without significantly changing the conversion efficiency.



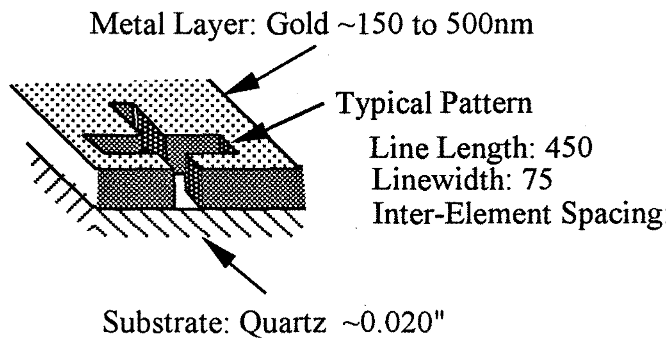
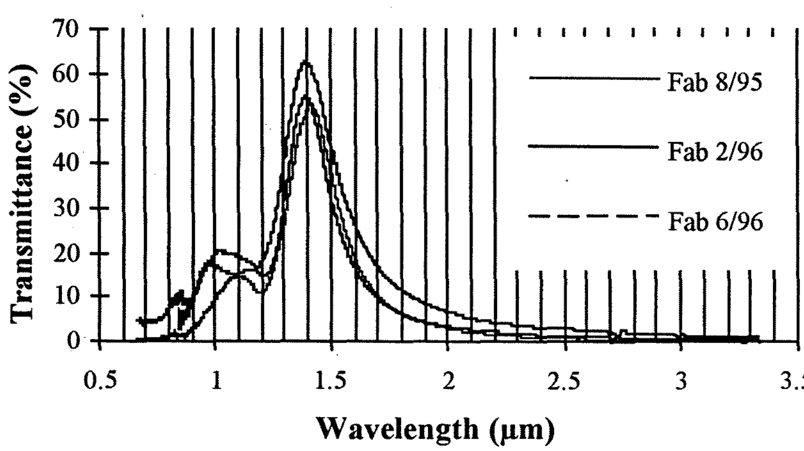


Figure 2. Photomicrograph of Gold EDTEK TPV IR Filter With Schematic Diagram

With the assistance of a U. S. Department of Energy Small Business Innovative Research grant, EDTEK has built a pilot production line for the filters and has demonstrated their reproducibility from batch-to-batch and lot-to-lot over a period of one year as shown in Figure 3. We have done a process cost analysis and estimate that the filters will cost about $0.50/sq. cm in modest production.



a. Batch to Batch Reproducibility of Fabricated Filters

b. EDTEK Filter Production Facility

Figure 3. Demonstrated Pilot Production Capability For TPV Filters

Next to the IR bandpass filter, the PV cell that can efficiently convert mid-infrared radiant energy to electricity is the most important key to efficient TPV conversion. Due to the physics of photovoltaic conversion, the PV cell can efficiently (~48% theoretical) convert the narrow wavelength band of energy transmitted to it by the IR bandpass filter to electricity.

Under license from The Boeing Company and funding from the U. S. Department of Energy, EDTEK has optimized the TPV performance of low-bandgap GaSb (0.7 eV) PV cells and also developed a pilot production capability for the TPV cells. Figure 4 illustrates typical electrical characteristics for the cells. Figure 5 shows the yield obtained for each of six GaSb wafers of cells and the yield from batch to batch for six four-wafer batches. We have also developed technology for fabricating the cell/filter elements into PV converter arrays.

