Nov. 2013

Waste Heat to Electricity

Project Plan – Version 2

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Group: May14 - 25

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Executive Summary:

We have been tasked with utilizing the pyroelectric effect to convert waste heat into electrical power. Industrial processes, from power generation to manufacturing, generate large quantities of waste heat. This heat is a free, relatively untapped source for energy generation, as it is typically sent into the environment without a second thought. Waste heat has already been converted, but a dense, inexpensive form of recovery and conversion has yet to be developed. As the need for sustainability grows, the focus on increasing plant efficiency by harvesting energy from waste heat will intensify. Thus the timeliness of our research.

In reading background literature and characterizing circuits & materials, we are developing a process to utilize the pyroelectric effect. In particular, we have been able to design, fabricate, and test polymeric and liquid crystals that exhibit permanent dipole alignment. Also, to limit power losses in the harvesting circuit, optoisolation will be used throughout. Although previous teams did not mention loss calculations, we feel that this effect could decrease power density.

Existing low-grade thermal heat recovery systems have proven to be expensive, sometimes thousands of dollars per kiloWatt hour (kWh). The primary goal of this project is to meet or exceed previous results. Once a high conversion efficiency is reached, adapting the device model to real world installations can be undertaken. To accomplish this, three phases are occurring in parallel planning and linear development. These are 1) processing/developing materials, 2) designing a harvesting circuit, and 3) building a device housing. With every new design update, the impact on an eventual harvesting device must be taken into account. As the voltage bias of particular materials is discovered, refined circuits have had to be mapped out. When physical limitations are discovered, a constrained model is drafted.

The following project plan outlines component details and states the specific nature of the physical properties we will be researching and how using these properties has led to a device design.

Concept Sketch

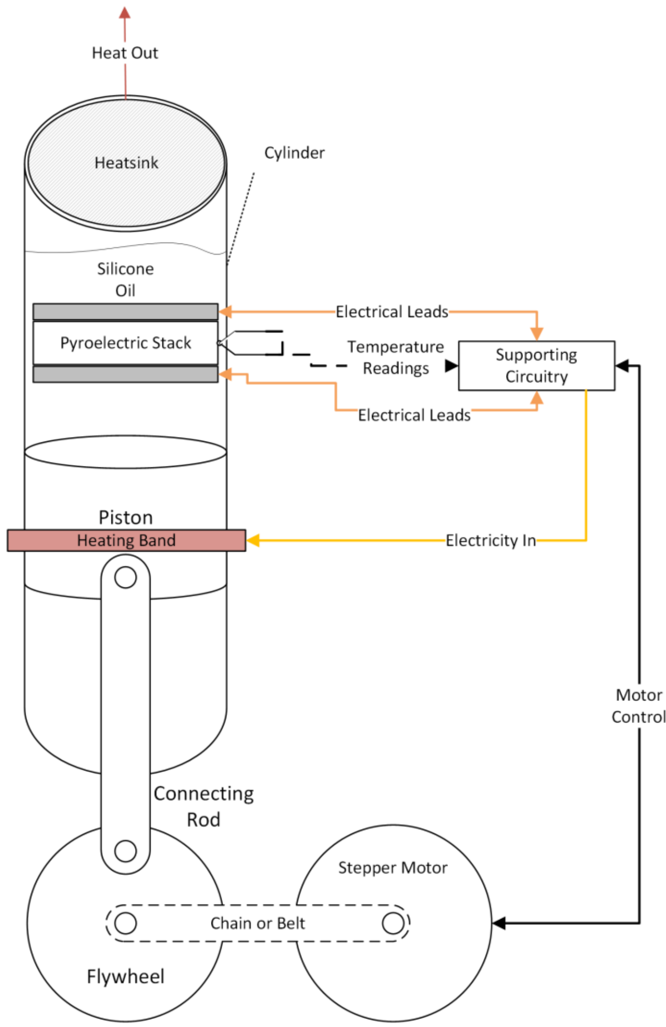

Figure 1 - Concept sketch of pyroelectric generator including heat transfer system and stack

The device will consist of three subsystems, a mechanical heat transfer system, an element of pyroelectric material with appropriate electrical contacts, and a supporting circuit as shown in Figure 1 above.

