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Nighttime and Daytime Electrical Power Production from the Nighttime Solar Cell

Ronald J. Parise
Parise Research Technologies
101 Wendover Road
Suffield, CT 06078
Phone: (860) 668-4599

G. F. Jones
Department of Mechanical Engineering
Villanova University
Villanova, PA 19085
Phone: (610) 519-4985

ABSTRACT

The Nighttime Solar Cell™ works on the principle of a simple thermoelectric generator (TEG) operating in the temperature differential that exists between deep space at an effective temperature of 4K and the surrounding ambient temperature (nominally at 300K). Thus the ambient or surroundings of the device are the source of thermal energy while deep space provides a thermal sink. The cold junction of the TEG is insulated from the surroundings by a vacuum cell, improving its overall effectiveness.

This research is an on-going effort to develop a clean, reliable, safe, inexpensive, alternate source of electric power at night. The model discussed herein investigates the many design parameters that influence electrical power production during daytime operation. Previous research has shown that the 6cm x 6cm cell can produce about 7mW of continuous electrical power from the TEG module during nighttime operation.

Using a model developed for this work, we investigate the operation of the cell during the day without photovoltaic cells present. Therefore the cell converts solar thermal energy into electrical energy by reversing the operation of the TEGs. That is, the nighttime cold junctions now become the daytime hot junctions heated by the sun, and the nighttime hot junctions become the daytime cold junctions cooled by the ambient air. In this mode of operation the model includes thermal radiation from the sun for three selected solar fluxes. These correspond to approximately full-sun, half-sun and quarter-sun exposure during summer and winter operation.

The thermal model has also been expanded to include a twelve-banded model for radiation transmission through the atmosphere for nighttime electrical energy production. The results of the model will provide performance data for material selection and parameter requirements for building a prototype Nighttime Solar Cell™.

INTRODUCTION

The primary drawback to solar (photovoltaic) panels is the lack of nighttime energy production. Costly battery backup is needed if the electrical load powered by the photovoltaics is required at night. The batteries are subject to failure and require maintenance. Solar panel installations are normally in remote locations where service is difficult to provide and often inconvenient.

The Nighttime Solar Cell™ is a unique solid state device that produces electric power at night, similar to daytime solar power; or it can produce electricity by day, with or without solar power accompaniment, or used to augment the operation of solar panels by electric power generation at night (Parise, 1998).

There are many configurations and uses that the cell can assume. The original function of the Nighttime Solar Cell™ is to produce electrical energy both day and night (Parise, 1999). Daytime electrical energy production takes place from one of two methods (or a combination) of direct energy conversion. The first method can be solar cells connected in parallel with the TEGs, converting light into electrical energy when the sun is visible. In this configuration, the TEGs also produce electrical power from the solar thermal energy. The TEGs would produce electricity at night with the photovoltaic cells acting as an electrical conduit.

The second method would not utilize photovoltaic cells but involve the conversion of thermal energy from the sun into electrical energy by reversing the operation of the TEGs. That is, the nighttime cold junctions now become the daytime hot junctions; the sun is the thermal source for operating the system. In this mode of operation, part of the control system that provides electrical power to the load requires circuitry that monitors electrical current flow direction: daytime operation will have a reverse current flow direction from nighttime operation because the junction temperature of the TEGs will reverse (hot junctions become cold junctions and vice versa). This is the primary mode of operation the model considers in this study.

Note that the Nighttime Solar Cell™ could use an alternate energy source (thermal waste stream, ground water, etc.) at a higher temperature than the ambient, if available at the site of the solid state device. This would improve system performance and add to system reliability.

Obviously the Nighttime Solar Cell™ technology is in its infancy with the many uses and designs in which it can be configured. With today's technology, a cell can be manufactured to produce electricity both day and night for low wattage applications for such typical electronic devices as a cell phone, laptop, radio, etc.

THERMAL MODEL

A thermal model was developed from fundamental principles for this work. The model determines the temperature difference between the hot and cold junctions of the TEGs. Figure 1(a) shows the physical configuration and parameters utilized in the model when using deep space as the thermal sink during nighttime operation. The orientation of the cell is such that the cold junction plate (CJP) is parallel to the horizontal. The thermal source, the ambient, supplies energy to the module at T_∞.

