May
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# Waste Heat to Electricity

Final Report

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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 energy. 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, optoisolators 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. 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.

1) Processing/developing materials
2) Designing a harvesting circuit
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.

# 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 1 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].

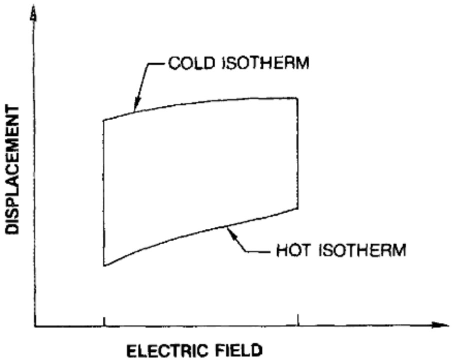

**Figure 1 - An Electric Ericsson cycle. It consists of two isotherms and two constant voltage segments. [1]**

Recently, a new class of materials (liquid crystals) has shown promise for pyroelectric energy generation due to its very large ECE. Liquid crystals are typically long carbon chains with 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 (known as 5CB). This liquid crystal already has some basic research done in regards to its pyroelectric properties which made it a good candidate.

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[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.

# Block Diagram

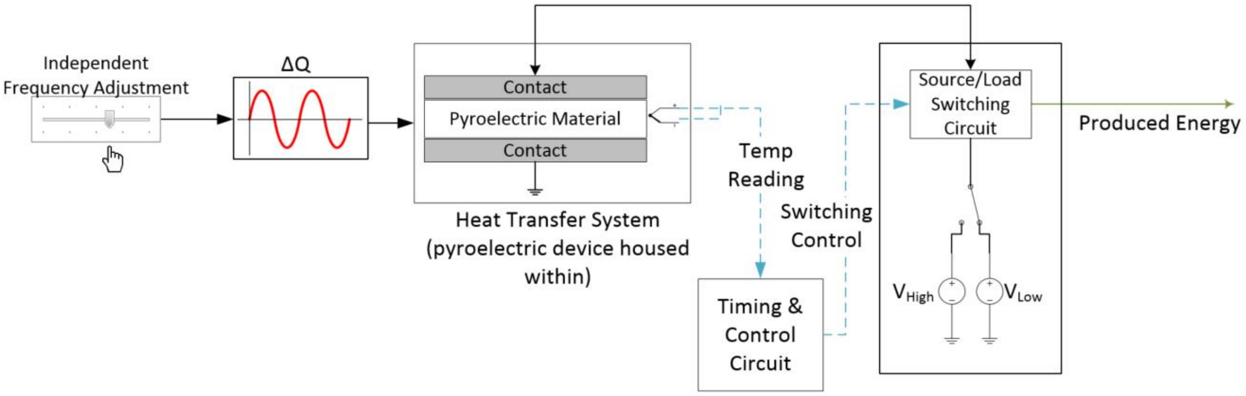

**Figure 2 - Block diagram of pyroelectric generator**

Figure 2 (above) is a block diagram of the overall system. Thermal oscillations were applied to the pyroelectric material via a heat transfer system. The device was submerged in dielectric oil and the temperature was controlled by placing it in contact with a heat source or heat sink. The timing and control circuit measured the temperature of the fluid as well as that of the device. It controlled the electrical switching circuit accordingly. This provided constant monitoring of the material’s state within the pyroelectric cycle (Figure 1) and allowed for changes in temperature and field to be accurately controlled.

The switching circuit controlled the application of a high voltage polarizing field, as well as the transfer of energy to the energy harvesting circuit. For our first implementation of this design, our goal was to dissipate the energy gained in a resistor. By comparing measurements of input and output energy, we were able to accurately trace the location of the device in the Olsen cycle.

# System Description

The initial steps of this project were relatively simple in nature. Pyroelectric elements were fabricated from liquid crystals, and barium titanate elements were purchased for proof of concept measurements in the designed circuit. This required a Sawyer-Tower circuit to determine the time-varying electric field strength along with the polarization of the material. Once the pyroelectric effect is demonstrated for each material, the project may advance to a new 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 would 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 were functional and nonfunctional requirements for this project. We took 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 alternating 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 was 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 was to produce the largest positive net energy flow ever recorded. With the advance of the polymer industry, new materials are available that will theoretically produce higher yields.

Our project had several extremely dangerous components, which will be discussed in depth later in the paper. Due to these hazards, we developed several safety procedures to prevent injuries. 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 Olsen cycle
2) Improve the efficiency of a known pyroelectric material
3) Research multiple pyroelectric materials to compare efficiencies in different applications

Like the functional requirements, we had a non-functional goal. We had spent a large amount of time going through previous research papers and our electrical engineers noticed 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 circuits. We understand that this may be to protect their design from plagiarism, but with this technology still in its infancy a clearer breakdown is necessary. As a group, we kept the circuits clean and easy to follow, allowing for others to reference and build on our design and discoveries.

# Developmental Heat Transfer System

A heat transfer system can be utilized to provide automated control of sample temperature through the pumping of fluid between heat exchangers of varying temperatures. A piston design, such as that shown below, has been successfully utilized by research groups such as Pilon's at UCLA [4]. However, this automated heat transfer system is not necessary to demonstrate the pyroelectric effect and achieve energy generation.

For the time being, the focus of this project will be directed towards the design, fabrication, and performance evaluation of pyroelectric elements and their supporting circuitry. An automated heat transfer system will only be pursued after the pyroelectric effect has been demonstrated in the materials chosen and supporting circuitry and cycle parameters have been optimized to yield maximum performance of the pyroelectric material.

In lieu of the automated system, a heat source (a hot plate) and a heat sink (a block of metal) will be utilized to heat and cool a reservoir containing the pyroelectric element submerged in silicone oil (Figure 3). By submerging the pyroelectric element in silicone oil, larger electric fields can be provided across the material without risking dielectric breakdown of the surrounding medium. Higher field strength will increase device performance and efficiency. A thermocouple will also be placed in contact with the pyroelectric element to measure temperature and determine when to move the reservoir.

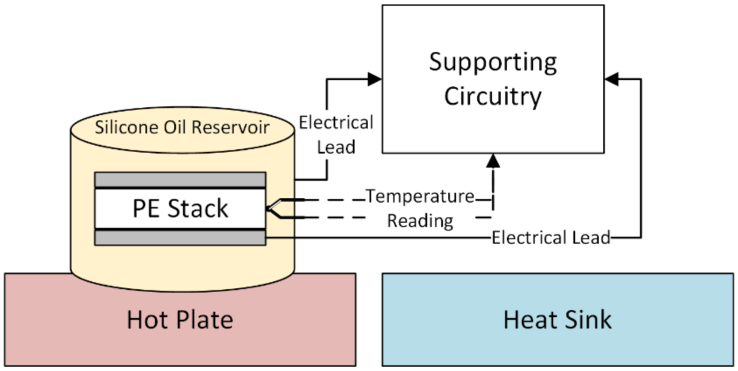

**Figure 3 – Schematic of Developmental Heat Transfer System**

# Liquid Crystal Pyroelectric Elements

4’-Pentyl-4-biphenylcarbonitrile (5CB) will be the first liquid crystal utilized for testing, its structure is shown in Figure 4. This liquid crystal was chosen because it shows a high polarizability, and a high change in entropy when transitioning from an ordered state to an unordered state. High polarizability is needed to align the molecules in a timely manner, while the high entropy change allows for greater energy conversion per cycle.

