ENERGY FROM DEEP SPACE THE NIGHTTIME SOLAR CELL^{TM} ELECTRICAL ENERGY PRODUCTION

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ABSTRACT

The primary objective of the Nighttime Solar Cell^{TM} is to produce electric power at night. The lack of energy production when there is no incident solar energy is a major drawback to photovoltaic cells. Nighttime utilization of the new device produces electrical energy using a 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 using deep space. The model discussed herein investigates the many design parameters that influence electrical power production including semiconductor configuration, cold junction plate area and depth of vacuum required in the cell for acceptable performance.

The "hot" junction can be supplied energy from a low grade thermal stream, previously considered too low a temperature source to recover the energy economically, greatly improving electrical energy production. Cell performance using this low grade thermal energy is presented.

Specific design configurations can be used for electrical energy production both day and night, regardless of weather conditions. For example, when only a thermoelectric generator is utilized, shielding from direct sunlight can produce power from deep space without photovoltaic cells. Nighttime Solar Cell^{TM} performance with this configuration is discussed.

Finally, solar thermal energy can heat the daytime hot junction, utilizing the ambient as the thermal sink. This power-producing configuration is also investigated, showing great promise for daytime operation of the cell.

The thermal model will be utilized for parameter selection in the design and subsequent building of a prototype Nighttime Solar Cell^{TM}.

INTRODUCTION

The original function of the Nighttime Solar Cell^{TM} is to produce electric power both day and night in a terrestrial application.[1] This solid state device, operating in a vacuum, utilizes a combination of photovoltaic cells for daytime operation and thermoelectric generators for nighttime operation. The photovoltaic-thermoelectric device operates in a vacuum, called a Vacuum Pod, to isolate the components from the ambient temperature, improving electric power production capability.

However, this investigation focuses on energy production using TEGs only. This means of operation can be employed during the day with shielding from direct sunlight, or, in a reverse mode of operation for the TEG module, by direct heating from the sun.

Consider the amount of energy that is available from nighttime operation of the cell. A blackbody at 300K, typically the ambient temperature at the surface of the earth, can radiate 450 W/m^2. (This is about one-half the energy available at the surface of the earth due to solar energy.) Utilizing deep space as a thermal sink having an effective temperature of 4K,[2] a temperature differential can be created between the surface of the earth and this thermal sink in a device with TEGs to produce electrical power.

The energy spectrum between 8μm and 13μm is nearly transparent under all atmospheric conditions for radiating energy to deep space, with smaller windows occurring in a few other bands. This represents approximately 40% of the total energy radiated at 300K.

Therefore, depending on the efficiency of the TEGs that are selected or developed, upwards of 180 W/m^2 of energy can be utilized. In dry, arid climates, more energy would be available, improving the operation of the cell significantly. The Nighttime Solar Cell™ is independent of the tilt of the earth, time of day, weather, etc., which are all problems that plague solar cells.

In reality, temperature differentials are on the order of 40K to 100K, and TEG module efficiencies are around 4% to 7%. Hence, during nighttime operation, cells can produce about 4.5 W/m^2 to 5.0 W/m^2 with today's technology, under all atmospheric conditions. Therefore this means of energy production can be utilized in many applications where small, reliable energy requirements are needed for remote monitoring sites, sensors, etc.

The operation of the Nighttime Solar Cell™ is currently at the mercy of available materials that operate in this temperature range. The development of new materials, an ongoing research effort worldwide, will vastly improve the operation of the device. Heat transfer studies of the system have shown new designs that will improve these numbers even without new material breakthroughs. This research effort reflects those advances.

THERMAL MODEL

The thermal model determines the temperature differential between the hot and cold junctions of the TEGs when using deep space as a thermal sink. Figure 1 shows the physical configuration and parameters utilized in the model. The thermal source supplies energy to the module at T_∞. The energy travels through the TEG elements (the p-n material), through the cold junctions into the cold junction plate (CJP).

Figure 1 shows the height of the TEG elements to be L, and the height of the distance from the CJP to the window to be L_a. The TEG cold junctions are made of copper and the CJP is made of aluminum. The thermal losses in both these components are three orders of magnitude less than in the TEG elements or the space above the CJP when air is present. Therefore these losses will be neglected in the model.