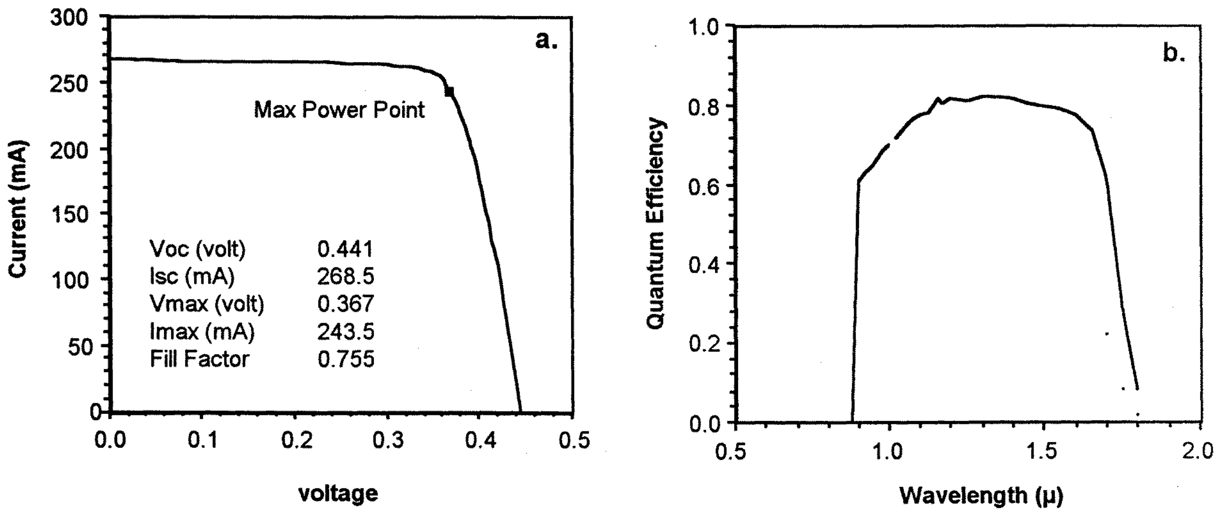


Figure 4. a.) Typical GaSb Cell Current-Voltage Characteristics at ~50x Solar Concentration b.) Typical Quantum Efficiency of GaSb Cell

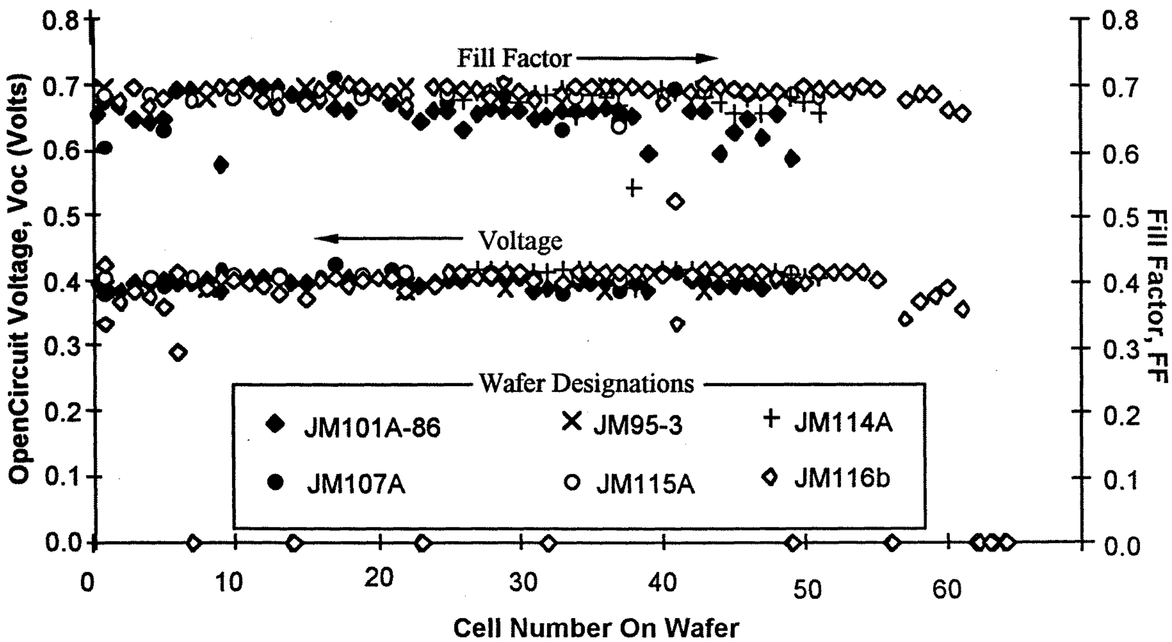


Figure 5. Cell Fabrication Process Repeatability For Open Circuit Voltage (Voc) and Fill Factor (FF) Over Six Production Runs of Four Wafers Per Run

EDTEK, working with two vendors of GaSb crystals, has performed an extensive cost analysis for the production of both the crystalline starting materials and the in-house production process of the GaSb PV cells. In modest production, the cells can be produced for about $7.65/sq. cm.

