SMALL SOLID-STATE REFRIGERATION SYSTEM

by

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SMALL SOLID-STATE REFRIGERATION SYSTEM

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ABSTRACT

Rural Nicaraguan villages need low-cost, low-power, easily maintainable home appliances. Refrigeration is of value for the applications of medicine and/or food storage. The research herein investigated whether a thermoelectric refrigeration system could be designed using less than 20 Watts of power with solar power cells previously installed on numerous houses located in rural villages within Nicaragua. This study is focused on the material properties and thermal performance of the system, as well as the manufacturability of the design. Modes of heat transfer that were tested included convection and conduction. It was concluded that conduction would be the better mode of heat transfer for an application with such low-power requirements. Early prototyping indicates that the design of the system meets the necessary temperature and power requirements for the proposed environment. Further prototyping and testing will be needed to prepare the design for low-cost, high-volume production.

INTRODUCTION

Identifying the refrigeration needs of Nicaraguans, the first step in the design process was to define the project requirements and constraints for the refrigeration system.

Rural Nicaragua presents a cultural and socio-economic landscape largely unseen in the United States. Figure 1 contains a photograph of a village home located just outside the municipality of Nueva Guinea, Nicaragua. The photo was taken during a trip report whereby 15 homes were evaluated for a solar cell installation project, which is running in tandem with the refrigeration project and will serve as the main power source for the refrigeration system.

Figure 1: Village Home in Nueva Guinea

As shown in Figure 1, many of the locals do not live with access to electricity.

Figure 2: Schools in Nueva Guinea

Shown in Figure 2 are a few of the schools located within the municipality, many of which do not have access to essentials such as lighting.

Figure 3: Health Center in Nueva Guinea

Of particular importance to the refrigeration project is its goal to properly store medical supplies. Pictured in Figure 3 is one of the health centers evaluated for the solar project. With many locals needing medications stored at specific temperatures, the lack of refrigeration within the home makes access to these medications difficult. In a study by Braune et al., it was shown that there is a degrading effect on insulin when not properly stored in the temperature range of 2 °C and 8 °C [1]. A recent need has been the transportation and distribution of affordable COVID-19 vaccines to developing countries. COVID-19 vaccines such as Johnson & Johnson, AstraZeneca, and Sinovac require refrigeration temperatures between 2 and 8 °C, where they may be stored for up to 6 months [2]. The need to transport the system led to an important design element, whereby backpack straps are attached to the outside to make transportation and travel through the mountains easy.

The following performance constraints for the refrigeration system were determined, with temperature requirements and the socio-economical context of the intended users in mind.

1. The system must always maintain a temperature between 2 to 8 C.
2. The system must use minimal power, less than or equal to 20W.
3. The design must minimize the cost of production.

4. The design should be straightforward and require only moderate technical knowledge, allowing local technicians to assemble and test with minimal sourcing of parts from outside the country.
5. The system must be transportable to rural, mountainous areas.

THERMOELECTRIC TECHNOLOGY

The feature element of the refrigeration design is its use of thermoelectric technology to cool the entire system. Thermoelectric devices utilize the Peltier effect, essentially acting like a small, solid-state heat pump [3]. It is commonly packaged as a 1.5-inch by 1.5-inch square module, referred to as a Peltier device, Peltier cooler, or thermoelectric cooler (TEC). When a DC voltage is applied to the TEC, heat will move from one side of the module to the other, causing one side to cool down and the other to heat up. An image of a TEC module is shown in Figure 4.

Figure 4: Thermoelectric Cooler (TEC)

In theory, it behaves similarly to a traditional mechanical cooling system. The same principles of thermodynamics and heat transfer that are used for a mechanical refrigerator are utilized in thermoelectric coolers. As an illustration, a mechanical refrigerator utilizes liquid refrigerant and a compressor to alter the refrigerant's phase. A compressor exerts pressure on the refrigerant, which causes it to pass through a condenser, causing it to cool into a liquid state. It then passes through the coils of the system where the refrigeration compartment is located, absorbing the heat in the compartment and transitioning into a vapor. The cycle is then repeated.

A thermoelectric cooler behaves similarly but in a smaller package. Instead of a liquid refrigerant, a doped semiconductor material is used. A DC power source is applied, causing electrons to move, acting as the compressor. As the electrons move, they absorb the heat from the cold side of the module. The hot side is attached to a heat sink that absorbs the heat of the electrons as they pass through. The electrons then circle back around to the cold side at a lower temperature, and the cycle is repeated.

The appeal of a thermoelectric device for this application is its ease of use, as well as the low cost of TEC modules, especially when purchased in bulk. Traditional mechanical refrigerators would require metal coils, the use of liquid refrigeration, a compressor, and a condenser. More complex parts would be needed for such a system, which means higher costs, and repairs would need more technical expertise and troubleshooting. A TEC can be easily installed and replaced if necessary. The TEC used in the refrigeration system prototypes were in the price range of $4-$5 range per module.

Not to mention, the TEC offers a reliable method of cooling. The TEC module used can reach a 40 °C difference in temperature (104 °F) between the hot end and the cool end when properly utilized. If material selection is chosen in such a manner that the temperature of the "hot" end can be minimized (i.e., the "hot" end stays close to room temperature), the TEC can easily reach temperatures near and below freezing.

