Range Security Sensors Powered Locally
With the Nighttime Solar Cell™

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ABSTRACT: The Nighttime Solar Cell™ is a clean, silent, inexhaustible source of low-wattage electric energy for powering remotely located electronic devices such as infrared, motion, vibration, emissions, etc., sensors and/or video monitoring to ensure the security and integrity of the Range periphery. This solid state device works on the simple principle of a thermoelectric generator operating in the temperature difference that exists between the ambient or surrounding temperature (nominally 290K) as the thermal source and deep space at approximately 4K as the thermal sink. Thus the Nighttime Solar Cell™ produces electric power continuously at night, and during the day utilizing one of several modes, depending on whether photovoltaic cells are used, reducing or eliminating the need for on-site electrical energy storage or power source maintenance. A thermal model has been developed from fundamental laws that predict the device can produce up to an estimated $17W/m^2$ as a remote electric power source, depending on site location. Several simple benchscale prototype cells have functioned well under all weather conditions. Field studies must now be performed with prototypes that have all the design attributes of the thermal model to demonstrate the usefulness of this reliable nighttime/daytime energy source. The Nighttime Solar Cell™ is a direct energy conversion device that utilizes aerospace technology for use in a military application: Range Management. This research provides a unique opportunity to supply remote power packs for Range sensors and security.

INTRODUCTION: The lack of available electrical energy production at night from passive energy sources such as photovoltaic cells (PVCs) is a major drawback to their current use in many applications. The Nighttime Solar Cell™ has been developed to fill this need.

Figure 1 shows a schematic of the Nighttime Solar Cell™, illustrating a single cell with a thermoelectric generator (TEG) module inside. The module consists of the many pn-junctioned elements connected in series to produce electric power when exposed to a temperature difference. Figure 1 is labeled for nighttime usage or with no daytime incident solar energy.

The nominal size of the device shown is 2"x2"x1-3/8" (5cmx5cmx3cm), and operation is as follows. Only the base of the cell is in thermal contact with the TEG module; the remainder of the module is isolated in the vacuum of the cell. Thermal energy is transferred from the surroundings through the base, into the hot junctions of the TEG. The energy then travels through the individual TEG elements from the hot junctions to the cold junctions, producing electrical energy. The thermal energy then leaves the cold junctions and enters the Cold Junction Plate (CJP). The CJP has one surface in thermal contact with the TEG (by conduction heat transfer), and the opposite side in contact with the vacuum of the cell, facing the spectral window and out of the cell aperture. This surface of the CJP, facing out of the aperture, has an emissivity close to 1 (about 0.96), and is in thermal communication through the atmosphere with deep space by radiation heat transfer.

The net amount of energy that is emitted from the CJP and radiated to deep space controls how well the Nighttime Solar Cell™ functions. The higher the net exchange, the greater the amount of electrical energy that is produced.

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 via one of three methods (or multiple combinations) of direct energy conversion: (i) solar cells connected in parallel with the TEGs, converting light into electrical energy when the sun is visible, the TEGs acting solely as an electrical conduit; (ii) conversion of solar thermal energy into electrical energy by reversing the operation of the TEGs (no PVCs present), hence the nighttime cold junctions now become the daytime hot junctions; the sun is the thermal source for the system and the ambient air or surroundings become the thermal sink; (iii) utilize shadowing, position of installation, or filtering from direct sunlight so that the device continues to use deep space as the thermal sink. Thus the device operates with the added advantage of producing electrical energy during low angles during winter in northern locations as well as during dawn and sunset hours.

Using the single cell shown in Figure 1, many cells can be assembled to produce a Nighttime Solar Cell™ panel. This panel will function similarly to the way PVC panels function, except they can be used for energy production at night, although at a lower wattage output. The Nighttime Solar Cell™ panels can be combined with PVC panels as shown in Figure 2 for applications with higher electrical energy requirements. The system is designed and installed so that the PVC panel faces the sun and the Nighttime Solar Cell™ panel faces away from the sun, seeing only deep space. The use of the Nighttime Solar Cell™ panel illustrated in Figure 2 corresponds to mode (iii) described above.