Figure 1(a) shows the height of the TEG elements to be L, and the distance from the CJP to the window to be L_a. The TEG junctions are copper and the CJP is aluminum. The thermal conductivities of copper and aluminum are sufficiently large so that the temperature gradients are small through the thickness of each.

Figure 1(b) illustrates the daytime operation of the cell, where the CJP now becomes the hot junction plate (HJP). The HJP is now oriented normal to the solar beam radiation when the sun is at solar noon, and the model accounts for the movement of the sun from horizon to horizon assuming the usual periodic motion of the sun (Duffie and Beckman, 1974).

The CJP (or HJP) is $20 cm^2$ and the aperture opening is slightly larger to avoid physical or thermal interference. The thickness of the CJP is 5mm to reduce the temperature gradients associated with the fin effect which results from the TEG module being smaller than the CJP.

The surface of the CJP is assumed to be a gray, diffuse surface with $\epsilon_c = \alpha_c$ at temperature T_c. The surface facing the nighttime sky is assumed to have an emissivity, ϵ_c, of 0.90.

Deep space is modeled as a black body at temperature $T_s = 4K$. The model utilizes 12 transmission bands shown in Fig. 2 for radiative transfer through the atmosphere (Hudson, 1969), although less than 1% of the energy occurs below $5\mu m$ at 300K or less. The view factor between the CJP and deep space is assumed to be unity.

The exterior of the window is exposed to the ambient temperature, T_∞, through a specified heat transfer coefficient, $h_w = 10\ W/m^2K$ corresponding to weak free convection of air at the surface. Temperature variations through the window are neglected.

The TEG elements are bismuth telluride. The specific design configuration of the TEG elements and module are based on standard sizes available from industry. The CJP and cell size are based on the size availability of the ZnSe window (nominal size: 2" x 2").

With solar heating of the CJP during the day, three values of normally incident solar radiation are used in the model: 200 W/sq.m, 500 W/sq.m and 800 W/sq.m. Only the local ambient temperature, of values 300K and 275K as specified in the model, provides the thermal sink for this mode of operation.

As done in the past (Parise and Jones, 2000) the model includes the effect of not having a full vacuum in the cell. That is, there will now be a slight trace of air at the low pressure of about 25 torr. With this air, the only effect that will be considered in the model is between the CJP and the ZnSe window, referred to as the air gap.

Free convection does not occur because the low density of the air results in a Reyleigh number for the air gap less than the critical value (Eaton and Blum, 1975). The air gap is 1cm.

The thermoelectric properties of the Seebeck coefficients (α_n, α_p), thermal conductivity (λ_n, λ_p), and the electrical resistivity (ρ_n, ρ_p) are assumed to be constant. The length of the thermoelectric elements in the direction of heat flow is L.

EQUATION DEVELOPMENT

The thermal model has been developed in a previous study (Parise et al., 1999) and the results will be summarized here.

Radiation Model

The net radiative heat flux on the CJP comes from four sources: the radiosity of the CJP, J_c, the fraction of energy from the night sky that is transmitted through the window, emission from the window, and the fraction of the J_c that is reflected from the window. Thus

$$q_c = (1 - \rho_w)J_c - \tau_w \sigma T_s^4 - \epsilon_w \sigma T_w^4, \quad (1)$$

where the ρ_w, τ_w, ϵ_w refer to the radiative properties of reflectivity, transmissivity and emissivity of the window and T_w is the window temperature.

An energy balance on the window accounts for the convective heat transfer rate at the external surface of the window and the net radiative energy that it absorbs. Therefore

$$h_w(T_\infty - T_w) = 2\epsilon_w \sigma T_w^4 - \epsilon_w \sigma T_s^4 - \epsilon_w J_c + (k_a/L_a)(T_c - T_w), \quad (2)$$

where h_w is the convective heat transfer coefficient at the surface of the glass. When the effect of air is present, k_a is the thermal conductivity of the air gap in the cell, and T_c is the temperature of the CJP. With no air present, k_a equals zero.

All radiative properties in eqns. (1) and (2) are written as the sum of the contributions from their respective bands. For example, ϵ_w in the term $\epsilon_w \sigma T_s^4$ in eqn. (2) may be written as

$$\epsilon_w = \epsilon_1 F(0, \lambda_1 T_s) + \sum_{i=2}^{11} \epsilon_i F(\lambda_i T_s, \lambda_{i+1} T_s) + \epsilon_{12} F(\lambda_{12} T_s, \infty) \quad (3)$$

where F(x,y) is the blackbody emissive power fraction over the band of λT defined by the values of the first (x) and second (y) arguments in F(x,y) (Dunkle, 1953). In eqn. (1), the radiation properties of J_c are based on the band model at temperature T_c.