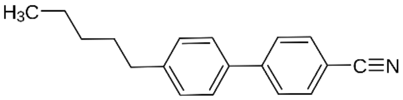

**Figure 4 – Structure of 4’-Pentyl-4-biphenylcarbonitrile (5CB)**

5CB was also chosen as the material of choice because of extensive existing research on its behavior in electric fields over a range of temperatures. Such research showed a substantial polarization and entropy change at the nematic-isotropic transition temperature as a result of significant anisotropy in the dielectric constant. Additionally, the magnitude of this energy change can be further increased by the application of larger electric fields to the material [5].

The liquid crystal pyroelectric stacks will utilize Instec Inc. homeotropic liquid crystal holders (Figure 5 and Figure 6). The Instec system has specially processed ITO coated glass slides that cause the liquid crystals to align. Additionally the narrow spacing between the glass plates allows for the insertion of the liquid crystals between the plates by capillary action. These precise carriers will also allow high certainty about the dimensions of the active area of our device, which is crucial for gathering accurate results. Metal wires will be attached to the exposed ITO electrodes at either end of the liquid crystal holder, providing electrical contact.

Later experiments will be performed with the liquid crystals 4’-Hexyl-4-biphenylcarbonitrile, and 4’-Octyl-4-biphenylcarbonitrile. These liquid crystals are 5CB liquid crystals with longer carbon chains (by 1, and 3 carbon atoms respectively). These extra carbon atoms will broaden the Curie temperature range and increase the entropy of transformation. By mixing these polymers the device may be tuned to have a wider operating region, and ultimately increasing efficiency for real world application.

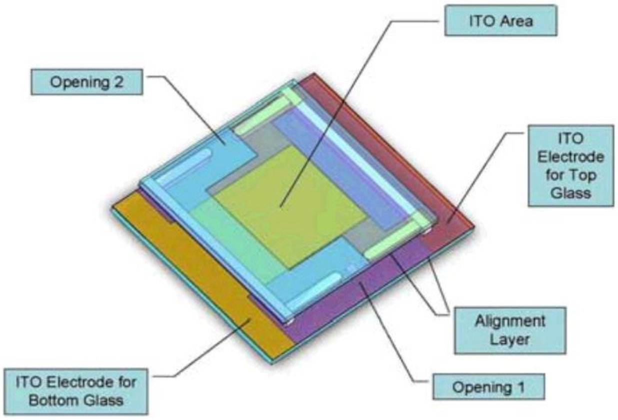

**Figure 5 – Instec Homeotropic Liquid Crystal Holder [6]**

| | |
|---|---|
| Liquid Crystal Thickness | 5 microns |
| Contact area | 100 microns$^2$ |
| Voltage across stack | 400 volts |

**Figure 6 - Design Specifications for Instec Homeotropic Liquid Crystal Holders [6]**

# Harvesting Circuit Design:

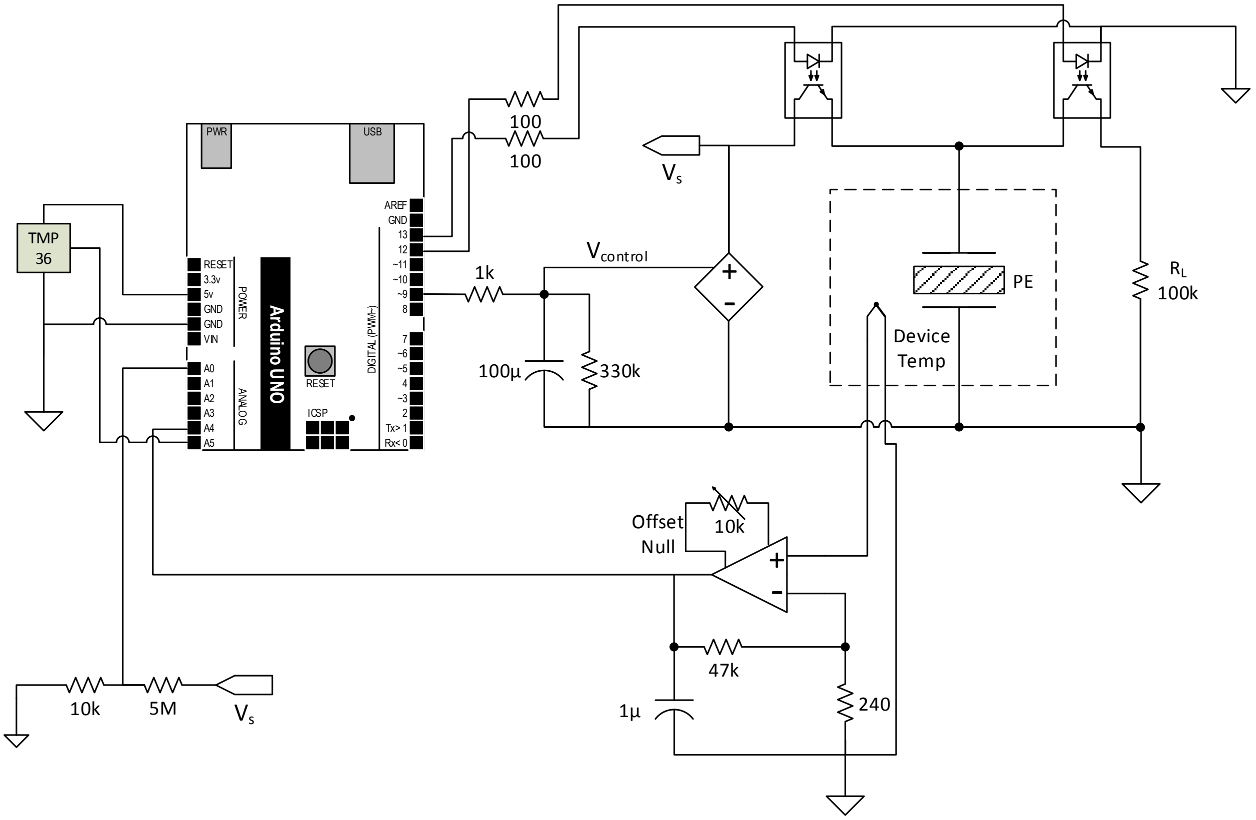

**Figure 7 - Schematic of the harvesting circuit, utilized to harvest energy with the pyroelectric effect.**

In order to achieve our objective, we used a thermocouple (pin A4) and an ambient (pin A5) sensor to obtain a temperature profile for our pyroelectric. The thermocouple signal was too weak for the Arduino to measure, so an amplifier was used. This signal was utilized to drive the device through the state transitions. We also used an adjustable 1kV DC-DC converter to put the appropriate electric field across the pyroelectric element. The magnitude of the source was controlled by PWM through pin 9 and measured at pin A0. The voltage measurement was scaled down through a voltage divider to protect the Arduino from high voltage. These voltages are the final triggering element that drive the state transitions.