CONVECTION DESIGN

The next element to consider was the method of heat transfer for cooling the refrigeration compartment. Two methods were considered in this research: convection and conduction.

The first method considered was convection, or more particularly, forced convection, whereby fluid flow is caused by a mechanical device [4]. In the initial design, the mechanical design used was a fan. The proposed design utilized a plurality of small, low-power fans attached to the inside of a small pipe-like structure. With a TEC attached to a cooled heat exchanger, the heat exchanger was also enclosed in the pipe-like structure. The fans would force air to pass through the cool heat exchanger, circle to the refrigeration compartment, and be drawn back through the pipe-like structure to cool down once again. This cycle repeated over long times would eventually cool the inside air of the refrigeration compartment. An illustration of this design can be seen in Figure 5.

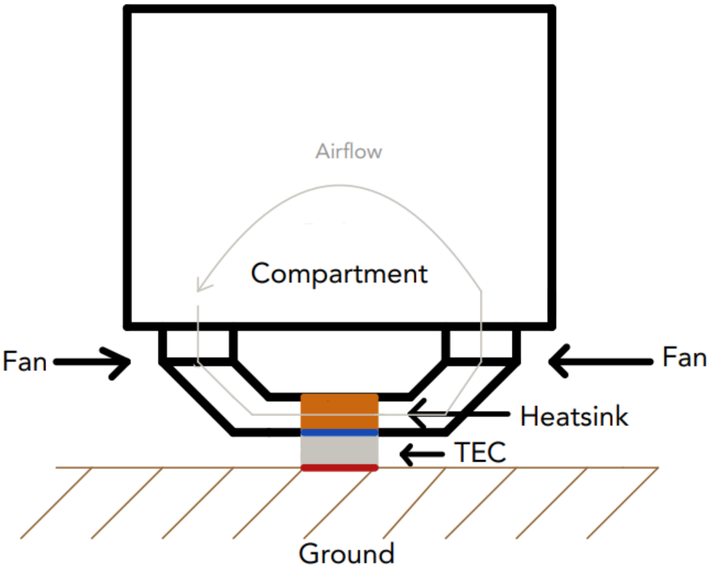


Figure 5: Convection Refrigeration System Design

To test this design, a series of interconnecting components were 3D modeled. These were then 3D printed. These interconnected components created a channel for airflow, held the fans, and allowed for a heat sink to be inserted. The two open ends of the air channel were then inserted into the bottom of a sealed Styrofoam box.

The fans and TEC were powered and allowed to run for approximately 30 minutes. While no temperature data was taken, qualitative data was measured. While the air within the Styrofoam box was somewhat cooler, it was noticeably far from the temperature requirements.

There were a few clear problems with this design approach. For one, it was difficult to find fans that blew at a significant rate and did not draw too much power—the fans blew air at a rate far too low, and the tradeoff was poor considering that stronger fans would have required substantially more power.

Additionally, it would have been difficult to produce the system in high volume with low-cost materials. The initial prototyping of this design utilized Fused Deposition Modeling (FDM) Technology to 3D print ABS polymers. To enclose the fans in the pipe-like structure while also making them replaceable if broken required tight geometric dimensioning and tolerancing. This is difficult to accomplish without a manufacturing method that is highly precise in its tolerances. Additive manufacturing, namely 3D printing, was readily available to us for prototyping. This, however, is not a resource readily available in this region of Nicaragua. PVC piping would be the most likely material that could have been used, but this would have required complex cutting and attachment methods.

CONDUCTION DESIGN

This lent itself to the next method of heat transfer used, namely conduction. The result of this research led to this method being chosen for the main prototype and design. An illustration of this design can be seen in Figure 6.

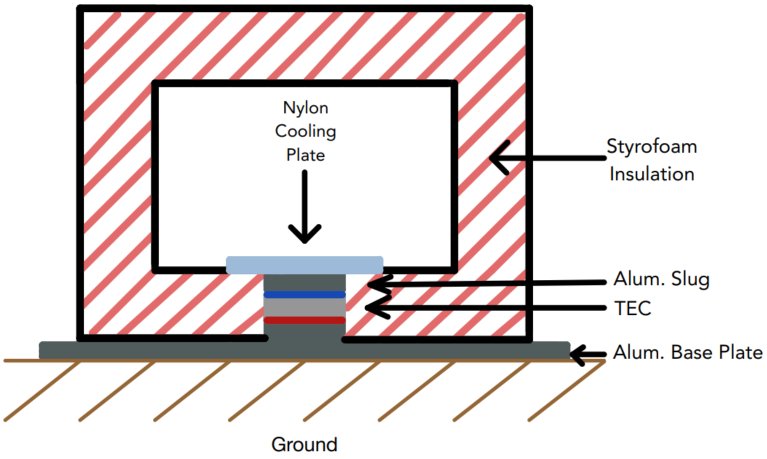


Figure 7: Conduction Refrigeration System Design

Conduction is the transfer of heat through matter via the interaction between the particles. When more energetic (“hotter”) particles of a matter interact with less energetic (“cooler”) particles, the energy will travel from hot to cold. It’s the classic example of touching a hot pan; the heat from the pan transfers to your hand and can burn you. There are elements of conduction within the aforementioned convection system design (namely, between the thermoelectric cooler and the heatsink), but it was not the direct method of heat transfer that cooled the compartment of the refrigeration system.