In this system, silicone oil is used to electrical insulate the pyroelectric stack, preventing arcing, in addition to transferring heat to and from the pyroelectric stack. Heat will be removed utilizing a heat sink at the top of a cylinder, and heat will be applied at the bottom through the use a resistive heating band for simplicity. In real world applications, this heating band would be replaced with a source of waste heat such as steam or exhaust.

The pyroelectric material will be either liquid crystals, a ferroelectric polymer, or a colloid of ceramic nanosheets. These materials will be fabricated into an appropriate form for ease of characterization and integration into the heat transfer system.

Finally, a supporting circuit will be utilized to monitor the system status through thermocouples, control heat flow by actuating the piston via the stepper motor, apply the proper polarizing fields to the pyroelectric element, and connect the element to the harvesting load to utilize generated energy.

Block Diagram

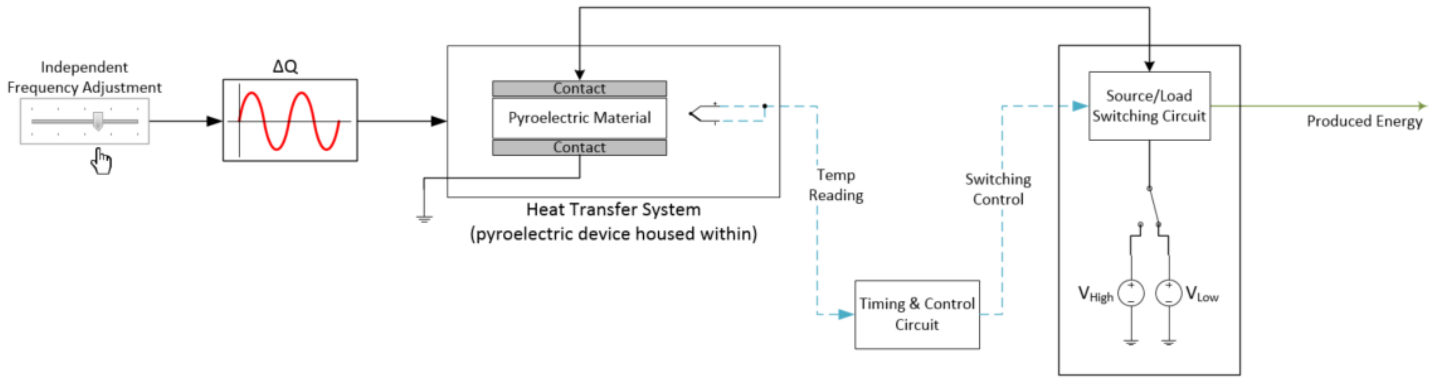

Figure 2 - Block diagram of pyroelectric generator

Figure 2 (above) is a block diagram of the overall system. Waste heat will be sourced and transferred to a fluid within the heat transfer system. A piston will control the fluid's temperature by placing it in contact with a heat source or heat sink. The timing and control circuit will measure the temperature of the fluid as well as that of the device. It will control the electrical switching circuit accordingly. This will provide constant monitoring of the material's state within the pyroelectric cycle (Figure 3) and allow for changes in temperature and field to be accurately controlled.

The switching circuit will control the application of a high voltage polarizing field, as well as the transfer of energy to the energy harvesting circuit. This energy harvesting circuit will convert the produced electrical energy into a more usable form. For our first implementation of this design, our goal will be to dissipate the energy gained in a resistor. By comparing measurements of input and output energy, we will be able to determine the electrical efficiency of the system.

Background

Pyroelectric[1] energy conversion was first studied by Randall Olsen during the early 1980's. Olsen discovered that a pyroelectric generator could be made by cycling a pyroelectric material, between a high temperature and a low temperature as well as cycling between high and low applied electric fields [1]. Figure 3 illustrates the thermodynamic cycle. By tracing out this thermodynamic cycle energy could, in theory, be harvested. However, Olsen ran into the problem that the pyroelectric materials available at the time had a relatively small electrocaloric effect[2] (ECE). This meant that his device could not be used to harvest a significant amount of energy [2] [3].