## Temperature Measurement

This device will experience temperatures in the range of 25-150°C depending on the materials used for the pyroelectric medium. For this range, type T thermocouples (copper and copper/nickel leads) are well suited for temperature measurement. They provide accurate measurement for temperatures from -250-350°C, with a standard error tolerance of 1.0°C or 0.75% (whichever is greater). The metals used will resist oxidation and degradation in environments with moisture, which they may experience in our heat transfer system. Type T thermocouples will output voltages ranging from 0 to 10 mV, with a 39 microvolt / degree C difference between the hot and cold junctions, therefore staying well within the range of acceptable input values for the microcontroller.

Since thermocouples measure a relative temperature between the hot and cold junctions, an absolute temperature sensor must be utilized in order to determine the temperature that the cold junction experiences (room temperature). A TMP36 low voltage temperature sensor was chosen for its accuracy and ease of implementation with the Arduino UNO.

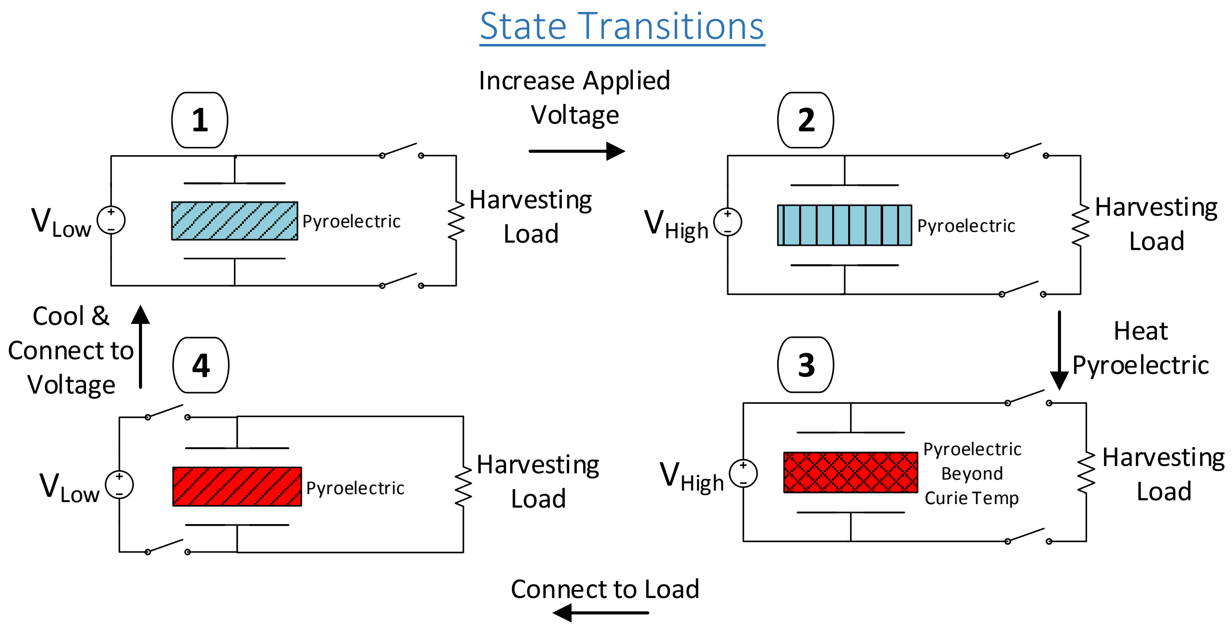

**Figure 8 - State diagram of pyroelectric energy harvester.**

The state transitions driven by the harvesting circuit are shown above. The element starts near room temperature with a low applied voltage from the variable DC power supply. The applied voltage is increased, aligning the dipoles and polarizing the material (2). The pyroelectric material is heated above its Curie temperature while the high voltage continues being applied (3). After the pyroelectric reaches a predetermined temperature, the variable DC power supply is disconnected and the harvesting load is connected to drain the harvested energy (4). Finally, the material is cooled and the low voltage is reapplied, returning the element to state 1.

# Deliverables

Due to the nature of our project, we split our deliverables in two separate timetables, December and May. In December, we presented a preliminary pyroelectric device, and a concept circuit. For May we have a tested pyroelectric device, and a harvesting circuit. 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) . Depending on the results, this development could revolutionize the thermal energy harvesting industry.

# Risk Management/Safety

Proper care was taken to ensure safety when operating the pyroelectric device. The primary safety concern was in regards to the inherent voltages in excess of 400V. This presented an acute risk for electrocution. Indeed, there were a few times when arms were numbed due to large electric discharges into them. Shock risk was 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 in the future, but was not utilized for this project. 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.

The final safety concern was working with polymer fabrication. The solvents used for P(VDF-TrFE) fabrication were toxic, and if the polymer had ignited it would have produced fluorine gas. Thus all polymer fabrication was done in a fume hood. In addition to working in a fume hood, nitrile gloves, a lab coat, and safety glasses were worn to protect against splashing of the polymer or solvents.

# Task Assignments/Breakdown

**John:**

-Project management and timeline

-Communication (weekly report)

-Control systems

-Circuitry design

**Josh:**

-Web page design

-Circuitry design

-Electrical device research

**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

# Current Bill of Materials

## Liquid Crystal Materials

| Supplier | Part Number | Name | Unit | QTY | Price | Total | Purpose |
|---|---|---|---|---|---|---|---|
| Sigma Aldrich | 328510-1G | 4’-Pentyl-4biphenylcarbonitrile | Gram | 1 | $ 72.30 | $ 72.30 | Liquid crystal material |
| Sigma Aldrich | 338648-1G | 4’-Hexyl-4biphenylcarbonitrile | Gram | 1 | $ 90.20 | $ 90.20 | Liquid crystal material |
| Sigma Aldrich | 338680-1G | 4’-Octyl-4biphenylcarbonitrile | Gram | 1 | $ 84.80 | $ 84.80 | Liquid crystal material |
| Instec Inc. | SB100A005uT180 | Homeotropic alignment LC cells | Holders | 40 | $ 14.00 | $ 560.00 | Liquid crystal cells |
|  |  |  |  |  | **TOTAL** | **$ 807.30** |  |

