Prototype Data from the Nighttime Solar Cell™

Ronald J. Parise
PARISE RESEARCH TECHNOLOGIES, 101 Wendover Road, Suffield, CT 06078, USA

G.F. Jones
Dept. of Mechanical Engineering, Villanova University, Villanova, PA 19085, USA

The Nighttime Solar Cell™ produces electric energy by utilizing the temperature difference that exists between the temperature of deep space at about 4K and the ambient air at the surface of the earth, typically around 290K. The nominal 7cm x 7cm x 3cm prototype cell has been tested over a nine-month period, and the performance was determined by measuring the no-load voltage output. The cell produced a steady voltage output with a turndown ratio of about 30:1, from clear, low-humidity nights to heavy rainstorms, corresponding to the widely varying relative humidity of New England (from 21% up to 100%). This shows that the atmospheric absorption of the IR energy is the most influential parameter for system operation. The efficacy of the Nighttime Solar Cell™ has been well demonstrated. The low-voltage output (1.2mV to 38mV) is due to the absence of a vacuum in the prototype cell. The presence of the vacuum is expected to improve operation at least ten-fold.

Nomenclature

A_n = cross-sectional area of n-doped TEG element
A_p = cross-sectional area of p-doped TEG element
h_w = convective heat transfer coefficient at the glass surface
I_{out} = optimum current produced by TEG junction
J_c = radiosity of spectral plate
L_n = length of n-doped TEG element
L_p = length of p-doped TEG element
q_c = net radiative heat flux on the spectral plate
q_h = heat flow rate to TEG hot junctions
R = resistance of TEG junction pair
T_c = temperature of cold junction
T_h = temperature of hot junction
T_s = temperature of the sky (deep space)
T_w = temperature of the window
T_∞ = ambient temperature
V_{oc} = open circuit voltage
α = combined Seebeck coefficient for TEG element junction, $(|\alpha_n| + |\alpha_p|)$
α_n = Seebeck coefficient of n-doped TEG element
α_p = Seebeck coefficient of p-doped TEG element
β = area ratio of spectral plate to TEG area
λ_n = thermal conductivity of n-doped TEG element
λ_p = thermal conductivity of p-doped TEG element
ε_w = emissivity of the window
κ = thermal conductivity of TEG junction
η = fin effectiveness of spectral plate due to overhang of TEG module
ρ_n = electrical resistivity of n-doped TEG element
ρ_p = electrical resistivity of p-doped TEG element
ρ_w = reflectivity of window
σ = Stefan-Boltzmann constant
τ_w = transmissivity of window

President, AIAA Member

I. Introduction

The Nighttime Solar Cell^{TM} is a clean, silent, passive, solid-state device that has been developed to produce electric power day and night from a renewable energy source. The device produces electric energy by utilizing a thermoelectric generator (TEG) as a heat engine in the temperature difference that exists between the temperature of deep space at about 4K and the surface of the earth, nominally at 290K.[1]

Expanded use of photovoltaic cells (PVs) will improve the quality of our environment, add to the security of our energy supplies, and assure the continued economic well-being of the country. However, PVs cannot produce electricity at night, requiring expensive on-site energy storage, which has been the scourge of their broader usage. The Nighttime Solar Cell^{TM} will produce electric power at night on an array panel that is similar to PVs.

The driving force that creates the temperature difference across the TEGs is the net radiative heat flux between the flat plate inside the evacuated chamber and deep space, as seen through the spectral window. A thermal model, developed from fundamental laws over the past four years, predicts the operation of the Nighttime Solar Cell^{TM}.[2-5]

The prototypes are single cells that will be built as arrays in large flat panels for commercial and domestic applications. The device operates similarly to daytime PVs in that this is a pollution-free, inexhaustible source of electric power, utilizing panel arrays of cells. However, the Nighttime Solar Cell^{TM} produces electric power utilizing TEGs. For nighttime electrical energy production the TEGs operate in the continuous temperature difference that exists between the nighttime sky (deep space) and the earth's surface, and capitalizes on the laws of nature that allow infrared (IR) energy to pass unattenuated through the atmosphere into deep space.[6] Hence, the surface of the earth is the thermal source of energy to drive the device, and deep space is the thermal sink. For daytime operation, the sun provides the thermal energy to operate the cell while the ambient air can be the thermal sink.

Therefore the Nighttime Solar Cell^{TM} will operate 24 hours a day. Research has shown that the 2”x2” Nighttime Solar Cell^{TM} can produce about 460mW-hrs over a 24-hour period, slightly more than one-third of the power that a similar sized, commercially available solar panel can produce.[4] Furthermore, the Nighttime Solar Cell^{TM} panel arrays will provide about one-sixth the electric power at night that PVs can produce during the day, typically when electrical energy requirements are less, using the same array surface area.