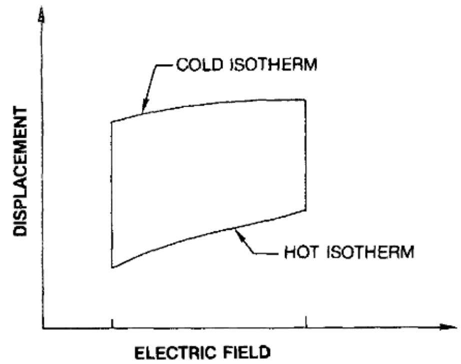

Figure 3 - An Electric Ericsson cycle. It consists of two isotherms and two constant voltage segments. [1]

Recently, a new class of materials has shown promise for pyroelectric energy generation due to its very large ECE. This class of material is liquid crystals. Liquid crystals are typically long carbon chains with some double bonds or benzene rings, in addition to functional groups such as nitrile, which polarize the molecule. These parameters cause some liquid crystals to have a high entropy phase transition called a nematic transition. High entropy phase transitions are the key to the large ECE observed in pyroelectric polymers and the system is designed to take advantage of this effect. This transition may also be tuned by changing the length of the polymer chain. The longer the polymer chain is, the higher the nematic-disordered transition temperature becomes. In this project the liquid crystal chosen to be used was 4-Cyano-4'-pentylbiphenyl. This liquid crystal already has some basic research done in regards to the pyroelectric properties which made it a good candidate.

[1] The pyroelectric effect is the ability of a material to create a momentary voltage with a change in temperature. It is the opposite of the electrocaloric effect.

[2] The electrocaloric effect is the ability of a material to undergo a reversible change in temperature with a change in applied electric field. It is the opposite of the pyroelectric effect.

System Description

The initial steps of this project will be relatively simple in nature. Pyroelectric elements will be fabricated out PVDF and liquid crystals, and circuits will be developed to characterize the pyroelectric effect in the materials. This will require a Sawyer-Tower circuit to determine the electric field strength along with the polarization of the material. Once the pyroelectric effect has been demonstrated, the project will advance to its second stage. In this second stage, the primary focus will be enhancing the performance of the device. At this point the element will be installed in a silicone oil filled housing, allowing for greater electric fields to be applied to the material. This will help increase the energy density of the pyroelectric device. Additionally in the second stage, cycle parameters such as frequency will be tuned to provide maximum performance for each material.

Once the material, circuitry, frequency, and cycle boundaries (temperature and electric field) have been optimized for maximum performance, the project's focus will shift towards creating a system which can be used to harness waste heat. Such a system would be similar to that shown in the concept sketch. A source of heat will heat silicone oil, which will be used to both electrically insulate and transfer heat to and from the pyroelectric elements in the housing. By utilizing a source of waste heat, energy that would previously have been discarded can be converted into usable electricity. The entire heat exchange system can easily be controlled by a microcontroller, but interfacing with the high voltage pyroelectric element creates additional complications. The pyroelectric element must be isolated from the microcontroller in order to prevent the high voltage from permanently damaging the microcontroller. Ultimately, a switching circuit must be designed to allow for charging and discharging of the pyroelectric element while keeping the microcontroller electrically isolated.

Requirements

There are functional and nonfunctional requirements in this project. Over the next eight months, we will be taking the necessary steps to accomplish all of the following requirements.

Functional

1) Convert waste heat into electrical work
2) Apply electric field to a pyroelectric element
3) Expose pyroelectric material to oscillating thermal cycle
4) Utilize an organic functional pyroelectric material
5) Create circuit to measure generated electrical work
6) Design a system to ensure operator safety

The goal of this project is to take waste heat of a system and convert it, via a pyroelectric cycle, into usable electricity. Over the years, energy harvesting has been accomplished by other research, but our objective is to produce the largest positive net energy flow ever recorded. This might seem like a lofty goal, but with the advance of the polymer industry, new materials are available that will theoretically produce higher yields.

A secondary objective is to develop a modular system. This will allow us to quickly swap out our pyroelectric materials and circuit devices in order to perform testing and retune the circuit for different materials. Having a modular setup will greatly enhance our ability to test and choose the best pyroelectric material design.