The CJP is 20cm^2 and the aperture opening is slightly larger to avoid physical or thermal interference. The thickness of the CJP is 5mm to minimize the fin effect from the TEG module being smaller.

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 treated to have an emissivity ϵ_c of 0.96. The CJP then radiates thermal energy to deep space through the window covering the aperture of the vacuum cell.

The input temperature to the module, T_∞, can also be used to portray the temperature of a low grade thermal waste stream for the addition of thermal energy to the pod, incrementally improving the performance of the Vacuum Pod.

Deep space is modeled as a black body at temperature $T_s = 4$K. Initial model development will have a three-band radiation capability for energy transmission through the window. The two wavelengths that separate the three bands are cutoff wavelengths λ_l and λ_u. The radiation surface properties, for absorptivity (α), reflectivity (ρ), and transmissivity (τ), are given subscripts 1, 2, and 3 to designate their values in each of the three bands. In any band, emissivity and absorptivity are assumed to be equal, $\epsilon = \alpha$. Initial model results will use a single band between $8\mu m$ and $13\mu m$ where approximately one-third of the total radiative energy spectrum is transmitted. This is well within the spectral capability of zinc selenide (ZnSe), the material chosen for the window. The view factor between the CJP and deep space is assumed to be one.

The exterior of the window is exposed to the ambient temperature, T_∞, through a specified heat transfer coefficient, h_W. Temperature variations through the window are neglected.

Bismuth telluride is the material selected for the TEG module based on the expected operating temperature range of the pod. The specific design configuration of the TEG elements and module are based on standard sizes available from industry. The CJP and Vacuum Pod size are based on the size availability of the ZnSe window (nominal size: 2" x 2").

The model is utilized to show the effects of heating the CJP during the day by incident solar energy. In this mode of operation for the Vacuum Pod, the current in the TEG module will be reversed. The heating at the CJP is input as a thermal flux at the surface. Radiation shape factors, other input from the surroundings, and any cooling effects that may occur due to deep space are neglected. No additional cooling is used at the now cold junction of the module; only the ambient temperature of the air is the thermal sink.

Finally, the model is used to determine the effect of not having a full vacuum in the cell. That is, there will now be a slight trace of air in the Vacuum Pod. With this air, the only effect that will be considered in the model is the gap between the CJP and the ZnSe window, referred to as the air gap.

Except at extreme pressures, the thermal conductivity is a function of temperature. When the pressure is very high, or when the pressure is reduced to a level where the gas is at rarified levels and the mean free-molecular path between collisions is on the order of a physical dimension of the space (the gap between the CJP and the window in this case) will the conductivity be affected. That is, at low pressures, the conductivity becomes a function of pressure.

When not fully evacuated (a full vacuum would be on the order of 10^{-5} torr) the geometry of the pod can influence the physics of the thermal model with the entrapped air by both thermal conduction and the buoyancy effects of free convection. Eaton and Blum[3] have shown that pressures on the order of 1 to 25 torr in an enclosed area negate the effects of natural convection. For nighttime operation of the cell, the cooler surface is lower than the warmer surface and only conduction heat transfer is present; there is no natural convection.

However, depending on the pressure in the pod during daytime operation, air can produce buoyancy effects when the sun provides the thermal energy to the module. Therefore the analysis considers the operation of the cell when the pressure is increased from a full vacuum to 25 torr.

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.

One mode of daytime operation the TEG-only module in the Vacuum Pod could assume would be utilizing the ambient as the thermal source and deep space as the thermal sink, similar to the nighttime operation. However, shielding from direct sunlight would be required to prevent solar heating of the CJP. The thermal model will predict this mode of operation, assuming no incident solar energy strikes the CJP. This means of operation of the system is advantageous for 24-hour energy production where no storage is needed or wanted.

Therefore the same mode of operation can be used day or night using the thermal model with deep space as the thermal sink.

EQUATION DEVELOPMENT

The thermal model has been developed in a previous study[4] and the results will be summarized here.