## Polymer Materials

| Supplier | Part Number | Name | Unit | QTY | Price | Total | Purpose |
|---|---|---|---|---|---|---|---|
| Delta Technologies | CB-50IN-0107 | ITO coated glass slides | Piece | 20 | $ 8.00 | $ 160.00 | Substrates for polymer films |
| Piezotech |  | PVDF-TrFE 70/30 | Gram | 2 | $ 10.00 | $ 20.00 | Polymer powder |
| Sigma Aldrich | 227056-1L | N,N-Dimethylformamide | Liter | 1 | $ 85.40 | $ 85.40 | Solvent for dissolving polymer |
| Fisher Scientific | 02-896A | 1oz/30mL Polypropylene Bottles | 12ct Pack | 2 | $ 12.53 | $ 25.06 | Storing polymer solutions |
|  |  |  |  |  | **TOTAL** | **$ 457.30** |  |

## Electronic Components

| Supplier | Part Number | Name | Unit | Quantity | Price | Total | Purpose |
|---|---|---|---|---|---|---|---|
| Sparkfun | DEV-11021 | Arduino Uno | Board | 1 | $ 29.95 | $ 29.95 | Control Circuits. monitor outputs |
| Digkey | 1206DC105MAT2A-ND | 35V - 1uF - MLC - X7R | Capacitor | 5 | $ 0.23 | $ 1.13 |  |
| Digikey | 62-1163-ND | DC/DC 1kV converter | Unit | 1 | $ 189.02 | $ 189.02 | DC/DC converting |
| Digikey | MOC8204M-ND | Transistor Optocoupler | 6-DIP | 10 | $ 0.94 | $ 9.40 | Isolate gate logic control |
| Digikey | 922327-ND | 3 Row solderless BB | Board | 1 | $ 122.04 | $ 122.04 | breadboard |
| Digikey | TMP36GT9Z-ND | Temperature Sensor | Unit | 3 | $ 1.42 | $ 4.26 | Ambient Temp sensor |
| Digikey | 290-1911-ND | K-type Temperature Probe | Unit | 3 | $ 14.95 | $ 44.85 | Oil Sensor |
| Digikey | 290-1986-ND | Thermocouple F-sockets | Unit | 3 | $ 7.10 | $ 21.30 | Oil Sensor |
| Digikey | 993-1232-ND | AC/DC wall pack | Unit | 1 | $ 4.68 | $ 4.68 | DC/DC converting power |
|  |  |  |  |  | **TOTAL** | **$ 426.63** |  |

## Lab Supplies

| Supplier | Part Number | Name | Unit | QTY | Price | Total | Purpose |
|---|---|---|---|---|---|---|---|
| Fisher Scientific | A18P-4 | Acetone (Certified ACS) | 4L Bottle | 1 | $ 22.06 | $ 22.06 | Solvent for cleaning |
| Fisher Scientific | A412P-4 | Methanol (Certified ACS) | 4L Bottle | 1 | $ 16.12 | $ 16.12 | Solvent for cleaning |
| Fisher Scientific | 874-R10 | Best Butyl II Gloves | Pair | 1 | $ 50.47 | $ 50.47 | Personal protective equipment |
| Fisher Scientific | 34115 | 4.4 x 8.4 Lint Free Wipers | 280ct Box | 2 | $ 3.82 | $ 7.64 | Cleaning |
| Fisher Scientific | 23-400-118 | Cotton-Tipped Wooden Applicators | 1000ct Pack | 1 | $ 7.71 | $ 7.71 | Cleaning |
| Fisher Scientific | 13-711-9AM | Graduated Disposable Pipettes | 500ct Box | 1 | $ 14.29 | $ 14.29 | Transfer of liquids |
| Chem Stores | 21003145 | Disposable Nitrile Gloves 50pr/box | Box | 2 | $ 6.04 | $ 12.08 | Personal protective equipment |
| Ted Pella Inc. | 16085-1 | Carbon Conductive Sheet | Pack/10 | 1 | $ 39.75 | $ 39.75 | Contact fabrication |
| Ted Pella Inc. | 16072-1 | Copper Conductive Tape | Roll | 1 | $ 41.25 | $ 41.25 | Contact fabrication |
| Ted Pella Inc. | 16087-12 | Double Sided Kapton Tape | Roll | 1 | $ 52.10 | $ 52.10 | Contact fabrication |
| Ted Pella Inc. | 16051 | PELCO Water Based Carbon Paint | 50g Bottle | 1 | $ 9.95 | $ 9.95 | Contact fabrication |
| Ted Pella Inc. | 16032 | PELCO Colloidal Silver Paste | 25g Bottle | 1 | $ 59.50 | $ 59.50 | Contact fabrication |
|  |  |  |  |  | **TOTAL** | **$ 332.92** |  |

# Appendix I: Operation Manual

Operational Notes:

1. Connect the $V_+$ and $V_-$ pins to the appropriate power sockets as seen in Figure 9.
    a. Affix the pyroelectric element to the $PE_+$ and $PE_-$, these devices are not polar

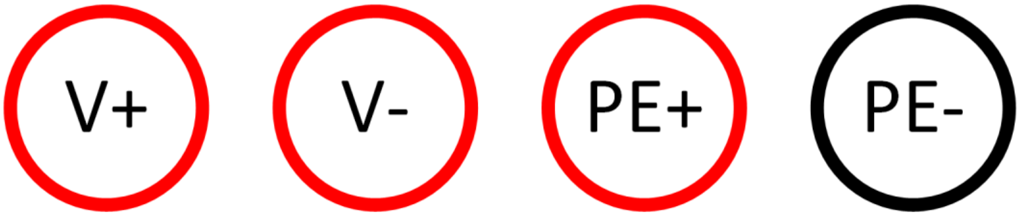

**Figure 9 - Power socket configuration. Note that the ground node is located in a separate bus and should not be confused with V-.**

2. Launch the Arduino interface on a PC, ensuring a proper USB connection between the device, Arduino and computer
    a. Run the pyroharvester.ino script
3. Launch MATLAB and run the serialcom.m script
4. Follow command line prompts
    a. Follow these prompts to move between states in the Olsen cycle
    b. To stop the cycle, press CTRL+C
    c. To restart the cycle, rerun the script
5. When finished, run resetserial.m
    a. This clears the data buffer, allowing communication to be reestablished in the future.

As this is an infrastructural project the operations manual contains very few steps. That being said, caution needs to be excised while working with this design, there are potentially hazardous components that can injure the operator.