The conduction design for the refrigeration system utilizes a series of conductive materials to quickly transfer the heat from the “hot” side of the TEC (shown in red in Figure 7) and dissipate it to the ground. Similarly, conductive materials are used to quickly cool the nylon cooling plate, which is what the items will rest upon inside the compartment. The presence of the nylon cooling plate will allow for the air within the refrigeration compartment to also cool, given that the compartment is properly sealed and insulated.

MATERIAL SELECTION

Material selection is the most important element of this particular design. Proper materials must be selected to allow for the desired distribution and flow of heat, as well as the insulation of the entire system.

The two most important thermal characteristics used in material selection were thermal conductivity (inversely, resistivity) and specific heat capacity. Conductivity is a measure of a material's ability to conduct or transfer heat. Resistivity, therefore, is a measure of a material's ability to resist the transfer of heat. Thermal conductivity is marked in units of Watts per meter-Kelvin ($\frac{W}{m*K}$). Materials are given a "k-value", which is a simple way of signifying those units. As an example, aluminum has a k-value of 237 and is highly conductive. Styrofoam, on the other hand, has a k-value of 0.033 and is highly resistive (or insulative).

Specific heat capacity is the amount of heat required to raise the temperature of a material by 1 °C. This is determined per unit mass of the material and is marked in units of Joules per kilogram-Kelvin ($\frac{J}{kg*K}$). Thermal conductivity is essentially the rate at which heat flows through a material, whereas specific heat capacity is the amount of heat a substance can hold. Water has a very high specific heat capacity ($4.182\,\frac{kJ}{kg*K}$), while dry air has a very low specific heat capacity ($1.005\,\frac{kJ}{kg*K}$).

The materials for the design were chosen based on these two thermal characteristics. The fundamental goals of the design are the following:

1. Transfer heat from the "hot" side of the TEC as quickly as possible. This allows the TEC to maintain a consistent temperature difference that reaches the temperature requirements on the cold side.

2. Cool a thermal mass inside the compartment that will maintain its low temperature for a long time, even when the TEC is shut off
3. Insulate the refrigeration compartment using a material with high thermal resistivity

To start, two aluminum slugs of the equivalent square area of the thermoelectric cooler were chosen to be adhered to the module using thermal glue on each side. The aluminum slugs are highly conductive, allowing heat to quickly flow away from the “hot “side of the TEC, and for heat to quickly be transferred through the “cold” side.

On the “hot side”, an aluminum base plate with a large area is attached to the bottom aluminum slug. This continues the effective flow of heat away from the TEC and creates a larger contact surface between the aluminum and the ground. The ground is the final place where the heat is dissipated.

On the “cold” side, the Nylon cooling plate was glued to the aluminum slug. Nylon offers a moderate specific heat capacity, allowing it to hold at its temperature for longer when cold.

The refrigeration compartment is lined with Styrofoam. Styrofoam is highly thermally resistive (insulative), allowing it to inhibit heat from the outside from entering the enclosed refrigeration compartment.

Except for the aluminum base plate, which remains as the bottom piece in contact with the ground, the entire system is enclosed with 30-gauge galvanized steel, adding rigidity to the entire system.

THERMAL-ELECTRIC REFRIGERATION MODEL

There exists a thermal-electric analogy relationship between materials and components in an electrical circuit. Physical materials in a system can be modeled to behave as a component within an electrical system.

Four main electric circuit elements can be used to model the physical thermal behavior of the refrigeration system: current sources (Amperes), voltage (Volts), resistance (Ohms), and capacitance (Farads) [5]. Their respective thermal analogies are shown in Table 1 below.

Thermal/Physical Element	Electric Circuit Element
Power Source (TEC)	Current Source
Temperature	Voltage
Thermal Capacitance	Capacitor
Thermal Resistance	Resistor

Table 1: Thermal-Electric Analogous Elements

Note that the Thermal Capacitance is the product of an object's specific heat capacity and its mass. Thermal resistance (planar wall thermal resistance, for the outer walls of the refrigeration compartment) considers an object's thermal conductivity, but also considers the thickness of the material and the area that it covers. The thicker the material, the more thermally resistive, while the larger the area of the material, the less thermally resistive.

The respective masses, thickness, and areas of all physical components of the refrigeration prototype were used to calculate the equivalent electrical component. The design's layout, namely the way that heat moves through the system, was used to determine whether electrical components would be connected in series or parallel to one another.

A rough thermal-electric model of the refrigeration system was created prior to the initial testing of the prototype and is shown in Figure 8.

