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TherMobility™

Thermobility WPG-1

Thermoelectric Energy Harvesting System

™

Application Note APN0016_rev1.1

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Introduction

The Thermobility WPG-1 is a first generation thermoelectric energy harvesting system designed to provide the user with a convenient alternative to traditional wired or battery power sources for autonomous systems. In conjunction with an adequate heat source and energy storage device, the WPG-1 can provide an extremely long life energy source, freeing the user of routine battery changes and the associated overhead. The Thermobility WPG-1 provides a regulated output ranging from 3.3 to 5.0 Vdc when applied to a heat source greater than 40°C. This unit is designed for market analysis. Direct feedback from the user to Nextreme on performance and applicability is encouraged. The design is flexible and can be customized to work with different RF networks and sensor types.

Thermoelectric Energy Harvesting

Energy harvesting is a method of capturing some type of waste energy and converting it to usable electrical power. Waste energy can take on a multitude of domains, most notably mechanical (in the form of vibration), light and heat (from almost any object). Energy harvesting is not a "one-size-fits-all" technology and the systems designed to harvest energy must be optimized for the energy domain of interest. The focus of this note is the harvesting of energy in the form of waste heat.

The presumption of any heat energy harvesting system is the existence of a heat source. In general, because power output is proportional to the square of the ΔT across the TEG, the hotter the heat source, the better. The heat source will not be discussed here but it should be understood that thermal mating of the TEG to the heat source and thermal impedance matching must be considered for maximum performance.

The basic element of any thermal energy harvesting system is the thermoelectric generator (TEG). Thermoelectric devices have been in existence for over fifty years. The use of these devices for converting heat into electrical energy was first discovered by Thomas Johann Seebeck in 1826. The effect of converting a flow of heat into electrical energy, now referred to as the Seebeck Effect, is illustrated in Figure 1. Here, two dissimilar semiconductor materials (P-type and N-type based on their doping characteristics) are placed electrically in series but thermally in parallel such that as heat passes through the "couple", half the heat travels through the P-type leg and half through the N-type leg. A temperature differential between the top and bottom of the couple occurs that is a function of the thermal conductivity of the elements and their geometry (footprint and height). This temperature differential, *ΔT*, produces a voltage that, when matched to the optimally sized electrical load, will provide a power output as described:

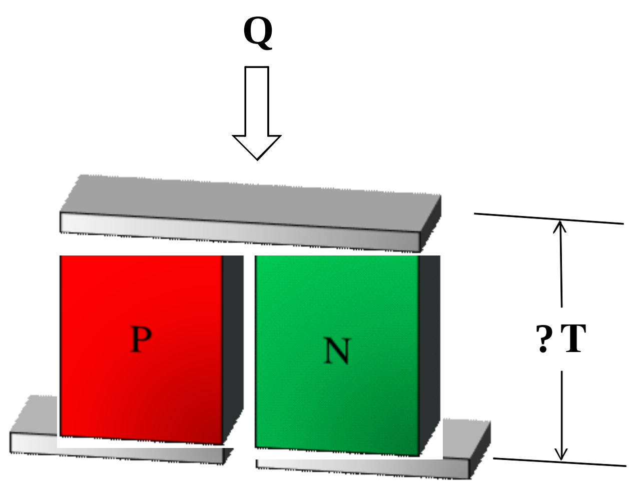

Figure 1: ***Heat flowing through a PN couple will create a temperature differential ΔT. Power output is proportional to*** ΔT^2.

$$P_{out} = \frac{L\alpha_{couple}^{\;2}}{32NA_{element}k^2\rho} \cdot Q^2 = \frac{N\alpha_{couple}^{\;2}A_{element}}{8\rho L} \cdot \Delta T^2$$

where:

Q=heat flux through TE device

L=height of the TE element

α_{couple}=Seebeck coefficient of the couple

N=number of PN couples

$A_{element}$=the cross sectional area of the TE element

k=thermal conductivity of the elements

ρ=electrical resistivity of the elements

The two expressions above show the output power as a function of heat flux, *Q*, and temperature differential, *ΔT*, respectively. Note that the output power is proportional to the square of either the heat flow or the *ΔT*. The open circuit voltage of the thermoelectric can be described in similar terms as:

$$V_{oc} = N\alpha_{couple}\Delta T = \frac{\alpha_{couple}QL}{2kA}$$

Figure 2 shows a generic power output and voltage response for a thermoelectric device. The idealized open-circuit voltage is linear with *ΔT* while output power is quadratic. Temperature dependent properties can affect the ideal characteristics of the device.

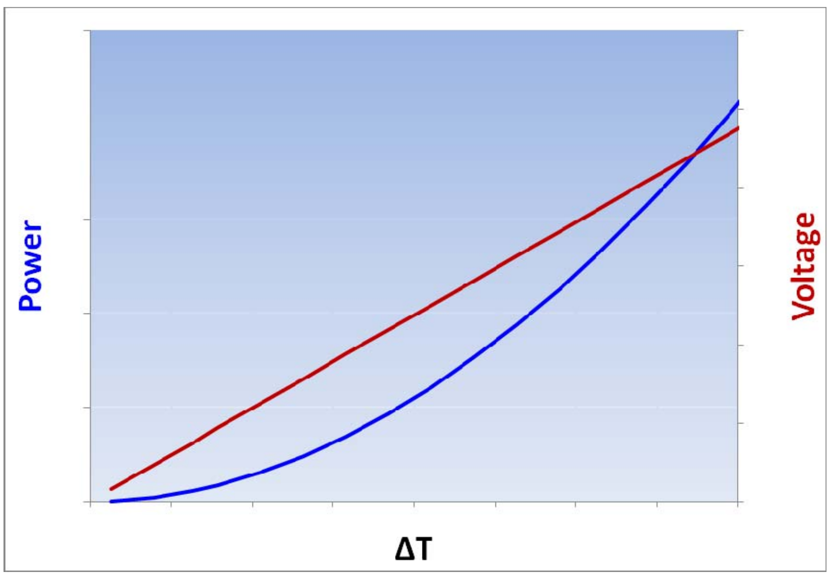

Figure 2: ***Power output and efficiency as a function of temperature differential across the TEG.***

The output characteristics of the TEG depend on the thermal boundary conditions (i.e., the ambient temperature, heat source temperature and heat flux), the TEG design and the heat sink used to reject the heat into the ambient. Design of the optimal TEG must consider all these parameters as well as the desired output I-V characteristics. Because thermal boundary conditions are variable, the output of the TEG will vary, necessitating the use of voltage conditioning and power management to any given electrical load.

The implementation of a thermoelectric power conversion and energy storage system requires several basic elements in addition to an assumed heat source and electrical load. These elements shown and numbered in schematic form in Figure 3 are: 1) a thermoelectric device (as described above), 2) a heat sink, 3) a power conditioning circuit, 4) an energy storage device and 5) a power management circuit. The design and optimization of the system and elements is highly dependent on the thermal boundary conditions. More information on the elements of thermal energy harvesting system can be found in the Nextreme whitepaper entitled "Design Considerations for TEG System Optimization"[1].

