Remote Use Incubator Design and Fabrication

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Abstract
This project documents the design and fabrication of a compact, portable incubator for use by humanitarian organizations that need to perform water quality testing in remote areas of the developing world. The incubator design was influenced by prior DemoSat projects. The prototype incubators will be field tested in rural villages in Laos and Ecuador. These remote sites either have no electricity or it is unreliable. Heat for the incubator must be provided by other sources. Two final designs are fabricated: a hybrid system that uses an organic phase change material and a single, small, lithium polymer (LiPo) battery as well as an all-electric unit powered by a LiPo. Incubator performance is monitored by a microcontroller and logged to a MicroSD card. Thermal efficiency is optimized using finite element computer modeling and prototypes are tested to verify that they meet design constraints. Knowledge gained from this project will be used to enhance future DemoSat designs.

1. Background
Coliforms are a family of microbes found in the feces and digestive systems of humans and warm-blooded animals. Escherichia coli or E. coli, contracted through fecal-oral transmission, is a member of the fecal coliform group that is easily identified and cultured. Most strains are harmless, but some can cause serious and even life threatening illness [1]. The presence of E. coli in water, assumes the presence of other harmful pathogens, thus it is used as an indication that the water being tested is not safe to drink. Engineers Without Borders (EWB) tests for the presence of E. coli in water to determine if it is potable.

To detect E. coli in water, a sample must be cultured at a constant temperature in an incubator. The fecal coliform grows best at temperatures ranging from 34 to 38 °C. It has an optimum growth at 37 °C, the human body core temperature [1]. Maintaining a consistent incubation temperature standardizes the growth rate of coliforms for a meaningful test of E. coli enumeration. After a specified incubation period is complete, samples are examined for E. coli and coliform colonies. The contamination level of the water is determined based upon a manual count of the colonies.

There are several products available for culturing bacteria. EWB uses 3M™ Petrifilm™ – Coliform Count Plates (Petrifilm). Petrifilm provides a ready to use culture site with a prepared agar solution which make it easy to use. It is cost-effective, simple, and convenient. The Petrifilm plates have dimensions 10 cm × 7.5 cm, and can be stacked up to 20 plates (height of 20 plates in a stack is 2 cm).

The incubator used by EWB-FLC from 2004 to 2011 is based on a concept developed by Amy Smith at MIT. It uses a phase change material (PCM - described in more depth in Section 2.5) for temperature regulation. The PCM is encapsulated in plastic spheres which are kept in an insulated cooler. The PCM is thermally charged by soaking it in hot water until it melts. The energy gained by this process is then used to regulate the incubator temperature as the PCM undergoes a phase change from liquid back to solid. The material used in the balls has been engineered to change phase at 37 °C and hold a near-constant temperature until all of the material has solidified. During this exothermic solidification process heat energy is transferred into the surrounding environment which keeps the incubator contents at a uniform 37 °C.

The PCM heated incubator is very simple, which is always a goal of good design; however there are some noticeable drawbacks. PCM becomes increasingly unreliable as the material degrades through repeated cycles of heating. This is especially true if the PCM is overheated. Users must carefully monitor the temperature of the water bath during each charging. These PCM encapsulated spheres are no longer available on the market so the degraded ones cannot be replaced. In addition, the number of balls needed to achieve 37 °C incubation is dependent on the ambient temperature. This means that in order to assure an adequate volume of PCM is present for the given field conditions, the user must carry more balls than will ultimately be needed, increasing the weight and bulk of the incubator. Moreover, the location of the culture plates within incubator is set manually by the user and if not correctly positioned the test may yield inaccurate results.
Other portable incubators are available on the market but they do not meet the requirements for a remote use incubator that can be used on EWB projects. For example, Millipore manufactures a typical portable incubator with outside dimensions of 33x37x30 cm. This incubator is powered by battery and requires 6 W to operate. It weighs 8 kg with the battery. The Millipore incubator is too large and, at over $1500 per unit, too expensive [2]. Overall, there is no great technology for remote use incubation.

1.1 Goals and Objectives

The environment that EWB-FLC works in makes water testing challenging. Most locations are not easily accessible and electricity is unreliable. All testing supplies must be carried in by volunteers. Making the incubator small and light-weight is a decided advantage. Given the rugged work environment and the fact that it is must routinely pass through commercial airline luggage handling systems, it must also be durable.

A new incubator is designed to address these issues. The main goal of the project is to design and prototype a remote use incubator capable of holding a constant temperature for a 24 hour period. In general, it should be durable, compact, light-weight, require negligible user attention, be independent of local electricity sources and, most importantly, yield accurate results. It should be simple to use and require minimal operator training. Lastly, it must be inexpensive.

The project objectives or constraints are that it must maintain temperature at 36 ± 2°C for a 24 hour period based on the growth temperatures of the fecal coliform. The incubator must fit up to 20 incubation samples. It must be smaller and more energy efficient than the Millipore unit. Specifically, it must weigh less than 8 kg, measure less than 32 cm on a side and must use less than 6 W-h for heating. It must also pass JEDEC and IPR testing for durability. Lastly, it must cost under $150 per unit.

2. Literature Review & Theory

2.1 Heat Transfer

The main theory behind the incubator design is heat transfer. Heat transfer is the transfer of thermal energy from one point to another due to a temperature gradient [4]. It takes place in one or more of the following three modes: conduction, convection, and radiation.

Convection (illustrated in black in Figure 1) is the transfer of energy between an object and its environment due to fluid motion, in most cases the motion of air [4]. It is governed by Newton’s law of cooling (Equation 1), which states that the heat flow is proportional to the difference of the temperatures of the two media. The proportionality coefficient \( h \) is called the convection heat transfer coefficient and is measured in \( \text{W/m}^2\text{K} \).

\[
q_{\text{conv}} = hA_s(T_s - T_\infty)
\]  

Conduction (illustrated in red in Figure 1) is the transfer of energy between objects that are in contact [4]. The Fourier heat conduction law (Equation 2) states that the heat flow through a material is proportional to the temperature gradient. The coefficient of proportionality \( k \) is a material parameter known as thermal conductivity measured in \( \text{W/mK} \).

\[
q_{\text{cond}} = kA \frac{dT}{dx}
\]  

Radiation (illustrated in orange in Figure 3) is the transfer of energy by emission or absorption of electromagnetic radiation and it is governed by the Stefan-Boltzmann law (Equation 3).

\[
q_{\text{rad}} = \varepsilon\sigma A_s(T_s^4 - T_\infty^4)
\]

In equations 1 through 3: \( T_s \) is the surface temperature of the body in Kelvins, \( T_\infty \) is the temperature of the surroundings or ambient temperature in Kelvins, \( dT/dx \) is the differential change in temperature through a material, \( A_s \) is the surface area in \text{m}^2, \varepsilon \) is the emissivity of the material, and \( \sigma = \text{Stephan-Boltzmann’s constant} = 5.67 \cdot 10^{-8} \text{W/m}^2\text{K}^4 \).