RADIATION MODEL

The net radiative heat flux on the CJP comes from three sources: the fraction of energy from the night sky that is transmitted through the window, emission from the window, and the fraction of the radiosity, 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 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 it absorbs. Therefore

$$h_w(T_\infty-T_w) = 2\epsilon_w\sigma T_w^4-\epsilon_w\sigma T_s^4 - \epsilon_w\sigma T_w^4+h_a(T_a-T_w), \quad (2)$$

where h_w is the convective heat transfer coefficient at the surface of the glass. When the effect of air is present, h_a is the thermal resistance of the air gap in the pod of height L_a and thermal conductivity $k_a(P)$, and T_a is the temperature of the air.

All radiative properties in eqns. (1) and (2) are written as the sum of three contributions from their respective bands. For example, ϵ_w in the term $\epsilon_w\sigma T_s^4$ in eqn. (3) may be written as

$$\epsilon_w = \epsilon_1 F(0,\lambda_l T_s)+\epsilon_2 F(\lambda_l T_s,\lambda_u T_s)+\epsilon_3 F(\lambda_u T_s,\infty), \quad (3)$$

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 $F(x,y)$.[5] In eqn. (1), the radiation properties of J_c are based on the band model at temperature T_c.

HEAT CONDUCTION MODEL

A steady-state, quasi one-dimensional heat conduction model with internal energy generation is used.[4] One boundary condition is the radiative heat flux (q_c) at the CJP, the second 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.

From this information, the temperature distribution in the thermoelectric elements may be written as

$$T_t(\eta) = -\phi\eta^2/2-\mathrm{Bi}\,\eta T_\infty +(\phi/\mathrm{Bi}+T_\infty-q_c/h_b)(1+\mathrm{Bi}\,\eta), \quad (4)$$

where ϕ is the energy generation parameter, $q'''L^2/\lambda_n$, where q''' is the rate of energy generation per unit volume; Bi is the Biot number, $A_r h_b L/\lambda_n$; and η is the dimensionless local coordinate, x/L.

The energy generation term is related to the Seebeck coefficients and one of the junction temperatures[4] as

$$\phi = \{A_r q_c L/[(T_c(\alpha_p-\alpha_n))]\}^2\rho_p/\lambda_p, \quad (5)$$

where ρ_p and λ_p or ρ_n and λ_n, properties of the TEG elements, may be used, respectively. The cold and hot plate temperatures, T_c and T_h, are

$$T_c = T_t(\eta = 1), \text{ and } T_h = T_t(\eta = 0). \quad (6)$$

This system of equations defines the thermal model for determining the temperature differential between the hot and cold plate junctions of the TEG module.

THERMOELECTRIC EQUATIONS

The thermoelectric generator (TEG) equations will be selected to maximize the thermal efficiency[6,7] 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

$$Z = \frac{(|\alpha_p| + |\alpha_n|)^2}{[(\rho_n \lambda_n)^{1/2} + (\rho_p \lambda_p)^{1/2}]^2}, \qquad (7)$$

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.[7] Therefore the equation for the current produced by the module to maximize the thermal efficiency is

$$I_{out} = \frac{(|\alpha_p| + |\alpha_n|)(T_h - T_c)}{R\,[x + 1]}, \qquad (8)$$

where

$R = (\rho_n l_n / A_n) + (\rho_p l_p / A_p)$, and

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

A_n is the area of n-type material, A_p is the area of p-type material, l_n and l_p are the lengths of the elements, and T_h and T_c are the temperatures of the hot and cold junctions, respectively.

The open circuit voltage for the thermoelectric generator is

$$V_{OC} = (|\alpha_p| + |\alpha_n|)[T_h - T_c]. \qquad (9)$$

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 full thermal model is not used to determine the parameters required for the prototype. The model is simplified in three ways: the hot junction plate is maintained at a constant temperature T_h; the fin efficiency of the CJP is considered unity; and all radiative interactions occur between the black sky and the surface of the CJP only.

The TEG elements utilized are p- and n-doped bismuth telluride with a 1mm x 1mm square cross-section with a length of 25mm. These were element sizes available from suppliers. For this geometry of the elements, the model is used to optimize the number of junction pairs, based on the power output of the cell.

