ANALYSIS OF BERKEN ENERGY
THERMOELECTRIC GENERATOR TECHNOLOGY

I have been asked by Berken Energy to make a detailed technical analysis of their uniquely produced thermoelectric technology. I visited the facility in Fort Collins, Colorado and was given a demonstration of the devices and the performance testing procedure of those devices. The following is my thorough assessment of the Berken Energy technology. The graphics have been provided by Berken staff at my request.

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Introduction to Thermoelectrics

The thermoelectric effect works by using a differential in temperature across a solid state material to create electrical power. The major effects that make up the thermoelectric effect are the Seebeck effect, and the Peltier effect.

Devices known as Thermoelectric Generators (TEG) work off the Seebeck principle to convert the flow of heat (from hot to cold) into electrical power with the use of thermoelectric semiconductors. A semiconductor is a material that is usually less electrically conductive than a metal and more electrically conductive than an insulator, such as glass. Semiconductors are also used to create devices such as transistors, LEDs, and solar panel photovoltaics (PV), and their electrical conductivity can be adjusted.

In the case of Berken Energy, semiconductors are used to create a reclaimed thermovoltaic (RTV™) device. When heat flow is applied through the device, the flow of electrical charge carriers creates power when applied to a resistive load. The beneficial utilization of this RTV™ device allows for the
creation of power from waste heat (heat which would otherwise have been lost to the environment). These devices have no moving parts can be operated continually as long as there is the supply of heat. Unlike their similar counterpart, photovoltaics require sunlight to operate, Berken Energy has developed a process and formulation for making RTV™ devices affordable and with a much lower temperature required to produce energy which will put them at the forefront of waste heat recovery in industrial environments.

The RTV™ module can be designed to either provide maximum power or maximum conversion efficiency. For power generation, the maximum power design approach is appropriate, as the source of heat usually originates from factories that would otherwise be wasted by release into the environment. It is estimated that about 60% of all energy created by various energy sources is returned to the environment as waste heat. Thus, there is a major incentive to reclaim this lost heat in the form of electrical power. Ultimately, electrical power plants based on RTV™ technology can be constructed to produce energy from waste heat.

**Analysis**

The Berken Energy RTV™ technology is based on a unique material fabrication technique to produce a polycrystalline thermovoltaic (TV) elements. This manufacturing process is performed at a low temperature relative to production of other energy-producing solid state devices which lowers the production cost significantly. These TV elements are made into n-type (negative) or p-type (positive) by employing appropriate chemical doping. A finished sub-module requires an array of connected n-type and p-type TVs that are thermally in parallel with respect to a heat source and electrically connected in series. A schematic of the sub-module array of n-type and p-type TVs with interconnected electrical conductors is shown in Fig. 1.

A larger RTV™ module, or cartridge, is shown in Fig. 2, which is comprised of sub-modules arranged electrically in series. The area of the RTV™ module is
approximately 38 square centimeters or 5.89 square inches. The fabrication of a cartridge involves placement and bonding between sub-modules and electrical interconnects to specific substrates that have a relatively high thermal conductivity. The electrical output from the cartridges is direct current, just as with solar modules. These cartridges can be combined electrically in parallel or series, just as with solar cells in a solar panel, depending on the desired output power in terms of current and voltage. The energy created passes through inverters to convert the DC output to AC, similar to solar cell technology. As long as there is a heat source energy will be generated. If for some reason the heat source is not consistent throughout the day or night then the energy can be stored in batteries.

The testing of these RTV™ cartridges is performed in the test apparatus shown in Fig. 3, which is a small standard heat exchanger to provide a temperature gradient perpendicular to the plane of the cartridge. A temperature gradient is produced by flowing heated mineral oil on the "hot side", and maintained by a thermostatic control device set to a desired value. The “cold side” temperature is determined by available room temperature or cold water in a domestic system. The temperature differential is measured by thermocouples that are adjacent to the opposite sides of the cartridge. The voltage and current produced by the RTV™ cartridges is measured by a standard multi-meter (volts, amps) across a resistive load. The load resistance across the device is varied so that the current-voltage (I-V) characteristics of the device load line can be determined. With the load resistance being very large, the “open circuit”, $V_{oc}$, voltage of the device is measured. When the load resistance is zero, the “short-circuit current” $I_{sc}$ is measured. This is the standard procedure for measuring all power-generating devices such as photovoltaic cells. A point in the IV curve that produces the maximum output power ($P = I \cdot V$) can be easily determined by the load line in the fourth quadrant of the I-V curve. This is usually the preferred operating point of the device in the field and given as $P_{max} = I_{sc} \frac{V_{oc}}{4}$. 
**Fig. 1** An illustration of a sub-module array of eight n- and eight p-type thermovoltaic elements electrically connected in series.