Hence the Nighttime Solar Cell^{TM} panels can be used in conjunction with any new or existing PV installation to produce electric power at night, thus providing renewable energy 24 hours a day, increasing the PV installation system reliability. The development of Nighttime Solar Cell^{TM} panel arrays can be used to augment installations of PV panels, used as a stand alone nighttime electrical energy producing device in conjunction with other clean, renewable energy sources, or utilized in a combination with both for unique remote energy applications.[7] When the Nighttime Solar Cell^{TM} panels are used to augment PV panels directly, the new device panel array would be mounted 90^{o} from the inclination of the PV panels, facing away from the sun with a clear view of deep space. In this arrangement, the PVs will produce electricity during the day, and the Nighttime Solar Cell^{TM} panel will produce electricity day and night.

The Nighttime Solar Cell^{TM} panels and PVs are comparable in terms of required real estate, passive operation and maintenance, and pollution-free operation. Solar panels obviously can operate during daylight hours only. However, if the solar panel system must operate at night, battery backup is required. Then system cost and maintenance requirements increase significantly. Although the primary focus of the research with the prototype has been for nighttime operation, the Nighttime Solar Cell^{TM} functions very well during the day, and future research will include monitoring the electrical energy output of the device during daylight hours when powered by the sun.

Previous bench-scale models have demonstrated that: (1) a temperature difference can be produced between the earth’s surface and deep space, (2) the TEGs will produce an effective voltage potential (hence electric power) in the cell at night, (3) a higher TEG junction count increases the cell voltage potential, which provides a more practical energy source, and (4) the effectiveness of existing PV solar panels is augmented by nighttime production of electricity. A Nighttime Solar Cell^{TM} panel array installation does not compete with PV systems, but rather enhances their operation and makes their utilization more practical.

II. Background

The Nighttime Solar Cell^{TM} is a heat engine (direct energy conversion device) that utilizes the ambient (or a low-grade waste stream) as a thermal source and deep space (nominally at 4K) as a thermal sink. The earth's atmosphere is transparent to upwards of 80% of the IR thermal energy in the 8micron to 13micron spectral band, thus allowing the free movement of thermal energy from the earth's surface into the vastness of deep space. About one-third of the total spectral emissive power occurs in the ambient temperature range between 270K and 290K. The Nighttime Solar Cell^{TM} is designed to transmit electromagnetic energy in this band.

Figure 1 shows the major components of the device and illustrates its operation. Energy from the thermal source enters the cell and passes through the TEG elements producing electric power. The energy is conducted into the Cold Junction Plate (CJP) where it is emitted radiatively across the vacuum of the cell, through the spectral window, and into the ambient air. The thermal energy then travels through the atmosphere into deep space, the thermal sink. The energy is attenuated slightly while traveling through the atmosphere. The temperature difference created between the thermal source (typically at ambient temperatures) and deep space (4K) drives the device.

To date, three Nighttime Solar Cell™ bench-scale models have been or are being tested. None of the bench models have been built or tested with the benefit of an internal vacuum in the cell. Performance is determined by measuring the open circuit voltage produced by the cell, which is a direct function of the temperature difference across the TEG elements,[2] and a good indication of how the device is operating.

The first bench model was built with an off-the-shelf, four-tiered, 57-junction TEG module, and used strictly for a "proof of concept" demonstration. The model showed that a voltage could be produced with the temperature difference created when the cell was exposed to the nighttime sky. Although much of the data was not quantified (ambient temperature, cloud cover, relative humidity, etc.), and two primary attributes of the device were absent (no vacuum in the cell and no optimized TEG module parameters), the cell was capable of producing upwards of 90mV on clear, dry (low humidity) nights. The test proved unequivocally the efficacy and utility of the Nighttime Solar Cell™. Especially during transient operation, the cell produced comparably to the thermal model, as expected.

The second bench model was built with off-the-shelf TEG modules and 3810 junctions. Even with a low temperature difference across the modules and no vacuum in the cell, useable voltages of 0.9Vdc to 1.75Vdc were produced. The utility of the device was demonstrated by driving a small dc motor and an electric clock. Although this prototype was not part of the tests performed for this research effort, the high junction count device will be discussed in the conclusions in light of the data collected here.

The data presented here is from the third generation bench model. The module was assembled from off-the-shelf components with TEG elements that met the specifications determined from the theoretical model. However, the 64-junction module has about 50% more elements than the optimum number, and the cell is not evacuated. Although not housed in a vacuum cell as required for optimum operation, the information from the prototype has demonstrated the performance of the device in all types of weather. This information has been very useful for two reasons: (1) the prototype has shown how well system components (the ZnSe window, the TEG module, etc.) will perform outdoors over time; and (2) the data demonstrates how the cell output will change under various operating conditions (high humidity, cloud cover, rain, snow, etc.).

III. Theoretical Model

The comprehensive thermal model was developed from fundamental heat transfer principles. The model includes convective heat transfer from the ambient surroundings to the hot junctions of the TEG module; heat conduction through the TEG elements into the cold junctions of the module to produce electrical energy and then into the CJP; heat generation (I^2R losses) in the TEG elements; and radiant IR thermal energy emitted from the CJP that exits the cell. The model also considers convection from the external side of the aperture window and reflection off the internal side of the window with the CJP, and the attenuation of the IR thermal energy traveling through the atmosphere into deep space. The information thus gained from the theoretical model was used to build the prototype.

