COMPOST THERMAL HEATING PROJECT

by

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research advisor, senior thesis instructor, and department chair and has been found to be satisfactory.

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ABSTRACT

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We investigate the possibility of harnessing the latent energy created by microbial decay in a compost pile. Preliminary measurements were conducted at a local compost facility to determine the typical thermal profile of a compost pile and its surrounding environment. These temperature conditions were replicated in the laboratory to investigate the possibility of producing electrical currents with two thermoelectric modules. The results indicate that a potential difference of roughly four volts can be attained, which, with the assistance of a self-powered DC-DC converter, can be augmented to twelve volts. This suggests that the thermal atmosphere within a well managed compost pile permits the production of small scale electrical currents useful for passive applications such as battery charging. We provide a proof of concept and use our data as a starting point for developing an equation which can predict battery charging time based on temperature and module characteristics.

ACKNOWLEDGMENTS

The project could not have been completed without the help of several individuals and organizations. I would first like to thank Professor Peter Melcher of the Ithaca College Biology Department; the data for part one of the project could not have been acquired without the CR-10X data logging unit he loaned us. I also want to thank all the individuals of the Cayuga Compost Facility, specifically John Proctor and Mark Wittig. Without their knowledge, cooperation, and guidance the compost experiments detailed below could not have been completed. The research during the summer of 2007 was a crucial part of the project and I want to thank the DANA internship committee for funding my work that summer. Most importantly I'd like to thank Professor Michael Rogers of the Ithaca College Physics Department. His support and guidance over the past three years has helped determine the direction and success of this project. I am also very grateful for Luke Keller's time and effort in the revising process of this thesis.

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Chapter 1

Introduction

The compost thermal heating project is an investigation into alternative, renewable energy sources that seeks to demonstrate the availability and efficacy of decentralized micropower. Growing concerns about the extent of anthropogenic environmental impacts have spurred international interest in sustainability. Colleges and universities around the globe have begun researching potential solutions to bring about positive environmental change.

1.1 Project Motivation

In order to realize such change the University Leaders for a Sustainable Future drew up a ten point action plan at an international conference in Talloires, France in 1990. The document has become known as the Talloires Declaration, an agreement where signatory institutions commit to incorporating progressive environmental thought into teaching, learning, and research. Ithaca College, under the direction of then president Peggy Williams, signed the declaration in the Spring of 2006. The project described here was inspired by many of the ideals set forth in the declaration.

Although the Talloires Declaration is a good start to addressing pressing environmental issues, it makes no concrete demands of its signatory institutions. For this reason it has been criticized by some as ineffective and trivial. In response to this, more binding agreements have been devised in an effort to encourage participating organizations to fulfill their pledges. A year after signing the Talloires Declaration former IC president Peggy Williams also signed the American College and University Presidents Climate Commitment. Although the agreement does not stipulate any official time span, it does require its member institutions to achieve carbon neutrality in the future. This involves the mitigation and eventual elimination of any fossil fuel emissions resulting from activities of the institution, including all electricity use, transportation, and heating.

The compost thermal heating project is a proof of concept aimed at reducing carbon emissions associated with electricity production. During the summer of 2007 I was awarded a DANA internship to conduct research here at Ithaca College with Professor Michael Rogers. The original project proposal involved determining the thermal resources of the composting operation on campus and whether they could be utilized to help reduce the carbon footprint of the college. Unfortunately between the time of my acceptance and the beginning of my internship the compost operation was moved off campus due to sanitation concerns. The college began to send its food waste to Cayuga Compost, a subsidiary of P&S Excavating that serves the composting needs of the greater Ithaca area (See Fig. 1.1). Over the course of a few weeks I made contact with Mark Wittig, the manager of the composting operation. In exchange for a few hours of manual labor each week he allowed me a small amount of his compost that I could perform tests on. After a few changes in project direction Professor Rogers and I began to consider the possibility using the thermal energy within the pile to produce electricity. Although this would no longer directly contribute to a reduction in the college's carbon footprint since the operation had been moved off campus, the motivation behind this potential renewable energy source had its roots in both the Talloires Declaration and the Carbon Neutrality Agreement.

Figure 1.1 The Cayuga Compost facility that serves the greater Ithaca area. Started in early 2006, the facility now has several windrows that can attain temperatures as high as 70C (160F).

1.2 Previous Work

The thermal resources of compost piles have been the subject of study for the past 20 years. Some of the recent investigations into possible uses of 'waste heat' occurred during the early 1980s [2]. Waste heat is a term often used in the thermoelectric industry to refer to thermal energy that is usually a byproduct of another process. Although it is imprecise physics language it is a term one needs to be familiar with when working with thermoelectricity. Pioneering individuals in the emerging green movement began trying to reduce dependence on fossil fuels whose volatility as an energy source was first exposed by the energy crises of the 1970s. During this time efforts were mainly concentrated on utilizing the thermal energy directly for space heating applications. In 1986 Bruce Fulford of the New Alchemy Institute, an organization dedicated to the redesign of human agriculture and other support systems, published the results of a two year study on a composting greenhouse. The study documents the design and construction of a new type of greenhouse in which passive solar heating was supplemented with a compost heating system. Studies prior to those conducted by the NAI have shown that aerobic decomposition by thermophilic bacteria in a compost pile can yield as much as 4 watt-hours of energy per gram of oxygen used (14.4 $\mathrm{MJ/kg}_{O2}$) [2]. Some of this energy allows moisture in the pile to vaporize. By allowing this water vapor to condense on nearby insulated greenhouse beds the NAI utilized the latent heat of vaporization to provide root-zone heating for the plants.

More recently other organizations have engaged in similar projects on a more commercial scale. Agrilab Technologies Inc., a subsidiary of the Acrolab Group of Ontario, Canada, has recently designed several heating systems with compost as the energy source. In late 2006 the company finished installing a compost fueled water heating system at Diamond Hill Custom Heifers farm [10]. Here a system of subterranean ductwork and aerating fans move water vapor from the compost beds to isobaric superthermal conductors that are partially immersed in a large water reservoir. The incoming water vapor condenses on these isobars and the resulting latent heat of vaporization is spread across the surface of the isobars at near sonic speeds because of their unique properties. Thus the water within the reservoir is heated quickly and efficiently as long as its temperature remains below that of the incoming water vapor.

The notion of producing electricity from a temperature difference dates much farther back than the work of Agrilab and the New Alchemy Institute. Thomas Johann Seebeck is credited with discovering the effect which now bears his name, although his initial beliefs about its cause were somewhat erroneous. Subsequent work by Jean Charles Athanase Peltier and Hans Christian Ørsted showed that a temperature differential can be used to produce an electrical current and vice versa. This collection of physical phenomena are often called the thermoelectric effect. Thermoelectric modules (sometimes referred to as thermoelectric devices, Peltier coolers, or thermoelectric generators) are small devices that operate on the principles of the thermoelectric effect [Sec. 3.1]. They can be used both as temperature controllers or power generators. Previous work has shown that they can provide effective sources of electrical power when other conventional fuels are not available [8,9]. Because the Seebeck voltages produced by the modules are relatively small, a DC-DC converter is often employed to augment the voltage at the cost of current. For larger applications several modules can be wired in series or parallel depending on the requirements of the system. Substantial work has been done to quantify the voltage, current, and power output of such arrays [9].

Their passive nature makes thermoelectric modules perfect for putting waste heat to use. Because they require no direct fuel source they can be employed in environmentally friendly ways. Many activities result in the production of energy by heating, much of which is lost to the surrounding environment. A compost pile is a perfect example of a system that creates waste heat that is often unused and escapes into the atmosphere. Previous research has shown that thermoelectric modules can be used in conjunction with existing sources of waste heat such as residential boilers and furnaces to generate electricity [1]. The results indicate that even small sources of energy can be converted into electricity using thermoelectric modules. The environmental and economic costs of this process are almost negligible after purchasing the modules since the sources of energy often already exist and are not being fully used.

1.3 Goals

We seek to take advantage of the latent energy of compost piles but in a different way than the aforementioned operations. There are many ways that high temperature reservoirs can be put to use besides direct heating. For example, the invention of the Stirling engine showed that a temperature gradient could be used to produce mechanical motion. In the case of the compost thermal heating project the aim is to produce electrical power from the temperature gradient between the inside of the compost pile and its surrounding atmosphere. This can be realized by using thermoelectric modules to drive a current. Unfortunately thermoelectric technology is still very inefficient and thus the voltages and currents produced on our temperature scale are only useful for passive applications such as battery charging. We provide a proof of concept and begin to develop an empirical relation from our data that we can use to predict the charging time for 12V batteries based on the type and number of modules as well as the temperature conditions they are exposed to. The project has essentially two parts: the first involves measuring the thermal atmosphere of the compost pile and the second describes the performance of the thermoelectric modules.

Chapter 2

Thermal Profile of a Compost Pile

2.1 Experimental Design

Work began during my DANA internship in the summer of 2007. I met with Mark Wittig of Cayuga Compost and he agreed to allow me a small amount of compost to run tests on in exchange for a few hours of manual labor each week. My goal during the summer was to map out the atmosphere of a compost pile in its thermophilic or high-temperature stage. The actual temperature measurements were taken with a thermistor array wired to a CR-10X data logging unit (DLU) from Campbell Scientific (See Fig. 2.1).

Before taking measurements I had to devise a way in which to protect the thermistors from the acidic environment inside the pile. I used ten segments of 1" diameter PVC tubing to act as sheaths for the thermistor wires. Holes were drilled into the business ends of the tubes in order to get an accurate temperature reading at its location within the pile. I then capped these ends to prevent organic material from coming into contact with the thermistors. On the sheaths I placed tick marks roughly one foot apart so that I could get an approximate depth of the sheath when it was

Figure 2.1 The CR-10X data logging unit used in mapping out the temperature profile of the compost pile. The control keypad (A) was used to set the sampling rate and program. Temperatures were recorded as voltage measurements in the actual DLU (B).

inserted into the pile.