Figure 2 shows the power output of the cell as a function of the number of elements or element pairs. Forty-four elements correspond to a module having 22 TEG junctions, the maximum energy output developed for this geometry. With this design, the cell will produce approximately 7mW of electrical power. Note the power output is maximized when the thermal conductance ($A_e \lambda_{n or p}/L$) and the electrical conductance ($A_e \rho_{n or p}/L$) are optimized for the chosen geometry. Although not shown, this corresponds to about 0.42 volts.

The temperature of the CJP varies from 208.6K with four junction pairs to 281.5K with 100 junction pairs. For the maximum electrical energy production with 22 TEG junctions, the CJP temperature is 252K. This corresponds to a 48K temperature differential across the TEG elements.

In Figure 3, increasing the temperature of the hot junction plate by utilizing low grade thermal waste heat can affect the operation of the 22-junction module significantly. For the example shown, only a 10-degree temperature rise in the thermal source will result in a 22% increase in the power output of the module. Therefore, with a low temperature source only slightly above the ambient available to drive the pod, a considerable increase in the electrical output can be achieved.

Figure 4 shows the power output of the 22-junction module when the CJP is heated by the sun. This daytime operation of the cell shows promise for higher electrical energy production during daylight hours, compared to nighttime energy production. However, this analysis does not take into account sun angle, cloud cover, shape factors, etc. Therefore this should only be considered a first attempt at demonstrating the feasibility of a possibly promising system.

Figure 5 illustrates the effect on the performance of the 22-junction cell with air at 25 torr in the Vacuum Pod. With an air gap of 1.2cm, well proportioned to the physical dimensions of the pod, the output of the cell is reduced by about 2% compared to the full vacuum. The 1.2cm gap is between the CJP and the aperture window cover.

This moderate reduction in energy output may show that the cost advantages for the lower vacuum in the pod will more than offset the slight loss of electrical power.

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 performance of the Vacuum Pod with solar heating of the CJP and utilizing low grade waste thermal heat shows the practicality of such a power producing device. Without the benefit of a full vacuum in the pod, the cell still provides sufficient electrical energy production for many applications, the decrease in power being slight. The advantages of a less costly cell will far outweigh the reduction in energy production.

CONCLUSIONS

The thermal model shows the performance of the Vacuum Pod to be satisfactory under several operating conditions and modes of operation, while providing valuable parametric guidelines for the design of the prototype Nighttime Solar Cell™. The electrical power output of the cell, nominally sized at 6cm x 6cm x 3cm, will produce 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.

Cell performance can also be improved significantly utilizing previously unusable, low grade thermal waste heat. 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.

CONTACT

For information regarding the operation of the Nighttime Solar Cell™, contact Ronald J. Parise at PARISE RESEARCH TECHNOLOGIES, Suffield, Connecticut 06078.

REFERENCES

1. Parise, Ronald J., Nighttime Solar Cell™, IECEC98, Colorado Springs, CO, 1998, Paper No. IECEC-98-133.

2. Bliss, Raymond W., Jr., Atmospheric Radiation Near the Surface of the Ground: A Summary for Engineers, Solar Energy, Vol. 5, p103, (1961).

3. Eaton, C.B. and Blum, H.A., The Use of Moderate Vacuum Environments as a Means of Increasing the Collection Efficiencies and Operating Temperatures of Flat-Plate Solar Collectors, Solar Energy, Vol. 17, p151, (1975).

4. Parise, R.J., Jones, G.F., Strayer, B., Prototype Nighttime Solar Cell™, Electrical Energy Production from the Night Sky, IECEC99, Vancouver, British Columbia, Canada, 1999, Paper No. 1999-01-2566.