Currently the authors are involved with three ongoing TPV programs, one (Butcher, Krishna, Horne, Morgan, Sundaram and Charters 1999) is funded by the U. S. Defense Advanced Research Projects Agency (DARPA) and the Army Communications Electronics Command (CECOM), one funded by the National Renewable Energy Laboratory, NREL, and a third by the California Energy Commission. In the DARPA program EDTEK, teamed with Brookhaven National Laboratory (BNL) has developed and built a laboratory scale 500W TPV system that uses diesel, JP8, or #2 heating oil as the fuel. This is a prototypical TPV testbed system. Key issues relating to a) burner and recuperator, b) filter/cell converter assembly and c) packaging of components are addressed in this on-going program. The testbed system built in this program is in operation at EDTEK and is undergoing evaluation. Results obtained thus far indicate that this system operates with an efficiency of 12.2%. This project also addresses issues relating to the design of high efficiency burners, identification of various sources of parasitic loss in the system, and extensive evaluation and operational testing. In this project the conditions presented to the burner represent some design challenges. The firing rate is far below what can be practically achieved with conventional oil burners and combustion air preheat is 1200 C. The burner is a low pressure, air atomized system being developed in parallel at BNL as a high performance burner for home heating applications (Butcher, Celebi, Wei, and Kamath 2000). Under this on-going DARPA/CECOM program, current work is also directed towards improving converter efficiency in terms of filter transmission and PV cell efficiency.

On the NREL sponsored project we have fabricated and successfully tested a small solar TPV cavity that achieved 21.4% efficiency. We are currently fabricating a 500W unit similar to the DoD unit except that concentrated sunlight will be the heat source instead of a diesel burner. This unit will be tested at the NREL solar concentrator facility in the near future.

Under the California Energy Commission (CEC) project we are developing a hybrid solar / natural gas TPV system intended for commercial and light industry applications that can utilize the simultaneous production of electricity and hot water. In this program, EDTEK and BNL will design and build a solar based TPV system that will utilize sun light (when available) or natural gas for heating the gray body. TPV system design concepts and operational details such as mounting of filters and cells are being developed under this program.

All of the above systems that are under development utilize an underlying baseline converter technology. The baseline TPV converter design was tested in both the diesel fueled testbed and a solar concentrator fueled testbed. Figure 6 presents test results from both these testbed configurations. The theoretical curve is based on calculations made using the measured response of the IR filter, prisms, and PV cells with the theoretical temperature dependence and spectrum for black body radiant energy. A three-dimensional ray tracing code traced the omnidirectional blackbody radiant spectrum through the TPV system to generate the predicted curve of Figure 6. Power out values as a function of temperature were measured for series connected PV cell arrays in the testbed system at the emitter temperatures indicated. These tests showed that the testbed converter operated exactly as predicted in our design model. To date, with the first testbed assembly, observed efficiencies are 12.2% for the diesel fueled unit and 21.4% for the solar concentrator fueled unit (no exhaust gas losses). Evaluation testing of the diesel testbed unit has just begun and is currently on-going. We expect to reach greater than 15% diesel fuel to electric conversion efficiency.