Once I had approval from Mark Wittig I began to setup my own compost pile for testing. The first step involved laying down a thin layer of weed mat to prevent new plants from taking root in the pile. On top of the mat I placed a long segment of perforated pipe; this would allow the oxygen necessary for aerobic decomposition to circulate through the interior of the pile. With the help of a bulldozer I took roughly 4 cubic yards of compost from their youngest windrow and placed it on the weed mat. I then began staking the PVC sheaths into the pile at my desired positions. Five of the ten sheaths I used to measure lateral fluctuations in pile temperature. These were spaced evenly left-to-right parallel to the horizontal axis of the pile. I used the other five to measure temperature changes with depth. These were inserted at the top of the pile at varying depths determined by the tick marks. I then threaded the thermistors down the sheaths, making sure to keep track of their respective locations on the DLU. The thermistors thus measured the temperature of the air in the pile and not the organic material itself. However, similar measurements in which a stainless steel temperature probe was inserted into the pile indicated little difference between the two methods. The top ends of the PVC sheaths were also capped to prevent them from acting as vents for the hot air within in the pile. A small shed nearby provided power to run the DLU. Fig. 2.2 shows a computer schematic of the final setup. Similarly, Fig. 2.3 shows the compost pile with PVC sheathes and thermistors in place.

2.2 Data & Error Analysis

During the first trial I monitored temperature continually for a twenty-four hour period. I avoided oversampling by using a thirty second interval between data points. In these 24 hours the pile was exposed to a variety of weather conditions. It began as a hot July afternoon but quickly turned into a cool, precipitous summer evening. This was fortunate for me because I wanted to examine the behavior of the pile in a variety of atmospheric conditions to determine the stability of the bacterial activity inside.

The results can be seen in Fig. 2.4. Notice that the most pronounced changes in temperature take place in the first hour. This is most likely due to the fact that I rearranged the organic material from its original position in the windrow. However after this initial relaxation period the temperature in each region tends to remain fairly constant with time. In the central region of the pile at depths of two, three, and four feet we get some interesting behavior. Not only are the temperatures highest at these locations but they also steadily increase over the 24 hour period. This indicates that there is ample organic material for the bacteria to convert into thermal energy. Most importantly however, neither rain nor fluctuations in ambient temperature between

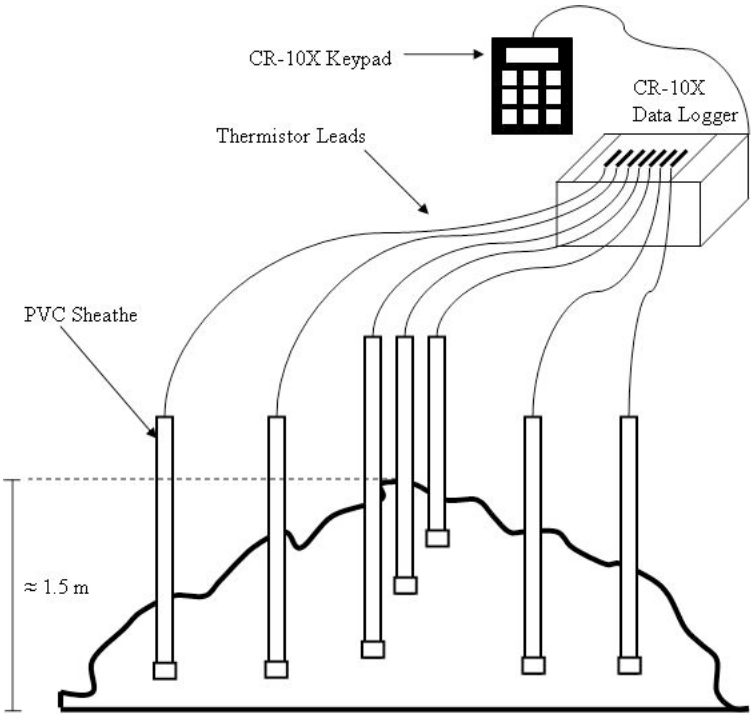

Figure 2.2 Determining the thermal profile of a compost pile. The CR-10X data logger was used to record the internal temperature of the compost pile at various locations. Long, thin PVC tubes were staked into the pile to act as conduits for the thermistors and also protect them from the corrosive environment within the pile. Small holes were drilled at the bottom of these sheathes to ensure accurate temperature readings while still keeping out organic material. The probes in the center were used to determine the temperature variation with depth, while those on the outside were used to determine the lateral dependence.

Figure 2.3 A photograph of the compost pile after the PVC sheathes and thermistors had been inserted. Originally five depth probes and five lateral probes were used to get precise temperature readings from a variety of locations within the pile. In this photograph one of the lateral probes was removed to measure atmospheric temperature.

night and day produce any measurable effects on the atmosphere within the pile.

I decided to execute a second run to ensure the temperatures within the pile could be sustained over extended periods of time. This time I monitored the pile over a ninety-six hour period with a data collection interval of two minutes. In this trial I also tracked the atmospheric temperature at the expense of losing a lateral probe. The results are presented in Fig. 2.5. Notice that the three hottest points of the pile (D2,3,4) are still holding constant at roughly 60° C. It is also interesting to note that the second run began three days after the end of the first. If we compare the end of Fig. 2.4 with the beginning of Fig. 2.5 it appears that the hottest points in the pile held constant at 60° C for those three days. However, it is essential to note that the hottest points do exhibit a net negative slope over the course of this run. This is due to two factors: no new organic materia was added to the pile since its creation over a week prior; also, the pile had not been turned or mixed in any way, something Cayuga Compost does to their windrows daily. This process aerates the pile and redistributes unused organic material. We conclude that these factors cause the decay in temperature exhibited toward the end of the second run.

The temperature measurements in the two graphs presented in this section are of course subject to a certain amount of uncertainty. The DLU specifications sheet from Campbell Scientific indicates an uncertainty of ±0.5° C in the temperature range of −35–50° C. Since some of the thermistors in this experiment measured temperatures outside this range we expect their uncertainty to increase slightly. We therefore estimate their temperature uncertainties to be ±1° C. Error bars depicting the magnitude of this uncertainty can be seen in Figs. 2.4 and 2.5. Also note that the time scale is also only as accurate as the clock on the DLU. Since my experiment took place over a number of days and the DLU records the measurements in 24-hour time I had to create my own time scale based upon the data collection interval. There

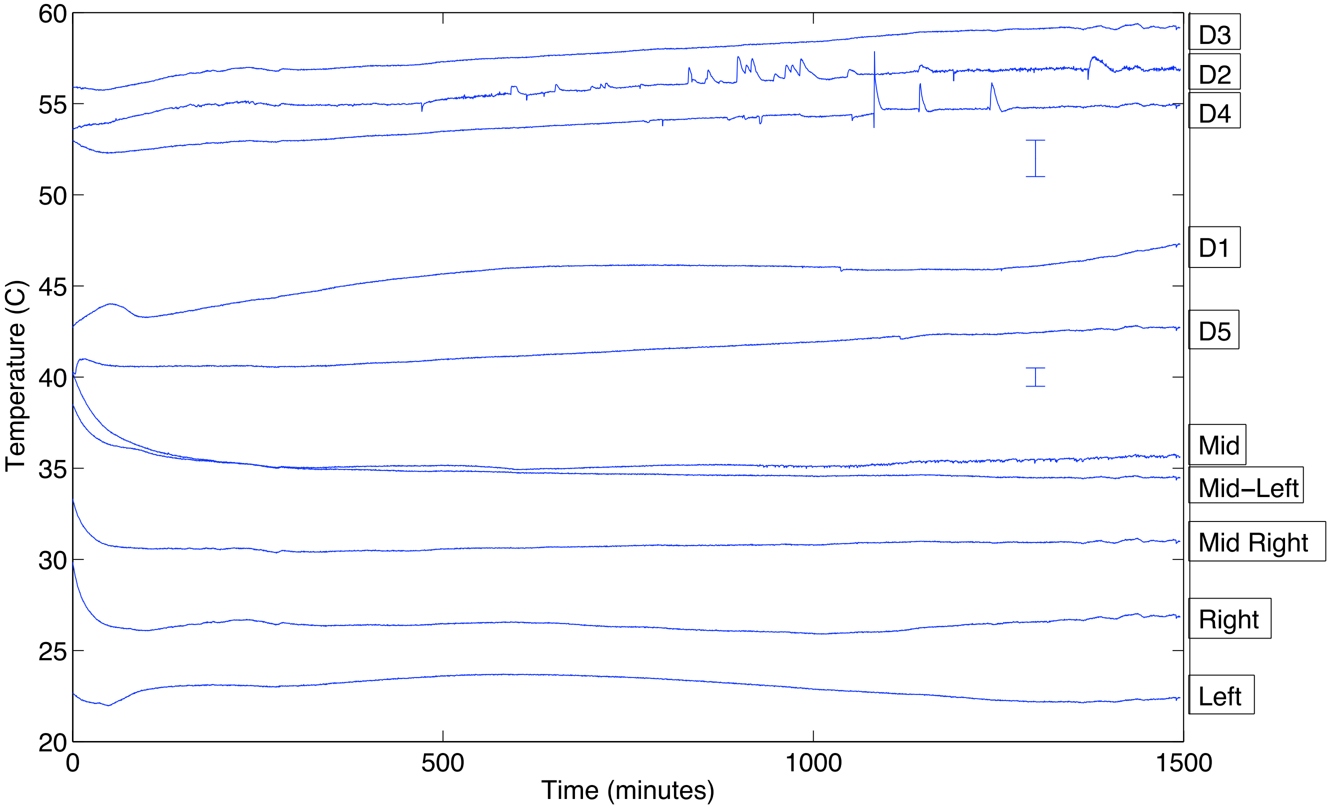

Figure 2.4 Temperatures at varying depths and lateral positions of the compost pile. The D labels refer to the depth probes where the number is the approximate depth of the probe in feet. The remaining labels (Left, Right, etc.) refer to the positions of the lateral probes. Note the thermal stability of the environment inside the pile; this measurement extended over a 24 hour period and yet the temperature fluctuations between day and night have little affect on the pile's temperature. Furthermore the probes closest to the center of the pile record the highest temperatures, exhibiting a cocoon-like temperature gradient.