1. There is a large DC-DC power supply that can output upwards of 1kV. While this supply can deliver a powerful shock, it is a relatively low power device (~1µA), and should not be able to cause death.
2. In order to cross the Curie temperature of the pyroelectric device, oil must be heated to temperatures exceeding 100°C. In the current set up, the device needs to be transitioned from a hot and cold state manually. These transitions allow for oil to be spilled on the operator.

With careful operation, these potential hazards can be avoided.

# Appendix II: Prior Design Concepts

## Automated Heat Transfer System

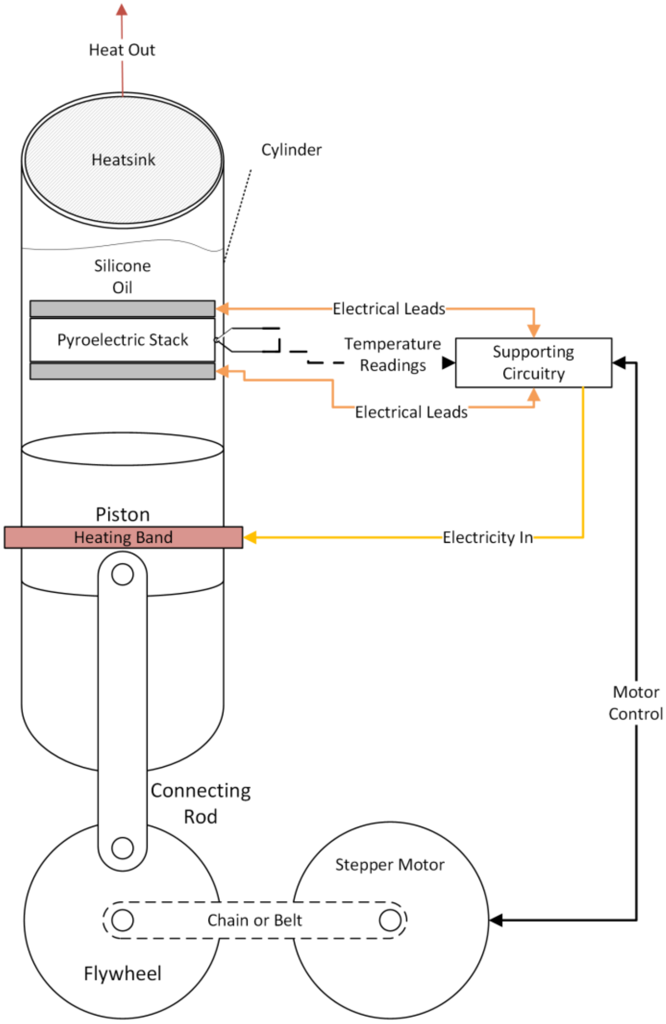

**Figure 10 - Concept sketch of pyroelectric generator including heat transfer system and stack**

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 10 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.

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.

*The automated heat transfer system was not implemented for a few reasons. Implementation of an automated heat transfer system would take a significant amount of time, and would not be necessary to demonstrate the pyroelectric effect and harvest energy from it. Additionally, no members of the group had experience with fluid dynamics, which would allow for better design and optimization of the heat transfer system.*

## Optoisolator & MOSFET Switching System

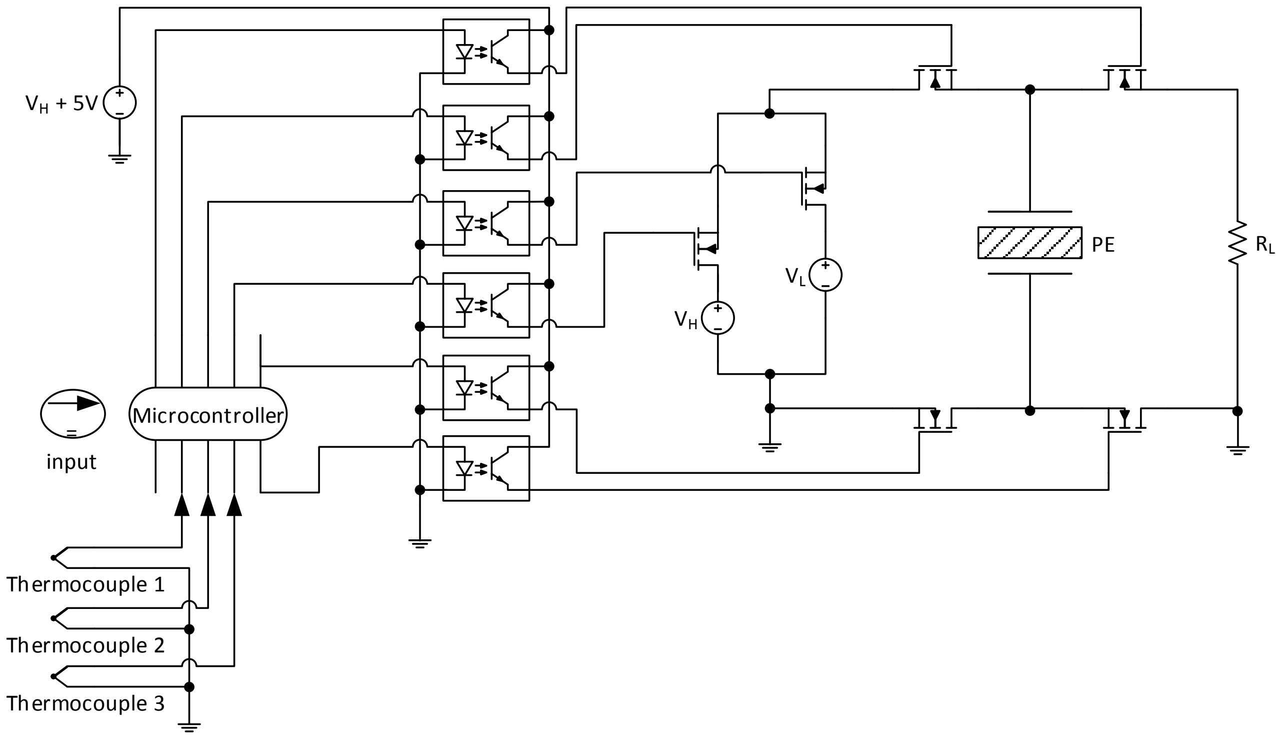

**Figure 11 - Harvesting circuit design schematic.**

While the PVDF devices will only require a nominal 50 volts at their terminals for maximum efficiency, the liquid crystal pyroelectric devices will require sustained terminal voltages of 400 volts. The harvesting circuit must provide a means to switch between charging and discharging the element according to the state of the system while maintaining these high voltages.

High voltages will be provided by a lab-grade, high voltage, triple output power supply for materials and devices requiring 300 V or below across their terminals. If voltages above 300 V are required (in the case of the liquid crystal devices), we will employ a number of modular DC-HVDC converters. Ultravolt Inc. is one company which makes such devices.