Heat Conduction and Thermoelectric Model

A steady-state, quasi one-dimensional heat conduction model with internal energy generation is used (Parise et al., 1999). One boundary condition is the heat flux, q_c, at the CJP, and on the opposite end of the TEG the second boundary condition is the convection heat transfer at the hot junction plate.

The area for heat conduction in the individual thermoelectric elements is A_e. The area ratio, A_r, is equal to A_w/A_e. This is the area parameter used in the development of the conduction model, where A_r is greater than 1.

The relationship between the heat flux at the CJP, q_c, and the temperatures of the hot and cold junctions of the TEG, T_h and T_c, respectively, is written as (Angrist, 1982)

$$q_c \eta A_r(A_p+A_n) = \kappa(T_h-T_c) + (|\alpha_n|+|\alpha_p|)T_c I_{out} + 1/2\, I_{out}^2 R \qquad (4)$$

where the fin efficiency of the CJP, η, is assumed to be unity for convenience, κ is the thermal conductance of a TEG pair,

$$\kappa = (\lambda_p A_p/L_p) + (\lambda_n A_n/L_n),$$

R is the TEG electrical resistance,

$$R = (\rho_n L_n/A_n) + (\rho_p L_p/A_p),$$

A_n is the area of the n-type material, A_p is the area of the p-type material, and L_n, L_p are the lengths of the elements. The electrical current produced by the TEG module, I_{out}, is defined below.

The thermoelectric generator equations will be selected to maximize the thermal efficiency (Culp, 1979; Angrist, 1982) of the module based on the semiconductor material properties and the geometry of the module. Therefore the maximum value for the figure of merit is

$$Z = \frac{(|\alpha_p| + |\alpha_n|)^2}{[(\rho_n\lambda_n)^{1/2} + (\rho_p\lambda_p)^{1/2}]^2}, \qquad (5)$$

where α_p, α_n are the respective Seebeck coefficients, ρ_n, ρ_p are the electrical resistivities and λ_n, λ_p are the thermal conductivities of the materials.

Utilizing the figure of merit, the calculation for the current output of the TEG module is based on optimizing the internal and external resistances of the system (Angrist, 1982). Therefore the equation for the current produced by the module to maximize the thermal efficiency is

$$I_{out} = \frac{(|\alpha_p| + |\alpha_n|)(T_h - T_c)}{R\,[x + 1]}, \qquad (6)$$

where

$$x = [1 + Z(T_h+T_c)/2]^{1/2}.$$

The open circuit voltage for the thermoelectric generator is

$$V_{oc} = (|\alpha_p| + |\alpha_n|)[T_h - T_c]. \qquad (7)$$

The selection of the TEG module will be based on utilizing off-the-shelf or near-off-the-shelf materials. That is, a minimum of modifications to existing tooling will be sought.

Therefore, both n-type and p-type elements are chosen with the same cross-sectional area and length. Typical assembly techniques of copper junctions, ceramic endfaces, etc., are used.

RESULTS

The TEG elements utilized are p- and n-doped bismuth telluride with a 1mm x 1mm square cross-section and a length of 25mm. For these element dimensions, the model is run to optimize the number of junction pairs, based on the power output of the cell. The thermal conductivity is considered constant at 1.35 W/mK, as specified by the manufacturer.

Figure 3 shows the power output of the cell when operated at night as a function of the number of TEG junctions. Twenty-two junctions correspond to a module having 44 TEG elements, the maximum energy output developed for this geometry. With this design, the cell will produce approximately 6.7mW of electrical power with a full vacuum in the cell; 6.3mW for a partial vacuum. Although not shown, the voltages corresponding to these powers are about 0.412 volts at an ambient temperature of 300K and 0.314 volts at 275K.

The model shows that the full vacuum is not justified based on the small improvement in performance when reducing the pressure in the cell below 25 torr.

For the maximum electrical energy production with 22 TEG junctions, the CJP temperature is 253K at 300K ambient temperature and 239K at 275K. These correspond respectively to a 47K and 36K temperature difference across the TEG elements.