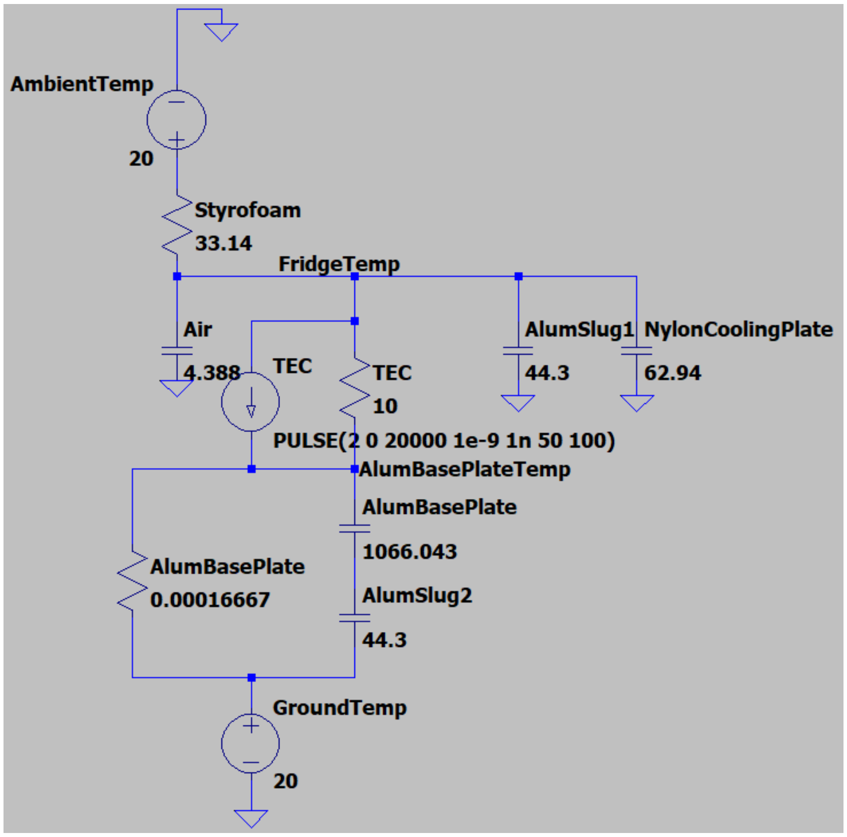


Figure 8: Thermal-Electric Model of Refrigeration System

The values for each element of this model were created using only the physical characteristics of the prototype (i.e., specific heat capacities known for the material, its thickness, its area, etc.). After tests were run, the values within this model were modified slightly to best reflect the actual performance of the system. This will be discussed further when discussing the test results.

The Thermal-Electric model served as the primary digital characterization of the refrigeration system and can be used moving forward to predict system behavior and overall system performance.

FINAL PROTOTYPE DESIGN

Figure 9: Final Prototype Design

The final prototype created utilizes a 12-inch long, 12-inch wide, 9-inch tall, 1.25-inch-thick Styrofoam box. It is encased by a 30-gauge galvanized steel sheet metal box, used to add rigidity to the system while being easy to bend and rivet into shape. It is then capped off with a sheet metal lid with extra Styrofoam insulation. Four eyebolts are attached to the outside corners of one side of the refrigeration system, such that backpack straps can be clipped to the outside and worn by a traveler as they hike to the rural villages with medical supplies.

The TEC is attached to the underside of the box using thermal glue to adhere the aluminum slug, nylon cooling plate, and aluminum base plate system together. This subassembly is shown on the right in Figure 9. The rest of the system rests upon this sub-assembly during use, with the cut out at the bottom of the box shown on the right within Figure 9.

TEC CONTROL METHOD TESTS

After a working prototype was constructed, different methods for controlling the input current to the TEC were experimentally tested. This section will evaluate whether or not each method meets the power requirements for the refrigeration system, evaluate the energy consumption of each method, and use the experimental data to improve the Thermal-Electrical model such that it more accurately reflects the physical prototype.

Constant Current Test

An initial test was run with the refrigeration system that involved monitoring the steady-state performance of the system. This test was run to establish a bassline for the proportional, or variable, current control method. It was also used as a starting point for refining the Thermal-Electric model.

For this test, a buck converter (which controls the amount of current supplied to the TEC from the power source) was adjusted to varying input voltage levels. At each voltage level (which corresponds to an associated amount of current), the current was held constant until the system reached a constant temperature for 1 minute, thus exhibiting steady-state behavior. The temperature at which this occurred was plotted against the input voltage level in Figure 10. A battery supplying 13 V served as the power source for this test.