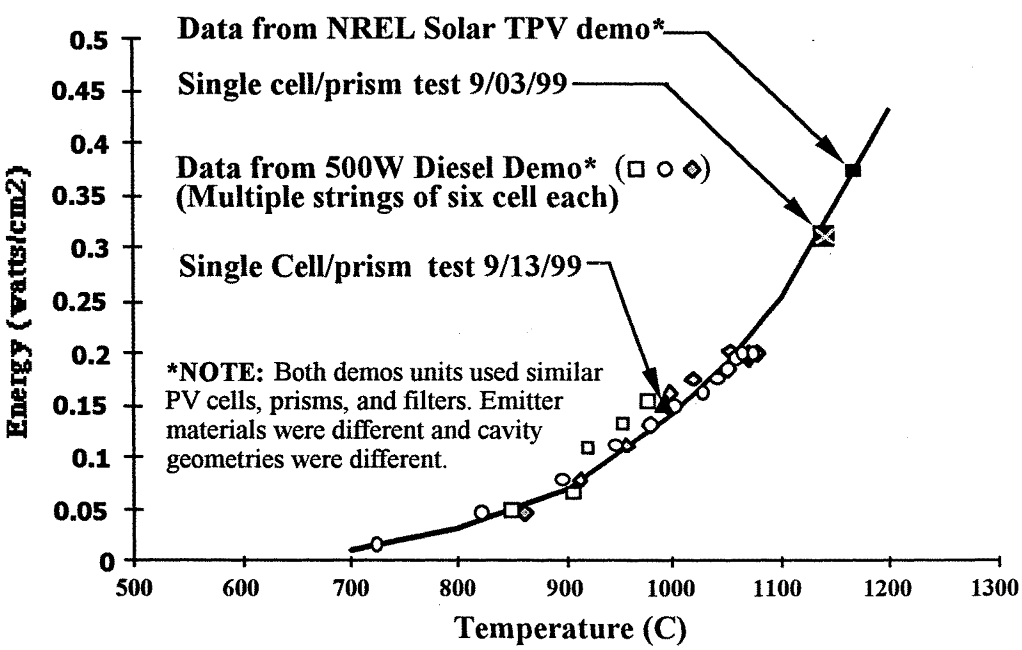


Figure 6: Comparison Of Measured And Theoretical TPV Power Out Versus Emitter Temperature

The baseline TPV converter utilizes a filter/prism/cell circuit boards concept that appears very promising but requires work to improve thermal control and develop high-volume manufacturing techniques. A basic state-of-the-art converter array consists of (from the heat source outward) the wavelength selective filter (the resonant mesh IR bandpass filter), a 2 x 2 prism array which is made up of individual prism elements, a 2 x 2 string of GaSb PV cells, a copper clad alumina substrate board whose top copper cladding is patterned with the appropriate conduction paths and contact pads to interconnect the four cells into a series string. This design utilizes PV cells and prisms developed on the DOD project. The PV cells have 10mm x 10mm active areas surrounded by 1.5mm side busbars on all sides. Each of the cells sees the same IR flux so that we can use a series string of four cells. The prisms intercept a continuous surface and the wavelength filter can be fabricated as a square being 31.5mm x 31.5mm. The prisms also concentrate the light onto the cells by a factor of approximately 2 as shown by the measured data presented in Figure 7, which increases the voltage and hence the conversion efficiency of the cells by about 10% overall.

The unilluminated areas between cells underneath the prisms offer convenient space for cell interconnections without parasitic losses. Interfacial reflective losses are minimized at the IR bandpass filter/prism interface by an adhesive which is refractive index matched to the filter substrate and the prism material. At the prism/GaSb TPV cell interface reflective losses are reduced through the application of the Si_3N_4 antireflection (AR) coatings and index matching adhesive. Additional AR coatings may be required to match prisms fabricated from higher index materials such as samarium doped glasses and silicon. Finally, the prisms reduce the requirement for expensive GaSb active area. Summarizing prism features; the concentrating prisms provide four functions: 1) They concentrate the IR energy onto the cell by a factor of two and reduce the amount of cell active area by a commensurate amount. 2) The increased cell current due to the concentration raises the cell voltage to give a higher electrical conversion efficiency, 3) The prisms intercept the incident IR rays over the entire surface of the heat source yielding an effective cell array "packing factor" of 100 percent, and 4) they provide an unilluminated area in which to make the PV cell interconnections without introducing parasitic absorption in the TPV system. The cells are laid up on a printed circuit formed by etching copper film that is laminated onto a ceramic substrate