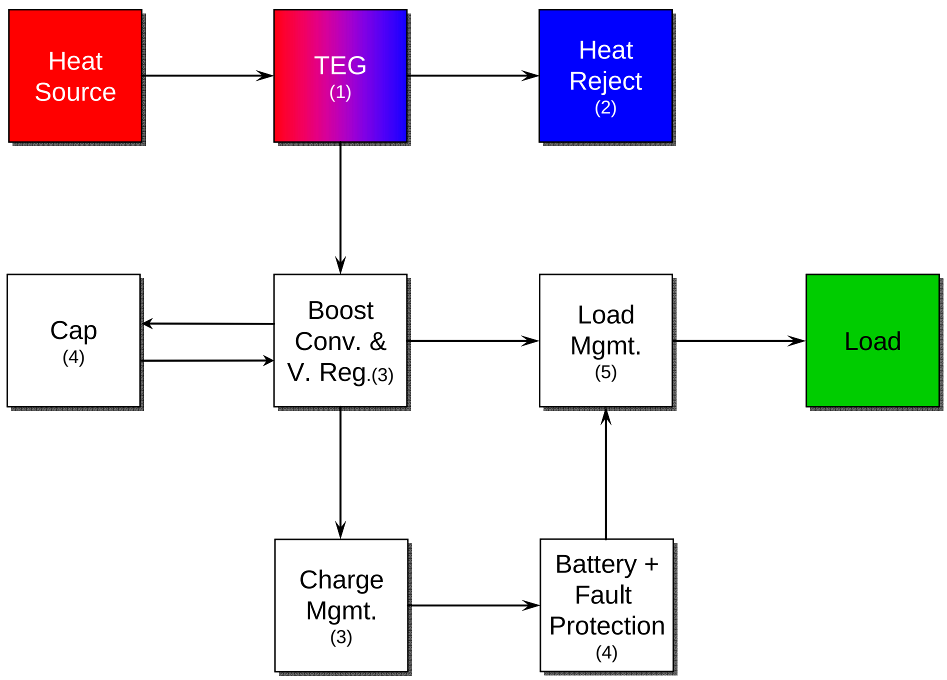

Figure 3: Generic schematic of thermoelectric energy harvesting system.

[1]http://nextreme.com/media/pdf/whitepapers/Nextreme_Whitepaper_Design_Considerations_for_TEG_System_Optimization_071310-1.pdf

Thermobility WPG-1 Design

The Thermobility WPG-1 is a self-contained thermoelectric harvesting system designed to provide a regulated voltage output of 3.3, 4.1 or 5.0 Vdc to electrical loads of 15kΩ or higher. The design consists of four major components as shown in Figure 4:

1. The voltage upconverter board incorporates the Linear Technologies LTC3108 Ultralow Voltage Step-Up Converter and Power Manager chip. The board has a single regulated output connected to two connectors: a standard two-pin header (0.1 inch pin pitch) and a 0.05 inch pitch 6-pin connector. The board has DIP switches enabling 2.35, 3.3, 4.1 and 5.0 Vdc output and a separate bank of DIP switches for switching between the output pins and an onboard blue LED indicator. Details can be found on the WPG-1 datasheet.