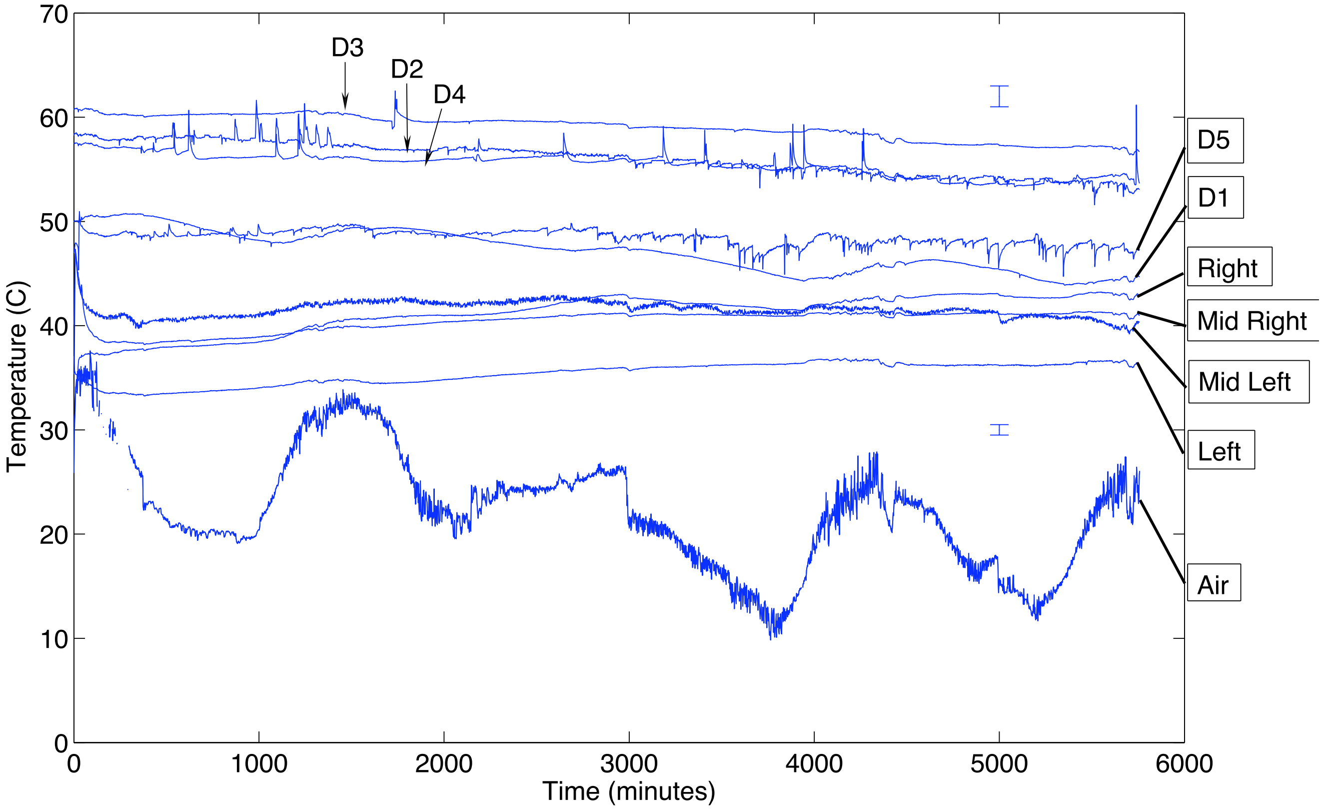

Figure 2.5 This is a second investigation of the same compost pile over a longer (96 hour) time period. In this trial the atmospheric temperature (bottom curve) was also recorded. Notice that the temperature within the pile is relatively constant despite the fluctuations between day and nighttime temperatures. This run began two days after the end of the first, suggesting that the pile maintained a constant temperature of upwards of 60° C. The gradual decrease in temperature of the hottest points in the pile towards the end of the run is attributable to a lack of fresh organic material and poor aeration, problems that a properly managed compost pile would not be subject to.

is the possibility of compounding time errors, but long and short clock counts are equally likely. Therefore over the course of the run the two should balance and leave us with a negligible time error. Moreover, the DLU is capable of producing 2.5μs pulses for other applications. Thus the clock counts must be accurate on the order of microseconds, a resolution much higher than necessary for the purposes of our experiment. Lastly, note that both plots, especially Fig. 2.5, exhibit noise in the data. We were never able to pinpoint the exact cause of the interference but suspect it may have been due to electromagnetic interference from electronic equipment in the shed nearby. I must also note that several data points were removed from the array containing the atmospheric temperature measurements. These points corresponded to some sort of error as indicated by their non-physical values of -6999° C.

Chapter 3

Laboratory Replication

After acquiring ample data describing the environment within a compost pile work began on purchasing and testing thermoelectric modules (TEMs). Two HZ-2 modules, a self powered DC-DC converter with variable output, and an aluminum heat sink were purchased from Hi-Z incorporated, a company based in San Diego that designs and distributes thermoelectric devices and accessories. The modules' performance was evaluated by exposing them to various temperature differences similar to those of the compost pile. A hotplate and ice water bath were used to mimic the compost and surrounding atmosphere respectively.

3.1 Thermoelectric Modules: Principles of Operation

Thermoelectric modules rely on the Seebeck effect to produce electricity. When a temperature difference is applied across two dissimilar, connected metals or semiconductors (known as a thermocouple) a voltage is produced. This is known as the Seebeck voltage. Its magnitude for a given temperature difference is determined by

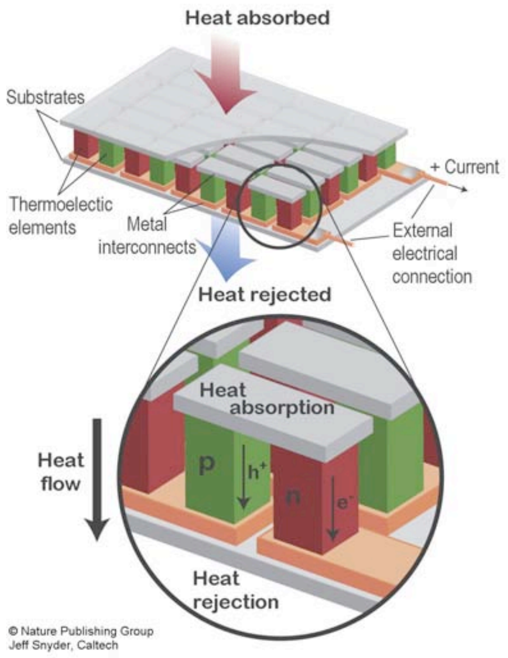

Figure 3.1 A visual guide to the interior of a typical thermoelectric module [6]

the Seebeck coefficients for the thermocouple pair. This effect can be manipulated so that electrical currents may be driven by temperature differences.

An individual thermoelectric module consists of alternating P and N type semiconductors wired electrically in series and thermally in parallel [9] (See Fig. 3.1). Lead Telluride is among the most common semiconductors in thermoelectric operations, although Bismuth Telluride and Silicon Germanium are becoming more frequently used as well [7]. Adjacent semiconductors are connected by a thin metal strip. Typical thermoelectric modules contain anywhere from 50 to 100 thermocouples.

Seebeck voltages across the module leads can be produced by applying a temperature difference across the faces of the module. If these leads are attached to a load, a current will flow. Consider an electron traveling in the metal interconnect between the thermocouples. To enter the P type semiconductor the electron must fill a hole and thus give up energy to the environment. At the top of the P type semiconductor electrons absorb the thermal energy applied to the hot side and are excited into the conduction band of the next metal interconnect. Upon reaching the edge of this interconnect the electrons must absorb more thermal energy to travel in the N type semiconductor. At the bottom of the N type semiconductor the electrons give up energy to travel in the next metal interconnect

The macroscopic effect of this process is heat flux through the module. When electrons enter and exit the N and P type semiconductors at the hot side they absorb the thermal energy provided by the external agent (in this project the compost pile). When the electrons enter and exit the P and N type semiconductors at the cold side energy is released. In a basic sense it is this heat flux through the module which drives the electrical currents we seek to capture.

It is important to note that thermoelectric modules can be used as both generators and temperature controllers. When used as a temperature controller the modules rely on the inverse of the Seebeck effect, namely the Peltier Effect. Instead of turning a temperature difference into electrical current the Peltier effect turns an electrical current into a temperature difference. For this reason they are often referred to as Peltier coolers. By running steady currents through thermoelectric modules very precise temperature can be attained at the faces. Peltier coolers are widely used in biomedical and computer technologies.

3.2 Module Selection

There are several corporations that manufacture thermoelectric devices including Custom Thermoelectric, Ferrotec, Tellurex, and Hi-Z, to name just a few. However, most industrial applications of thermoelectric modules require them to operate as temperature controllers instead of generators. Thus most distributers design their modules

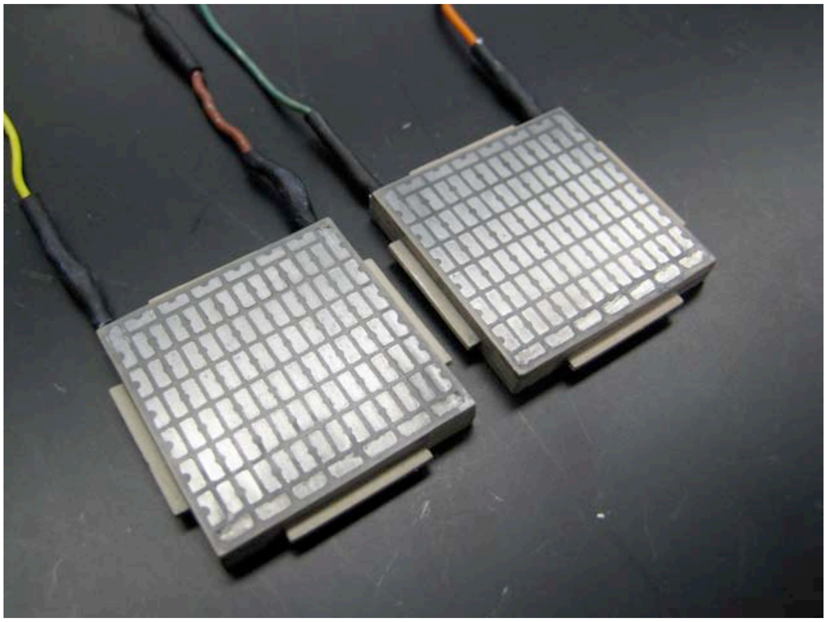

Figure 3.2 The two HZ-2 modules purchased from Hi-Z Inc. with metal interconnects between adjacent thermocouples exposed.

specifically to work in Peltier mode. Although all thermoelectric modules can be used as both generators or coolers, design considerations can make them more well suited for one or the other. Of the firms mentioned above only Custom Thermoelectric and Hi-Z advertised the possibility of using their modules as generators.