Finally, our project has several extremely dangerous components, which will be discussed in depth later in the paper. Due to these hazards, we will need to develop several safety procedures so nobody gets hurt. Lock-out-tag-out is a process used worldwide to ensure that no one is injured while working on hazardous elements.

Non-functional

1) Build device to emulate the Ericsson cycle
2) Improve the efficiency of a known pyroelectric material
3) Research multiple pyroelecrtic materials to compare efficiencies in different applications

Like the functional requirements, we have a non-functional goal. We have spent a large amount of time going through previous research papers and our electrical engineers have been noticing many of the papers have very disorganized wiring. To boost efficacy it must be easy to follow and ultimately replicate. From what we have seen, the circuit work is not clearly defined and, in the pictures the groups provided, it was difficult to see how they connected their circuit. We understand that this may be to protect their design from plagiarism, but with this technology still in its infancy a clearer break down is necessary. As a group we are going to try to keep the circuits clean and easy to follow, allowing for others to reference and build on our design and discoveries.

Deliverables

Due to the nature of our project, we are defining our deliverables in two separate timetables, December and May. In December, we will present a pyroelectric device and circuit to demonstrate the pyroelectric effect manually. Throughout the next five months we will be working on maximizing energy output and creating an autonomous heat transfer system. Maximizing the energy output will entail fine tuning our power harvesting circuit and using newer, yet untested, pyroelectric materials. Our ultimate goal is to create an autonomous system complete with pumps, heat exchangers, solenoids and a microcontroller. By creating an autonomous system, our energy harvesting circuit will have to become more complex in order to handle a wider range of temperatures.

In addition to the design elements of this project, we have the opportunity to help author research papers. The larger question that we are tackling is determining what, if any, advantages liquid crystals have in comparison to P(VDF-TrFE) [3] . Depending on the results, this could revolutionize the energy harvesting industry.

[3] P(VDF-TrFE) is a ferroelectric and pyroelectric copolymer comprised of polyvinylidene fluoride (VDF) and polytrifluoroethylene (TrFE). The ratio can be varied to alter transition temperature and other properties.