2. Pin-fin heat sink

3. Nextreme HV56 thermoelectric generator

4. Metal attachment plate that is applied to the heat source of interest.

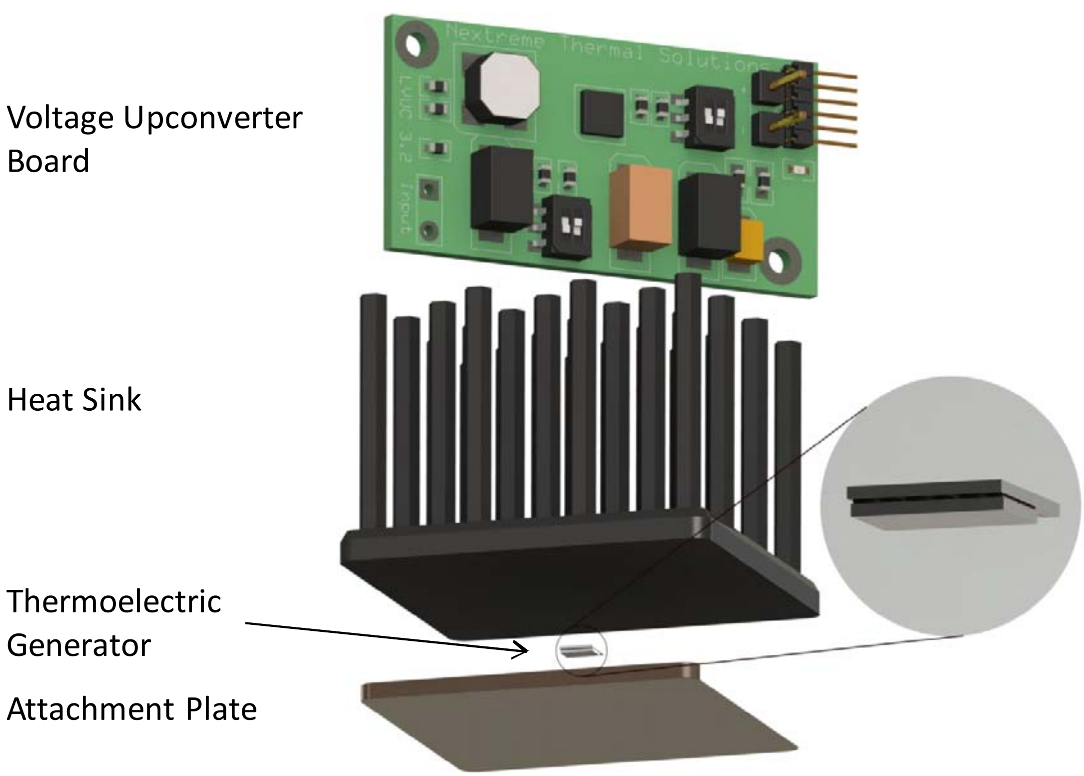

Figure 4: Exploded view of Thermobility WPG-1 unit.

How to Use the WPG-1

The WPG-1 is designed for easy use with any flat surface heat source. For simple bench-top testing, the WPG-1 can be placed directly on a laboratory grade hotplate with temperature control (Figure 5). No special accommodations for controlling the quality of thermal interface between the hotplate and attachment plate are required. No fan is required for continued operation as the WPG-1 was designed to operate under natural convection. Forced convection will improve the device performance.

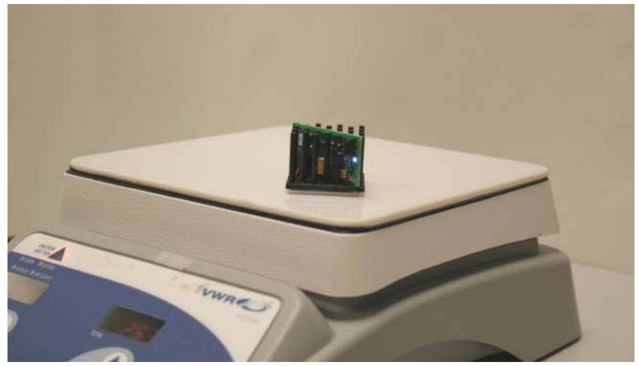

Figure 5: WPG-1 on a standard laboratory hotplate.

For evaluation with other surfaces, the attachment plate can be mated with either thermal grease for normal horizontal application or double-stick thermal pad for vertical mounting. Figure 6 shows the unit attached to the side of a laboratory oven using a thermoelastic pad.

The orientation of the WPG-1 is important to ensure maximum heat flux in natural convection mode that in turn leads to maximum output power. Figure 7 shows three distinct heat sink orientations, 1) downward, 2) upward and 3) sideways. The impact of orientation is minimized due to the heat sink's pin fin design. The worst orientation for the system is "downward" where hot air will flow upwards under natural convection. If the system can be placed with the fins pointing sideways or upwards the buoyancy of the air will drive convection effectively and the system performance will be improved. If forced air (typically driven by a fan) is present then the effects of heat sink orientation will be minimized and any system orientation may be used.