![Figure 1 Modes of heat transfer illustration](image)

Conservation of energy or the 1\(^{\text{st}}\) Law of Thermodynamics (Equation 4) is used to find the change in heat of a specified system.

\[
\Delta E_{\text{SYS}} = E_{\text{IN}} - E_{\text{OUT}} + E_g
\]

Where \( \Delta E_{\text{SYS}} \) is the total change in energy of the system, \( E_{\text{IN}}, E_{\text{OUT}}, E_g \) is the energy in, energy out and thermal energy generation within the system, respectively. Theoretically, each of the terms in
equation 4 includes kinetic energy (KE), potential energy (PE), and internal energy (U). For stationary, closed systems the KE and PE are negligible, and the internal or thermal energy term dominates. The components of internal energy are sensible, latent, chemical, and nuclear [4].

In terms of heat (where there is essentially no heat in) Equation 4 becomes:

$$q_0 - q_{OUT} + q_g = \Delta q_{system}$$  \hspace{1cm} (5)

Analytic solving this equation is a complicated process. To overcome this, simplifications and assumptions are made about the problem that reduce or relate many of the variables. These simplifications affect the final solution, but on the whole result in a close approximation. A common technique in heat transfer, something sort of analogous to what might be seen in an electric network, is using thermal resistances. Figure 2 shows the one dimensional thermal resistance network through an incubator wall.

The controlling equation to approximate heat out in Watts ($q_{0,1\rightarrow0,2}$) is the change in temperature over the sum of the resistances:

$$q_{0,1\rightarrow0,2} = \frac{\Delta T}{\Sigma R}$$  \hspace{1cm} (6)

![Figure 2 1-D Thermal Resistance Network](image)

The resistance associated with the chamber convection is $1/h_1A$. The resistance representing conduction a material is $L/k_1A$, where L is the thickness of the wall. The outer convection and outer radiation resistances are given by, $1/h_2A$ and $1/h_{rA}$, respectively. The radiation heat transfer coefficient for a body and large surroundings is given by

$$h_r = \varepsilon\sigma (T_s + T_\infty) + (T_s^2 + T_\infty^2)$$  \hspace{1cm} (7)

With the conditions shown in Figure 4, Equation 8 becomes:

$$q_{0,1\rightarrow0,2} = \frac{T_{0,1} - T_{0,2}}{1/h_1A + L/k_1A + (1/h_2A)^{-1}}$$  \hspace{1cm} (8)

Figure 3 is an analytical model that shows the effect of the thickness of insulation on heat flux. This relationship gives a general idea of how much heat will need to be generated with corresponding thicknesses of insulation.

The heat flux or heat out is represented by Equation 9. Equation 9 is multiplied by 6 to include all 6 sides of the box. This will give the worst case estimation because there will not be convection on the bottom surface during operation. The incubator is assumed to be placed inside where forced convection such as wind is minimized and the range for free convection is from 5 to 25 W/m²K. Variables from the controlling equation (Equation 9) for the model in Figure 3 are as follows: $\varepsilon = 0.9$ for a dull material, $h_1 = 5$ W/m²K, $h_2 = 25$W/m²K, and $k_1 = 0.05$ W/mK (a general value for thermal conductivity of insulation).

$$q_{0,1\rightarrow0,2} = \frac{(37K) - T_{0,2}}{\left(\frac{1}{5W/mK}A + \frac{0.05W/mK}{A} + \frac{1}{1/(25W/mK)}A + \frac{1}{1/h_2A}\right)^{-1}}$$  \hspace{1cm} (9)

Steady-state is assumed the entire time to approximate heat loss in the worst case. As the insulation thickness increases the heat out decreases. Specifically the resistance associated with thermal conductivity changes the most as the thickness of insulation is changed. For 1 cm thick insulation the conduction resistance is 17.5 K/W. Every time the thickness of insulation is doubled the conduction resistance increases by 50%.

![Figure 3 Heat Flux vs. Ambient Temperature for varying insulation thicknesses](image)

In the worst case scenario, with an ambient temperature of 0 °C, the heat out is a little over 6 W, and as seen in the graph as the insulation is increased the heat out decreases by about half. To verify this one dimensional heat transfer model three dimensional modeling was done. It resulted in a short...
transient period suggesting the steady-state approximation is appropriate.

2.2 Finite Element Modeling

An alternative to the analytic solution of the one dimensional heat transfer representation is to use finite element modeling.

The finite element method (FEM) is a numerical technique for finding approximate solutions to complex physical processes, including heat transfer [5]. Numerous commercial and open source FEM software packages are available [5]. For this project an FEM model of the incubator uses the design geometry, material properties, and expected boundary conditions of the prototype as it would operate under field conditions. The heat flux and temperature distribution across the incubator are predicted and compared to experimental values. The FEM model is used to gain insight into the intricacies of the design. This accelerates the overall design process by eliminating the need for some of the trial and error design iterations.

![Image](image.png)

**Figure 4** Left: VIP $K = 0.0025 - 0.01$
Right: closed cell foam, $K = 0.02 - 0.05$.

2.3 Insulation

Insulation is graded by its thermal conductivity ($k$ in W/mK) or thermal resistance ($R$ in ft$^2$/°Fh/Btu). Smaller $k$ values (or larger $R$ values) indicate better insulating abilities. A commonly used, efficient insulation is closed cell polystyrene, shown in Figure 4, with a $K$ value ranging from 0.02 to 0.05 W/m-K. The best insulation available is Vacuum Insulation Panels (VIPs), with $R$ values “7 to 8 times greater than conventional foam insulation materials [6].”

VIPs are made of a filler material and a thin film around the filler to hold in the vacuum and protect it from the elements. There is a direct correlation between the core materials pore size and its ability to maintain low thermal conductivity at higher internal pressures [6]. VIPs must have very small internal pressures to be effective. The materials that are used to create the filler material are not expensive but the methods that are used to create the micro and nano sized pores which make the panels efficient are [7].

VIP panels are also fragile. They must be protected and handled with care. They also lose their vacuum over time and are expensive compared to polystyrene insulation [6].

Polyurethane or polystyrene foam is a standard insulation material that is used extensively in the US and around the world [8]. It is extremely durable, inexpensive, and its thermal conductivity is only bested by vacuum insulation.

2.4 Phase Change Material

Figure 5 shows the behavior of a material transitioning from one phase of matter to another. There are four types of phase change: solid to liquid, liquid to gas, solid to gas and solid to solid. Heat is absorbed or released during all phase change processes. The absorbed or released heat content is called latent heat [9]. Latent heat storage is one of the most efficient ways of storing thermal energy. Materials absorb heat energy during the melting process and release it during the freezing process.