Plan Outline

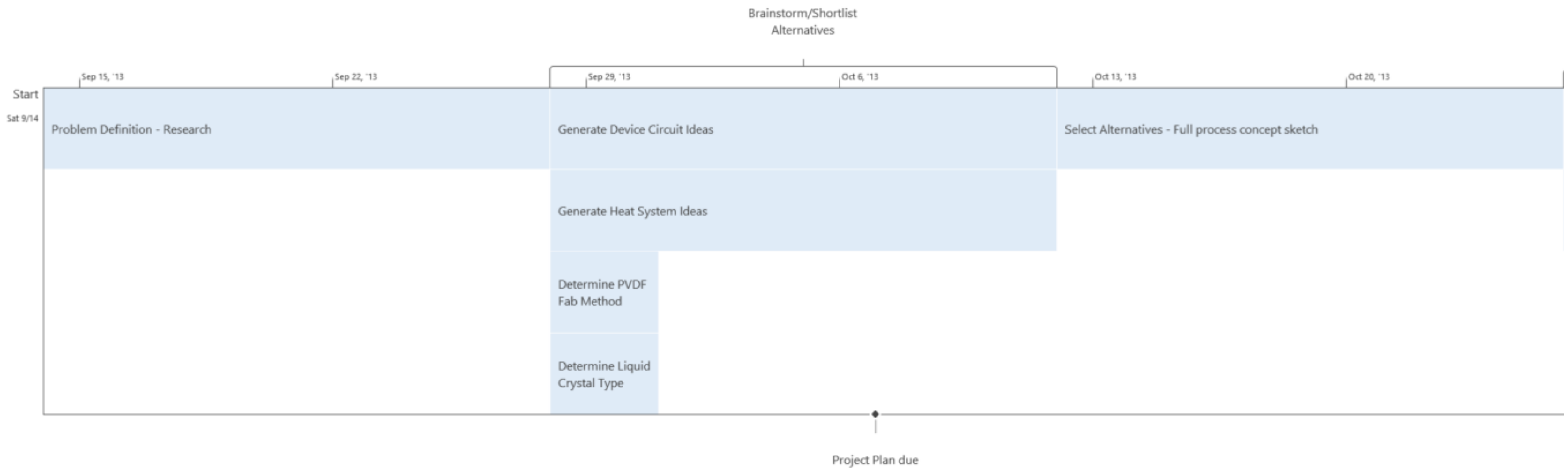

Figure 4 - Project Outline - September 14th to October 27th 2013

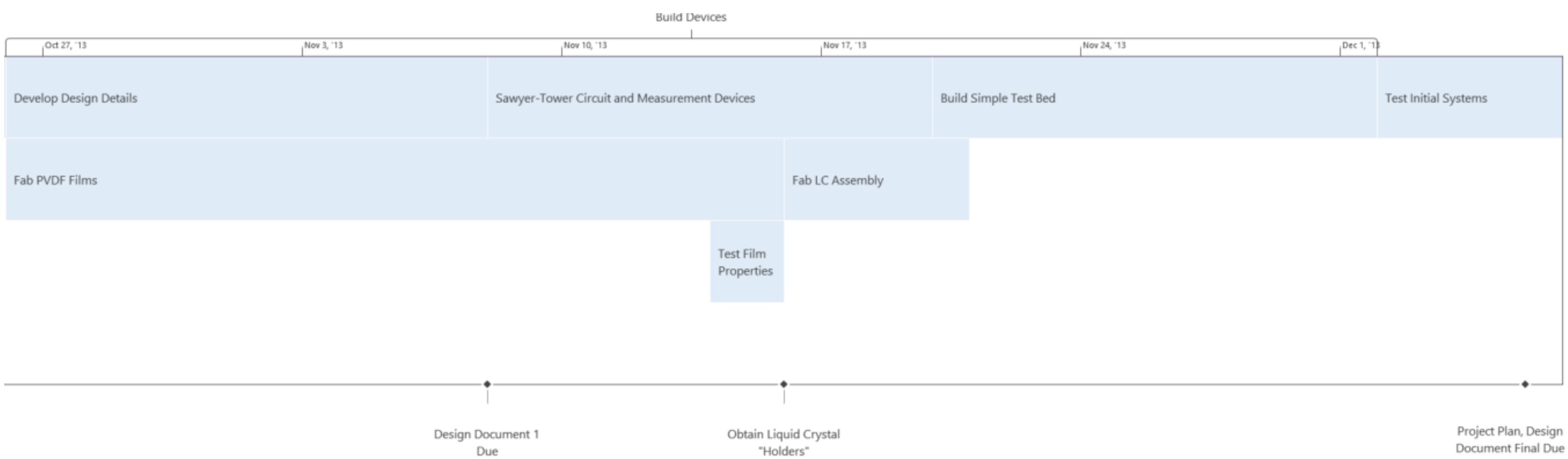

Figure 5 - Project Outline - October 27th to December 14th 2013

December 14th through January 12th are not shown in the timeline. This time range encapsulates finals week for the fall 2013 term and winter break for the 2013-2014 year. The project will be on hold over this timeframe. Additionally, spring break is marked on 6, where the project may also be put on hold.