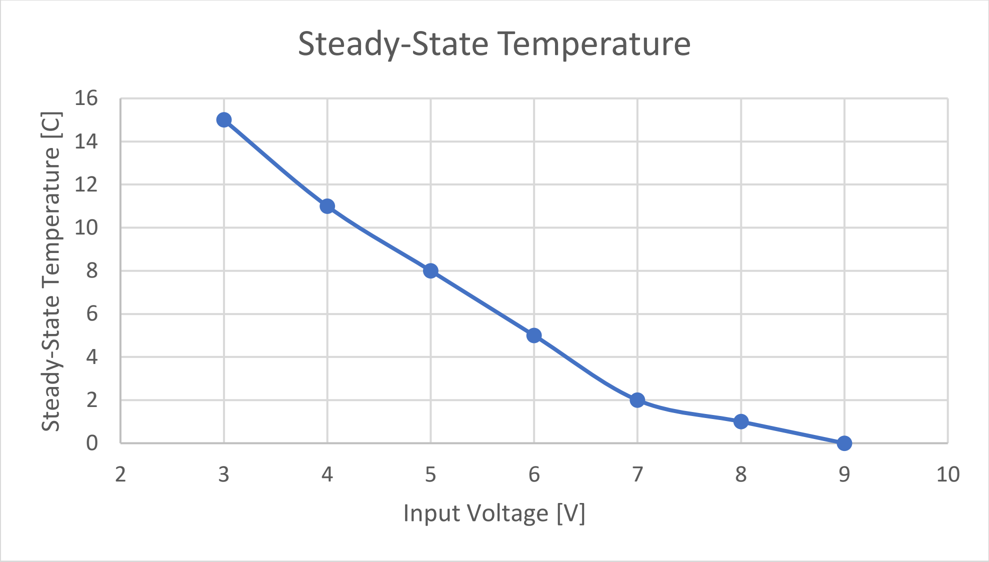


Figure 10: Steady-State Test

The results indicate that to remain in the 2 to 8 °C temperature range, the TEC must be supplied somewhere between 5 V and 7 V if the desired method of cooling was a constant power source.

Input Voltage [V]	**Input Current [A]**	**Steady State Temperature [C]**	**Power [W]**
3	0.06	15	0.78
4	0.2	11	2.6
5	0.41	8	5.33
6	0.73	5	9.49
7	1.11	2	14.43
8	1.55	1	20.15
9	1.71	0	22.23

Table 2: Steady-State Temperature Comparison

Table 2 demonstrates the relationship between voltage, current, and power for the TEC. To operate in the 2 to 8 °C temperature range, anywhere between 5.33 W and 20.15 W would need to be used at any given time. While this meets the project requirements, this is not the only method that can be used to control the TEC. The method in this test involves utilizing a constant power source that will always run at the same input voltage. To choose a middle number, such as an input voltage of 6 V at 9.49 W running for 24 hours a day, the total amount of energy the refrigeration system would use per day would be approximately 230 Wh (Watt-hours). Other control methods (to be discussed later) indicate that such a method of controlling the TEC would not be the most efficient.

Part of the importance of collecting experimental data is that it can be used to better characterize the digital model of the design. The results of this test allowed for improvements to be made to the Thermal-Electric model. The biggest changes implemented were in the magnitudes of the TEC current source and the TEC resistance. While all other resistance values were calculated according to theory, the TEC resistance was largely unknown before running the test. As for the current, following the results of this test, it was recognized that the Thermal-Electric model has a slightly different current-to-power consumption ratio than that of the actual refrigeration system. This is largely due to varying load values between the actual system prototype and the theoretical model that have yet to be discovered. As a result, the current values for the TEC in the Thermal-Electric model are now all 2.67 times the actual current amount produced in the physical system. As future tests are taken, the model can be continued to be refined in this manner.

To choose a value in the middle of the Constant-Current data, a current of 1.97 A was chosen to represent the 0.73 A input current in Table 2. The TEC resistance was then slightly changed to reflect the actual resistance of the system. The updated Thermal-Electric model is shown in Figure 11.

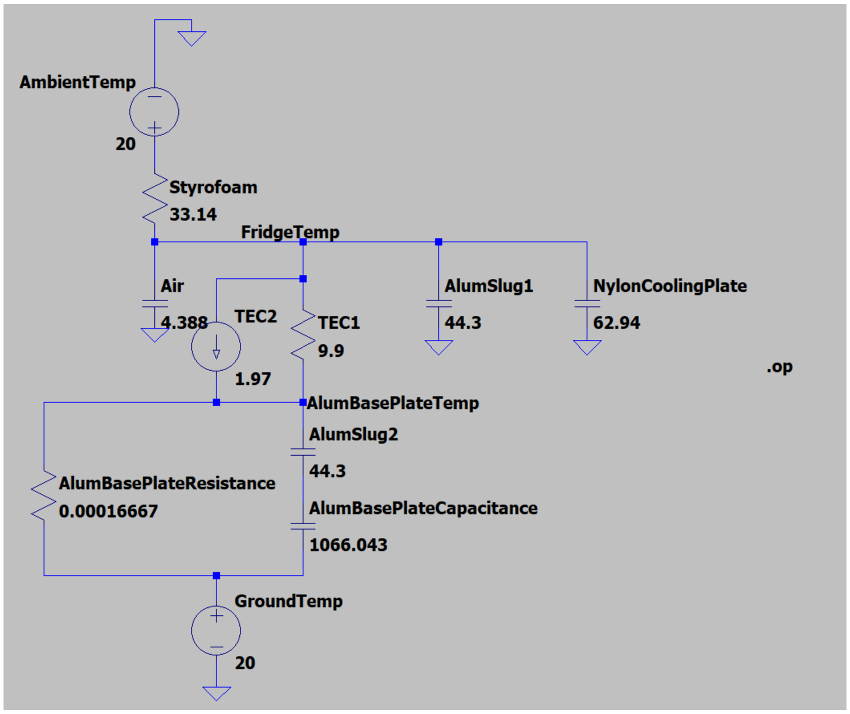
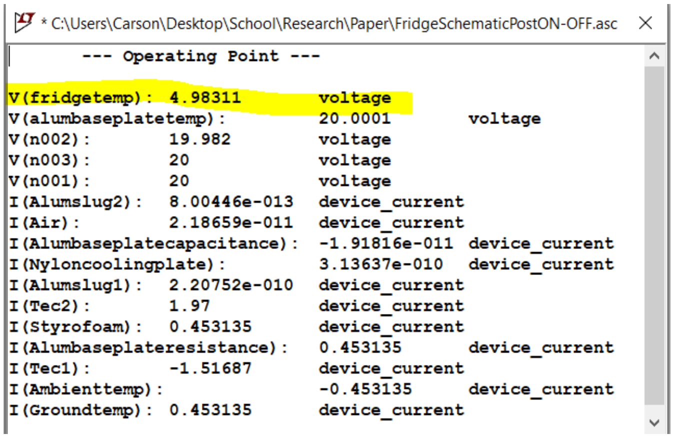