Figure 6: WPG-1 mounted vertically on side of oven using adhesive

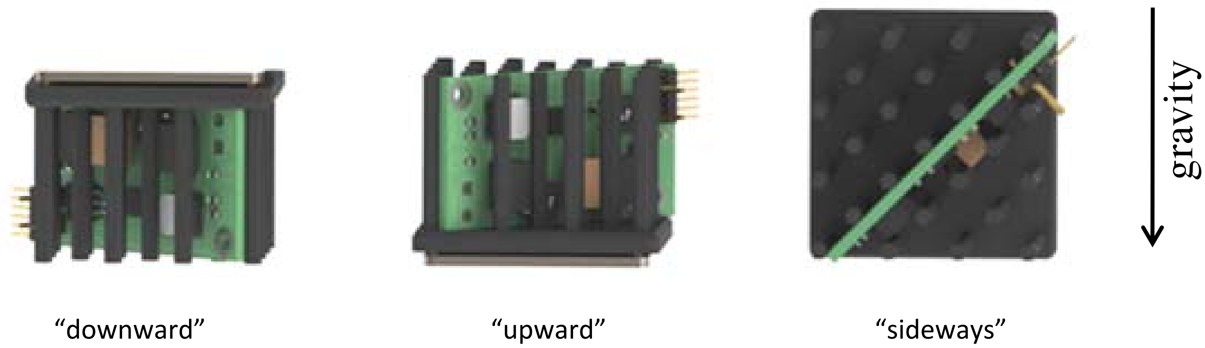

Figure 7: Basic heat sink orientations. The best orientation for “natural convection” (i.e., no forced air movement) is either upward or sideways. In forced air conditions, all orientations will provide adequate heat sinking.

Electrical connection can be made to the WPG-1 using either the 2-pin or 6-pin connectors shown in Figure 8. The 2-pin connector has a standard 0.1 inch pin spacing. The 6-pin connector is a Texas Instruments proprietary connector that mates to their EZ-430 wireless sensor node (see Example Application below). The board includes two separate banks of DIP switches for controlling the output voltage (SW1) from 2.35 to 5.0 Vdc and the load. The load can be either directed to the onboard blue LED or to the 2-pin or 6-pin output using SW2. Tables I and II provide switch configurations.

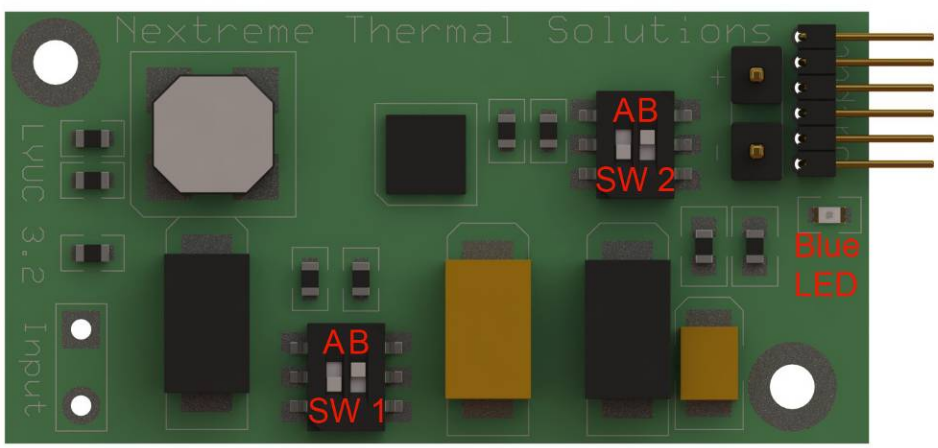

Figure 8: Layout of board showing electrical connectors. Also shown are the DIP switch banks for controlling the output (SW1 and SW2)

Table I: Output Voltage Setting for SW1

Output Voltage Setting		
SW1	A	B
2.35†	down	down
3.3	up	down
4.1	down	up
5.0	up	up

† No test data provided for this setting.

Table II: Output Load Settings for SW2

Output Load Setting		
SW2	A	B
LED Low	down	down
LED High	down	up
2 or 6 Pin Connector*	up	NA

* 2 Pin and 6 Pin are connected in parallel.