Figure 4 illustrates the daily energy produced by the 22-junction module when the device is operated day and night. The daytime performance of the cell is determined, to a large extent, by the number of daylight hours available (summer vs. winter use of the cell) as well as the solar flux (200 W/sq.m, 500 W/sq.m, or 800 W/sq.m). This figure greatly facilitates determining the operation of the cell in a particular geographical location. One only needs to know the expected peak solar flux and number of daylight hours.

For Fig. 4, the nighttime energy production is only a function of the ambient temperature at 300K (summer) or 275K (winter). The daytime energy production is determined from the prescribed solar flux. As shown in the example, for ten hours of daylight in the summer (at 300K ambient), 460 mW-hrs will be produced by the cell. As a comparison, this is about one-fourth the energy produced by a commercially available photovoltaic panel operating over ten hours (C. Crane, 2001), the solar panel obviously not producing any power at night.

Figure 5 shows the temperature of the HJP and the peak power output for the 22-junction cell as a function of incident solar flux for an ambient temperature of 300K. The peak power output indicates the maximum amount of daytime energy that is available from the cell.

DISCUSSION

The 22 TEG junction module design is selected for the prototype. This provides both convenience for the selection of a standard module and utility in the optimum power range of the device. The good performance of the cell with solar heating of the CJP shows the sound practicality of such a power producing device.

The addition of the atmospheric window bands incorporated in the model provides an accurate method for predicting the performance of the cell in various climates.

The period at dawn just when the sun appears on the horizon and in the evening when the sun sets are two transient conditions that must be considered further to determine device performance when the direction of the electric current changes.

Figure 4 can be utilized to predict the performance of the Nighttime Solar Cell™ for any location where the solar flux is known. Interpolation between curves provides a simple means for determining device energy production for any locale or sun angle.

CONCLUSIONS

The thermal model shows the performance of the Nighttime Solar Cell™ to be satisfactory under several operating conditions and modes of operation, while providing valuable parametric guidelines for the design of a prototype. The electrical power output of the cell, nominally sized at 6cm x 6cm x 3cm, will produce about 7mW of power at night. Four cells connected in series, a 12cm x 12cm panel, will produce about 1.6 volts. This corresponds to a single D-sized battery, with an almost infinite life.

Although the device cannot out-produce a photovoltaic cell in a 24-hour period, the cell still provides sufficient electrical energy production for many applications, with the added advantage of continuous energy production during nighttime operation.

The daytime operation without the use of solar cells can also be achieved successfully. Therefore this new mode of electric power production may be the next source of clean, reliable, safe and inexpensive energy.

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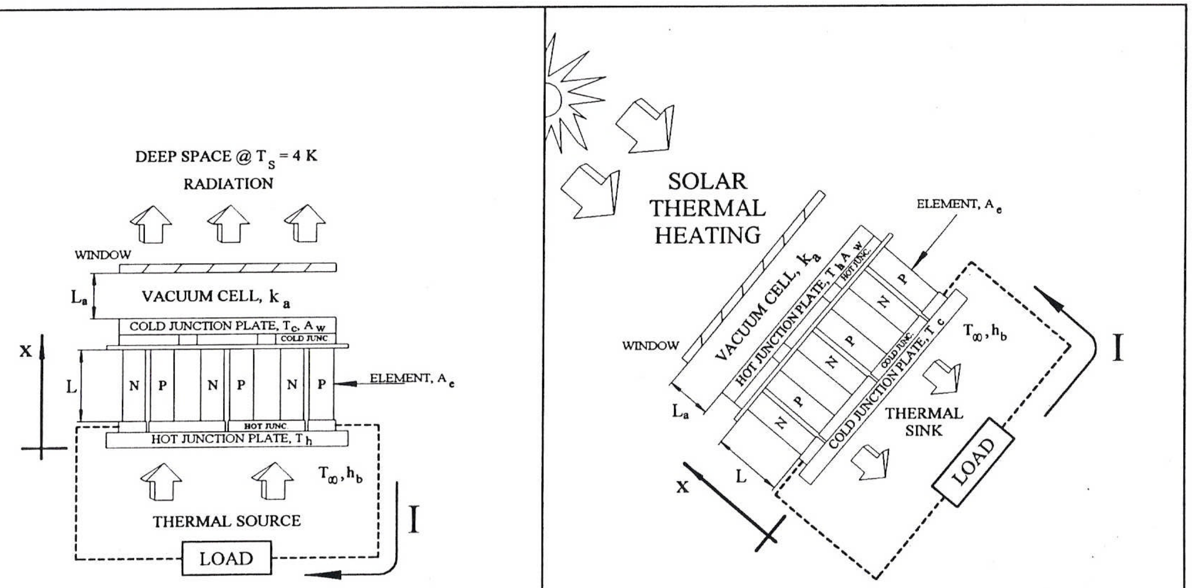