For the project we needed a small module that would be durable and able to output the power needed to run a DC-DC converter. The converter was necessary to augment module output voltage to 12V to make battery charging possible. Ultimately the decision was made to purchase from Hi-Z Inc. Their smallest and cheapest module, the HZ-2, is specifically designed for power generation. See Fig. 3.2 for a photograph of the HZ-2. It boasts a higher potential output power than the equivalently priced module from Custom Thermoelectric and is only slightly more expensive. Similarly, Hi-Z offers all the necessary accessories for the project: heat sink, DC-DC converter, insulating wafers, and thermally conductive grease.

The HZ-2 module is comprised of 97 bismuth telluride semiconductors wired electrically in series. With an applied temperature difference of 200°C the module can generate 2.5W of electrical power to an attached load. This corresponds to a load voltage of roughly 3.3V and a current of 800mA. The efficiency of the module, that is the percentage of applied thermal energy converted into electrical energy, is at a minimum 4.5% [4]. Keep in mind that the compost thermal heating project does not involve temperature differences this large so the output power of the modules will be reduced.

3.3 Experimental Design

Designing an experimental apparatus that worked well with the modules was difficult. There were several design considerations to take into account. When using TEMs it is recommended that some sort of thermal spreader is inserted between the heat source and the module [3, 8]. This ensures that the incoming thermal energy is applied equally across the surface of the module which allows for optimum performance. Thermal contact is another issue that can greatly affect module output. To ensure good thermal contact Hi-Z recommends compressively loading the module between the thermal spreader and heat sink with a pressure of 200psi [3]. There are also other issues including interface insulation and thermal bypass, which will be discussed when evaluating the final design. The two most important aspects of the experimental apparatus were designing an effective thermal spreader and addressing the issue of thermal contact via compressive loading.

In the process of laboratory replication we wanted to mimic the conditions found in compost piles as accurately as possible. Thus we needed a heat source that could maintain a constant 60°C and a heat sink that would modulate between day and nighttime temperatures. Since we were already investigating a temperature region where we expected low module output we decided to mimic winter conditions to maximize the temperature difference across the module.

Three different setups were investigated. The first involved clamping the modules between a hot plate and our heat sink. The setup was placed on a windowsill such that the heat sink was exposed to the outside air and the hot plate remained inside. The area around the setup was insulated to prevent the outside air from cooling the thermal spreader as well. However, this experimental design was abandoned when it became evident that the ratchet straps used to compress the modules did not apply pressure evenly across the module faces. Other experimental designs were also considered. Seeking to capitalize upon the cold weather in February, a few trials were conducted at the Clinton B. Ford Observatory in the woods behind the Ithaca College campus. The hope was that the cold side temperature would very nearly follow the ambient temperature and the hot side temperature would be regulated using a temperature controlled water reservoir. However this setup also had several setbacks. The hot water reservoir was not compressively loaded to the module, rather it only applied a force equal to its own weight across the hot side surface. Similarly, the air inside in the observatory was still and did not provide the forced convection across the heat sink that we were trying to mimic. Eventually the heat sink was placed in an ice water bath to compensate for this lack of convection. Yet the modules' output was still greatly compromised by the fact that the module's were not compressed in any way. This was reflected in low voltage measurements and the inability of the modules to activate the DC-DC converter.

Eventually a third experimental setup was devised that worked much better than the first two. The final apparatus, consisted of an ice water bath, a heat sink, a 0.5 inch thick aluminum thermal spreader, a hotplate, ceramic insulating wafers, and the modules. Thermistors were placed on the bottom of the thermal spreader and the top of the heat sink to keep track of the hot and cold side temperatures respectively. A thin layer of thermal grease was applied to the spreader and heat sink to help create a thermally conductive path across the modules. Ceramic wafers were pressed firmly into the thermal grease which held them in place. These wafers were attached to the areas on the underside of the thermal spreader and the top of the heat sink where they would be in contact with the module faces. This was necessary because the faces of the modules that Hi-Z produces have the metal interconnects between adjacent semiconductors exposed. It is therefore necessary to ensure they are electrically insulated from the spreader and heat sink, which are also metallic, to prevent electrically shorting the modules. Holes were drilled in the spreader so that it could be bolted into the pre-drilled holes of the heat sink. A single module was then bolted between the spreader and heat sink. This provided us with a way to put a considerable amount of pressure on the module inside. However it also created the opportunity for thermal bypass; the bolts connecting the spreader and heat sink acted as alternate thermal paths. Energy from the source can conduct through the bolts instead of the module, decreasing efficiency. However, for the purposes of our experiment the benefits of compressive loading outweighed the detriments of thermal bypass. Once the module was securely fastened between the spreader and the heat sink the entire apparatus was placed in a shallow plastic container. Ice water was added to the container until most of the heat sink was submersed. This was done to mimic the environment on a winter day and improve thermal contact between the heat sink and its surroundings, so as to make the cold side temperature as low as possible. The temperature of this thermal bath was also monitored via a thermistor. Then a hot plate was inverted and placed upon the spreader to act as our energy source. A diagram of the completed setup can be seen in Fig. 3.3. A photograph of the apparatus prior to insertion in the ice bath can be seen in Fig. 3.4.

The hot plate was turned on to begin each trial. The temperatures of the hot side, cold side, and thermal bath were recorded along with the open circuit voltage of the module leads. Data was recorded with two PASCO Science Workshop 750 USB interfaces. The thermal spreader temperature was monitored until a 60°C temperature difference between the hot and cold sides of the module were achieved. At this point the knob on the hot plate was adjusted every two minutes to maintain this temperature difference. On two of the runs the hot plate temperature was increased after ample data had been attained at $\Delta T = 60°\text{C}$. This was done to investigate the module's behavior at higher temperature differences.

3.4 Data & Error Analysis

3.4.1 Open Circuit Voltage Measurements

The first step was to determine the behavior of a single module with no load attached. We then gradually increased the complexity of the experiment. After each module's initial test the two were wired in series and tested again. To complete the open circuit voltage measurements we also did a trial in which the DC-DC converter was attached to the output of the series arrangement of modules. In this scenario the voltage output of the converter was also recorded.

During the test of the first module it became readily apparent that the experimental apparatus with compressive loading greatly improved the module's performance. Indeed, the single module was able to attain an open circuit voltage of approximately 2.3V whereas previous attempts without compressive loading had yielded measurements of only 1.3V. The open circuit measurements for module 1 can be seen in Fig. 3.5. One of the most striking aspects of the data is how closely the voltage

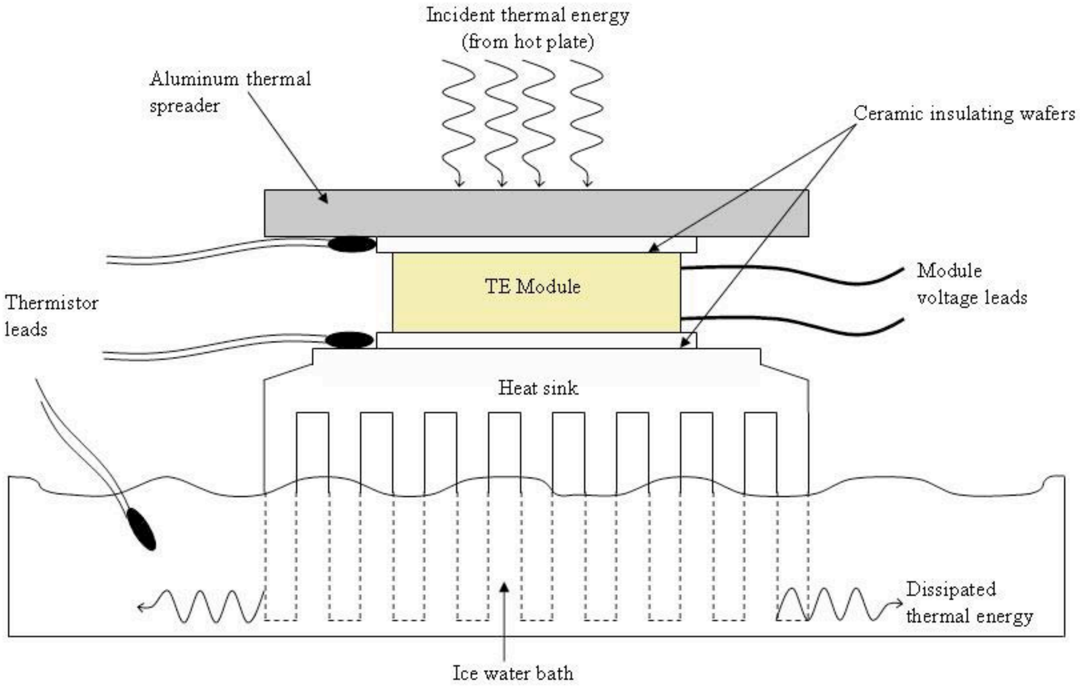

Figure 3.3 A diagram of the apparatus used to test the thermoelectric modules. The modules were bolted between an aluminum thermal spreader and aluminum heat sink (bolts not shown). Insulating ceramic wafers had to be placed at the interfaces to prevent electrical shorting across the module faces. Thermal grease was used at the wafer-aluminum interfaces to enhance thermal contact at the faces of the module. The entire apparatus was immersed in an ice water bath and had an inverted hot plate placed atop the thermal spreader. Thermistors recorded the temperatures of the underside of the thermal spreader (hot side), the top side of the heat sink (cold side), and the ice water bath.