5. Dunkle, R.V., Thermal Radiation Tables and Applications, Transaction of the ASME, Paper No. 53-A-220, 1953.

6. Culp, Archie W., Jr., Principles of Energy Conversion, McGraw-Hill Book Company, New York, NY, 1979.

7. Angrist, Stanley W., Direct Energy Conversion, Fourth Edition, Allyn and Bacon, Inc., Boston, Massachusetts, 1982.

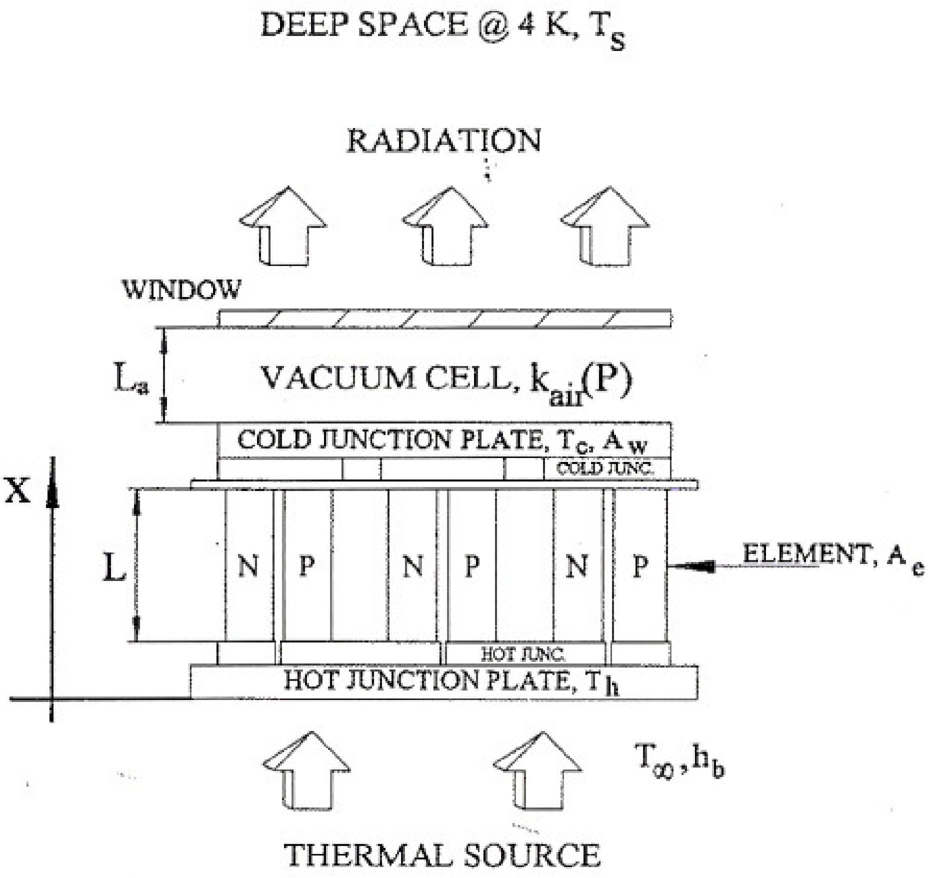

FIGURE 1: Model Configuration.