(a) Nighttime Operation
(Parallel to Horizontal)

(b) Daytime Operation
(Normal to Solar Noon
Beam Radiation)

Figure 1: Model Configuration.

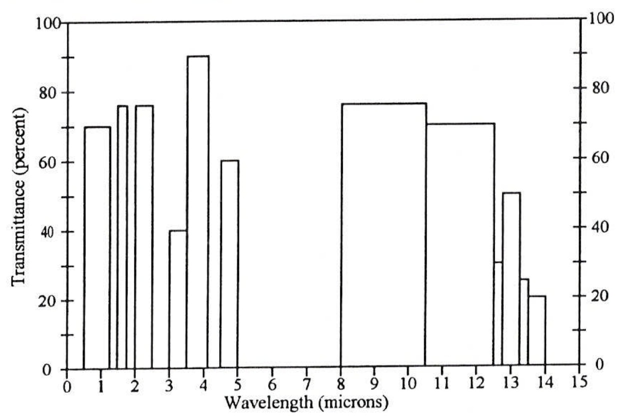

Figure 2: Banded Model for Atmospheric Transmittance at Sea Level

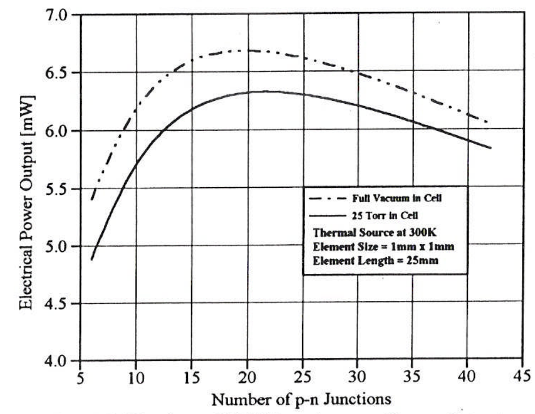

Figure 3: Number of TEG Junctions vs. Power Output of the Cell.

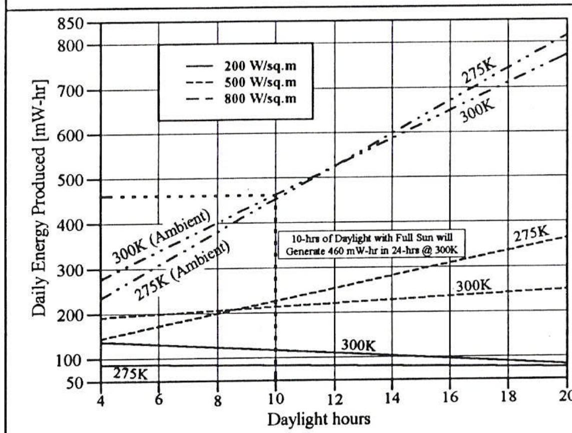

Figure 4: Daily Energy Production for Given Solar Flux and Number of Daylight Hours.

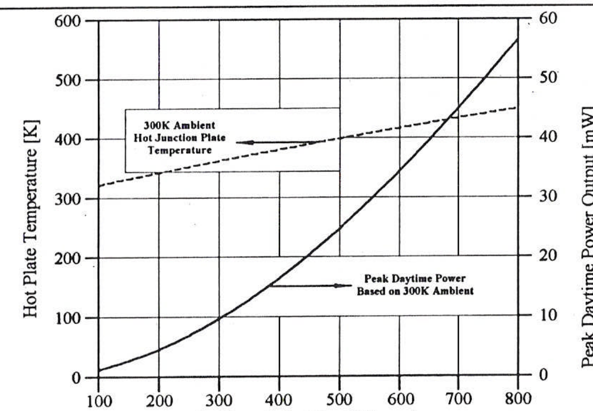

Figure 5: Hot Plate Daytime Temperature and Peak Power Output for Known Solar Flux at 300K Ambient.

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