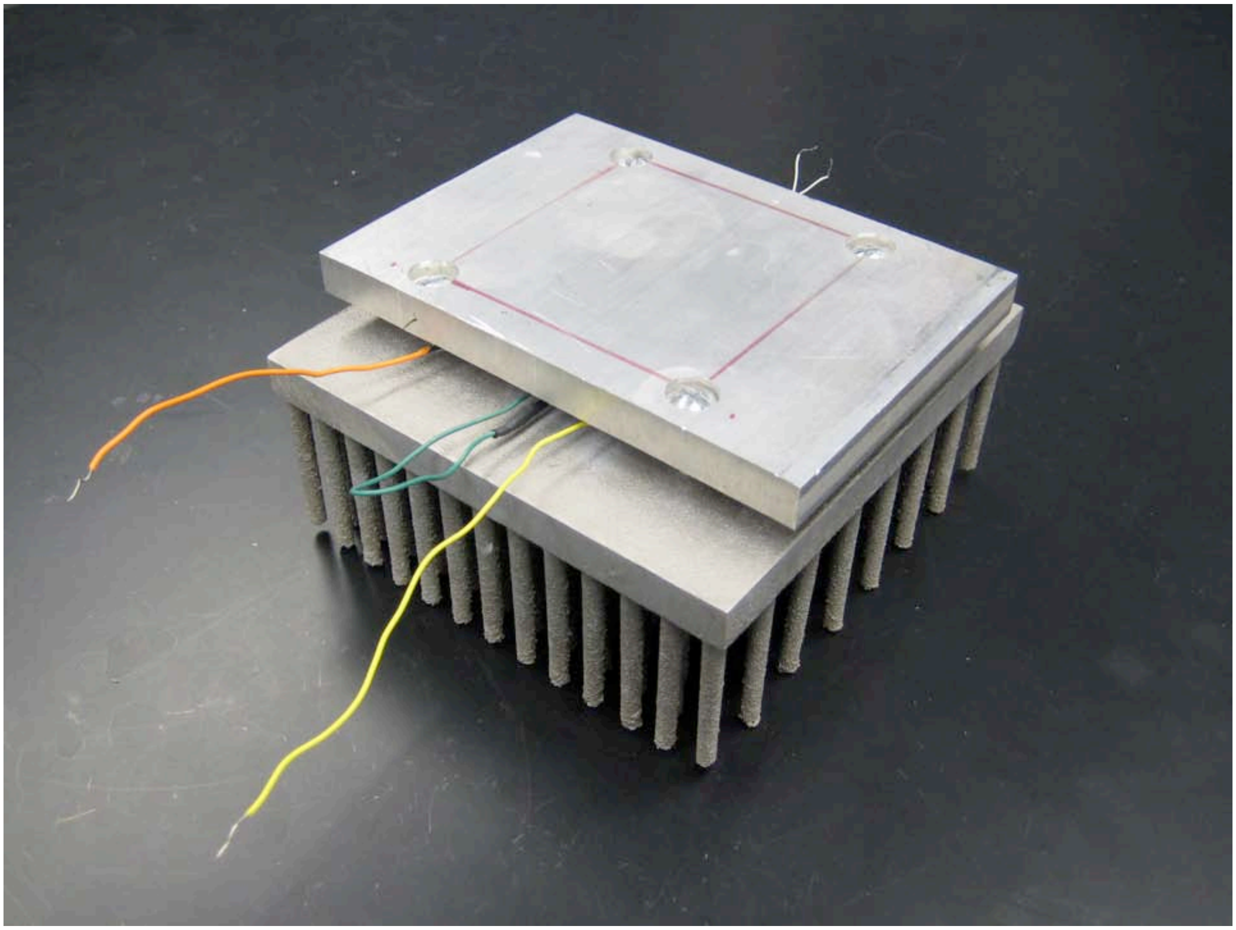

Figure 3.4 Photograph of the clamping mechanism used to compressively load the modules. Here the modules are already in their series configuration. The orange and yellow wires are the positive and negative voltage leads of the modules respectively. The green wire connects the two modules. The white leads of the thermistor used to measure the underside of the thermal spreader are visible in the background.

output curve follows the ΔT curve. This suggests, as we expect, that the output of the module is strongly correlated with the temperature difference it is exposed to. It is also important to note that the module is able to hold a relatively constant voltage provided a constant temperature difference. This is a crucial aspect for a passive battery charging system; we want the modules to maintain a constant output to power the DC-DC converter. The bottom plot records the thermistor measurements for the hot side, cold side, and thermal bath. Note that it actually took a source temperature greater than 60° C to achieve our desired temperature differential. This is illustrated by the fact that the hot side measurement is roughly 80° C while the cold side is some 20° C. Therefore our experimental design deviates slightly from the actual compost temperature conditions we found in part one of the project. This is a discussion point that we will return to later. Measurements for the second module can be found in Fig. 3.6. The results are almost identical to those of the first module, suggesting consistency between the two.

After each individual module was tested the two were soldered together in a series arrangement. This was done to increase the voltage output of the setup to ensure proper activation of the DC-DC converter for battery charging. The same tests were performed on the series combination and the results can be seen in Fig. 3.7. As we expect, the voltage output of the two modules wired in series is greater that of a single module. However, it is not exactly a factor of two greater as expected for series addition of voltages. During the setup for the series runs it became evident that the faces of the two modules were not precisely flat when laying next to each other on the heat sink. Therefore it was difficult to achieve completely flat thermal contact against the hot side of the array when screwing the thermal spreader into place. We conclude that the voltage output of the series combination is not the simple addition of the single module trials because thermal contact was decreased when placing both

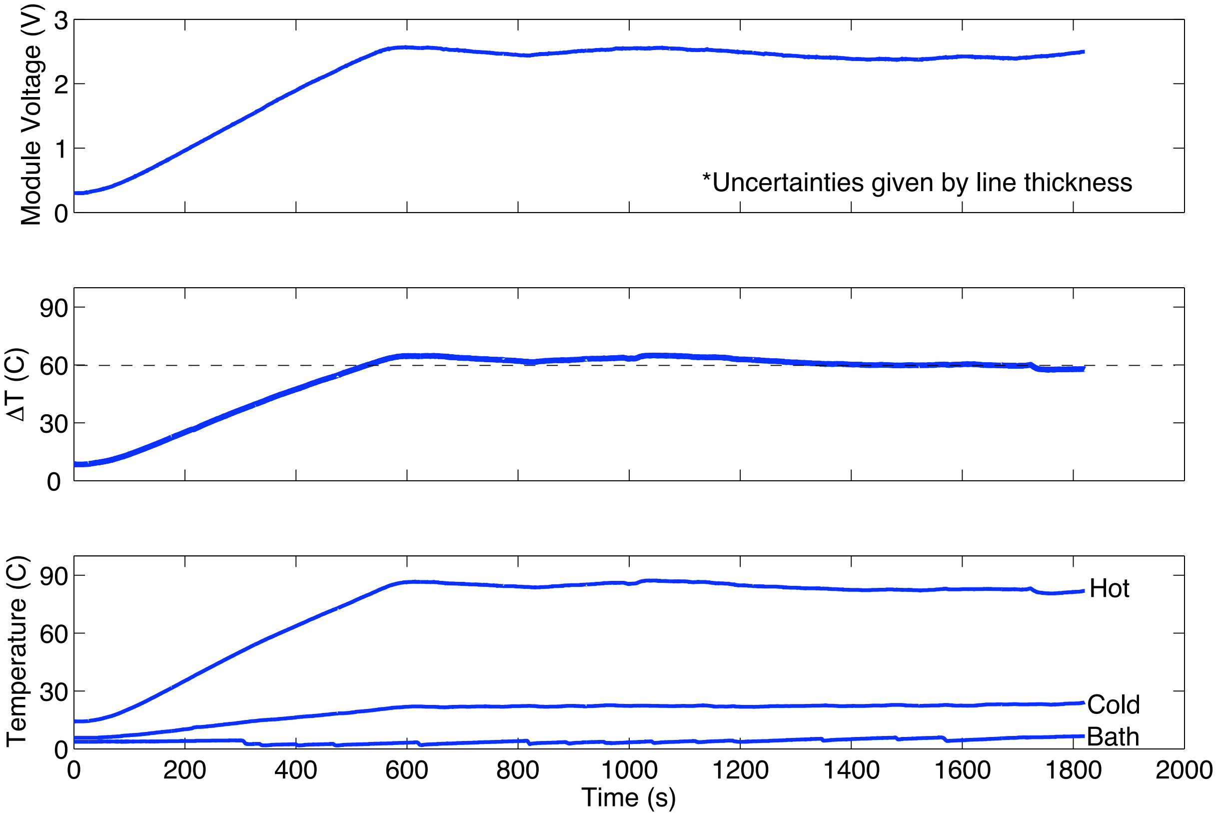

Figure 3.5 Graphical representation of voltmeter and thermistor readings for module 1. Each graph shares a common time scale. Notice the similarities between the module voltage and ΔT curves. As we expect the temperature differential seems to play the largest role in affecting module output. Observing the portion of the curves after 600s we conclude that the module is capable of yielding a relatively steady voltage output when exposed to a constant temperature difference.

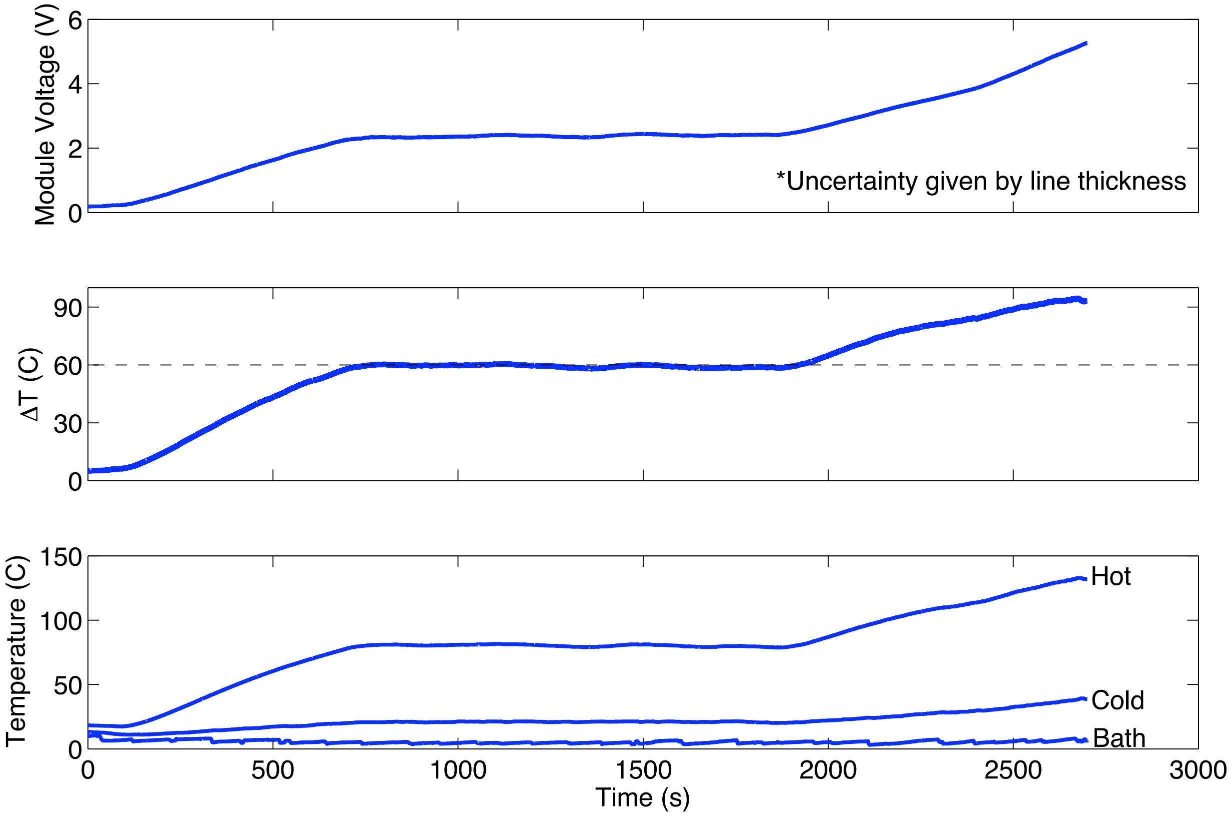

Figure 3.6 Data acquired for module 2. There are very few differences between these graphs and those in the previous figure, suggesting consistent performance across modules of the same type. At the end of this trial the temperature difference was increased greatly to examine module behavior in different ΔT regimes. See Fig. 3.8 for a direct relationship between voltage and temperature for both a single module and the series arrangement.

modules next to each other.