PCMs that convert between solid and liquid are frequently used as latent heat storage material. PCMs were not extensively utilized until the advent of viable encapsulation methods in the late 1970’s [14]. In the 1980’s PCMs began to be used in projects ranging from thermal storage in construction materials to NASA’s incorporation of PCMs into space suits to protect astronauts from the large temperature fluctuations experienced in space [9].

![Diagram](diagram.png)

**Figure 5** Phase change behavior when heat is added

The most useful PCM attribute occurs during the transition between solid and liquid states, the material maintains a nearly constant temperature. This means that a PCM can be used to absorb heat and keep a space cool during its melting transition, or it can give off heat and keep a space warm during its solidifying transition. During the complete melting process, the temperature of the PCM as well as its surrounding area remains nearly constant. The same is true for the crystallization process (freezing); during the
entire crystallization process the temperature of the PCM does not change significantly [10].

The duration of a PCM’s change of state depends on the ambient conditions surrounding the material. Use of insulation and a sealed environment slows the heat transfer from the PCM, extending the phase change period. These factors combined with the use of a PCM manufactured to undergo its liquid to solid phase change at a desired temperature allows the construction of an incubator that maintains a required temperature for a period of 24 hours when sufficient quantities of PCM are used.

Common PCMs include organic (paraffin and fatty acids), inorganic (salt hydrates) and eutectics (organic-inorganic combinations) [15].

3. Methodology and Testing

The incubator is comprised of four components: the shell, insulation, heat source and control system. Alternatives were developed and evaluated for each of these. The performance of the insulation and PCMs as well as the overall incubator performance is based on the measurement of temperature and time carried out in known ambient conditions. Temperature data is accurately measured using external thermocouples positioned at key location in and around the incubator. In addition, sensors incorporated into the incubator monitoring and control system measure the temperature on the heating plate and in the incubator cavity. The thermocouple data is logged to a computer and the onboard temperature sensor data is sent to a MicroSD card that is part of the system. The thermocouples are calibrated to a mercury thermometer in a water bath. The temperature sensors are accurate to ± 0.2 °C [16] and are calibrated to the thermocouples.

4. Design Alternatives

4.1 Casing and Insulation

The performance of the incubator is directly related to the quality of its insulation. The two highest rated insulations available are VIP’s and polystyrene. The ideal insulation to use is the type with the lowest thermal conductivity and greatest reliability.

VIPs offer the best thermal conductivity. The K value for VIPs ranges from 0.0025 to 0.01. However, VIPs are fragile and expensive.

In an attempt to reduce cost (relative to commercially available VIPs) a prototype VIP was fabricated using a vacuum-based food sealer in series with a second, lab grade vacuum pump. Cardboard packing material soaked in resin was used as the filler material. The absolute pressure was measured with pressure transducers. Results of this test were unsuccessful for reasons discussed in section 5.1.

Polystyrene foam is not as thermally efficient as VIPs. It has R 5 per inch [6]. This is equivalent to a k value of 0.28. However, polystyrene is readily available, inexpensive and durable. Polystyrene is also easy to shape using basic hand or power tools.

The only casing alternative being pursued is fiberglass. Fiberglass is easy to obtain and work with, light weight, durable and inexpensive. It can also be shaped to fit any configuration of incubator.

4.2 Heat Source

The incubator design options include two possible heat sources, PCM and resistive electric heaters. These methods can be used independently or cooperatively in a hybrid incubator.

According to Entropy Solutions, manufacturer of the PCM used in this incubator, PCM must be enclosed within a sealed container to avoid degradation with use. Selection of the container involves a variety of criterion including availability, cost, size, volume, geometry and durability. One of the first variables to be considered is the shape of the containers. It is important that the containers efficiently fit into the incubator. Calculations show that increases in the incubators internal dimensions relate to higher energy demands.

Research and manufacturer recommendations suggest using a rectangular container. PCM inside rectangular containers takes less time to melt [15]. Comparisons between the melting time for rectangular and cylindrical containers was performed and the results show that the rectangular container requires half of the melting time of a cylindrical container of the same volume and the same area between the heat source and the container’s wall. It is, therefore, preferable to use rectangular containers for encapsulating the PCM [15]. Representatives from Entropy Solutions, the manufacturer of the PCM being used, suggest other advantages of rectangular shaped containers. Rectangular containers are more easily incorporated into the rectangular shaped incubation chamber and they provide for a solid temperature barrier along the walls of the incubation chamber.

PCM balls are ruled out due to volume limitations associated with their spherical geometry, as well as production difficulties. The method of filling the space surrounding E. coli cultures inside the incubation chamber with PCM balls, as in the current method, is not being considered because size constraints have limited the amount of open space surrounding the samples. Filling the small space surrounding the samples with PCM balls would mean that much of the space would go unused. The
implementation of rectangular containers takes advantage of all the space available.

Another heat source option is resistive electric heaters. Resistive heaters can be heating pads, coiled wire, or common resistors. Nichrome wire is commonly used for heating in items such as toasters and hair dryers. The power, $P$, radiated from electric heat components is a function of the voltage, $V$, and the resistance, $R$, of the component as shown in equation 4.

$$ P = \frac{V^2}{R} \quad (4) $$

A hybrid incubator design uses both the PCM and the electric heaters. The PCM maintains a constant 35 °C while the electric heaters raise the temperature to 37 °C. The PCM reduces the demand on the battery, extending its service life. Each individual component otherwise functions as it would on its own.

4.3 Electronics

Onboard electronics can be used for many functions besides heating the incubator. They are able to read and display temperatures, time the 24 hour incubation period and log test data. Discrete components can provide some of these functions independently but a microcontroller can provide all of them in a single system. The components required to do this include a display, temperature sensors, a power source, a microcontroller, read/write capable memory and heating elements.

Displays come in many sizes and configurations. LCD displays are available in different color schemes, with or without back lighting and with different numbers of character spaces on the screen. Common sizes are sixteen to twenty characters long and two to four rows tall.

Temperature sensors are selected by range and accuracy. More accurate sensors are more expensive. They can be purchased as surface mount or through-hole components. They are available with analog or digital output.

Of all the battery options on the market, Lithium Polymer (LiPo) batteries offer the highest energy density as well as being rechargeable. A battery pack is formed from individual 3.7 V cells wired in series to produce a higher voltage. These multi-cell LiPo batteries require the use of a balance charger which ensures each cell is charged to the same voltage. The chargers range from small units dedicated to 2-3 cell LiPo batteries to large units capable of charging many sizes and types of battery packs. The dedicated 2-3 cell chargers are more compact and less expensive. Solar cells are an option for in field charging. Panels rated for 12 V and useful amperages are available. Most locations EWB goes to do have electric grids, they are just unreliable. A standard charger can be brought to charge batteries when the grid is functional.