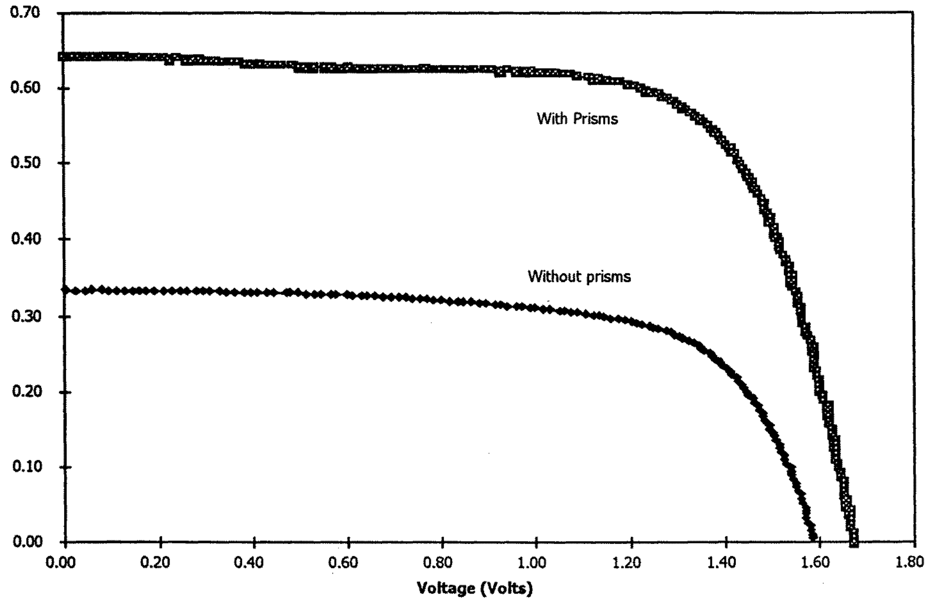


Figure 7. Measured performance of 4 series connected GaSb PV cells with and without concentrating prisms

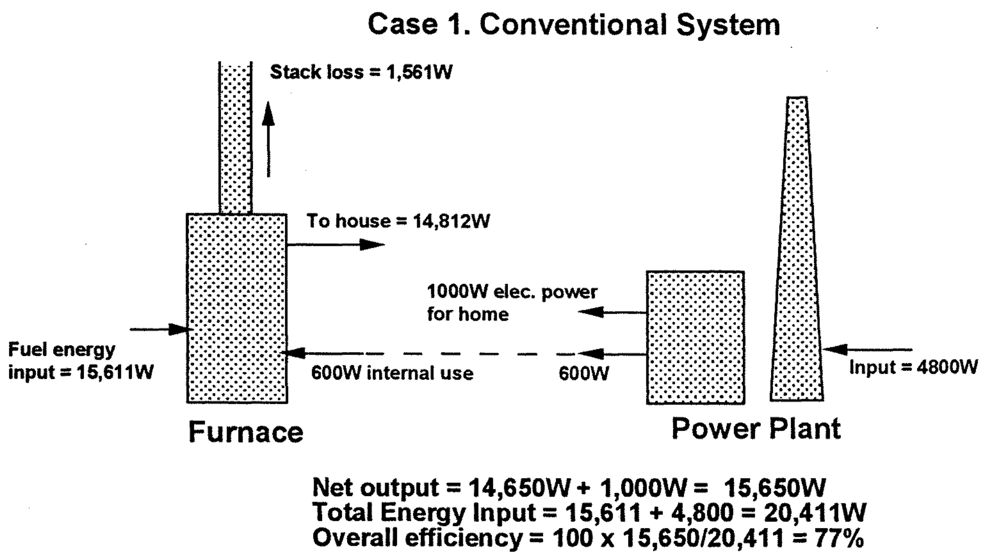
Due to the high energy density on the TPV photovoltaic cells, thermal control is a challenge. In the DARPA/CECOM testbed design cooling of the cells was achieved by forced air supplied by a low speed fan through a radial finned heat exchanger. The waste energy from the cells is first conducted from the copper clad alumina substrate and then spread over a larger area using water/copper heat pipes. From this base area, the heat was then conducted into the heat sink; an array of radial fins through which the forced air was passed.