Notice the increase in hot side temperature at the ends of the module 2 and series trials. Here the hot plate was turned up to determine the module's behavior at higher temperature differences. Notice in Fig. 3.6 that the module voltage nearly doubles after the steady state position while the increase in ΔT is only +50%. This suggests that the module output is not linearly related to the temperature difference. In an effort to determine the relationship between the two we plotted module output against temperature difference for this run and the series combination. The results can be seen in Fig. 3.8.

The final open circuit measurement was conducted with the series arrangement. This time, however, the DC-DC converter was attached to the output of the module array. In addition to the previous measurements the open circuit voltage output of the converter was also monitored. The results can be seen in Fig. 3.9. During the beginning of the run the output of the converter follows that of the modules exactly. Once the temperature difference reaches approximately 40° C the modules are producing enough power to activate the converter. This can be seen by the converter voltage spiking to 10V. It should be noted that the output was actually higher than this, but the PASCO voltage sensor we used can only record voltages between -10 and 10V. In fact, during this time the potentiometer on the converter was adjusted so that the output, as measured by a digital multimeter, was 12.0 ± 0.1V. During this time the module voltage drops significantly to provide the current necessary to activate the converter. However, after roughly one minute the module voltage resumes its steady increase with some minor fluctuations that gradually decrease over the course of the rest of the run. The result presented here is one of the most significant findings of this project. We have proved a temperature difference of 60° C can maintain a potential difference of 12V. The next step is to determine whether this setup can be used to

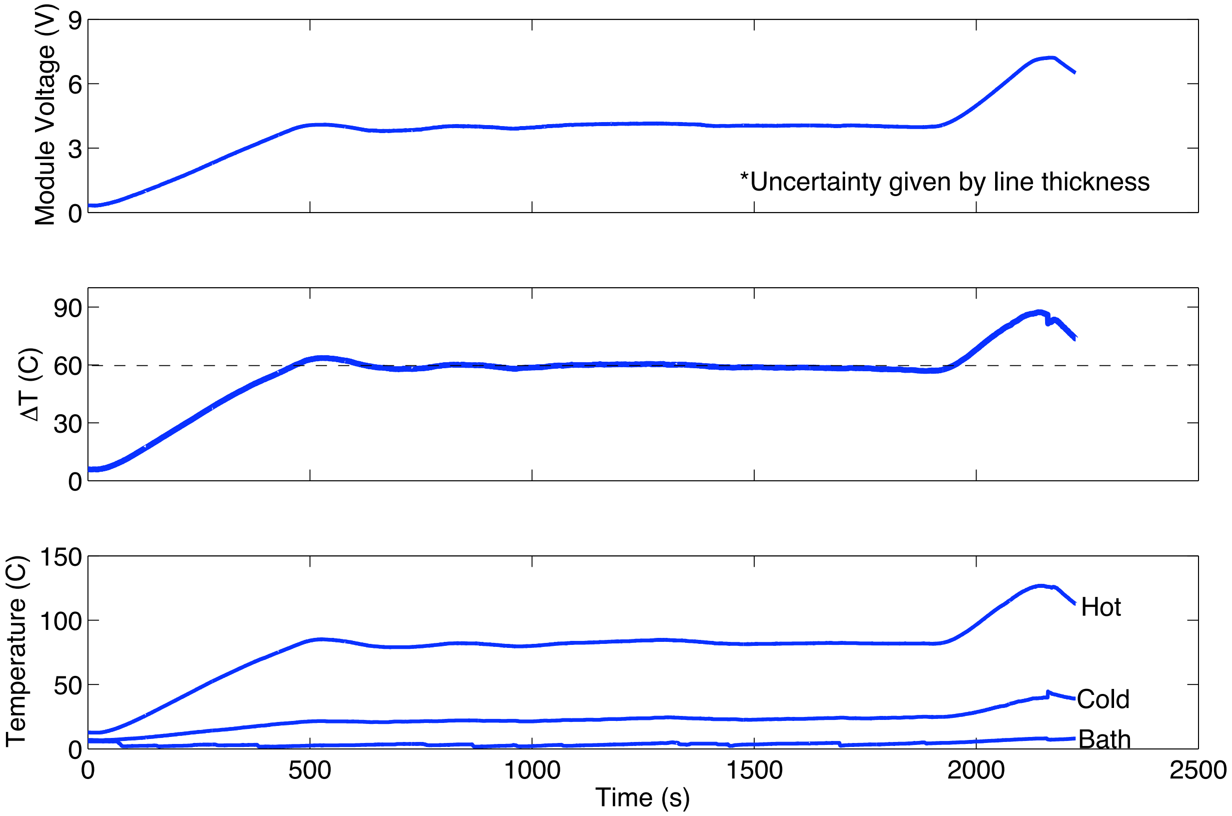

Figure 3.7 Measurements for the two thermoelectric modules wired in series. As we expect, the voltage measurements are greater for the same ΔT when compared to the single module trials. The voltage does not exactly double because the faces of the two modules were not exactly flat, making ideal thermal contact difficult. The temperature difference was also increased at the end of this trial to determine module performance at different ΔT values. See Fig 3.8 for details.

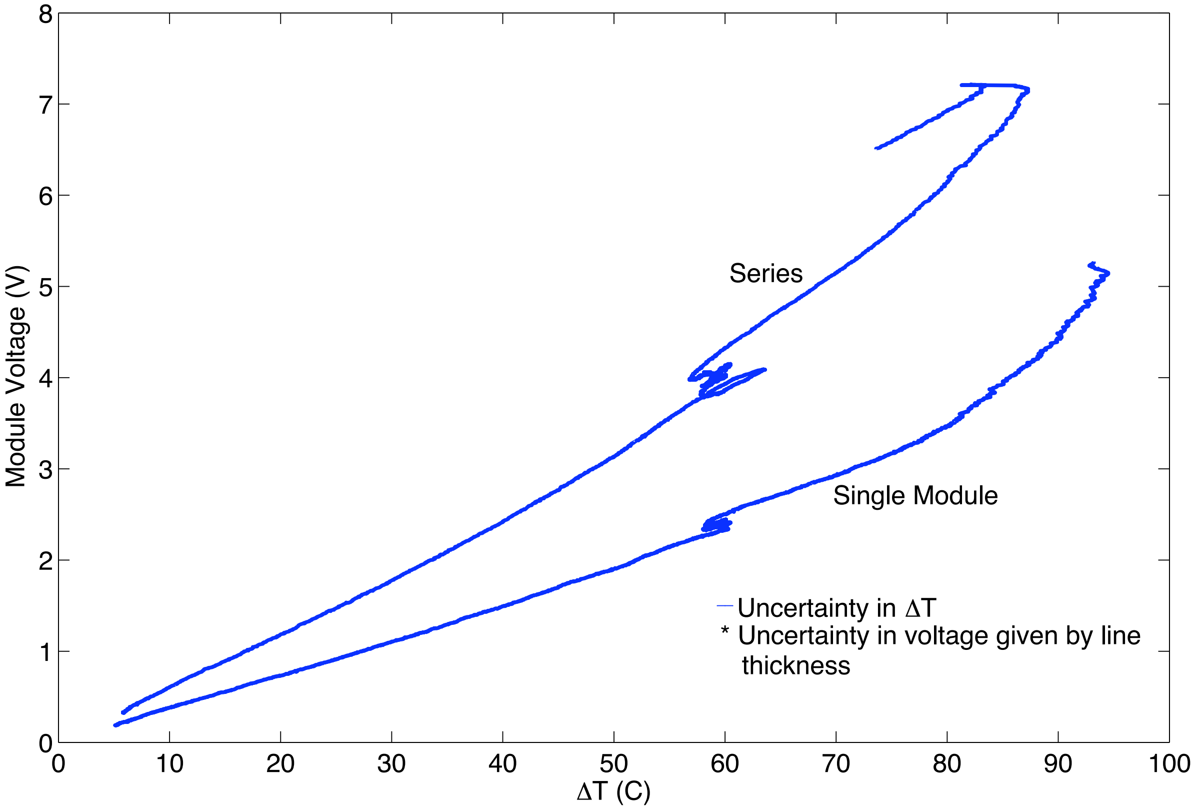

Figure 3.8 Graph relating module voltage output to temperature difference. The data above comes from the module 2 and series arrangement trials. In each case the dependent variables of the top and middle graphs were plotted against each other. The distortion around 60°C reflects the fact that many data points were recorded at this value to ensure the modules could output stable voltages. Notice that the behavior of the curve is not linear in either the case of the single module or the two wired together. In fact the behavior becomes parabolic at higher temperatures. The beginning of a hysteresis loop is visible in the series curve.

successfully charge 12V batteries.

The uncertainties in our data are not negligible but do not contribute significantly to the conclusions we draw. Due to our large sampling rate (2Hz) the line thickness is used to represent the uncertainty in our data instead of individual error bars. The uncertainty of the thermistor measurements (and hence the hot side, cold side, and bath temperatures) was ± 0.5° C. Note that the ΔT curves are slightly thicker than the others. This is due to the fact that ΔT values were calculated by subtracting the cold side data from the hot side data. Thus their errors are slightly larger (±0.7° C) due to error propagation. The voltage measurements have an uncertainty of only ±4mV. Since this project is largely a proof of concept these errors are not large enough to interfere with the inferences we make. The same values presented here hold for the figures in the following section.