5. Design Selection

5.1 Casing and Insulation

Because of cost and durability issues, buying pre made VIP is less preferable than closed cell polystyrene foam. The team tried to make VIP insulation with less than satisfactory results. The absolute pressure that was reached was measured with the National Instruments pressure transducers and is shown in Figure 6. The best vacuum reached was 7.5 kPa.

![Figure 6](image)

**Figure 6** Pressure reached by the vacuum sealer and with assistance from an external pump.

![Figure 7](image)

**Figure 7** Graph showing dependency of internal vacuum to the thermal conductivity of the VIP.

![Figure 8](image)

**Figure 8** Graph comparing the VIP and Styrofoam incubators. Note: Plot is of data points represented as a line for clarity.
This was compared to pressures that are needed for effective VIP insulation, shown in Figure 7. The 7.5 kPa pressure reached is not sufficient to provide adequate insulation. For a final test, an incubator made from the VIP panels was compared directly to an incubator made from Styrofoam insulation. The results are shown in Figure 8. The temperature inside the VIP incubator drops off much more quickly than that of the polystyrene incubator. This led to selecting Styrofoam for the incubator’s insulation.

Fiberglass is used as the casing to protect the foam and electronics. Fiberglass is relatively easy to work with and it can be shaped to fit any configuration of incubator. It is also extremely durable and can be used without professional help.

Figure 1 shows final prototype incubator design used for performance testing. It is made of 2.5 cm thick polystyrene insulation sheets with a final wall thickness of 5 cm. It has two cavities, a lower incubation cavity and an upper electronics cavity. The seal around the incubation chamber is a double groove to reduce infiltration. It weighs in at 2.2 kg with PCM, a battery and electronics onboard. It measures 30.5 x 23 x 23 cm.

Figure 9 Final prototype incubator design used for performance testing.

5.2 Electronics

Much of the electronics system design used in the incubator is from projects funded by Colorado Space Grant Consortium, specifically the robotics challenge and BalloonSat program. In many ways this project is testament to the spin-offs space research provides. The heater circuits and microcontroller systems were direct carryovers.

Systems are managed by an Arduino-based design. The Arduino platform is well supported by examples and forums online. Libraries for running an LCD and recording to an SD card are included with the Arduino software package. This allows for quick prototyping with minimal software debugging.

The microcontroller runs all the incubator subsystems. It simplifies monitoring, allows for continuous data logging and provides temperature regulation. The incubator is capable of heating and running solely off of electricity if a local power supply is available or if sufficient batteries are brought along.

The ATMEGA-328P microcontroller is the processor used in newer Arduinos. The 328 is a 5 volt controller with fourteen digital in/out pins and six analog pins. The analog inputs are filtered through a 10-bit analog-to-digital (ADC) converter, providing 1024 partitions. The default analog range is 0-5 V but the upper limit can be adjusted by connecting a lower voltage to the Analog Reference pin and making a few adjustments to code. By setting the analog reference voltage lower, finer analog resolution can be achieved. By dividing a smaller range, 0-2 V for example, by 1024 each partition is valued at 0.00195 V while the default range of 0-5V values each partition at 0.00488 V. This greater resolution is utilized to get more accurate readings from the analog temperature sensors.

Three LM35CAZ TO-92 analog temperature sensors are used in the incubator, one on each heater plate and one to monitor cavity temperature. The sensor is accurate to within ±0.2 °C at 25 °C [16]. It outputs a linear +10 mV/°C. Peak voltages in the operating range of the incubator are typically around 1.7 V. Each sensor uses one analog input on the microcontroller and is fed by a regulated 5 V supply. The temperature sensors are calibrated against a set of T-type thermocouples to confirm accuracy.

Temperature values are displayed on a Microtivity IM162, 16x2 characters, black-on-green LCD module. The IM162 is a standard 5 V, parallel load LCD with adjustable contrast and backlighting. With 4-bit addressing it uses six digital pins on the 328. Battery voltage levels are also displayed. One digital pin is used to trip a MOSFET tied to the ground of the LCD. When the pin is low it breaks the LCD power circuit to save energy.

Data is logged using an Adafruit Industries MicroSD breakout board. It includes 3.3 V regulation of power and communications to protect the MicroSD card. Adafruit also provides Arduino code for the breakout and an active technical support forum. The breakout uses 5 V power and 4 digital pins for communication. Power from the 3.3 V regulator is fed to the Analog Reference pin of the 328 through a resistor. This provides a 2.88 V analog reference value.

Two analog pins are used to switch two IRFIZ24N MOSFETs. These MOSFETS switch power on and off to resistive heating elements inside the incubator. The heating elements are 50 Ω coils of...
32 Ga. Nichrome wire. The Nichrome coils are epoxied to the back of anodized aluminum plates. There are two heating plates in the incubator. When powered by a 3-cell LiPo battery each heating plate can produce approximately 2.5 W of heat. Note the actual output depends on battery voltage at the time of operation. One end of each Nichrome coil is tied to full battery voltage with the ground side switched by a 24N MOSFET.

The system is powered by a 3-cell, 5.8 A-h LiPo rechargeable battery. Each cell is rated for 3.7 V, for a total rating of 11.1 volts. Cells typically charge to 4.3 can be drained to 3 V. This gives an operational range of 9-12.9 V. Power from the battery is fed into an LM7805 5 V regulator with smoothing capacitors. The 5 V regulated supply powers the rest of the system. Discharging below 3 V per cell permanently damages the battery so a circuit with a TLV272 OPAMP and an IRFIZ24N MOSFET automatically shuts off of the LiPo battery when it reaches 9V. A resistive voltage divider circuit is used to divide the battery voltage by 2/3. When the LiPo reaches 9V the TLV272 turns off the IRFIZ24N, killing the ground for the battery and disconnecting it from the system. A 3 V coin cell battery provides the reference voltage for the TLV272.

The electronics are assembled on a custom, two-sided printed circuit board. Doing so reduces cost and power requirements compared to using an off-the-shelf Arduino and a SD data logging shield. Current draw drops from 40 mA to 18.5 mA for the base system. Circuit diagrams, PCB layouts and materials lists are included in Appendix IV. The circuit can easily be adapted back to an Arduino and shield if end users wish to do so by copying the 24N switching system and OP-AMP circuit to protect the battery. Data logging code may need to be modified depending on the hardware used and pin assignments may be changed as well.

The ATMEGA-328P must be preprogrammed before inserting it into the circuit board. This is done by placing a 328, with the Arduino bootloader installed on it, into an Arduino and then opening and uploading the code to the chip. The newly programmed chip can be inserted into the board and tested for functionality.