Figure 12: Updated Thermal-Electric Model after Constant Current Test

The spice diagram shown in Figure 12, when run by a constant current, produces the steady-state voltage and temperature values shown in Figure 13.



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          --- Operating Point ---

V(fridgetemp):  4.98311         voltage
V(alumbaseplatetemp):           20.0001         voltage
V(n002):        19.982          voltage
V(n003):        20              voltage
V(n001):        20              voltage
I(Alumslug2):   8.00446e-013    device_current
I(Air):         2.18659e-011    device_current
I(Alumbaseplatecapacitance):    -1.91816e-011   device_current
I(Nyloncoolingplate):           3.13637e-010    device_current
I(Alumslug1):   2.20752e-010    device_current
I(Tec2):        1.97            device_current
I(Styrofoam):   0.453135        device_current
I(Alumbaseplateresistance):     0.453135        device_current
I(Tec1):        -1.51687        device_current
I(Ambienttemp):                 -0.453135       device_current
I(Groundtemp):  0.453135        device_current
```

Figure 13: Voltage/Temperature Values According to Thermal-Electric Model

Of most importance are the values for the refrigeration system temperature and the aluminum base plate. The data demonstrates that the system temperature is right around 5 °C, as the experimental test originally measured. Additionally, the aluminum baseplate temperature remains right around room temperature (20 °C), showing that the current system is preventing the aluminum base plate from getting too hot and hurting the delta T of the TEC itself.