The harvesting circuit will consist of the pyroelectric element, which will be alternately connected to a power supply (at $V_{Low}$ or $V_{High}$) or a load resistor, $R_L$. Switching will be controlled by a low power microcontroller. The microcontroller will also take thermocouple voltage readings to determine the system's state.

### Optoisolators and Switching MOSFETs

The circuit design utilizes optoisolators to convert low power logic output from the microcontroller to high gate voltages on the high power MOSFETs used to switch the circuit between charging and discharging configurations. In order to ensure high enough gate voltages on the MOSFETs, we will use a voltage source set slightly higher than $V_{High}$ plus the transistor threshold voltage, $V_T$ .

The optoisolators consist of a single LED which shines light at the base of a phototransistor when powered by a logic high signal from the microcontroller. The base current flows into the phototransistor no matter its collector-emitter voltage. Even a small collector-emitter current will expose the connected MOSFET gate to $V_{High}$ + 5V because of the MOSFET’s high input impedance. When the microcontroller turns off the optoisolator, the MOSFET gate voltage will drop as a result of leakage current within the transistor.

It is important to note that selection of the optoisolators and the microcontroller will go hand-in-hand, as we must match the power input/output specifications of both devices.

We will monitor the voltage on $R_L$ to determine the energy produced each cycle. Input electrical energy will be determined by monitoring current through each of the three voltage sources. This will help us determine the efficiency of our system. At the very least, we aim to maintain positive net electrical energy production.

## Control System

After manually recreating the Olsen cycle, our next goal is to create an automatic system as indicated above. Data collection and analysis will be critical in creating not only the automatic system, but ensuring that it will be able to perform within operating parameters. The most efficient way to control our system will be with the aid of a microcontroller.

Our microcontroller will be used to govern the switching of our harvesting circuit. It is important that the interface board will allow us to not only monitor the thermocouples, but also allow us to send the appropriate signal to the optocoupler isolators to trigger the MOSFETs. After analyzing the array of microcontrollers on the market we came to the conclusion that an Arduino UNO microcontroller will allow us adequate control at minimal cost. As long as the necessary thermocouples are present, the microcontroller will be capable of controlling the harvesting circuit, regardless of how heat transfer is managed, i.e. automatic or manual.

In order to maintain a continuous temperature oscillation around the Curie temperature, we will drive a piston vertically. The most efficient way to achieve this is with a stepper motor. By knowing the characteristics of the dielectric oil and piston assembly, we were able to determine the necessary motor parameters to perform such a task using kinematics.

Preliminary dimensions for the heat transfer system are a cylinder 1.5 inches in diameter, a piston ½” thick, 4” of silicone oil, a stroke of 2”, and a stroke time of 0.1 seconds, the approximate size necessary for the motor can be calculated using the mass of the moving parts. This results in a motor with a power of 1.2 watts while applying 5.9N-cm or 8.4oz-in of torque, at 300rpm. Ultimately, we choose a 32.5 oz-in stepper motor from Sparkfun. While larger than necessary, it is readily available and well documented. SparkFun provides a driver with will allow us to easily control the stepper. With the microcontroller and stepper motor we will be able to accurately recreate the Olsen cycle.

*This design was discarded for multiple reasons. First, the MOSFETs were an unnecessary addition to the optoisolators, increasing complexity of the circuit with little to no improvement in efficiency. Implementation of heat transfer system control logic into the harvesting circuit further complicated device design and is unnecessary at our scale of testing.*

## Sawyer-Tower Circuit

In phase one of the device interface circuitry, we will be using a Sawyer-Tower circuit (Figure 12) to characterize the pyroelectric device. It will determine the voltage and charge displacement parameters of the device.

Using basic circuit analysis techniques, we will be able to determine the pyroelectric device's state without disturbing it significantly. Connecting a capacitor of a known value in series with the pyroelectric device allows us to measure the charge displacement by the relationship V= q/C. A slight complication when measuring this voltage is the leakage current associated with using a measurement device with relatively low impedance, such as an oscilloscope (roughly 1 MΩ). With the currents generated by the pyroelectric element being on the order of micro amps, we cannot afford any leakage current from the oscilloscope. The most efficient alternative is to use a standard voltmeter which has approximately 8 MΩ. Furthermore, we anticipate the output signal of the pyroelectric will be a direct coupled signal and will be better interpreted by the voltmeter.

Similar to the capacitor, the measure of the potential across the voltage divider will provide a scaled reading of the terminal voltage. This is a fairly standard electrical engineering technique that allows us to regulate the voltage across two resistors in series; which allows us to determine the electric field strength.

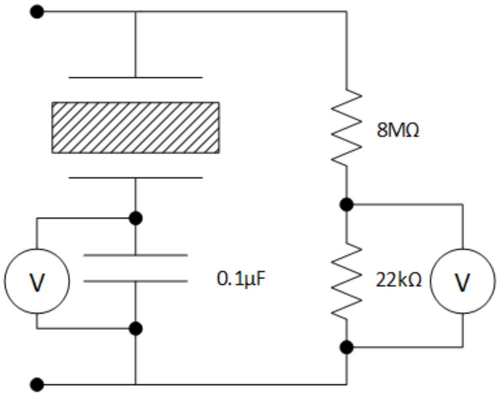

**Figure 12 - Sawyer-Tower Circuit for Pyroelectric Characterization**

This process has not been attempted on liquid crystals before, therefore we are not expecting this process to work without some refinement. Once we have gathered data to characterize our PVDF and liquid crystal devices, we will be able to finalize the energy harvesting circuits for the second phase. The design for this phase will involve sequentially switched components, which will be addressed in subsequent sections.

*While this circuit is useful for device characterization, it cannot be used in the harvesting design as it will drain power. Thus it was not implemented into the final design.*

## Polymeric Pyroelectric Elements

The construction of the polymeric pyroelectric stacks (Figure 13) will be accomplished using spin coating techniques. The copolymer of choice poly[(vinylidenefluoride-co-trifluoroethylene], P(VDF-TrFE), in a 70 PVDF to 30 TrFE ratio, will be solutionized in Dimethylformamide (DMF). After dissolving the polymer, the solution will be applied to the surface of indium tin oxide (ITO) coated glass substrates. These substrates will be immediately spun at ranges of 750rpm to 3000rpm on a metal chuck. The centrifugal forces will cause the polymer solution to disperse evenly across the surface of the substrate, with speed and time controlling the thickness of the films. The substrate and film will be dried at elevated temperatures of 60 to 80 degrees Celsius, removing the solvent and forming a solid film. Spin coating was chosen because it allowed for a more even and thinner dispersion of material compared to other methods, such as hot pressing. Thickness uniformity is crucial to apply a homogeneous electric field across the film. In addition it was the most readily available and previously researched method of fabrication for P(VDF-TrFE) films. Film thickness and uniformity will be measured utilizing contact profilometry. This will determine the most ideal processing conditions to yield the desired film thickness and quality ( Figure 14).