The user interface is a single, waterproof momentary switch beside the LCD. If the switch is depressed during regular operation the microcontroller turns the display on. The display shows the incubation duration, temperature of both heating plates and the battery voltage as long as the button is depressed then shuts back off.

When the incubator is turned on it goes through an initial setup. First it checks to see if the cavity temperature is above 38 °C due to overheated PCM packets being present. If the temperature is too high it warns users not to start the test. The incubator alerts users when the cavity is at operating temperature by displaying a message on the LCD. After this it checks to see if a MicroSD card is present for data logging. If not it warns users and notifies them to press the button to continue. If a card is present it bypasses this message. After this the incubator begins a 24 hour timer. Once the 24 timer is complete it shuts down the heaters, stops logging and flashes the LCD on and off to alert users the test is over.

For thermal control the microcontroller reads temperature sensors attached to each heating plate. If the temperature is below 37 °C it turns the associated heater on. If it is above 37 °C it turns it off. The system cycles through four times per second. Every ten seconds the system writes recorded temperatures and heater states to the MicroSD card.

The total code written is about 11 pages long. It is written so that key user-adjustable variables are defined at the very beginning. This includes the target temperature, delay between sensor readings and calibration values for the temperature sensors. By changing the value of these variables the incubator’s behavior can easily be altered to user demands. Data is recorded to the MicroSD card in comma delineated format. The code appends a new, sequential, 2 digit number to each log file. It can write up to 99 files to the MicroSD card before it runs out of digits and stops writing new files. Each file can record as long as it has space on the MicroSD card. A 2 GB card is more than sufficient for 99+ 24 hour data logs but larger cards can be used.

5.3 Heating

As discussed in performance testing, electronics are capable of running the incubator long enough if users carry several batteries or provide other external power supplies. The PCM is capable of maintaining a 35 °C temperature but not 37 °C. This is an acceptable testing temperature but is at the lower end of the threshold.

The final PCM container used in the incubator prototype is a translucent, 125-mL, high density polyethylene bottle. This bottle is used because it allows the user to visually determine the state of the PCM inside, and has a high temperature tolerance. In addition, the bottles are small enough in size to fit efficiently into the incubator, and can be re-opened if, for any reason, the user wishes to remove the PCM inside. The prototype incubator holds four of these PCM bottles with a total volume of 500-mL of PCM.

The project advisor and EWB team requested that three incubators be built. One is a hybrid system which can run solely off either PCM or electronics (assuming adequate power is supplied), or both. The
hybrid includes electronics for data logging. Two additional incubators will run solely off of electricity.

6. Performance Testing
Detailed instructions on all testing procedures are outlined in Appendix I. The incubator is tested for thermal performance, electrical performance and durability, structural integrity and water intrusion. Thermal performance tests are performed in a 23 °C room and a 1.7 °C commercial refrigerator.

The important characteristics of the phase change material are its freezing temperature and the duration of the freezing temperature inside the incubator. The melting and freezing temperature of PCM is determined by placing samples in a melting point apparatus. Performance of the PCM profiles is tested by logging the temperature and temperature duration of a PCM profile in an open environment, and logging the temperature and temperature duration inside an incubator run PCM profiles alone.

Additional testing of the performance of the PCM heated incubator in environments of differing ambient temperature is performed by placing the PCM heated incubator inside a refrigerator for a period 24 hours and logging temperature data.

Electrical performance is tested for accuracy, precision, longevity and efficiency. These are tested by running the incubator solely off of electronics and recording temperatures, battery voltages, heater cycling and battery longevity. Current draw from each component is also monitored.

Electrical durability testing conforms to JEDEC and IPR specifications outlined in Appendix I. A shake test is replaced with three drop tests. The water infiltration test is performed in a home shower.

Most of the structural testing is the same as the electrical testing. A key aspect of the structure is protecting the electronics and incubation cavity. If the electronics fail, the structure has failed its job to protect them. These shared tests include the drop and water penetration tests. The incubator is also subjected to a compressive stress test to simulate being loaded by luggage handlers at airports.

7. Results

7.1 Computer modeling
Using the material properties, interactions, and boundary conditions shown in Appendix I the model in Figure 10 was constructed.

The model stabilized very quickly, suggesting the steady state assumption for the analytical model is justifiable. The model also indicates that heat loss is highest at the inner corners of the incubator but least at the outer corners. This suggests that the final incubator should have rounded corners both inside and outside.

Figure 10  Heat Flux Magnitude

7.2 PCM heated incubator
Tests using four 125-mL bottles of PureTemp 37 PCM from Entropy Solutions yield promising results. Figure 11 shows the ability of a hybrid incubator to operate on PCM alone. Here, the temperature range inside the incubator is maintained between 35 ± 1 °C for 21 hours, where the ambient temperature is 23°C. This shows that the volume of phase change material is not large enough, however there is potential to maintain the incubator chamber at a constant temperature for an extended amount of time.

Figure 11  Hybrid prototype test with PureTemp 37 PCM as the heat source.

7.3 Electrically heated incubator
Tests of the electric incubator show very stable temperatures during operation. Figure 12 shows the first 15 minutes of a 20 hour test run inside a 0.7 °C refrigerator including initial heating times. Power was supplied by a 3-cell, 5.8 A-h LiPo battery. The heaters are two 50 Ω, Nichrome-wound, anodized aluminum plates. The target temperature was set at 37.1 °C.
Figure 12 Electric incubator test run in 0.7 °C refrigerator using two NiChrome wound heating plates and a LiPo battery.

The data shows almost no hysteresis around the 37 °C target. The jumps in measurements are due to the resolution limitations of the temperature sensors and microcontroller. Additional testing showed that the cavity temperature closer to center held around 36 °C. The rest of the test was very stable, showing constant temperatures for the heating plates and the cavity temperature. Power consumption by the heater plates averages 1.8 W-h over the duration of the test. This corresponds to 90% accuracy compared to the calculated power consumption. At the end of the 20 hour test battery voltage dropped from an initial 12.56 V down to 11.66 V. Voltage began to drop linearly at 0.033 V/h after approximately 5 hours of testing. Even in this cold environment the pack could have lasted well past the 24 hour test period. When operating in a warmer environment the battery packs last substantially longer. Tests show the 5.8 A-h battery lasts 66 hours (2.75 days) in a 23 °C room.

7.4 Hybrid system

The hybrid system works well for extending battery life. The electronics still function as expected and maintain 37 °C. However, the use of the PCM as a temperature buffer reduces the demand on the electronics. Battery life is extended by as much as five times without recharging so long as the PCM bottles are preheated before each 24 hour cycle.

7.5 Structural Testing

Structural testing had mixed results. The incubator and electronics both passed mechanical testing. A team member weighing approximately 220 lbs, stood on top of the incubator and bounced on it without damaging the structure. The dozen JEDEC drop tests performed did crack early 2-layer thick fiberglass but did no major damage. The electronics are based off of BalloonSat designs which survived two flights to 100K feet in altitude and the resulting landings with no adverse effects. They are expected to survive any rough handling the EWB trips will create.