3.4.2 Battery Charging

In the final stage of the project we sought to determine if the 12V output of the DC-DC converter could be utilized to charge batteries. The experimental design was identical to that of the open circuit measurements except now a battery was attached to close the circuit. We used a 12V rechargeable lead acid battery with a power rating of 23W for 15 minutes. Two sets of data were collected detailing two different charging methods. In the first trial the battery was attached to the output of the converter before the hotplate was turned on. That is we began the trial with a closed circuit. During the second trial the battery was attached to the converter output after it was activated.

The results from the first trial can be seen in Fig. 3.10. Before the experiment began the voltage across the battery terminals was measured at 9.7V. When the terminals were attached to the output leads of the converter the battery voltage

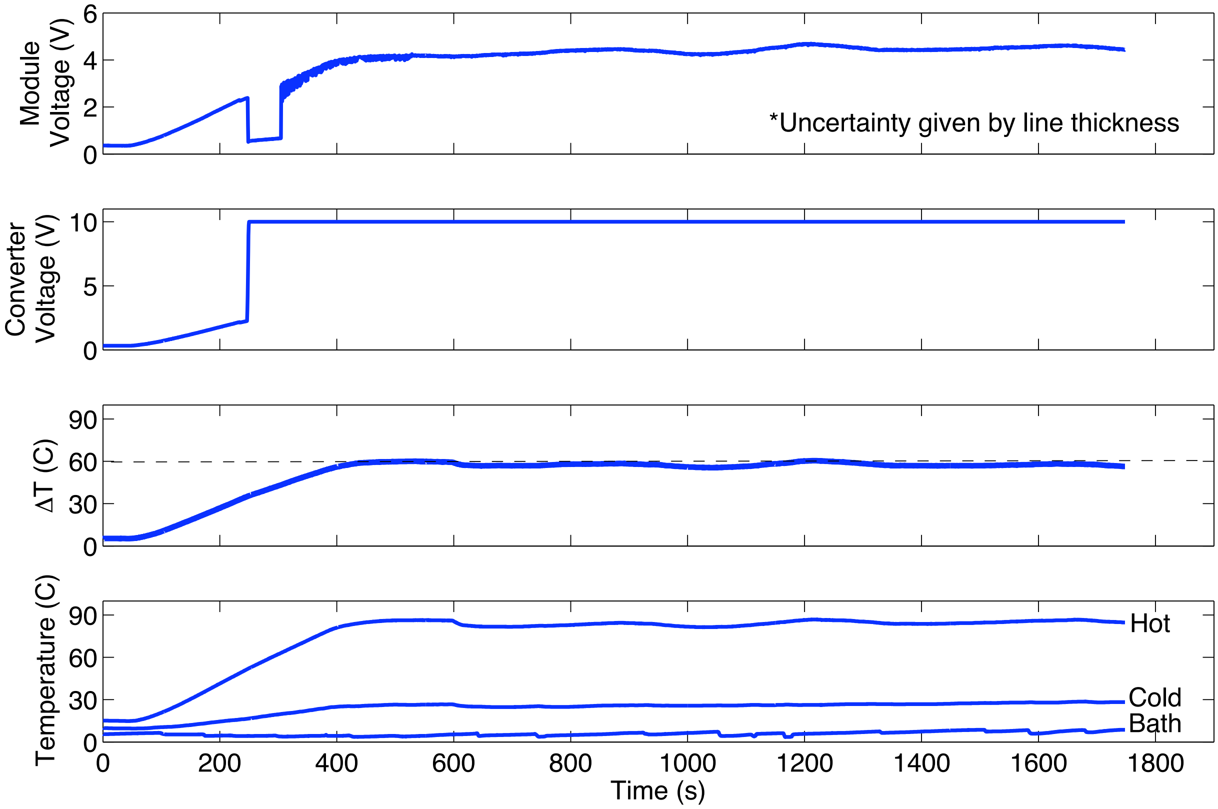

Figure 3.9 Measurements recorded for the series arrangement with DC-DC converter attached. Initially the converter output voltage follows that of the modules. However, once the modules reach a threshold power output the converter activates. This is represented by the large jump in converter voltage and sudden drop in module voltage. The reader should note that the output of the converter was actually 12V as measured by a digital multimeter; the voltmeter we used had a maximum reading of ±10V. The module voltage returns to its steady increase after approximately one minute with some minor fluctuations that damp out soon afterwards. Therefore it seems the temperature differential found between a compost pile and its surrounding environment can be used to create the voltages necessary to charge batteries.

dropped to approximately 8.7V suggesting that current was actually traveling back into the converter. This had no affect on the converter input however, which remained as expected at 0V. After turning the hot plate on the module voltage approaches 1.0V asymptotically. Evidently starting with a closed circuit eliminates the sudden drops in module voltage as seen in Fig. 3.9 and instead puts a ceiling on the module output. The battery voltage (and hence converter output voltage) remains constant at 8.7V for the first minute and then begins a rapid parabolic increase as the converter activates. Approximately eleven minutes after the converter activates the circuit is broken as indicated by the sharp rise in module voltage at 700s. This was done by detaching the module output from the converter input. Note that the battery voltage gradually decays back to its original value, indicating negligible charging. The circuit is closed again at 800s and charging continues. At 2200s the circuit is broken once more. Notice that this time the battery voltage curve does not drop indicating that the terminal voltage was at least 10V. An attached multimeter indicated that the battery voltage did actually drop from 10.5V to 10.2V. Nonetheless, in approximately thirty minutes of charging the voltage at the terminals increased from 9.7 to 10.2V.

In the second trial the battery was exposed to a longer charging interval. The data is presented in Fig. 3.11. In this trial the battery terminal voltage was recorded instead of the converter output. Open circuit measurements showed us that the converter output follows the module output until a threshold voltage is reached where the converter activates. After this time the converter outputs a steady 12V. When the battery is attached the converter output matches the terminal voltage, and so we are not losing any information by not explicitly recording the converter output. The beginning of the run looks very similar to the open circuit measurements with the converter attached. The module voltage steadily increases, dropping at approximately 280s as the converter activates, and then continues its ascent. The initial battery

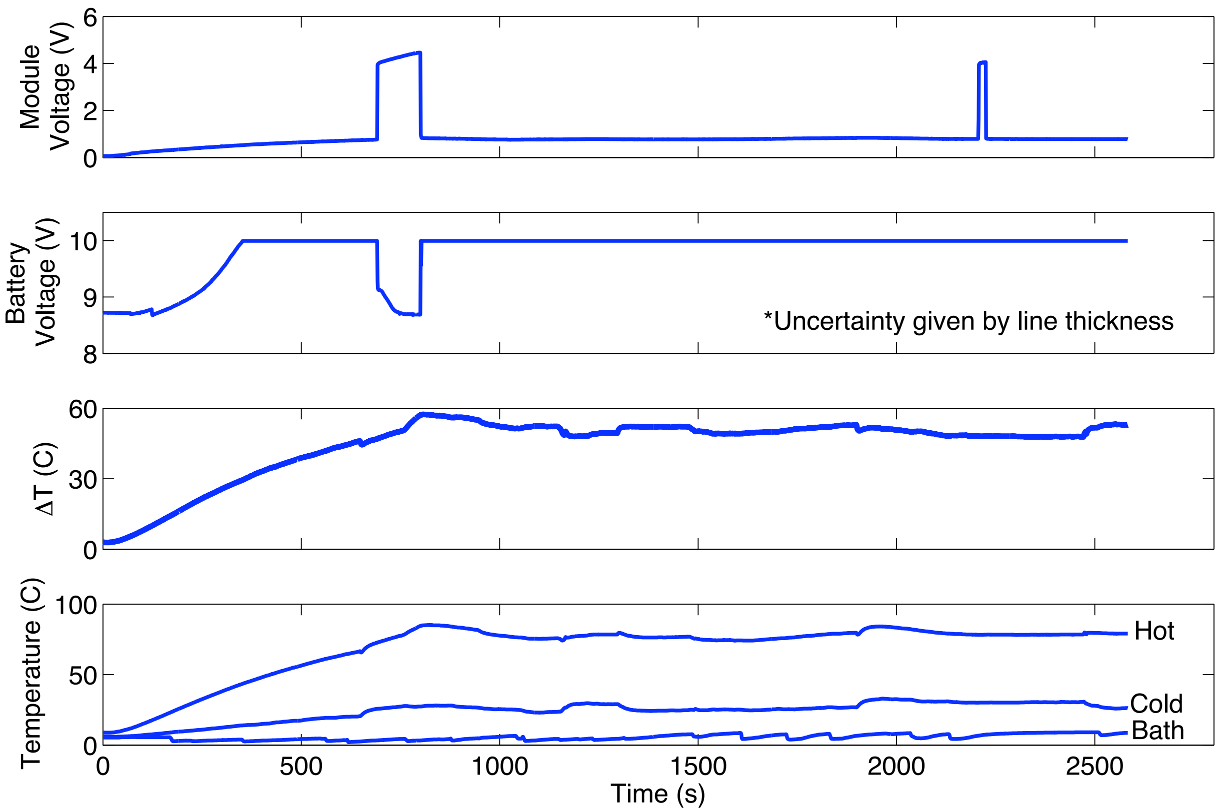

Figure 3.10 Data collected for the first battery charging trial. In this scenario the circuit was closed (i.e. battery connected to converter output) at $t = 0$s. Unlike the open circuit measurements the module voltage is held down since they must constantly supply the power necessary to charge the battery. After approximately one minute the converter activates, depicted by the sudden parabolic increase in battery voltage. After ten minutes of charging the circuit is broken and the battery voltage returns to its original value, indicating that negligible charging has taken place. The circuit is then closed again to allow charging for another twenty-three minutes. The circuit is broken again and the battery voltage remains at 10V, indicating the battery voltage has increased from its original value. The final voltage of the battery as determined by an attached multimeter was 10.2V. Thus the battery charged roughly 0.5V in just over thirty minutes.

voltage is 3.40V. At 625s the battery is attached to the converter output and the module voltage drops to produce the current demanded by the load. Notice the wild oscillations in both the module and converter output after the battery is attached. These oscillations damp out eventually but put stress on the converter circuitry, which is designed for steady DC currents. In this respect it seems that starting with a closed circuit is a better charging method. At 3600s the battery is detached from the converter output and the hotplate is turned off. The terminal voltage decreases exponentially to a value of 6.85V. Hence in roughly fifty minutes the terminal voltage increased from 3.40 to 6.85.