A. Radiation Model

The driving force that creates the temperature difference across the TEGs is the net radiative heat flux between the flat plate inside the evacuated chamber and deep space, as seen through the spectral window. Radiation heat transfer with the spectral plate inside the vacuum and in thermal contact with the TEGs includes the radiosity of the plate, the fraction of energy from the night sky that is transmitted through the spectral window, emission from the window, and the fraction of the radiosity that is reflected from the window. The net radiative heat flux on the spectral plate is

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

where J_c is the radiosity, T_s the temperature of the sky, T_w the temperature of the window, and ρ_w, τ_w, and ε_w the radiative properties of reflectivity, transmissivity, and emissivity of the window.[3] The model also includes convection on the outside of the spectral window and can include the effects of conduction inside the chamber for a less than perfect vacuum. An energy balance on the window is

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

where h_w is the convective heat transfer coefficient at the glass surface, T_∞ the ambient temperature, T_c the spectral plate temperature, k_a the thermal conductivity of air, and L_a the air gap between the spectral plate and the window.[4]

B. Heat Conduction and Thermoelectric Model

A steady-state, quasi one-dimensional heat conduction equation with internal energy generation (in the TEG elements) is solved to determine T_c. One boundary condition is the heat flux, q_c, at the spectral plate, and the other is a specified temperature, T_h, at the other junction of the TEGs. The equation includes the geometric and thermal characteristics of the TEG elements:

$$q_c\eta\beta(A_p+A_n) = \kappa(T_h-T_c) + (|\alpha_n| + |\alpha_p|)T_cI_{out} + \tfrac{1}{2} I^2_{out} R \quad (3)$$

where η is the fin efficiency of the spectral plate which overhangs the TEG module, κ and R are the respective thermal conductance and electrical resistance of a TEG junction pair, defined as

$$\kappa = (\lambda_p A_p/L_p) + (\lambda_n A_n/L_n), \quad \text{and} \quad R = (\rho_n L_n/A_n) + (\rho_p L_p/A_p), \quad (4)$$

where A_n, A_p, L_n, and L_p are the respective cross-sectional areas and lengths of the p-type and n-type TEG materials, $\beta = A_{CJP}/A_n$, the area ratio of the spectral plate (CJP) to the TEG area (A_p or A_n), α_n, α_p, ρ_n, ρ_p, λ_n, λ_p the respective Seebeck coefficients, electrical resistivities and thermal conductivities of the n-type and p-type TEG materials. The electrical current produced by the TEG module, I_{out}, is determined from standard TEG module equations.[8,9]

The equation for the open circuit voltage of the TEG module output is

$$V_{OC} = (|\alpha_p| + |\alpha_n|)[T_h - T_c]. \quad (5)$$

Hence, the theoretical power from the TEG module can be determined and matched to the measured output. Also, the thermal performance of the spectral plate, or CJP, has been quantified to demonstrate the improved effect based on plate thickness. With the increased radiation transmission into deep space, the CJP acts as a heat spreader.[5]

IV. Description of Prototype

The prototype has a Delrin® 100 (Dupont trade name for polyoxymethylene or acetal) polymer body and aluminum base assembled for waterproof use outdoors. The top aperture of the body is covered and sealed with a 5cm x 5cm ZnSe window, 2mm thick. Two hermetically sealed electrical connections through the body wall are used for measuring the cell output. The TEG module is 25.4cm high and has 32 junctions of n- and p-doped bismuth telluride elements with standard ceramic substrate assembly. Figure 2 is a photograph of the TEG module used in the prototype before assembly. Figure 3 shows the aluminum base with the TEG module attached being assembled with the Delrin® body and the ZnSe window assembly. The electrical connection screws protrude through the body wall as shown in the photograph.

The CJP is 0.5mm thick copper; 44.5mm x 44.5mm square, and the spectral side facing deep space is painted with a stove-black paint having an emissivity of 0.94. The TEG module is held in place between the CJP and the base by compression mounting with thermal grease on both end faces. In Figure 3, the CJP is not visible inside the cell body.

The combined Seebeck coefficient, α, for the TEG junction elements for the prototype is 4.1×10^{-4}V/C, as provided by the manufacturer.[10]

The prototype Nighttime Solar Cell™ is mounted outdoors on a roof (Figure 4) in a location with a clear view of deep space. The device is mounted with a slight tilt (5º) to allow water runoff. The electrical leads are connected to an electronic VOM. The device was removed from the roof after two months for about two days to ensure there was no leakage. The device is inspected visually every month to be sure there are no water leaks in the cell.