On-Off Test

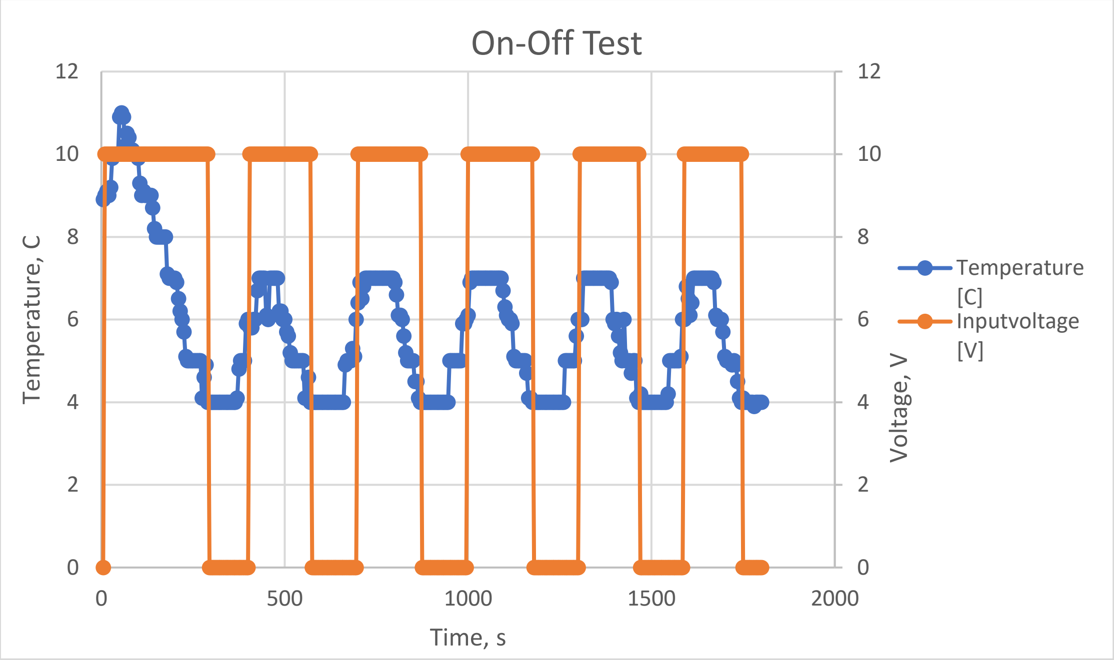

Figure 14: On-Off Test

For the On-Off test, the buck converter was turned on and off to determine how quickly the temperature of the cooling plate changed. A battery supplying 13 V served as the power source for this test.

Shown in orange in Figure 14, the voltage supplied by the buck converter was switched between 10 V and 0 V, corresponding to 1.48 A of current and 0 A of current, respectively.

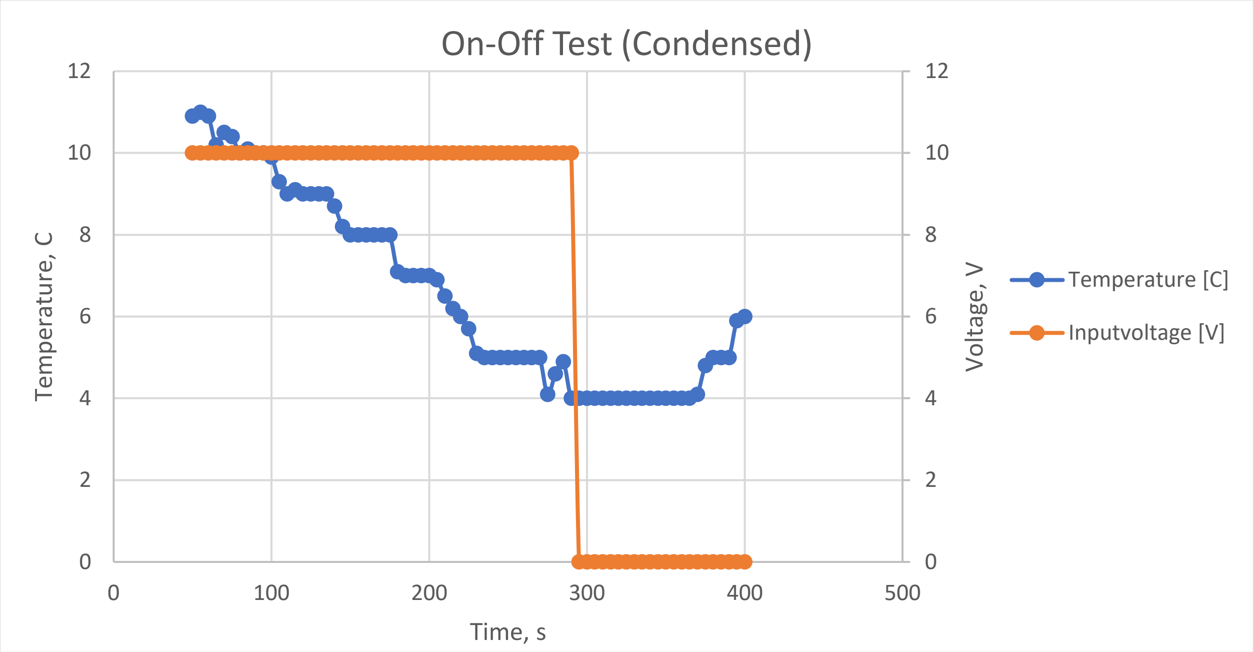

Figure 15: On-Off Test (Condensed)

More easily seen in the condensed plot in Figure 15, the input voltage was run at 10 V until the temperature of the plate reached 4 °C. At this point, the voltage was turned off to zero, until the temperature of the plate reached 6 °C. Of importance to note, the temperature initially took 290 seconds to decrease from 11 °C to 4 °C.

On average, it took 121 seconds for the temperature to rise from 4 °C to 6 °C after the power was shut off. It took 170 seconds on average for the temperature to decrease back down to 4 °C after the power was re-applied. This means that the refrigeration system was running, on average, a 58% duty cycle. With a supply voltage of 13 V and an input of 1.48 A at a 58% duty cycle, this means that the system would utilize approximately 270 Wh daily.

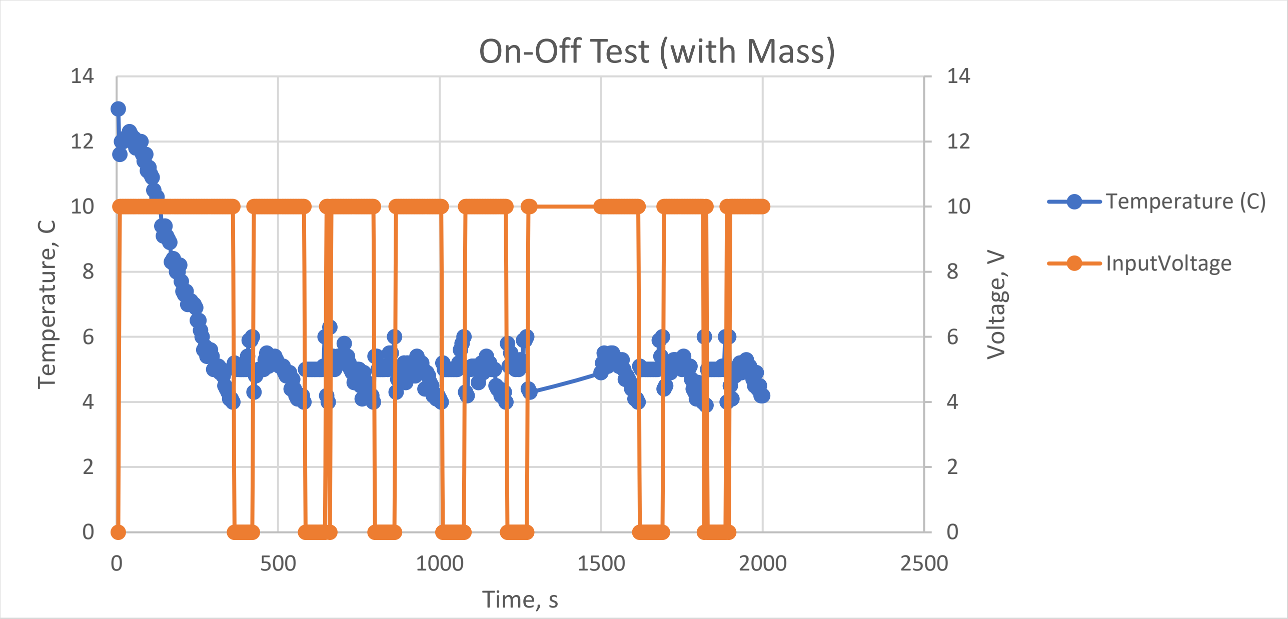

Figure 16: On-Off Test (with Mass)