The major concern for the electronics is water infiltration. The incubator failed IPR testing. Small pools of water formed in the upper electronics cavity as well as in the incubation chamber. Revisions are expected to help reduce or eliminate this infiltration.

7.6 User Interface

User interface testing led to some confusion. Users were not familiar with the two sets of cables coming from LiPo battery packs. One user tried to plug the battery's balance charge cable into the circuit along with the power plug. Users were initially unable to locate the microSD card. Otherwise the system worked well. Users responded favorably to the LCD screen and single button interface.

8. Conclusions

The test results suggest that an all-electric incubator is the most effective, user friendly solution. It eliminates the need for preheating PCM which saves end users up to two hours of setup time. It also eliminates the risks of overheating the PCM and killing the samples. Test results indicated that the amount of PCM needed to heat the incubator would need to be nearly doubled to last 24 hours in a 0.7 °C environment, compromising the goal of minimizing the total size of the incubator.

The battery life is good enough that two 5.8 A-h battery packs can run the incubator for the entire trip if temperatures are mild. In more extreme climates, extra batteries and charging systems should be carried or the hybrid incubator should be used.

The team did not find a fully satisfactory means of waterproofing the incubator cavities. The incubator should not be exposed to excessive moisture. The electronics should be coated with epoxy to help prevent damage.

Overall the design was a success. Both designs met performance requirements. The electric incubators came in under size, weight and power goals. When three batteries are included the cost per incubator is a little over $200, $50 above the target price. The hybrid also totals around $200 per unit, but met all other goals. Three incubators will be heading to Laos and Ecuador this summer for field testing.

The heating methods and control systems from this project can be used for any future DemoSat projects requiring temperature regulation. The durable, light weight case design and more efficient electronics will be used for a launch this summer.
9. References


3 3M™ Petrifilm™ Plate <http://www.3m.com/product/information/Petrifilm-Plate.html>


16 National Semiconductor data sheets

Appendix I. Testing Plan & Procedure

3M Petrifilm Plates
1. Following EPA procedure for “Testing Total Coliforms and Escherichia coli in Water” 6 plates will be prepared using the same sample.  
\[http://www.epa.gov/microbes/1604sp02.pdf\]
2. 2 different orientations will be tested. 3 plates will be placed horizontally in a laboratory incubator (located in the Chemistry Department at Fort Lewis College) and 3 plates will be placed horizontally in the incubator.
3. After the 24 hour incubation if the manual count of E.coli and Coliform of the plates placed in the new incubator yield the same results as the plates in the lab unit, then it can be concluded that the new incubator maintains proper growth conditions.

Insulation / Body Testing
Determine housing and lid for final design.
1. Compare the functionality of each lid and locking mechanism option.
   a. Prepare a survey that asks about the ease of opening, compactness, and versatility. Allow fellow students and teachers to complete the survey after inspecting the designs.
2. Run durability tests on each lid and housing option.
   a. Drop the incubator from 59 inches, twelve times (JEDEC).
   b. If hinges are part of the design, drop the incubator from 59 inches twelve times with the lid open.
   c. Use a force scale to apply a torque to the edge of the open lid until failure. This will determine the maximum force that can be applied to the lid.
   d. Place a 100 lb. weight (twice the maximum airline luggage standard) on top of the incubator to simulate supporting a heavy load during transport. Check materials for signs of stress or fracturing.

Determine validity of self-made vacuum based insulation.
1. Build vacuum insulation out of fiberglass and a one way valve that fits a hand pump. An absolute pressure gauge must be incorporated into the fiberglass to monitor the internal vacuum.
2. Use the hand pump to evacuate air from the vacuum chamber. Pump as much air out as possible and record the lowest pressure and time for duration computation.
3. Check the vacuum every hour until the vacuum is nearly gone. If vacuum degradation is slow, check daily. Record the time and pressure.
4. Run a heat transfer test following the electronics and heat transfer testing procedures to determine its thermal conductivity.

Electronics
Testing electronics accuracy and longevity
1. Run the incubator with the heating elements evenly distributed across two anodized aluminum plates as per instructions in Appendix IV. Plates should be installed horizontally inside the incubator.
   a. Use MOSFET switches to turn the heaters on and off based on target temperatures and readings from the thermocouples (see step 2).
2. Monitor internal and external temperatures and battery voltage.
   a. Attach one thermocouple to the center of each aluminum plate.
   b. Hang one thermocouple in the center of the incubation chamber.
   c. Attach one thermocouple to the interior and one to the exterior wall of the incubator. Try to get them directly across from each other.
3. Determine the power consumption requirements.
   a. Run the incubator in an air conditioned environment (room with a thermostat) until the batteries die. The regulated environment allows for calculating average power consumption.
   b. Record internal and external temperatures, battery voltage and the time to an SD card in comma delineated format.
4. Environmental effects on power requirements.
   a. Run the incubator for a minimum of two hours in ambient temperatures of 0.7 °C.
   b. Record internal and external temperatures, battery voltage and the time to an SD card in comma delineated format.
   c. Calculate and plot expected battery life versus ambient temperature.

Electronics Durability
1. JEDEC Drop testing:
   a. Due to lack of lab equipment, a simple drop test will be used. Turn on the incubator and drop it from 59” twelve times. Check for any failed electronics.
2. Ingress Protection Rating (IP Rating):
a. IPR testing standards require that spraying water, at up to 60° angle from vertical, shall have no harmful effect on the equipment.
   i. Place incubator in 60° angle from vertical, 0.7 L/min, spray for the five minute test duration. Check for intrusion.

3. Test charging system to see how long it takes to recharge fully drained batteries.
   a. Fully drain batteries by running incubator until it ceases to function.
   b. Using specified charger (TBD) record time until battery is fully charged:
      i. When plugged into a wall outlet.
      ii. Using specified solar panel (TBD).
   c. Retest charge time with a fully drained battery while the incubator is running
      i. Monitor voltage delivered to each system to ensure incubator is running optimally.