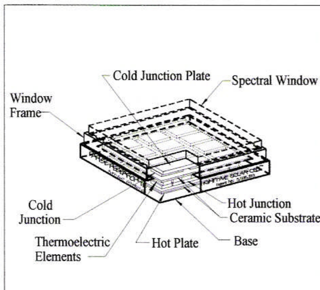

Figure 1: Single Cell Configuration

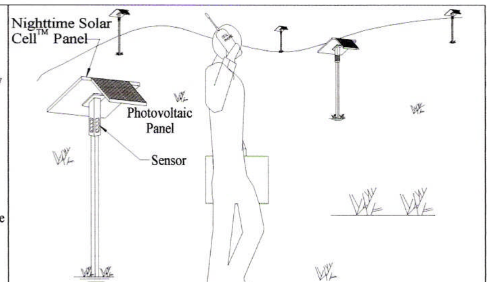

Figure 2: Remote Range Sensors with Typical Panel Arrangements

There is a fourth method to be considered: both photovoltaic and thermoelectric modes acting in parallel during daytime operation. This requires studying carrier densities, p-n junction combinations and thermal characteristics of the photovoltaic materials to determine system configurations, feasibilities and efficiencies along with potential power generating capabilities.

There are many variables and parameters that must be sorted out to take full advantage of this new energy source. A fundamental research effort is underway to achieve this end.

BACKGROUND and THERMAL MODEL: The primary objective for producing electric power from a TEG module is to maximize the temperature difference between the hot and cold junctions. The thermal model developed predicts this temperature difference, and hence the performance of the Nighttime Solar Cell™. Research thus far can be summarized as follows.

Radiation heat transfer, with the CJP inside the vacuum, includes the radiosity J_c of the plate, the fraction of energy from deep space that is transmitted through the spectral window and not attenuated in the atmosphere, emission from the window, and the fraction of the radiosity that is reflected from the window. The net radiative heat flux of the CJP is

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

where T_s is the temperature of deep space, T_w the temperature of the window, ρ_w, τ_w, ε_w are the radiative properties of reflectivity, transmissivity and emissivity of the window [Parise and Jones, 2000].

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

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

where η is the efficiency of the CJP, which overhangs the TEG module, $\kappa = (\lambda_p A_p/L_p) + (\lambda_n A_n/L_n)$, the thermal conductance of a TEG junction pair, and $R = (\rho_n L_n/A_n) + (\rho_p L_p/A_p)$, the TEG electrical resistance. Also, A_n, A_p, L_n, and L_p are the respective cross-sectional areas and lengths of the n-type and p-type TEG materials, and α_n, α_p, ρ_n, ρ_p, γ_n, γ_p are the respective Seebeck coefficients, electrical resistivities and thermal conductivities of the n-type and p-type TEG materials. The area ratio $A_r = A_s/A_e$ is the area of the CJP, A_s, to the area of a TEG element, A_n or A_p.

The theoretical power produced by the TEG module is determined from standard TEG equation analysis [Angrist, 1982]. This is for an optimized figure of merit, Z, based on the TEG element's geometry and material properties.

The most dramatic change in the temperature difference between the hot and cold plates is with respect to the area ratio A_s. Practical concerns will limit the size of the CJP area. The temperature difference created under normal ambient temperature changes, when the surrounding air is used as the thermal source, has very little effect on cell performance, except when low grade thermal waste streams can be utilized.

Preliminary research considers p- and n-doped bismuth telluride (BeTe) TEG elements that are readily available in a 0.5mm x 0.5mm square cross-section and a length of 25mm [Parise, et al., 1999]. For this geometry, the thermal model is used to optimize the number of junction pairs, based on the power output of the cell. Forty-four TEG elements (22 junctions) developed the maximum energy output for this geometry of approximately 7mW of electrical power with a

48K temperature difference across the TEG elements [Parise and Jones, 2000]. Figure 3 shows typical performance curves for an evacuated cell.