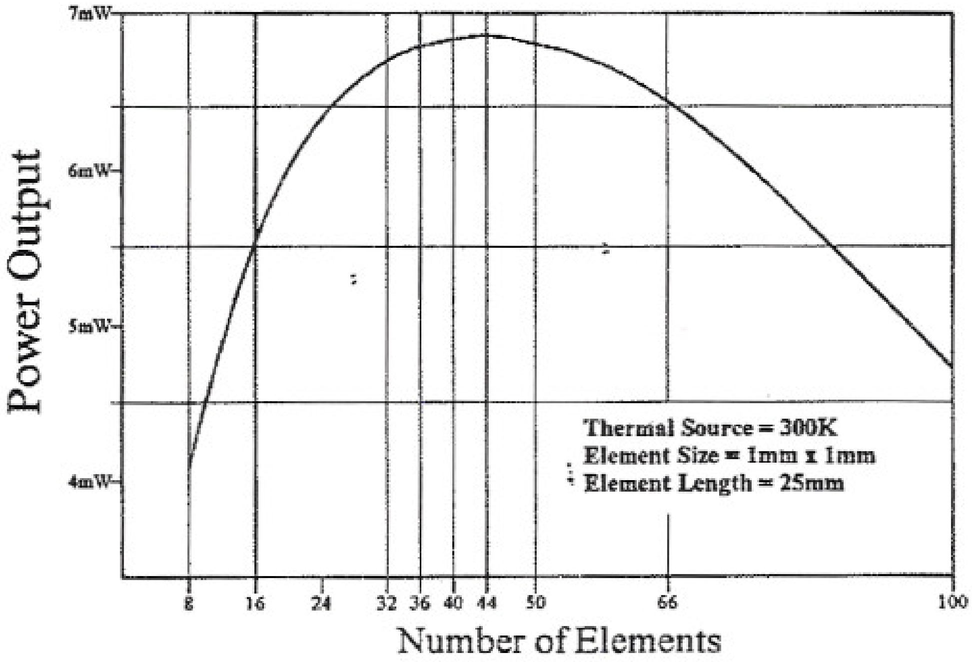

FIGURE 2: Number of TEG Elements vs. Power Output of the Cell.

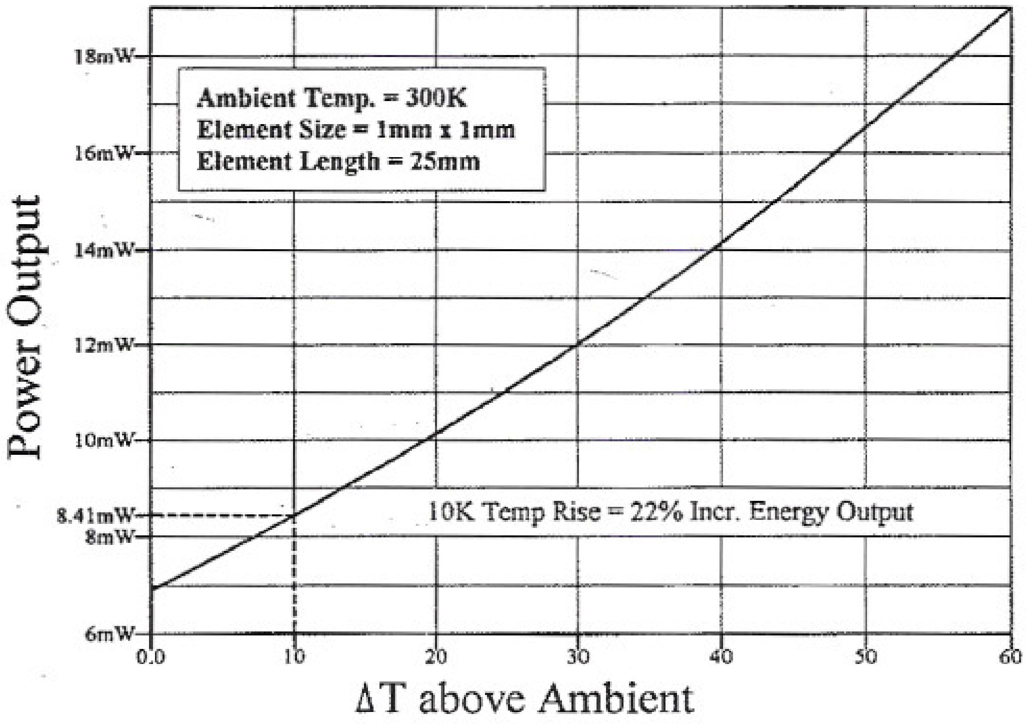

FIGURE 3: Low-Grade Thermal Source vs. Power Output of Cell.