V. Data Collection and Parameters Measured

Data collection took place over a nine-month period, October 2003 to June 2004, covering ambient temperatures from 35C to –16C. The open circuit voltage output of the cell was measured. Local conditions of dry bulb temperature and sky condition (clear, partly cloudy, cloudy, rain, snow, etc.) were recorded, along with the date and time of day. Local relative humidity readings were recorded until the meter stopped functioning. However, the US Weather Bureau (USWB) maintains a full weather monitoring station (Bradley International Airport, Hartford, CT) less than 3.5miles from the prototype site, with no extreme topographical or geographical changes in between. In addition, the dry bulb temperature and relative humidity readings between the two sites corresponded almost exactly. Therefore relative humidity and wet bulb temperature readings were used from the USWB site as needed, and the performance of the prototype Nighttime Solar Cell™ was correlated with local weather conditions.

The open circuit voltage produced by the cell is measured as the output. The voltage potential is considered a good measure of the energy output of the cell – obviously the higher the potential, the higher the available energy.

VI. Results

Although data was collected regardless of weather conditions, the prime interest here is clear nights to illustrate the maximum voltage potential capabilities of the Nighttime Solar Cell™. Data was recorded for cloudy conditions, rain and snowstorms, and will be reported in the future. Obviously, under these conditions, cell performance will not be optimum. In fact, operation of the device in the widely varying relative humidity of New England (from 21% up to 100%) showed that atmospheric absorption of the IR energy by the moisture in the air was the most influential parameter for system operation.

Figure 5 shows a typical cloudless night performance of the cell (2/15/04 to 2/16/04). In early evening, the potential of the cell increased through the evening to a certain time, then the output decreased quickly, and continued to decrease at a slower yet sporadic rate throughout the rest of the night, as shown in the figure. There were no perceptible clouds in the sky, yet the cell output decreased as shown.

After observing the performance of the cell for different weather conditions, it was obvious that the cell output was greatly influenced by the moisture in the air as demonstrated by the increasing relative humidity with decreasing cell output as shown in Figure 6. As the temperature typically drops in the evening and the relative humidity increases, the cell output also decreases. The curve fits shown in Figures 5 and 6 are used to emphasize the "typical" trend that was observed on many occasions for the time of day and particular data set.

Since the dew or frost condition on the spectral window influenced the cell output, Figure 7 shows cell output when the window was clear of such influence. This data was taken early in the evening for various days when there were no clouds in the sky, and when no moisture had yet collected on the window. Moisture accumulation on the window (dew or frost) reduced the cell voltage potential approximately 15%.

The maximum voltage produced by the cell was 38.61mV on 4/16/04 when the lowest recorded relative humidity reading was 21%. Utilizing Equation (5), the maximum ΔT produced across the TEG module and CJP was 2.91C (5.24F). As a comparison, on 3/27/04 at 5:15am, with a heavy cloud cover and rain, the cell output was 1.26mV, and the calculated temperature difference was 0.27C (0.49F).

VII. Discussion

The performance of the Nighttime Solar Cell™ tracks very accurately the atmospheric and meteorological conditions that prevail in the sky above the cell. In early evening as the sun sets, the upper atmosphere is still heated by the sun and is comparatively warmer than the lower atmosphere which is starting to cool radiatively to deep space, no longer influenced by the sun's rays, as shown in Figure 5. After sundown (approximately 5:16pm on 2/15), the upper atmosphere is still radiating back to earth at a higher temperature, and as incident solar radiation decreases, the Nighttime Solar Cell™ does not experience the full cooling effect of deep space; hence the cell output has not reached full potential.

As the upper atmosphere cools, the voltage potential of the cell increases as shown until about 8:00pm. However, around 8:00pm, another phenomenon takes place. Ice crystals start to form on the aperture window, reducing slightly the visibility of the CJP of the nighttime sky, which attenuates the IR energy leaving the CJP, when the cell output starts to decrease, as shown in Figure 5. The ambient temperatures that day were very low (the temperature dropped from –7C at 5:00pm to –14C at 7:00am the next morning). At such low temperatures, the amount of moisture in the air is on the order of less than $2 g/m^3$ of air (compared to $17 g/m^3$ at 20C). Even at such a low moisture content, small crystals of moisture (ice) formed on the glass, slightly obscuring a clear view of deep space. Hence, the output decrease is due to an obstruction on the window. In arid climates where such low air moisture contents are normal and the dry bulb temperature is not as low, the formation of ice on the window would not occur. This demonstrates the increased performance the Nighttime Solar Cell™ will experience in arid climates.

The performance of the prototype was coupled to the ambient air temperature. If the TEG hot junctions could be thermally connected to the constant year-round 10C (50F) temperature of the earth's soil, or to a low-grade thermal waste stream, the performance of the device would be improved substantially. Therefore, other thermal sources for the device can be used to improve the electrical output.

As noted, the prime interest of this data collection was for operation of the device at night. However, cell output was observed when the sun was shining directly on the cell. In this mode of operation, the CJP became the source for thermal energy to the Nighttime Solar Cell™, and the ambient became the thermal sink, the potential reversing across the cell. That is, the potential produced was a negative voltage, as expected. This further verified the practical application of the device for daytime operation.