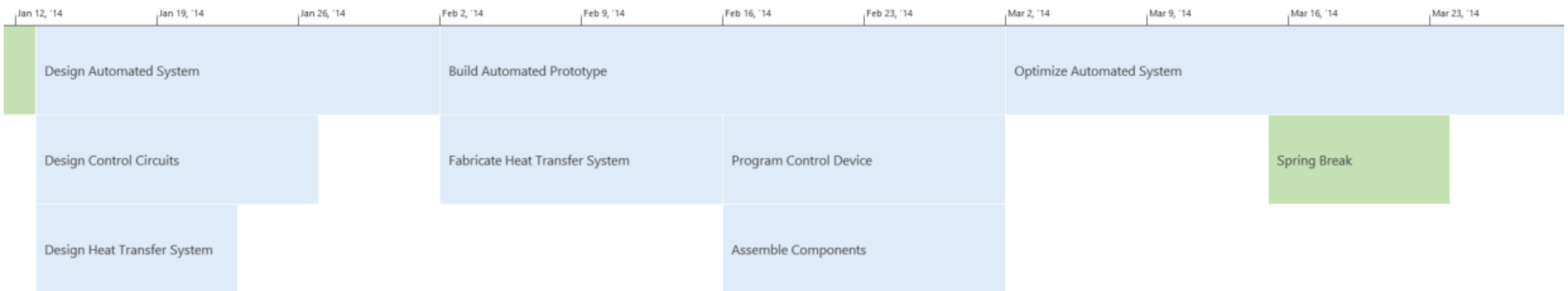

Figure 6 - Project Outline - January 12th to March 29th 2014

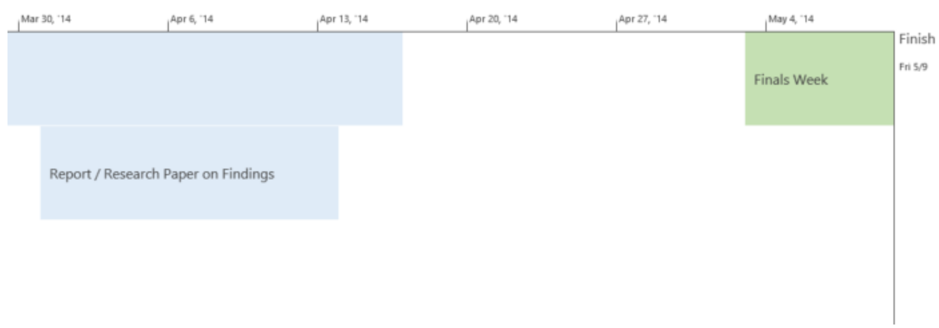

Figure 7 - Project Outline - March 30th to May 10th 2014

Risk Management/Safety:

Proper care must be taken to ensure safety when operating the pyroelectric device. The primary safety concern is in regards to voltage in excess of 400V. This presents an acute risk for electrocution. Shock risk can be mitigated with the use of rubber gloves and a 'one hand' method to prevent arcing through completion of a circuit. A lockout/tag out system may also be implemented. This will ensure that whenever any subsystem of the device is not connected, source voltage cannot be supplied to the pyroelectric material. Being that a pyroelectric is, in its nature, a dielectric, a ground path to safely discharge high capacitances is necessary as well.

Another safety concern with this system are the possibility of high temperature oils used in the device design. When working with the mechanical heat exchange fluids, leather gloves must be worn along with a heat resistant apron, and safety glasses. This will ensure that no burning of skin or clothing occurs, and that the eyes will be protected.

The final safety concern is working with polymer fabrication. The solvents used for P(VDF-TrFE) fabrication are toxic, and if the polymer ignites it will produce fluorine gas. Thus any polymer fabrication should be done in a fume hood. In addition to working in a fume hood, nitrile gloves, a lab coat, and safety glasses must be worn to protect against splashing of the polymer or solvents that may occur.

Task Assignments/Breakdown:

John:

-Project management and timeline

-Communication (weekly report)

-Control systems

-Circuitry design

Josh:

-Web page design

-Circuitry design

    -Pspice circuit design

-Electrical device research

Seth:

-Group mediator

-Ordering material and supplies

-Mechanical heating/cooling design

-Circuitry design

    -determine the circuit components

Tommy:

-Bibliography and Sourcing

-Liquid crystal device fabrication

-P(VDF-TrFE) device fabrication

-Thermodynamic curve generation

Trent:

-Group leader

-Liquid crystal device fabrication

-P(VDF-TrFE) device fabrication

-Material electrical property curves

-Management of bill of materials

References

[1] R. B. Olsen, D. A. Bruno and J. M. Briscoe, "Pyroelectric conversion cycles," *Journal of Applied Physics.,* vol. 58, no. 12, pp. 4709-4716, 1985.

[2] R. B. Olsen, "Ferroelectric Conversion of Heat to Electrical Energy - A Demonstration," *Journal of Energy,* vol. 6, no. 2, pp. 91-95, 1982.

[3] R. B. Olsen, J. M. Briscoe, D. A. Bruno and W. F. Butler, "A Pyroelectric Energy Converter Which Employs Regeneration," *Ferroelectrics,* vol. 38, pp. 975-978, 1981.