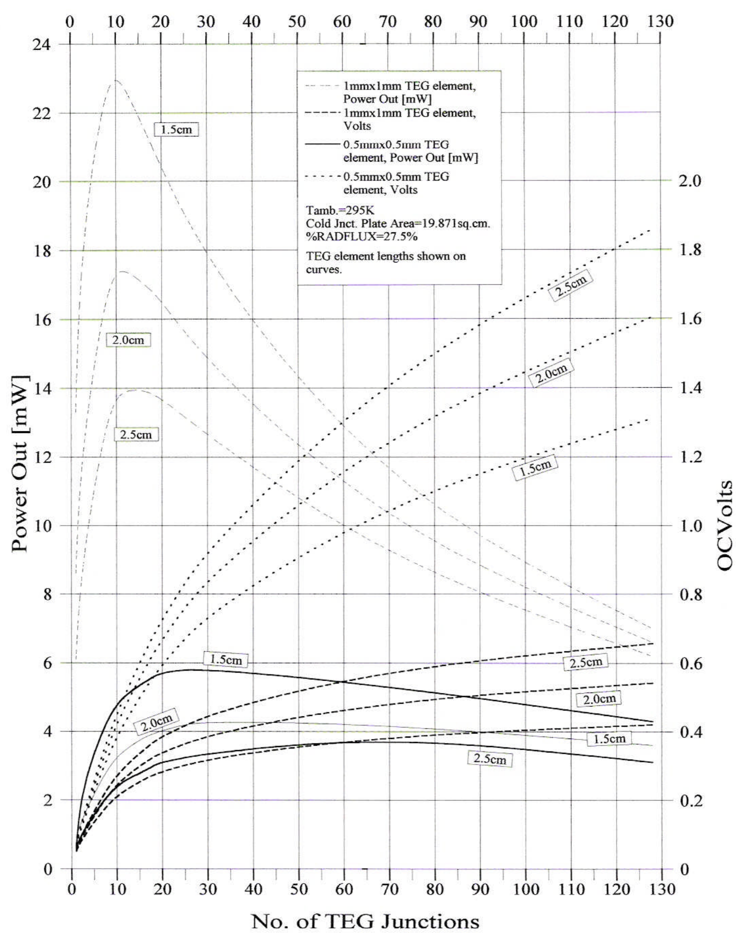

Figure 3: Nighttime Solar Cell™ Output [Theoretical Model]

The thermal model shows that a 10-degree temperature rise in the thermal source of the cell with the 22-junction TEG module will result in a 22% increase in power output. Since local atmospheric conditions dictate the performance of the cell, adding an additional thermal source only slightly above the ambient temperature will result in a considerable increase in electrical energy. Also, with an internal pressure of 25 torr, cell output is reduced by only about 2% compared to a full vacuum [Parise and Jones, 2001].

At this juncture in the development of the Nighttime Solar Cell™, the window material covering the cell aperture has determined the size of individual cells. Zinc sellenide (ZnSe), which is typically available in sizes up to 2 inches square (5cm), has the most favorable properties for low attenuation in the desired spectral band for IR transmission through the atmosphere, while having good mechanical properties to maintain the cell vacuum.

One design characteristic of the Nighttime Solar Cell™ worth noting is that the CJP area will be larger than the footprint of the TEG module. Thus the CJP will "overhang" the module, in effect as a fin. Hence for long, slender TEG elements, the weight of the CJP may be a consideration, especially since BeTe is somewhat brittle. The model has been used to determine that a very thin (1mm to 2mm, aluminum) CJP can be used with less than a 2% to 3% change in its "fin" effectiveness [Parise and Jones, 2003]. This also leaves the door open for a copper CJP with a higher thermal conductivity, although a heavier material.

The added surface area of the larger CJP improves cell output considerably. The radiative link between the cell and the thermal sink has already been demonstrated to be a strong function of CJP surface area [Parise, Jones, and Strayer, 1999]. This analysis shows that the CJP "fin" effectiveness remains quite high (>96%) for a 2mm CJP with a 5cm overhang (large surface area CJP). Therefore many small junctions with a large CJP will increase voltage output of the cell significantly. This puts nanotechnology at the forefront of making high junction density modules a further improvement in Nighttime Solar Cell™ performance.

Research on the design of the CJP shows that because the heat flux from the TEG module is so small, typically on the order of 10mW, the CJP can be very thin with little loss in effectiveness. Also, the CJP surface area can almost always be maximized for any given surface area constraint other than thermal considerations. This bodes well for future cell design.

In applications where many very small TEG junctions can be used, the surface area of the CJP (size increase) will improve considerably the voltage output of the cell with little degradation to overall cell performance. Nighttime Solar Cell™ power requirements can be optimized at higher power densities using shorter TEG elements. With added TEG junction densities utilizing nanotechnology, cell performance and output can be increased significantly.