Upper atmospheric conditions known as thermal inversions were recognized by the device. On a very few occasions, the cell produced a voltage potential opposite of what would be expected, i.e., a negative potential at night instead of a positive potential. Hence, the cell was operating at night as if it were during daylight hours with the sun warming the CJP. This curious phenomenon requires further investigation. However, it does illustrate the sensitivity of the Nighttime Solar Cell™ to atmospheric conditions.

Figure 7 shows how conditions in both the lower and upper atmospheres can influence the cell output. Since these evening readings were early enough to preclude moisture collection on the window, other atmospheric conditions have influenced the cell output. In this data set, no trend can be identified between the relative humidity and the cell output. Further information would be needed to determine atmospheric sky conditions above the cell site. This information will be determined in future research.

Calculating the maximum temperature difference (2.91C) that occurred across the TEG module with no vacuum present in the cell also indicates the energy-producing potential of the device. Calculations indicate[4] that upwards of a 47K temperature difference can be produced in an evacuated cell. However, even if the temperature difference were only two-thirds of this (33.6K), with a vacuum in the cell operating at the lowest recorded relative humidity (21%), the cell voltage potential would be almost 0.46 volts. Hence in an arid environment (typical relative humidity less than 10%), an evacuated cell can be expected to produce upwards of 0.6 volts. In addition, the TEG module in the prototype used about 50% more TEG elements than the model predicted. The higher TEG element count reduced the ΔT, lowering the voltage potential. Hence lowering the element count will increase the ΔT and improve cell operation. Therefore, three Nighttime Solar Cells™ would have the voltage potential of a single dry cell battery with no further optimization of junction count, and an almost infinite life.

It was also observed that the sun did not have to set for the cell to produce a voltage potential characteristic of nighttime operation. As soon as the cell was in the shadow of the building upon which it was mounted, the Nighttime Solar Cell™ produced a positive voltage potential. Moreover, the potential increased into the evening until dew or frost started to form on the window, as discussed previously.

Utilization of the USWB data at the location 3.5miles from the test site was considered to add little error to the data readings. This is because the relative humidity and wet bulb temperatures are considered fairly constant over large regions, especially with no gross changes (elevation or large bodies of water) from the point of measurement to the site location.

The completion of data acquisition and correlating the actual performance of the prototype to the performance of the theoretical model is not quite complete at this time. This will be addressed in future research.

VIII. Conclusions

The data provided by the prototype Nighttime Solar Cell™ demonstrated the usefulness of deep space as a thermal sink for terrestrial heat engines, even though the prototype cell did not have an evacuated interior to better isolate thermally the TEG module from its surroundings. The TEG module also did not have an optimal design based on the parameters determined from the thermal model to maximize performance. Nonetheless, the data generated clearly gave the information necessary to evaluate the device's energy producing capability.

The prototype did indicate the sensitivity of operation to high humidity conditions, as well as its performance during various weather conditions. The device produced the highest voltage potential (or energy output) at the lowest recorded relative humidity reading. Therefore, the US Southwest or other arid regions where the relative humidity is low are expected to be the prime locations for use of the device. This prototype did not have all the attributes that were included in the thermal model. Therefore, the next generation prototype will have the benefit of the vacuum, which is expected to improve cell operation ten-fold.

The prototype cell produced almost 40mV. The device has been operating over an extended period of time, and has produced a steady voltage output with a turndown ratio of about 30:1 (maximum:minimum range), from clear, low-humidity nights to heavy rainstorms. In geographical areas that do not experience high humidity, it is expected that the turndown ratio will be considerably less, while the absolute output will be significantly higher.

An earlier prototype was built and used to observe device function based on a large TEG junction count, but no quantitative data was reported. The success of the high-junction-count prototype indicates the higher voltages that can be achieved. With the advent of TEG modules with micro-junction elements, and the results presented here, a high-junction-count device can be used that will produce higher voltages with the same prototype sized cell.

The prototype Nighttime Solar Cell™ showed that the earth/deep space temperature difference can be used to produce electric power. In addition, the prototype cell demonstrated unequivocally that the climatic conditions throughout affected its operation. Thus, the Nighttime Solar Cell™ could conceivably be used as a meteorological instrument to track and predict atmospheric conditions above the cell. When the direct path between the CJP and deep space is obscured in any way, the cell is very sensitive and registered the change. Therefore, the Nighttime Solar Cell™ can be a multi-use device for energy production or weather monitoring.

Dedication

This research is dedicated to Joey Parise and Eric Jones, two young teenage boys whose early passing from this life prevented the realization of their hopes and dreams of sports, education and life’s many joys.