**Phase Change (PCM)**

**Determine melting and freezing points of phase change material.**

1. Cut open a room temperature phase change ball from the current EWB incubator.
2. Plug in and turn on the melting point apparatus.
3. Turn on a digital temperature probe and place it into the melting point apparatus.
4. Take a sample of the solid PCM from the ball.
5. Grind the PCM taken from the ball into a fine powder.
6. Press the open end of a capillary tube into the powder so that powder is forced into the tube.
7. Powder should occupy about 1 mm from the end of the capillary tube.
8. Hold a 1 meter long, clear plastic tube vertically with the bottom of the tube placed on a table. The plastic tube should be large enough in diameter so that the capillary tube can fit inside it long ways, but small enough so that the capillary tube inside is held mostly upright.
9. Hold the capillary tube, closed end down, in the top end of the plastic tube.
10. Drop the capillary tube inside the plastic tube. The capillary tube will bounce inside the plastic tube after hitting the table.
11. Repeat step 8 until the powder in the open end of the capillary tube moves to the closed end.
12. Turn the temperature dial on the apparatus to the lowest setting.
13. Once the powder in the capillary tube has all been forced into the closed end, place the capillary tube into the melting point apparatus.
14. Look through the eyepiece on the apparatus and gradually increase the dial. When melting is first observed in the sample, record the temperature from the temperature probe.
15. Keep observing the sample until it has completely melted. Record the temperature at which the material has completely melted. The recorded temperatures from step 13 and 14 are the range of temperatures over which the PCM melts.
16. Turn the dial on the melting point apparatus all the way down.
17. Observe the sample through the eye piece on the apparatus and record the temperature at which solidification begins.
18. Keep observing the sample until it has completely solidified. Record the temperature at which the sample has completely solidified. The temperatures recorded in steps 17 and 18 are the range over which the material freezes.
19. Repeat steps 5 through 18 for the new phase change material.

**Compare new PCM in profiles to PCM balls.**

1. Measure a quarter liter of PCM balls by water volume displacement.
2. Heat the PCM balls in boiling water until the PCM inside the balls is completely liquid.
3. Place the PCM balls into a 11.5x8.25x5 inch Styrofoam container and cover with lid.
4. Turn on and place a digital temperature probe through Styrofoam lid into the container.
5. Measured and log temperature at one minute time intervals until there is a steady temperature decrease after the constant temperature change of state.
6. Calculate volume of PCM profiles and determine number of profiles necessary to get as close as possible to a quarter liter of phase change material.
7. Heat the PCM profiles in boiling water until the PCM inside the profiles is completely liquid.
8. Repeat steps 3 through 5 for the PCM profiles.

**Compare temperature duration and fluctuation of the new PCM with current PCM.**

1. Fill one 2 mL plastic container with the current PCM.
2. Fill another 2 mL plastic container with the new PCM.
3. Heat both containers on a hot plate until the phase change material in both has completely liquefied.
4. Remove both containers from heat and place on a surface at room temperature.
5. Place a digital temperature probe in each container.
6. Record the temperature on both digital temperature probes at 1 minute intervals until both of them have completely solidified.

Determine if there is a significant temperature gradient associated with PCM profiles and PCM balls.
1. Heat the PCM balls until completely liquid by placing them in boiling water.
2. Fill 11.5x8.25x5 inch Styrofoam cooler half way full with heated PCM balls.
3. Place a piece of liquid crystal thermal paper cut to fit the width and depth of the container on top of the PCM balls.
4. Place more PCM balls on top of the thermal paper to fill the Styrofoam container.
5. Place lid on Styrofoam container, and let sit until a constant temperature is reached (about 15 minutes).
6. Remove lid and PCM balls from Styrofoam container.
7. Observe temperature gradient on thermal paper.
8. Heat PCM material encapsulated in profiles until completely liquid by placing them in boiling water.
9. Place profiles on bottom and around edges inside the Styrofoam cooler.
10. Suspend a piece of liquid crystal thermal paper cut to fit the width and depth of the container in the middle using thin wooden supports.
11. Repeat steps 5 through 7.

Computer Modeling
Using Finite Element Method (FEM) in Abaqus to optimize design
1. Material and sizing - 2D planar
   a. A 20x20x20 cm box with an inner compartment of 10x10x10 cm will be modeled within Abaqus.
   b. The outer boundary will be set to a range of temperatures from 0 to 23 °C.
   c. The inner boundary will be set to the desired 37 ± 0.5 °C.
   d. The materials thermal conductivity (k) will be set to 0.025 to 0.04 W/mK.
   e. This will be modeled over varying time periods 0hr - 12 hr - 24 hr.
   f. This highly simplified model will determine what material (based on thermal conductivity) should be used as the insulation and casing. It will also determine optimal size of the incubator.

2. loss - 2D planar
   a. Steps 1-5 of the test for ‘Material – 2D planar’ will be repeated but radiation, conduction, and convection will be added to the model.
   b. This complex model will determine what mode of heat transfer has the greatest effect on the incubator.
   c. 3D
      1. The same test done in 2D planar will be done in 3D.

Model properties:

<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Specific Heat</th>
<th>Thermal Conductivity</th>
<th>Electrical Resistivity</th>
<th>Electrical Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 6061 – T6</td>
<td>2700 kg/m³</td>
<td>896 J/kg°C</td>
<td>167 W/mK</td>
<td>3.990E-08 ohm-m</td>
<td>2.506E+07 S/m</td>
</tr>
<tr>
<td>Polystyrene foam</td>
<td>24.829 kg/m³</td>
<td>1.21 J/kg°C</td>
<td>0.028 W/mK</td>
<td></td>
<td></td>
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</table>

Interactions

<table>
<thead>
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<th>Interaction</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Outside Insulation</td>
<td>10 W/mK</td>
</tr>
<tr>
<td>2 - Aluminum Plate</td>
<td>5 W/mK</td>
</tr>
<tr>
<td>Surface Film Cond.</td>
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</tr>
<tr>
<td>Sink Temperature</td>
<td></td>
</tr>
</tbody>
</table>

Boundary Condition

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Plate Surface</td>
<td>310.15 K</td>
</tr>
</tbody>
</table>

Usability
Final product test- Test final prototype incubator against laboratory incubator (located in the Chemistry Department).
1. Following EPA procedure for “Testing Total Coliforms and Escherichia coli in Water” 10 plates will be prepared using the same water sample.
2. 5 of the plates will be placed in the laboratory incubator and 5 of the plates will be placed in the prototype incubator.
3. Verify that the manual count of bacteria cultures in the prototype is the same as in the laboratory incubator.
4. **Humidity** - The required humidity range of the Petrifilm plate will be tested to determine if the incubator requires a humidity modifier (such as a moist sponge or an open dish of water).
   a. 3M recommends that if the films appear too dry during incubation that the user places an open dish of water inside the incubator for moisture. Therefore there is no clean cut way to test humidity limits.
   b. Following EPA procedure for “Testing Total Coliforms and Escherichia coli in Water” 6 plates will be prepared using the same water sample.
   c. 3 plates will be incubated for 24 hours with no added moisture. 3 plates will be incubated for 24 hours with added moisture.
   d. The requirement for added moisture will be determined.

**Usability of prototype**
1. Allow 5 people with no experience using an incubator to: set up, maintain, and use the incubator and complete an incubation cycle. They will have access to a simple Users Guide for the incubator prototype.
   a. Get feedback from the test subject.
   b. Make changes accordingly.