The thermal model shows the Nighttime Solar Cell™ performs well under several operating conditions and modes of operation, while providing valuable parametric guidelines for the design of the prototypes.

RADIANT ENERGY TO DEEP SPACE: Consider the amount of energy that is available from nighttime operation of the cell. A blackbody at 295K can radiate 450 W/m^2 (about one-half the energy available during the day at the surface of the earth due to incident solar energy), and the atmosphere is transparent to about 40% of the infrared thermal energy radiated to deep space at this temperature.

Therefore, depending on the efficiency of the TEGs that are selected or developed, upwards of 180 W/m^2 of energy can be utilized. Water vapor in the atmosphere accounts for the major portion of the energy absorbed in particular spectral bands as discussed below. Thus in dry, arid climates, or, at times during the year when there is relatively little moisture in the air, upwards of 240 W/m^2 may be radiated to deep space, improving cell operation significantly.

The model predicts temperature differences between the hot and cold junctions of the TEG module in the vacuum to be on the order of 50K. With TEG efficiencies around 3% to 7%, during nighttime operation the cells can produce about 7.2 W/m^2 to 16.8 W/m^2 with today's technology, under all atmospheric conditions.

For the propagation of thermal energy from the surface of the earth into deep space, there are basically three regions of the atmosphere that influence the energy's movement. From ground level to an elevation of about 10km is the Troposphere. This is the region that has water as well as the other constituents of air. Above this layer to about 85km is the Stratosphere, which again has the usual components of air, with no water, but including ozone. Above 85km is the Ionosphere with primarily helium and hydrogen, both of which do not affect the movement of electromagnetic energy. The CO_2 remains relatively constant throughout all levels, and although the H_2O is confined to the Troposphere, this is the most changing variable to the movement of radiation in the atmosphere.

The transfer of thermal energy in the form of electromagnetic waves is a function of temperature and wavelength, as described by Planck's Law, with a maximum of energy transmission for different temperatures in particular bandwidths [White, 1988; Siegal and Howell, 1981]. The thermal energy that leaves the earth's surface and travels through the atmosphere as electromagnetic waves, due to ambient temperatures, occurs in the long infrared wavelength range (approximately 4μm to 50μm) [Salby, 1996].

Several physical phenomena must be considered when accounting for the movement of infrared thermal energy through the atmosphere. Diatomic gas molecules, of which the atmospheric composition is over 99%, alone, do not influence the movement of infrared energy through them. The non-diatomic molecules, primarily CO_2 and H_2O, influence the electromagnetic energy only in particular bands [Siegal and Howell, 1981].

Increased elevation from the earth's surface through the Troposphere results in a decrease in temperature called the lapse rate. This is advantageous because the air holds less moisture, thus reducing the amount of energy that is radiated back to the CJP of the Nighttime Solar Cell™. In the Stratosphere where there is no moisture, the air temperature starts to increase. But radiation energy transmission by gases is a strong function of pressure [Edwards, 1976], and the air is so thin that there is very little radiation back to the CJP from the CO_2 at the higher elevations.

As it turns out, the two primary gases in the atmosphere that absorb the most thermal energy, CO_2 and H_2O, also absorb (thus emit) the least amount of energy in the bandwidths that are normal ambient temperatures. Carbon dioxide has two strong thermal energy absorption bands between 4μm and 5μm, then again between 15μm and 20μm, with relatively little absorption from 8μm and 15μm. And H_2O has two strong absorption bands from 5μm to 8μm and 13μm to 22μm, with very little absorption between 8μm and 16μm [Hottel, 1927; Salby, 1996].

Thus it is generally accepted that the atmosphere has a spectral window between 8μm and 13μm (with smaller windows occurring in a few other bands). In this band at atmospheric temperatures, approximately between 27% and 32% of the radiated energy can travel freely through the atmosphere into deep space with very little attenuation. This is the band that has been used in previous work [Parise and Jones, 2000, 2001] to model the radiant heat transfer from CJP of the Nighttime Solar Cell™.