Acknowledgments

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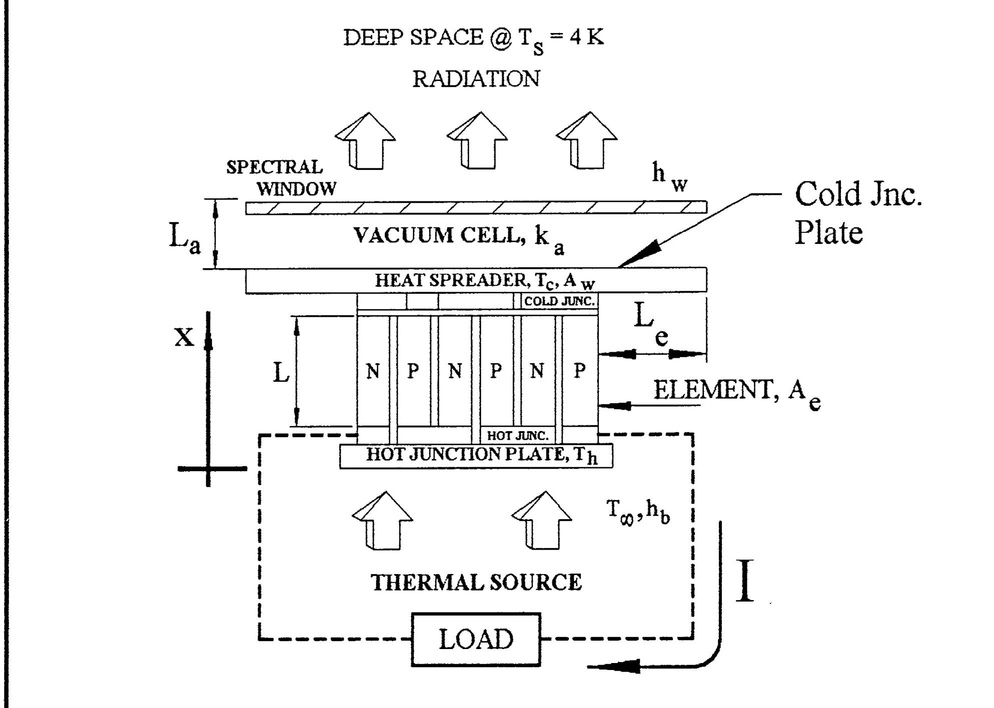