The top contact will be fabricated by the application of conductive paint or tape across the entire top surface of the film, followed by attachment of a wire lead. To create a contact with the indium tin oxide film, a cotton swab will be soaked in DMF, and utilized to remove a corner of the polymer film, allowing for a wire to be attached to the indium tin oxide with conductive tape or paint. As a result, a metal-insulator-metal capacitor structure will be created, allowing for capacitance versus applied temperature and electric field measurements. Various contact materials including silver paint, graphite paint, graphite tape, copper tape, and evaporated aluminum will be tested to find which yields the best electrical contact.

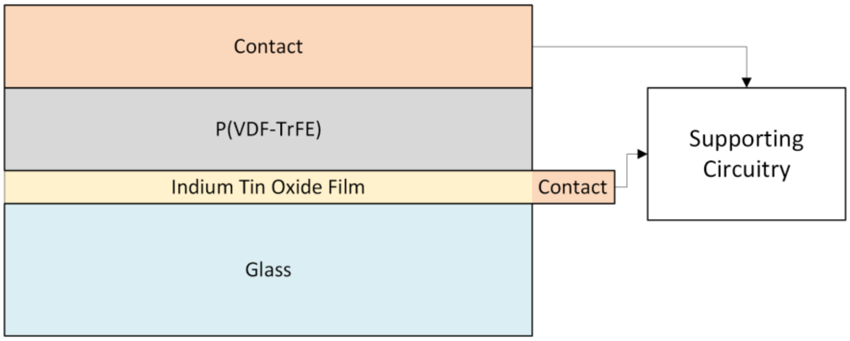

**Figure 13 - Cross Section of Polymer Pyroelectric Elements**

| | |
|---|---|
| ITO thickness | 120-160 nm |
| Polymer film thickness | 1 micron |
| Voltage across stack | 30-50 volts |

**Figure 14 – Design Specifications for Polymer Pyroelectric Elements**

*Lab made polymer films were not implemented due to poor process control and unintentional porosity of the surface. By using commercial films, it is guaranteed that the films will have highly uniform thickness and minimal to no porosity, preventing shorting between metalized layers.*

# Appendix III: Other Considerations

## Pyroelectric vs. Electrocaloric Effect

The pyroelectric and electrocaloric effects are complementary phenomena. When researching materials and processing parameters, we looked at papers for both effects. In fact, the paper on liquid crystals which originated this project involved the electrocaloric effect. When searching for barium titanate capacitors to use as a backup and basis for comparison we found a paper which utilized X7R rated capacitors from AVX. When attempting to utilize these capacitors for our pyroelectric measurements (involving a temperature range of 50 – 150 degrees centigrade), there was a substantial leakage current across the capacitor. Upon troubleshooting the problem and consulting the datasheet we determined that while the capacitors are rated up to the temperatures utilized, the resistance of the insulation goes down by over a factor of 20. The electrocaloric effect can take place around room temperature, while the pyroelectric effect requires more substantial temperature changes in order to harvest energy. While the materials are capable of demonstrating both effects, the different conditions utilized to harness each effect can cause unforeseen problems.

## Procedures from Papers

In our initial background research we investigated the procedures utilized by other groups to fabricate polymer films as well as create capacitor structures for use with liquid crystal materials. We derived our polymer film fabrication procedures from these papers. Despite the range of solvents specified, solution concentrations, spinning parameters, and post processing conditions we struggled to create a uniform, dense P(VDF-TrFE) film. Hot pressing (a technique utilized by another group) was also unsuccessful, failing to even melt the polymer significantly. The holders utilized to construct liquid crystal capacitors were purchased because they were used in the paper which discussed the electrocaloric effect in liquid crystals. 5CB liquid crystals were chosen for their high entropy nematic phase transition as well as their usage in the referenced paper. In their studies, that group was able to apply up to 90MV/m across the liquid crystal specimens without breakdown. In our studies we were unable to apply greater than 40MV/m across the liquid crystals before they would begin to have a high leakage current which would further reduce the field to 25MV/m. While papers often make processes appear simple at face value, there are often unexpected difficulties in implementation.

# Appendix IV: Code

## serialCOM

```
%clean up if last run ended prematurely
if exist('s')
    fclose(s); %close connection
    delete(s); %clear from memory
    clear s; %clear from workspace
end
%-------------------------------------------------------
clear all
close all

%Open the serial port by
s=serial('COM7','BaudRate',9600);
fopen(s);

%initialize
rx_prev = [];

sourceVoltage = [];
loadResistorVoltage = [];
pyroelectricCurrent = [];
pyroelectricTemperature = [];
%-------------------------------------------------------

%% Set up the figure

xIndex =now;
sourceVoltage = 0;

figureHandle = figure('NumberTitle','off',...
    'Name','Voltage Characteristics',...
    'Color',[0 0 0],'Visible','off');

% Set axes
axesHandle = axes('Parent',figureHandle,...
    'YGrid','on',...
    'YColor',[0.9725 0.9725 0.9725],...
    'XGrid','on',...
    'XColor',[0.9725 0.9725 0.9725],...
    'Color',[0 0 0]);

hold on;

plotHandle =
plot(axesHandle,xIndex,sourceVoltage,'Marker','.','LineWidth',1,'Color',[0 1 0]);

% Create xlabel
xlabel('Sample','FontWeight','bold','FontSize',14,'Color',[1 1 0]);

% Create ylabel
ylabel('Supply Voltage','FontWeight','bold','FontSize',14,'Color',[1 1 0]);

% Create title
title('Real Time Data','FontSize',15,'Color',[1 1 0]);


%% Run Collection Loop
```

```
voltageDataCount = 1;

while 1
    rx = fscanf(s, '%s%c');
    display(rx);

    if strcmp(rx_prev,'Vs: ')
        sourceVoltage = [sourceVoltage, str2num(rx)];
        voltageDataCount = voltageDataCount + 1;

    elseif strcmp(rx_prev,'Vl: ')
        loadResistorVoltage = [loadResistorVoltage, str2num(rx)];
    elseif strcmp(rx_prev,'PEuA: ')
        pyroelectricCurrent = [pyroelectricCurrent, str2num(rx)];
    elseif strcmp(rx_prev,'T: ')
        pyroelectricTemperature = [pyroelectricTemperature, str2num(rx)];

    end

    rx_prev =  rx;


    xIndex(voltageDataCount) = voltageDataCount;
    set(plotHandle,'YData',sourceVoltage,'XData',xIndex);
    set(figureHandle,'Visible','on');

end

fclose(s); %close connection
delete(s); %clear from memory
clear s; %clear from workspace
```

## clearSerialFromMemory.m

```
fclose(s); %close connection
delete(s); %clear from memory
clear s; %clear from workspace
```