Application to a Residential Warm Air Furnace

The authors at present are developing concepts for the integration of this TPV technology with residential warm air furnaces. The concept involves very small furnaces which will operate with much higher run times than conventional systems. One approach here involves the refit of a small, minifurnace which is installed in parallel to the existing warm air furnace. The minifurnace has an integral TPV generator and meets most of the heating load of the home. The warm air furnace is considered to be an ideal application for TPV for two primary reasons: 1) the return air from the home provides an excellent, low temperature heat sink to which to direct cell waste heat, keeping the cells at a temperature where high performance can be sustained, and 2) furnaces typically comsume more electric power than other heating appliances.

The benefit of a TPV topping cycle in a minifurnace is improved efficiency of primary fuel use. The benefit is particularly evident when the system is connected to the utility grid for cogeneration. To illustrate, a heat balance is presented in which an efficiency number is developed. This is the efficiency with which both heat and 1,000W of electric power are delivered to a home. The following assumptions have been used:

1. 10% of the furnace fuel energy input is lost up the stack.
2. At the conventional power plant electric power generation efficiency is 33%.
3. Conventional furnace internal power use is 600W, for the minifurnace internal power use is 200W (blower, burner, controls).
4. TPV converter output is 1,200W (200 internal, 1,000 for home).
5. Heat delivered to the house is 14,650W (50,000 Btu/hr) for conventional furnace.
6. Minifurnace is sized to produce 1,000W of electric power net with10% fuel input to net electric power output efficiency.



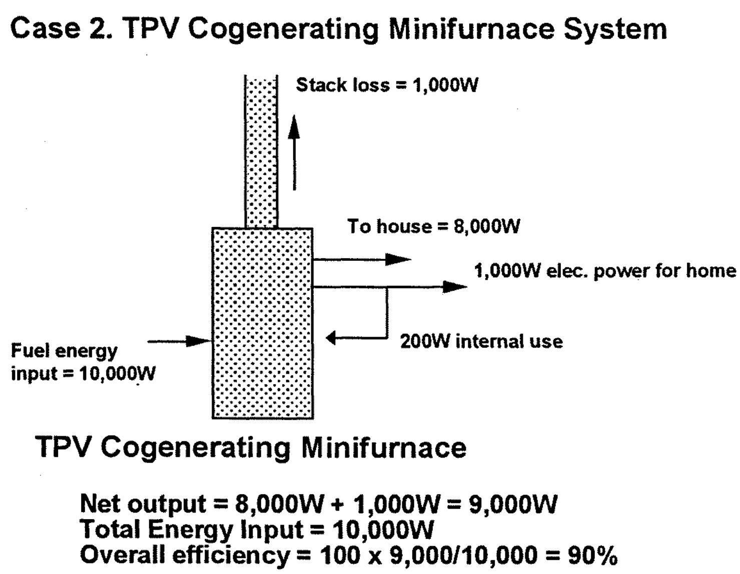


Figure 8. Energy Balance Comparison of Conventional vs TPV Minifurnace

Based upon the above analysis the energy conservation benefits are considerable ~~with~~ an overall efficiency improvement from 77% to 90%. The TPV furnace has been sized smaller than a conventional furnace and this provides several benefits. Most conventional warm air furnaces are considerably oversized and this leads to frequent cycling. The TPV system under conceptual development has an output slightly lower than typical design loads and will run with a very high load factor during the heating season, leading to economical use of the installed TPV power generation capacity. The existing conventional furnace will fire only on the coldest days. Furnace off-cycle energy losses will be reduced.

The fuel-to-electric power efficiency which can be achieved in a TPV furnace cogeneration system is very much dependent upon the level of combustion air preheat used. The approach currently be developed involves minimal levels of air preheat and this will translate to electric efficiencies in the 10% range, much lower than can potentially be realized. Several practical reasons contribute to this approach. First, with minimal levels of air preheat essentially conventional burners can be used, eliminating the need to develop and certify new burners. Second, using relatively cool air eliminates NO_X concerns which must be faced with hot air. The authors, however, consider this an introductory approach with considerable potential for higher efficiency designs in the future.

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