FIGURE 1: Schematic of Cell Configuration

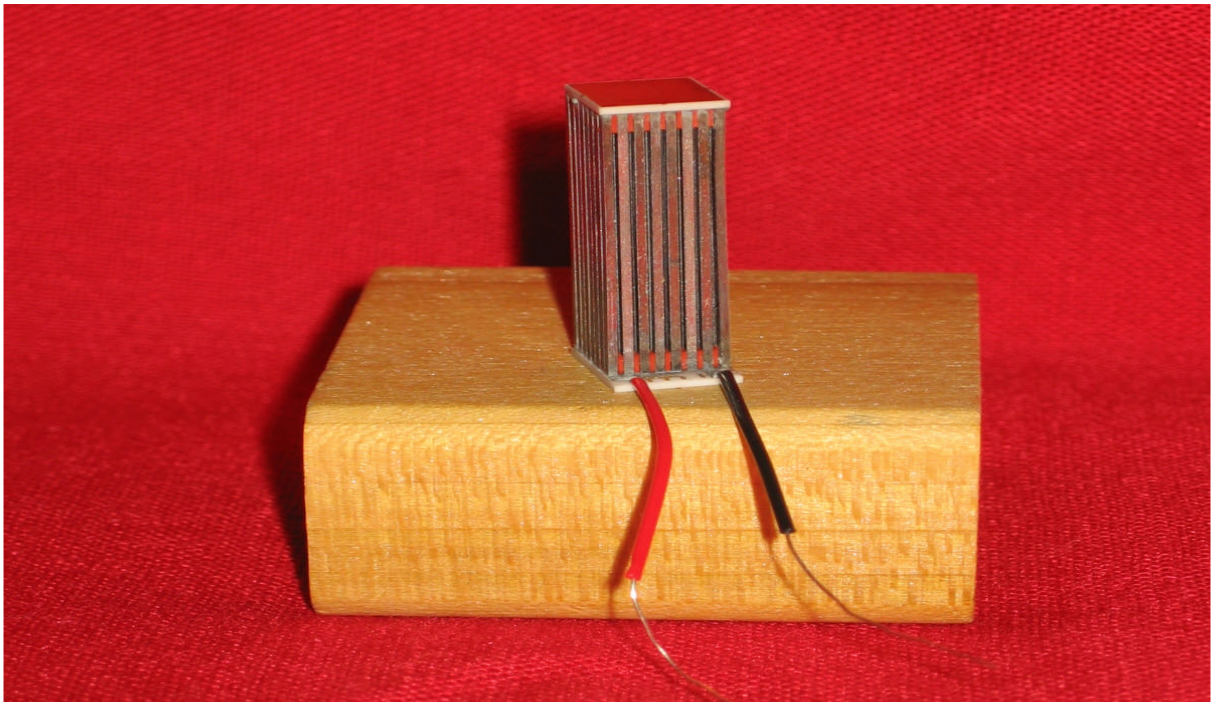

FIGURE 2: TEG Module Used in Prototype

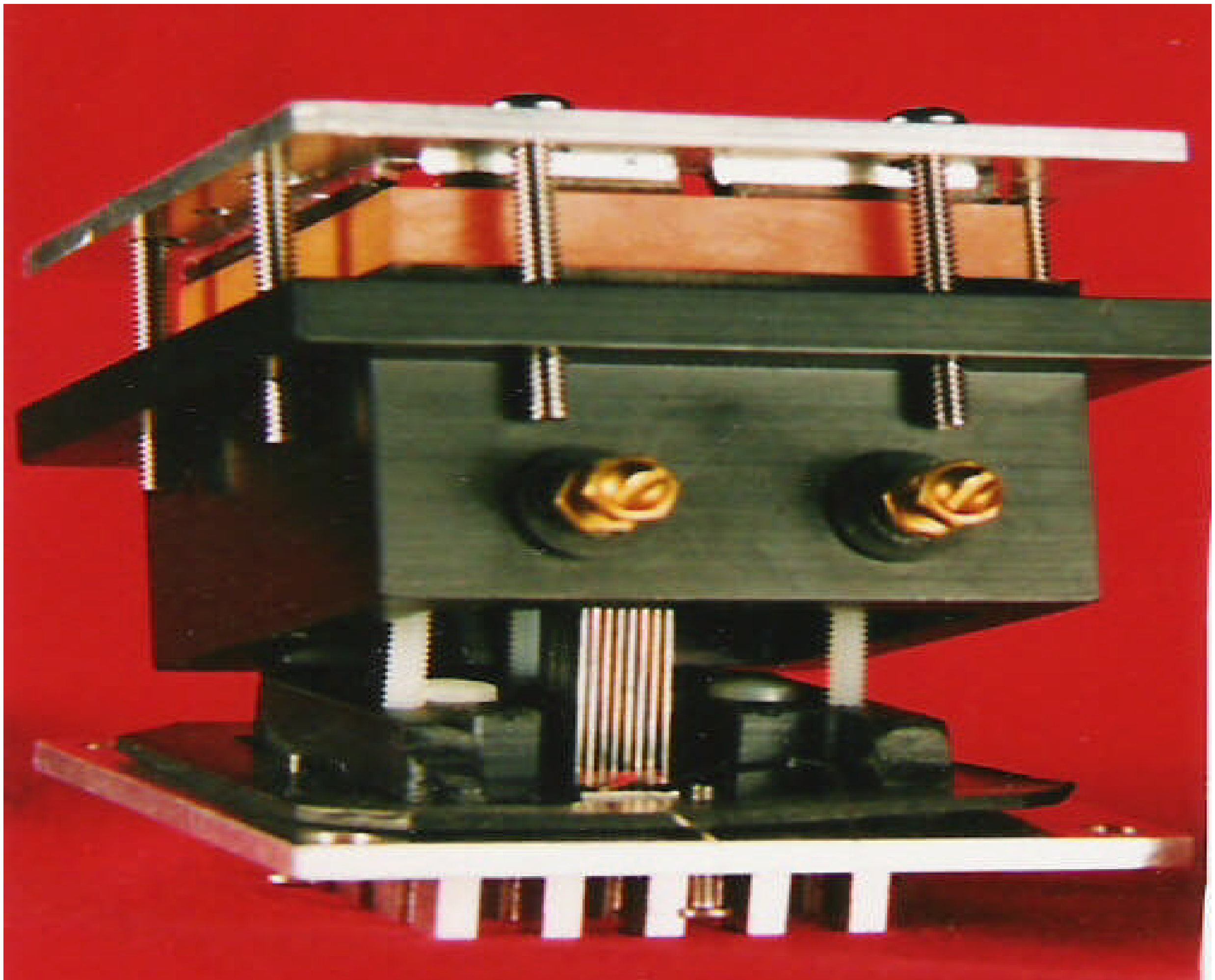

FIGURE 3: Prototype Nighttime Solar Cell™ In Assembly

FIGURE 4: Prototype Nighttime Solar Cell™ Located on Roof

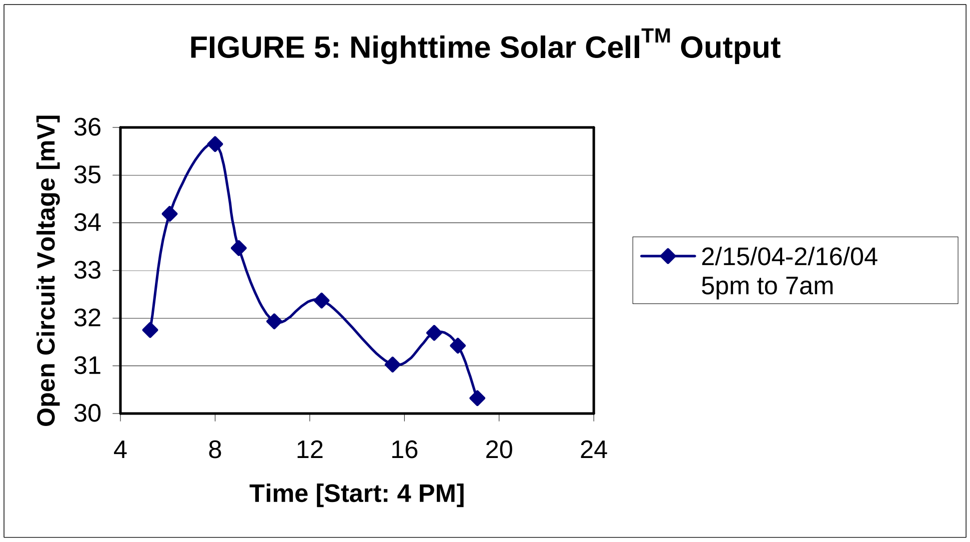
FIGURE 5: Nighttime Solar Cell™ Output
Open Circuit Voltage [mV]
36
35
34
33
32
31
30
4
8
12
16
20
24
Time [Start: 4 PM]
2/15/04-2/16/04
5pm to 7am