## pyroHarvester.ino

```
// These constants won't change.  They're used to give names
// to the pins used, circuit characteristics:
const int vDivIn = A0;  // Analog input pin that the voltage divider is attached to
const int srcFilterOut = 9; // Analog output pin that the filter/buck converter is
attached to
const float voltageDiv = 501.0; // Inverse Gain of the voltage divider (500k and 1 k)
const int srcIsolator = 12;  //harvesting power source switch trigger
const int loadIsolator = 13;  //harvesting load switch trigger

//Global
int sensorValue0 = 0;        // ADC value read from the HVDC voltage divider
int sensorValue1 = 0;        //ADC value read from TM36 temp sensor.
int sensorValue2 = 0;        //ADC value read from thermocouple 0.
int sensorValue3 = 0;        //ADC value read from 100 ohm resistor in series with PE.
int sensorValue4 = 0;        //ADC value read from load voltage divider.
int state = 0;              //state of the Q-V cycle

//Material-specific prameters
float tCold = 50; //100
```

```
float tHot = 90; //150
float vLow = 50; //50
float vHigh = 100; //500

//Current (temporal) sensor readings
volatile float Vs = 0;          // Calculated voltage value at HVDC terminal
float ambient = 0;          //Ambient Air Temperature
float deviceTemp = 0;       //Temp at thermocouple 0 tip (C).
float Vl = 0;          // Calculated voltage on 100k load
float PEuA = 0;          // Calculated current through PE in mA


// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
  pinMode(srcIsolator, OUTPUT);
  pinMode(loadIsolator, OUTPUT);


  digitalWrite(loadIsolator, LOW);


  digitalWrite(srcIsolator, HIGH);
}


void loop() {

  writeSrcV(0);
  writeSrcV(120);


}

void harvester(){

    if (state == 0){//initialization state
      Serial.println("Initialization State. Cool the Sample.");

      //wait for temp to equalize
      if(deviceTemp <= tCold){
        //activate source switch
        digitalWrite(srcIsolator, HIGH);

        //ramp voltage to start point
        writeSrcV(vLow);
        state = 1;

        Serial.println("State machine initialized.");
      }

     return;
    }
    if (state == 1){
      Serial.println("State 1 --> 2 (UL). Cold Isotherm.");

      writeSrcV(vHigh);

      for (int i=0; i<100; i++){
        readSensors();
        printSensors();
        delay(1); //calc later -  this waits for PE to charge
```

```
      }

      digitalWrite(srcIsolator, LOW);
      state = 2;
      return;
    }
    if (state == 2){
      Serial.println("State 2 --> 3 (UR). Heat the sample.");

//      if(Vp > vHigh){
//        //activate load switch
//        digitalWrite(loadIsolator, HIGH);
//        delay(1);
//        //deactivate load switch
//        digitalWrite(loadIsolator, LOW);
//      }



      while(deviceTemp < tHot){
        readSensors();
        printSensors();
      }

        state = 3;

      return;
    }
    if (state == 3){
      Serial.println("State 3 --> 4 (LR). Hot Isotherm.");

      //this happens quickly.
      //activate load switch
      digitalWrite(loadIsolator, HIGH);

      //Wait for device to discharge to lower limit
      while(Vl > vLow){
        readSensors();
        printSensors();
      }

      //deactivate load switch when PE is sufficiently discharged
      digitalWrite(loadIsolator, LOW);

      state = 4;
      return;
    }
    if (state == 4){
      Serial.println("State 4 --> 1 (UR). Cool the sample.");


      writeSrcV(vLow);
      //activate source switch
      digitalWrite(srcIsolator, HIGH);


      //wait for temp to equalize
      while(deviceTemp > tCold){
        readSensors();
        printSensors();
      }
```

```
      state = 1;
      return;
    }
   Serial.println("No state detected - debugging error");
   return;
}

void readSensors(){
  //NOTES:
  //ADCConst = 5/1023  ---  scale factor for ADC
  //thermocoupleScale = 41/1000000   ---   scale factor for type K (yellow)
thermocouple (volts to degrees C)



  // read the input on analog pin 0,1:
  sensorValue0 = analogRead(A0);
  delay(1);
  sensorValue1 = analogRead(A5);
  delay(1);
  sensorValue2 = analogRead(A4);
  delay(1);
  sensorValue3 = analogRead(A1);
//  delay(1);
//  sensorValue4 = analogRead(A2); //This ADC pin is dead!

  // Convert the analog reading (which goes from 0 - 1023) to a voltage (0 - 5V), plus
any voltage divider scaling or temp-voltage relationship:
  Vs = (float) sensorValue0 * voltageDiv * 5/1023;
  ambient = (float) sensorValue1 * 500/1023 - 50; //voltage-temp (C) relationship from
ADAFRUIT
  deviceTemp = (float) sensorValue2 * 1000000 * 5 /1023 / 196.83 / 41 + ambient; //
multiplication first to account for order of operations
  PEuA = (float) sensorValue3 * 6.667 * 5/1023; //
  //Vl = (float) sensorValue4 * voltageDiv * 5/1023;
}

void printSensors(){
  //Serial.println("Ambient sensor ADC: ");
  //Serial.println(sensorValue1);
//  Serial.println("Ambient: ");
//  Serial.println(ambient);
//


  Serial.println("Vs: ");
  Serial.println(Vs);

  Serial.println("Vl: ");
  Serial.println(Vl);

  Serial.println("PEuA: ");
  Serial.println(PEuA,5);

  Serial.println("T: ");
  Serial.println(deviceTemp);
}

void writeSrcV(int voltage){
  Serial.println();
  //calc duty cycle - admittedly this is approximate
   float dutyCycle = voltage/10;
```

```
   //Set the voltage source PWM duty cycle
   int pwmValue = floor(dutyCycle*255/100 * 0.81);
   analogWrite(srcFilterOut, pwmValue);

   delay (100);

   //Tune the voltage
   for (int i=0; i<20; i++){
     readSensors();
     printSensors();
     if (voltage == 0){
       readSensors();
       printSensors();
     }
     else if (Vs > voltage + 1){
       dutyCycle = dutyCycle - 0.1;
       pwmValue = floor(dutyCycle*255/100 * 0.81);
       analogWrite(srcFilterOut, pwmValue);
     }
     else if (Vs < voltage - 1){
       dutyCycle = dutyCycle + 0.1;
       pwmValue = floor(dutyCycle*255/100 * 0.81);
       analogWrite(srcFilterOut, pwmValue);
     }
     else{
       return;
     }
     delay(10);
     //Serial.println(i);
   }
}



//MATLAB serial example  deviceTemp > tCold
//http://robocv.blogspot.com/2012/01/serial-communication-between-
arduino.html?q=arduino
```

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