Application Example: Wireless Sensor Node

Advances in distributed sensors and sensor networks have led to an increased interest in the use of continuous power sources to replace or augment existing power storage systems. The use of waste heat is an attractive source of energy for many applications where μW-mW power is required. The Thermobility WPG-1 provides a low-cost and easy-to-use autonomous energy source for sensor systems.

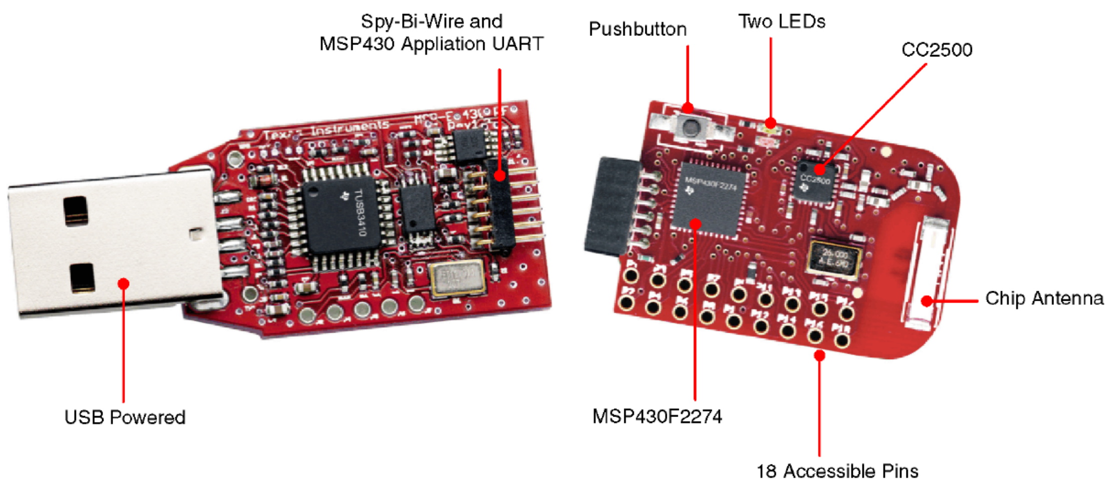

Figure 9: TI eZ430-RF2500-SEH with USB powered access point (left) and node (right). Source: eZ430-RF2500 Development Tool, User's Guide, SLAU227E, Sept. 2007, Revised April 2009, Texas Instruments.

The Texas Instruments eZ430-RF2500-SEH is a low cost, USB plug and play, ultra-low-power wireless development tool for energy harvesting applications (Figure 9). The system is based on TI's ultra-low-power MSP430 MCU integrated onto one board along with TI's CC2500 Low-

Power 2.4 GHz RF Transceiver. With the TI software and UBS wireless hub installed on a PC it is easy to quickly evaluate potential applications for wireless networks powered by the WPG-1. The PC-based demo displays real-time information on the voltage produced by the WPG-1 and the temperature of the node communicated wirelessly to the USB access point. An Eclipse-based integrated development environment is bundled with the eZ430-RF2500-SEH to allow additional customization of the eZ430 target board for your application. However, no programming is required for simple evaluation of the potential of the WPG-1 and the plug and play system allows the simultaneous evaluation of signal strength at a given distance.

The WPG-1 has been designed with a 6-pin connector for directly interfacing to the eZ-430 node unit. The node provided with the eZ430-RF2500-SEH comes with an on-board temperature sensor for easy evaluation. An example of the WPG-1 providing power to the eZ430 system is shown in Figure 10. The WPG-1 can be configured with other output pin configurations for interface to any system of interest. (NOTE: the load requirements for the eZ430-RF2500-SEH and the standard eZ430-RF2500 are different. The power consumption of the standard version is approximately 10 times higher than the –SEH version and will not work properly with the WPG-1.)

(a) (b)

Figure 10: (a) WPG-1 with eZ-430 sensor and transmit node at 49.9°C transmitting data to (b) eZ-430 access point connected to laptop computer.