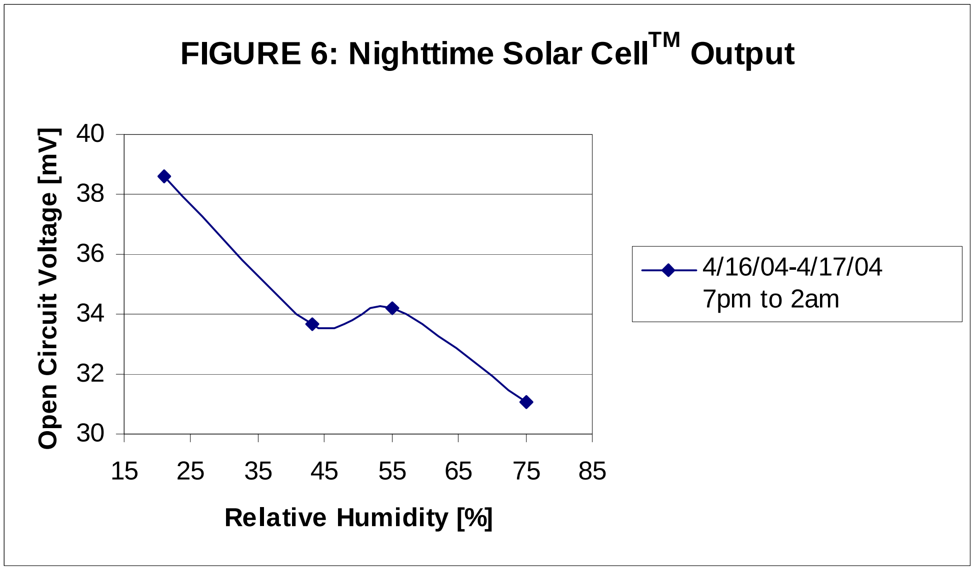
FIGURE 6: Nighttime Solar Cell™ Output
Open Circuit Voltage [mV]
40
38
36
34
32
30
15
25
35
45
55
65
75
85
Relative Humidity [%]
4/16/04-4/17/04
7pm to 2am

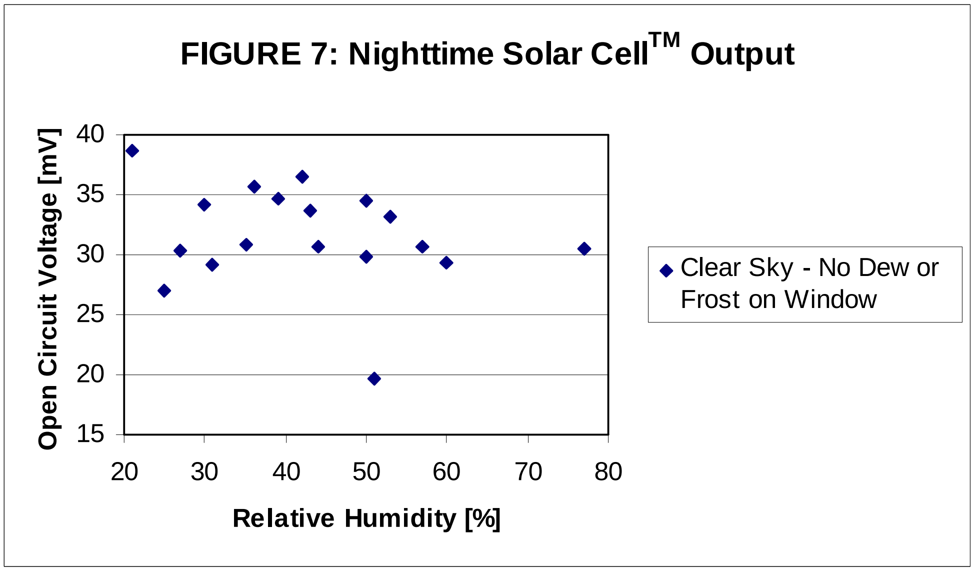
FIGURE 7: Nighttime Solar Cell™ Output
Open Circuit Voltage [mV]
40
35
30
25
20
15
20
30
40
50
60
70
80
Relative Humidity [%]
Clear Sky - No Dew or Frost on Window