Now consider the temperatures at which the thermal energy is transmitted from the CJP. During the summer, with an average nighttime temperature of 290K, the peak thermal energy radiated for this temperature occurs at a wavelength of 9.99µm. During the winter, with an average nighttime temperature around 270K, the peak radiated thermal energy occurs at 10.73µm. Therefore the region of the spectrum that allows the most electromagnetic energy to travel freely through the atmosphere occurs right at the peak range of the temperatures that take place in the ambient [Parise, 2002].

Ozone (O_3), which occurs in abundance in the upper Stratosphere, does absorb (and re-emit) thermal energy in one narrow band around 9.6µm. This affects the radiated thermal energy at the CJP by a few percentage points.

There may be some energy transmitted back from the H_2O vapor in the Troposphere, but this is only in particular bands. The high altitude water vapor temperatures are two orders of magnitude higher than deep space making the difference (to the fourth power) negligible compared to that of the difference with deep space at 4K, and the pressure is reduced. And although there are slight traces of other molecules (methane, ammonia, etc.), as well as dust, aerosols (hydrocarbons) and the like, the primary components of the atmosphere that influence the radiation transfer of energy with deep space are the CO_2 and H_2O.

Thus the Nighttime Solar Cell™ takes advantage of the free movement of thermal energy through the atmosphere in the non-absorbing spectral window that exists in the 8µm to 13µm band for energy production. Therefore this means of energy production can be utilized where small, reliable energy requirements are needed for remote monitoring sites, sensors, etc.

PROTOTYPE DEVELOPMENT: To date, three Nighttime Solar Cell™ prototypes have been or are being tested. The tests are taking place in a high-humidity region of the US (New England), and this humidity is proving to be the strongest influence in the function of the cell. Also, none of the prototypes have been built or tested with the benefits of an internal vacuum.

Cell performance is being determined by measuring the open circuit voltage produced. The output voltage of a TEG module is a direct function of the temperature difference across the TEG elements [Angrist, 1982], hence a good indication of how the device is operating.

The first prototype, NSC-1, was built with an off-the-shelf, four tiered TEG module; the largest tier had 62 elements, the smallest had four elements. There were a total of 114 TEG elements (57 junctions). The elements were 1mm square and 2mm long. The primary goal of NSC-1 was to demonstrate that a temperature difference could be produced in the cell, and a voltage produced by the module. Although much of the data was not quantified (ambient temperature, cloud cover, relative humidity, etc.), the cell was capable of producing upwards of 90mV on clear, dry (low humidity) nights.

For most electronic sensor devices to operate reliably, power sources require voltages in the 3Vdc to 5Vdc range, with amperage requirements in the milliamp or microamp range. Hence only milliwatts are required for the devices to function. Higher voltages can easily be stepped down, improving reliability even further, and the TEGs have unique operating characteristics that are being employed. With this understanding, the next two prototypes being built and tested have far different goals.

One characteristic of TEGs being utilized when building the next generation prototype is that the voltage output of the module is a direct function of the number of TEG junctions. With no vacuum in the cell, the temperature difference remains small, but the number of junctions can be increased significantly to produce a usable voltage.

Hence prototype NSC-2 has been built with standard off-the-shelf TEG modules with a total of 7620 TEG elements or 3810 junctions to demonstrate the utility of the device. And with the recent development of thermoelectric microgenerators, many junctions in a small device can produce practical Nighttime Solar Cell™ panels.

In this generation of prototypes, NSC-3 has been built with a TEG that was manufactured primarily from off-the-shelf components. However, the device was built with TEG elements that meet the specifications for a practical Nighttime Solar Cell™ (supplied by Marlow Industries, see References). The module has 32 junction pairs of pn-doped BeTe, with elements that are 24.1mm long. Voltages are being measured as a quantitative determination of the cell's output.

Although not housed in an evacuated cell, the information from this prototype has demonstrated how the device will operate in all types of weather conditions over an extended period of time. This information has been very useful for two reasons: (1) the prototype has shown how the system components (the ZnSe window, the TEG module, etc.) will perform outdoors over time, and (2) how the cell output will change under various operating conditions (high humidity, cloud cover, rain, etc.). In fact, the cell has produced a steady nighttime voltage output with a turn down ratio of about 30:1, from clear, low-humidity nights to heavy rainstorms. Hence the utility of the device has been well demonstrated and is steadily being quantified.