In both trials the ΔT across the modules was approximately 50° C, which is less than the 60° C we were aiming for. This is due to difficulties we had holding down the cold side temperature. In previous experiments the cold side temperature was holding just above 20° C whereas these trials show it leveling off at approximately 30° C. We are currently unsure of the reason for this increase in cold side temperature but expect it may be due to increased thermal conductivity through the modules. It should be noted that at this point the modules had been sitting in the apparatus for a few weeks, giving the thermal grease time to settle into the microscopic imperfections in the spreader and heat sink surfaces.

Notice that the voltage increase of the battery in a given period of time is strongly dependent upon the starting voltage. In trial one the terminal voltage increased roughly 0.5V in thirty minutes whereas in trial two the terminal voltage increased approximately 3.40V in fifty minutes. In this respect the terminal voltage mimics that of a charging capacitor. At lower voltages the rate of increase is much greater than at higher voltages.

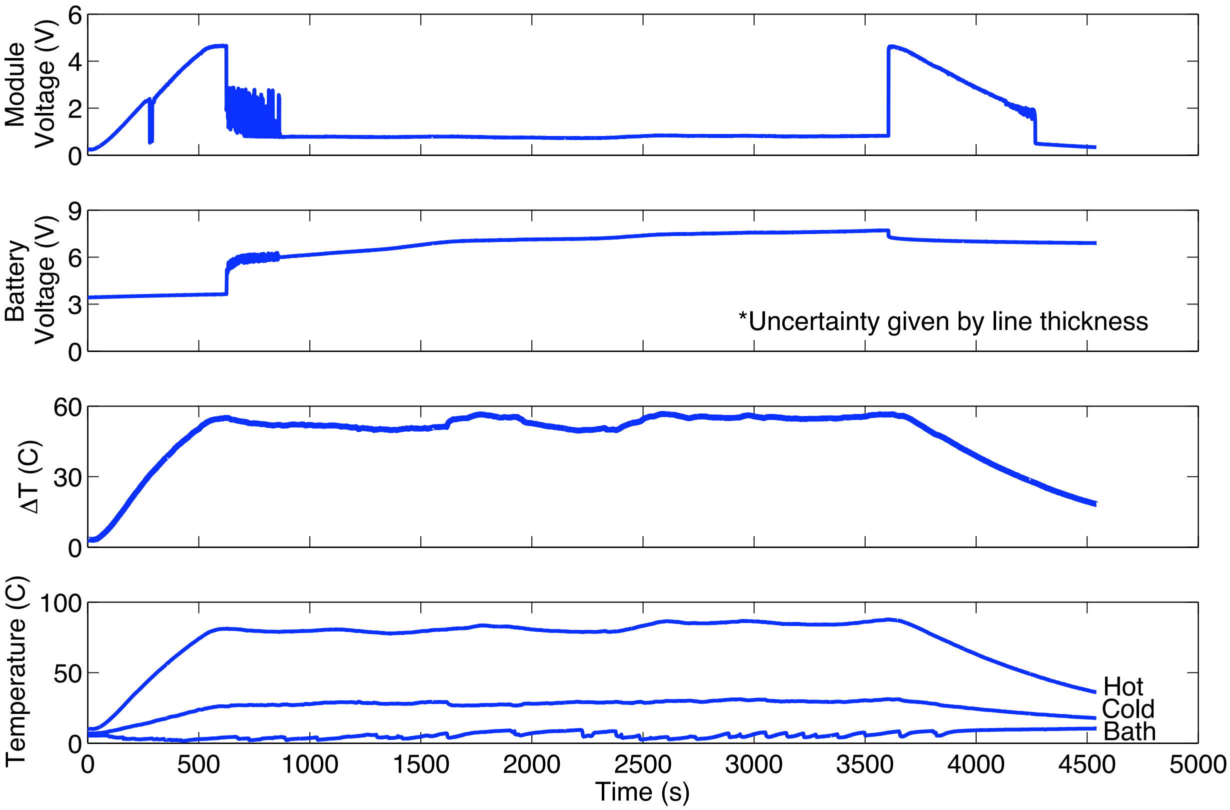

Figure 3.11 Measurements for the second battery charging trial. In this scenario the circuit was initially open. The battery is attached to the converter output at $t = 625$s. Notice the wild oscillations in the module voltage and, to a lesser extent, in the battery voltage immediately after the battery is attached. The source of these oscillations is still unknown but we suspect they put stress on the converter circuitry, which wants to see steady DC currents. After roughly fifty minutes the battery is disconnected and the hot plate is turned off. Notice that the battery voltage decays exponentially to its final value after being removed from the circuit. In approximately fifty minutes the battery voltage increased by 3.40V. When compared with the data from Fig. 3.10 it appears the battery charging time will be similar to that of a capacitor; the rate of voltage increase of the battery is higher at low voltages and lower at high voltages.

Chapter 4

Conclusions

Based on the the results of the project we can draw several important conclusions about the feasibility of using thermoelectric modules in conjunction with compost piles to produce electricity. We have determined that a properly managed compost pile can yield constant internal temperatures in excess of 60° C. Therefore a compost pile has the potential to act as an energy reservoir. We have also demonstrated that thermoelectric modules can operate at a temperature difference of 60° C. A single module may be used or multiple modules can be wired in series or parallel depending on the requirements of the application. Although the power output of a series configuration of two modules at this ΔT is small (less than 1W) it is still enough to activate a self-powered DC-DC converter. The converter can be calibrated to augment the module voltage output to $10-12$V making battery charging possible. Moreover, we've found that the charging behavior of a 12V lead acid battery is very similar to that of a capacitor. We suggest that a compost facility could use the thermal energy of the compost for electrical power generation. This could be used for passive applications like battery charging or to power the heaters attached to diesel engines in the winter.

The results of our experiment allow us to predict the form of an expression for the charging time of batteries when using thermoelectric modules. Our data leads us to suggests that the output power of a thermoelectric array is directly proportional to the number of modules as well as the temperature difference they are exposed to. The time it takes to charge a battery depends on the power output of the thermoelectric array and the maximum voltage of the battery. Hence t_c, the charge time of the battery in question, should relate to those variables in the following manner.

$$t_c = \alpha \frac{V_{max} - V_{initial}}{N\Delta T} \tag{4.1}$$

where α is a constant, V_{max} is the maximum voltage of the battery, $V_{initial}$ is the voltage prior to charging, N is the number of modules, and ΔT is the temperature difference between the hot and cold sides. Further work is needed to determine the exact relationship between the variables and the constant α.

Chapter 5

Summary and Future Work

The compost thermal heating project has succeeded as a proof of concept. A temperature difference similar to that between the inside of a compost pile and the atmosphere on a winter day can be used to generate useful electricity. With the help of a DC-DC converter this electricity can be used to charge batteries. Thus we suggest that a compost pile is indeed a potential generator for passive electrical applications. Although it is unlikely that a compost pile could be used to power an entire household, it is a unique form of renewable electrical and thermal energy.

Although the project has been successful in this respect there are still many things that need to be determined. We have proved that the modules can be used as effective generators for a 60° C temperature difference between 80° C and 20° C. In this respect our project has strayed from the actual behavior of the compost pile because we have no evidence that suggests compost piles can reach these temperatures. Ideally similar measurements would be completed for a 60° C temperature difference between 60° C and 0° C. This would more accurately model the thermal atmosphere we found in part one of the project and demonstrate the feasibility of our idea in a more robust manner.

There is also the matter of designing a housing for the modules so they can be used in conjunction with an actual compost pile. Our data from part one show that the high temperature regions of the pile are in its center. Thus the separation between the hot and cold reservoirs may be several feet while the modules themselves are less than one inch thick. An apparatus needs to be developed that enables the modules to have opposite faces simultaneously in contact with the center of the compost pile and atmosphere respectively. This is an engineering problem that must be solved before this kind of electricity generation becomes practical.

More experiments also need to be completed in order to substantiate the equation for t_c. This involves precise determination of the modules' power output under various temperature conditions and with different loads attached. This should be done for both a single module, the series configuration described in our experiment, and a parallel configuration. Similarly, the response of different types of rechargeable batteries needs to be investigated to see if such a charging device can be used with all rechargeable batteries.

Finally a cost benefit analysis of the modules would be a very worthwhile investigation. Since thermoelectric technology is still in its infancy efficiencies are low and prices are relatively high. It would be interesting to determine the payback period for a battery charger comprised of thermoelectric modules. This would involve quantifying the amount of electricity saved by using the modules in place of other conventional forms of electrical power.

Appendix A

Energy Removal Via a Working Fluid

The initial direction of the compost thermal heating project did not involve battery charging. Rather, the goal was to determine the possibility of using the energy produced by composting as a means of space heating. This idea originated from our desire to replicate the achievements of the New Alchemy Institute and Agrilab (Sec. 1.2) in an academic setting. We chose to evaluate the possibility of using a working fluid (in our case water) to transfer energy from the pile to an environment elsewhere.

Experiments were done during the end of the Summer of 2007 to see whether such a method of space heating would be effective. A new compost pile was set up with clear plastic tubing coiled throughout the inside. A small water pump was attached to one end of the tubing and immersed in a large 50 gallon barrel of water. The other end of the tubing fed back to the barrel, forming a closed loop. Water was pumped from the barrel through the compost pile and finally back into the barrel. Thermistors were placed in both ends of the tubing to determine the water's temperature on its outbound journey and on its return after having been pumped through the compost pile.

The experiments yielded mixed results. After the first few minutes of pumping the water at the return end of the tubing was slightly hotter than that going out. However, over time both the water leaving and arriving at the barrel reached an equilibrium temperature governed mainly by the temperature of the surrounding atmosphere. Ideally the barrel of water would have been insulated to avoid these effects but we had neither the time or materials to do so. There was also the concern about whether the beneficial effects of heating the water would outweigh the electrical costs of running the pump. Moreover, the results indicated that continually pumping water through the compost pile tended to reduce the temperature inside. This could prove problematic if the temperature was decreased enough to inhibit the activity of the thermophilic bacteria, thus 'killing' the pile. Also, having a large segment of plastic tubing within the pile would make turning the pile and adding new organic material quite arduous. For these reasons, Professor Rogers and I thought it best to change the direction of the project. Instead of pursuing space heating via active pumping of a working fluid we began to examine the possibilities of passive electricity generation via thermoelectric modules.

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