**Fig. 2.** Berken Energy’s RTV™ cartridge: one side is heated while the opposite side is cooled for the production of electrical energy. Either side can be heated (or cooled) to produce electrical energy.
RTV™ Performance with Varied Temperature Difference

The data from a three-cartridge system connected in series is shown in Fig. 4. The thermoelectric device theory predicts that the $V_{oc}$ will increase linearly with the temperature, $\Delta T$. This behavior describes the Berken Energy devices shown in Fig. 4a and 4b as $\Delta T$ is varied from $7.3^\circ$ C to $65.5^\circ$ C. One sees from Fig. 4 that at $\Delta T=65.5^\circ$ C, the maximum power produced by the system is 2.5 W. This represents a real power production of about 22 mW/cm$^2$.

Fig. 3. The demo setup consists of two heat exchangers with up to six cartridges assembled inside.
Fig. 4a. A RTV™ cartridge I-V load line (power generating quadrant) output performance as a function of temperature difference with a resistive load is shown for three cartridges connected in series. The temperature difference in Celsius was varied from 7.3 to 65.5 °C.

Fig. 4b. The RTV™ cartridge power output performance in watts for three cartridges connected in series, corresponding to Fig. 4a, as a function of temperature difference is shown.
Figure of Merit

The standard dimensionless figure of merit for a thermoelectric device is defined as $ZT$ where:

$$ZT = \frac{S^2}{\sigma \kappa T}$$

Here $\sigma$ is the sample conductivity, $S$ is the Seebeck coefficient, $\kappa$ is the thermal conductivity, and $T$ is the absolute temperature. This figure of merit compares to the conversion efficiency of a photovoltaic device. However, in the commercial photovoltaic world, the most critical figure of merit is the cost/watt of the photovoltaic device. The photovoltaic devices used in residential applications are single crystal silicon, multicrystalline silicon, or polycrystalline thin film material. The conversion efficiency of these devices is in the 15 to 20% range at the current time. Tandem photovoltaic devices are available that have efficiencies in the 40 to 45% range, but they are far too costly for residential/industrial use. The tandem devices are currently used exclusively for space applications where watt/Kg (weight) is the significant cost factor.

The same metric will in time emerge for the thermoelectric technology, although currently ZT is the predominant metric for the research laboratory. The current lead materials in the ZT metric are far too costly for large area deployment. The Berken Energy’s technology appears to be a good compromise between cost and performance. Projections of 1.0 dollar/watt of generated power appear to be quite realistic based on the low cost of materials and fabrication.
Applications

There are numerous applications for low cost thermoelectric devices. These waste heat recovery applications include:

A. High temperature industrial processes.
B. Automotive devices that use the waste heat produced by auto engines to generate supplemental electricity.
C. Geothermal electricity production from shallow earth thermal sources.
D. Solar energy conversion.

Application Detail

A. Companies always have the need to become more energy efficient and cost competitive. The conversion of their existing waste heat will decrease their production costs.
B. Geothermal harvest and conversion is a major part of the 2014 Department of Energy R&D priorities. The low cost/watt of the Berken Energy device could be a major player in this new direction.

Comparison with Photovoltaics

I will take as an example for comparison, the current multicrystalline photovoltaics technology. The popular Sharp Electronics multi-Si 230 watt module has dropped in price over the past few years. The current price of production is estimated at about $1.0/watt, having fallen over a factor of five or more over the past decade. The area of the 230 W module is 1.68 m² and the actual peak output is 236 watts at full sun exposure.

If a Berken Energy module of the same area were constructed and configured in a thermoelectric mode, the output at $\Delta T =65^\circ C$ is 368 watts. At a modest $\Delta T$ of 34° C, the output is the same as the peak output of the Sharp module or 236 W. Thus, the energy production is comparable or superior to that of a PV device
of the same area. Area is a primary consideration in the residential, flat plate application that dominates the marketplace.

As thermal storage is well developed technology, there is an advantage of the RTV™ module over the PV module. A RTV™ module can produce power 24 hours a day provided that a heat source is present, whereas PV devices are dependent on the sun. In addition, by device design, the power output can be increased well beyond the value used above.

**Summary**

In summary, I believe that the Berken Energy Reclaimed Thermovoltaic (RTV™) device is a major breakthrough in a low cost, large area technology. The applicability of this exciting new advancement in technology creates a disruptive opportunity in the global renewable energy sector.