A next generation prototype is currently being built by Marlow Industries which will have the capability of being evacuated. This device will be built with a TEG module of the same design used in NSC-3. Therefore this prototype will have all the attributes that a complete Nighttime Solar Cell™ would have. Although the TEG element count is slightly above the optimum number for the particular design of the TEG geometry (64 element actual versus 44 element desired), which will slightly reduce the output of the cell, the overall performance will be a very good indication of how a practical Nighttime Solar Cell™ will function in the field.

RANGE MANAGEMENT UTILITY: Based on the deep space/terrestrial temperature difference, IR energy attenuation in the atmosphere, and TEG module energy conversion efficiencies, research shows that upwards of 16.8 W/m^2 are available continuously from the Nighttime Solar Cell™ to power the remote sensors. With new TEG modules that are currently being developed, a 16.5cmx16.5cmx3cm (6.5"x6.5"x1-1/8") Nighttime Solar Cell™, weighing about 0.5kg (1.1 lbs.), can provide continuous 6Vdc as the electronic power pack.

The 6Vdc power sources can be available within nine months of the desired starting date of the research; a 27Vdc power source can be available in one to one-and-one-half years. Field testing of the power sources will then commence over a nine- to twelve-month time frame to determine year-round performance of the devices. Certainly test location will affect the operation of the power source due to moisture content of the atmosphere.

Therefore these small, low-maintenance 6Vdc power sources can be situated around the periphery of the range to power any local sensors needed for security or surveillance. Also, the new TEG modules that are being developed can provide even higher voltages as needed (on the order of 27Vdc or higher), depending on the particular electronic package requirements.

CONCLUSION: The Nighttime Solar Cell™ is a viable source for clean, silent remote electrical energy. Especially in regions of the southwestern United States where the humidity is fairly low, the device is most suitable. In fact, the Nighttime Solar Cell™ can function almost indefinitely with no maintenance or servicing, making it useful in the most remote, rugged terrain.

The device can also be coupled with PVC panels which would increase the available amount of energy stored on site. This can be used to augment or improve system reliability, as required. With the advent of the Nighttime Solar Cell™ producing electrical energy at night, this offers many new and outstanding options available to designers needing to monitor remote locations with power consuming electronic devices.

DEDICATION: The authors dedicate their research to their late teen sons, Eric Jones and Joey Parise. God rest their souls.

REFERENCES:

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

Edwards, D.K., 1976, "Molecular Gas Band Radiation", Advances in H.T., Vol. 12, pp 115-193.

Hottel, H.C., 1927, "Heat Transmission by Radiation From Non-Luminous Gases", Trans. AIChE, Vol. 19, pp 173-205.

Marlow Industries, Dallas, Texas, Mr. Mike Gilley, Phone: (214) 340-4900, May 2003.

Parise, R.J., 1999, "Nighttime Solar Cell", United States Patent No. 5,936,193.

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

Parise, R.J. and G.F. Jones, 2000, "Energy from Deep Space – The Nighttime Solar Cell™ - Electrical Energy Production", IECEC00, Las Vegas, NV, Paper No. AIAA-2000-2822.

Parise, R.J. and G.F. Jones, 2001, "Nighttime and Daytime Electrical Energy Production from the Nighttime Solar Cell™", *Proc.* IECEC01, Savannah, GA, July 24-27, 2001.

Parise, R.J., 2002, "Offset Global Warming with the Earth Cooler™", *Proc.* IECEC02, Sponsored by IEEE, Washington, DC, July 28-August 2, 2002, Paper No. IECEC 2002 20097.

Parise, R.J. and G.F. Jones, 2003, "Cold Junction Plate Optimization for the Nighttime Solar Cell™", *Proc.* IECEC03, August 17-21, 2003, Portsmouth, VA, Sponsored by AIAA, Paper No. AIAA 2003-6113.

Salby, M.L., 1996, *Fundamentals of Atmospheric Physics*, Academic Press, New York, NY.

Siegel, R. and J.R. Howell, 1981, *Thermal Radiation Heat Transfer,* 2nd Edition, McGraw-Hill Book Company, New York, NY.

White, F.M., 1988, *Heat and Mass Transfer,* Addison-Wesley Publishing Company, Inc., NY.