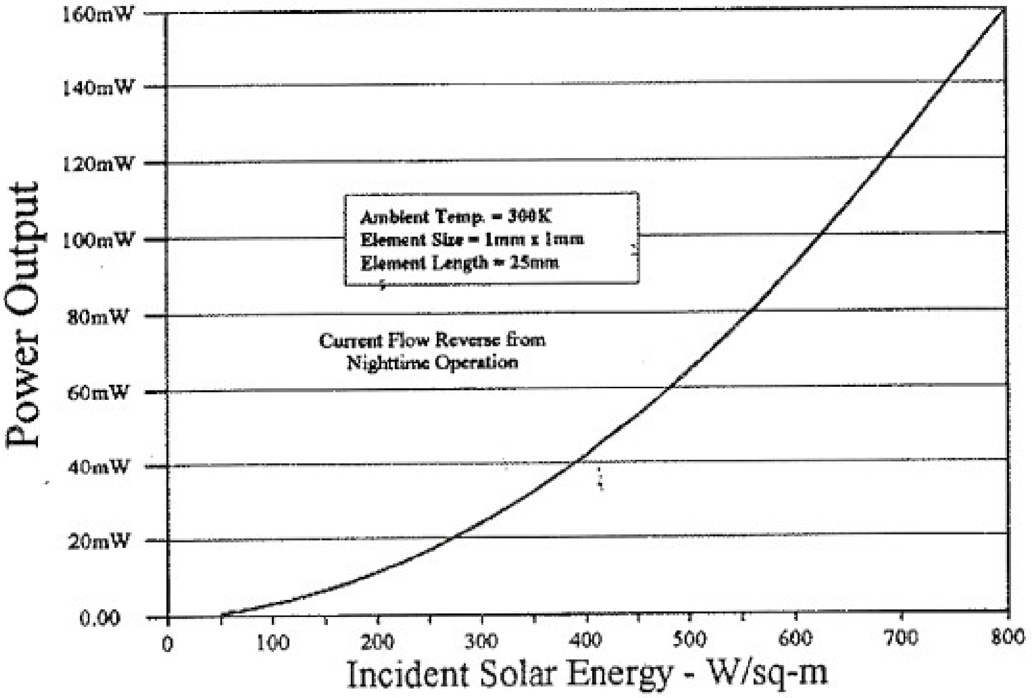

FIGURE 4: Incident Solar Energy on Cold Junction Plate vs. Power Output.

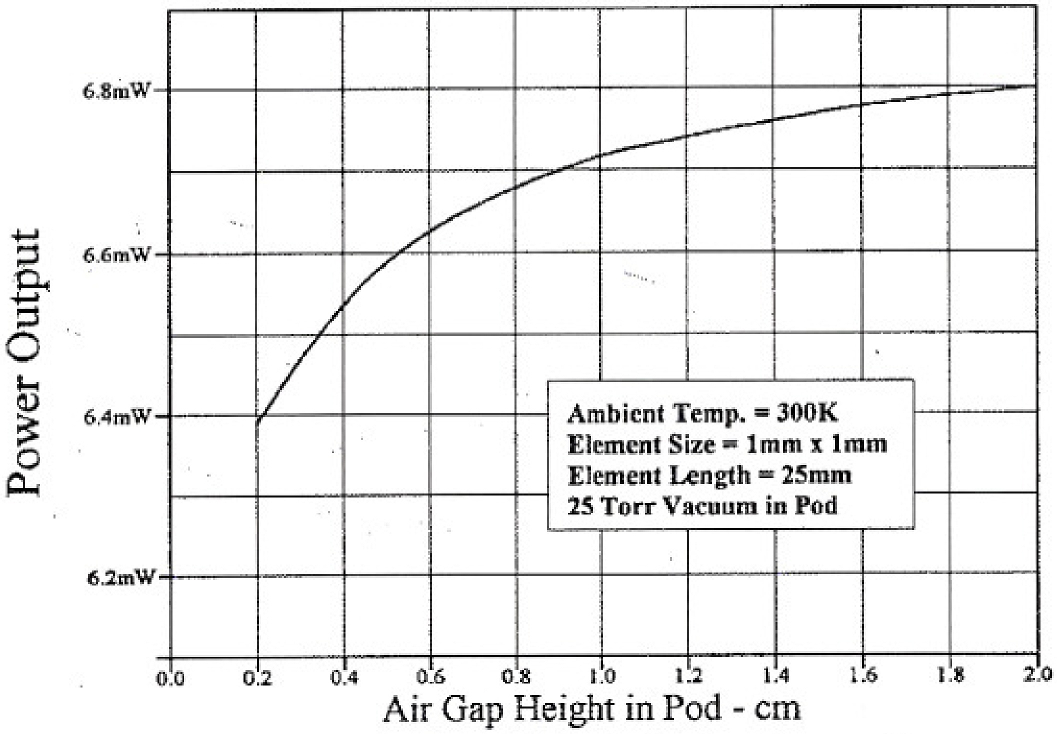

FIGURE 5: Air Gap Height in Pod vs. Power Output.