**Appendix II. Petrifilm: Coliform Count Plate Interpretation Guide**

This guide familiarizes you with results on 3M™ Petrifilm™ Coliform Count plates. For more information, contact the official 3M Microbiology Products representative nearest you.

Petrifilm Coliform Count (CC) plates contain Violet Red Bile (VRB) nutrients, a cold-water-soluble gelling agent, and a tetrazolium indicator that facilitates colony enumeration. The top film traps gas produced by the lactose fermenting coliforms.

AOAC INTERNATIONAL and U.S. FDA Bacteriological Analytical Manual (BAM) define coliforms as gramnegative rods which produce acid and gas from lactose during metabolic fermentation. Coliform colonies growing on the Petrifilm CC plate produce acid which causes the pH indicator to deepen the gel color. Gas trapped around red coliform colonies indicates confirmed coliforms.

The identification of coliforms may vary by country (see Reminders for Use section for incubation times and temperatures): AOAC INTERNATIONAL validated method Total coliform = 69 (colonies with gas)

No growth = 0
Notice the changes in gel color in figures 2 through 5. As the coliform count increases, the gel color deepens. Background bubbles are a characteristic of the gel and are not a result of coliform growth.
**Total coliform count = 79**
The counting range for the total population on Petrifilm CC plates is 15–150. Do not count colonies that appear on the foam barrier because they are removed from the selective influence of the medium. See circle 1.

**Estimated total coliform count = 220**
The circular growth area is approximately 20 cm². Estimates can be made on plates containing greater than 150 colonies by counting the number of colonies in one or more representative squares and determining the average number per square. Multiply the average number by 20 to determine the estimated count per plate.

Further dilution of the sample is recommended for an accurate count.

**Actual count = 4**
When high numbers of non-coliform organisms such as *Pseudomonas* are present on Petrifilm CC plates, the gel may turn yellow.

**TNTC**
Petrifilm CC plates with colonies that are TNTC have one or more of the following characteristics: many small colonies, many gas bubbles, and a deepening of the gel color.
Total coliform count = 2
Food particles are irregularly shaped and are not associated with gas bubbles.

Total coliform count = 8
Bubble patterns may vary. Gas may disrupt the colony so that the colony “outlines” the bubble. See circles 1 and 2.
Artifact bubbles may result from improper inoculation or from trapped air within the sample. They are irregularly shaped and are not associated with a colony. See circle 3.

Examples 1–10 show various bubble patterns associated with gas producing colonies. All should be enumerated.

Appendix III. Body Construction
All parts will be cut from 1” thick blue Styrofoam with a rated R value of 5 per inch.
1. cut out 1 12”x9” block (block A)
2. cut out 1 7”x7” block (block B)
3. Cut out 2 12”x5” blocks (block C)
4. Cut out 4 7”x5” blocks (block D)
5. Cut out 2 6”x5” blocks (block E)
6. Cut out 1 5”x5” block (block F)

The blocks for both the body and lid will be glued together with rubber cement. Put the blocks together how they are supposed to be without gluing them first to see where each one goes. When you are ready to glue, smear a very thin layer of the rubber cement over the entire surface which is to be glued. Press the parts together firmly.

Refer to the accompanying diagrams while reading the directions to help place the blocks in the correct position. Place block A on the table in front of you with one of the 9” sides closest to you. Place block B on top of block A with the 7” side closest to you but with a 1” gap everywhere between the edges of blocks A and B. Glue Blocks A and B together. You will now have something that looks like a two layer birthday cake.

Place both of the C blocks on block A in the left and right gaps created by block B. The C blocks should be perpendicular to blocks A and B with their 12” sides against block A and coming out toward you. All sides should be flush. The C Blocks should be glued to both block A and the side of block B.

Place one of the D blocks on block A in the top gap created by block B. It should be perpendicular to blocks A and B with its 7” sides
against block A. It should just fit between the C blocks. Glue it in place.

Place another of the D blocks on the lower edge of block A. It should just fit between the C blocks.

The two E blocks should now be placed up against, and parallel to the C blocks with their 6" sides on the B block and sticking out toward you. Slide them up so they butt up against the upper D block. They should stick out 1" farther than the C blocks. Glue them in place.

The final two D blocks can now be placed in between and perpendicular to the C blocks. One should be sitting on the B block and butted up against the ends of the E blocks. The other one should be sitting on A block and up against the D block that was just put in place. Glue them in place.

Lid: All parts will be cut from blue Styrofoam with a rated R value of 5 per inch. One part will be cut from 2" thick foam as stated in the directions, the rest will be cut from 1" thick foam.

1. Cut 1 10"x7" block from the 2" thick foam (block G)
2. Cut 1 5"x5" block (block H)
3. Cut 2 12"x3" blocks (block I)
4. Cut 2 7"x3" blocks (block J)
5. Cut 1 7"x1" blocks (block K)

Place the G block flat on the table in front of you with one of its 7" sides closest to you. Place the H block on top of block N with a 1" gap between the edges of the H block and the top, left, and right edges of the G block. Glue the blocks together. You will now have something that looks like a two layer birthday cake with the lower end of the G block sticking out from under the H block more than the upper end.

Place the I blocks out on the left and right edges of the G block. They should not be on top of the G block but on the table with their 12" sides down and pressed up against the G block. They should be perpendicular to the table. Glue them to the G block. Place the J blocks on the table above and below the G block. They should also be perpendicular to the table with one of their 9" sides on the table. They should fit up against the G block and in between the edges of the I blocks that are sticking out past the G block. Glue them in place. The K block goes 1" below the H block with either end touching the I blocks. Glue it to the G block.

**Appendix IV Electronics**

For code or PCB files please email Nick Laitisch at njlaitisch@fortlewis.edu or laitsch@yahoo.com.

Wiring schematic

PCB Top Plate:

PCB Bottom Plate:
Components: Note that the Arduino Uno is only for programming the chips for installing on the PCB.

**Electric heating plate**

The plate must be anodized aluminum, dimensions 4.25” x 3.5”. The Nichrome wire is measured by resistance, not length. Measure out to 52 Ω and cut. Carefully coil the wire into a pattern similar to that on this plate such that the two 1 Ω ends trail off one rear corner. The wire can be held in place with standard clear tape as seen in the photo. Once the wire is located properly coat the entire side of the plate liberally with epoxy to ensure the wire is fully covered. Once it is cured trim off any excess epoxy around the edges. The wire leads poking out of the epoxy will need to be copper plated before soldering stranded copper wire to the ends. Solder the connections so the copper wires can be glued to the heating plates to eliminate stress on the Nichrome leads. One Nichrome lead must be connected to battery voltage via the polarized connector, the other to the MOSFET switched ground on the same polarized connector. Color coding the wires helps a lot here.