The same test was run with a small aluminum block placed on the cooling plate. The same testing conditions existed, as well as the same procedure.

For the 2000 seconds run in Figure 16 (approximately 33 minutes), it took, on average, 68 seconds for the temperature to rise from 4 °C to 6 °C after the power was shut off. It took 170 seconds on average for the temperature to decrease back down to 4 °C after the power was re-applied. This equates to a duty cycle of 71%. This would result in energy usage of approximately 330 Wh daily.

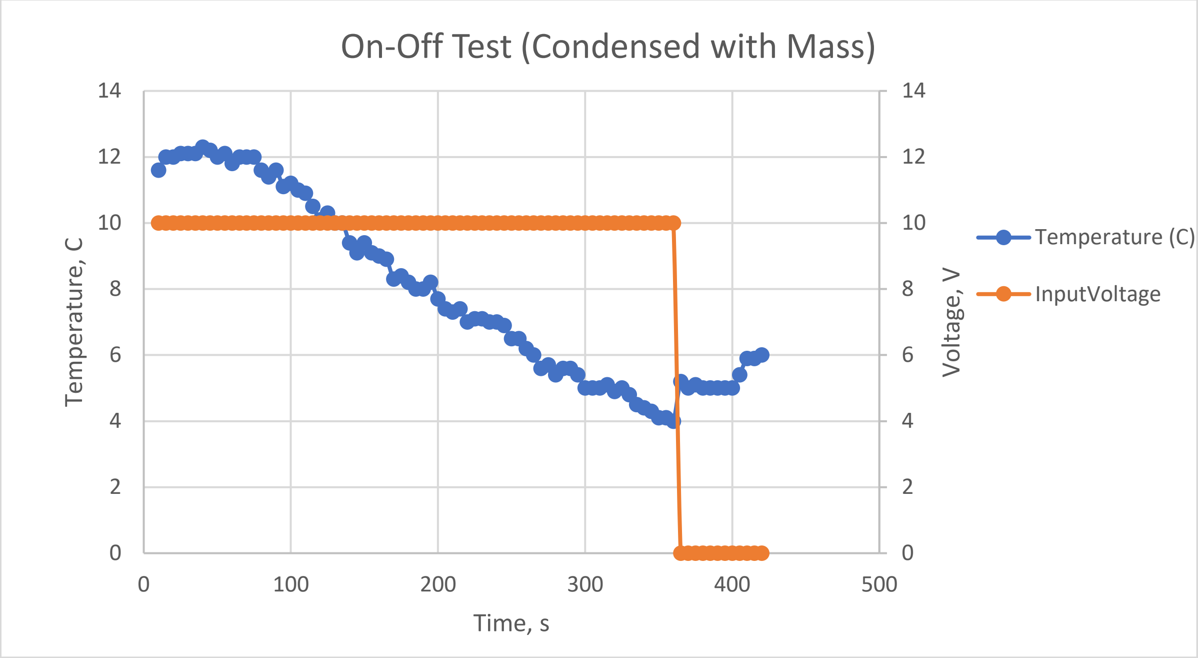

Figure 17: On-Off Test (Condensed with Mass)

Of importance to note, and which can be seen in Figure 17, it took approximately 360 seconds for the temperature to reach 4 °C, after initially starting at roughly 12 °C.

Test Condition	**Time (s) to reach 4 °C**	**Avg. Time (s) to Warm from 4 °C to 6 °C**	**Avg Time (s) to Cool from 6 °C to 4 °C**	**Estimated Daily Energy Usage (Wh)**
No Mass	290	121	170	270
With Aluminum Block Mass	360	68	170	330

Table 3: “No Mass” vs “With Aluminum Block Mass” Comparison

Table 3 illustrates the differences between the results of these two tests. For one, it took the refrigeration system prototype longer to cool initially with the aluminum mass placed on the cooling plate. This aligns with expectations, given that there is now more thermal mass that the system must cool. Additionally, the test with the aluminum mass warmed back up to 6 °C (after the input voltage was shut off) faster than without the mass. While this is true for the aluminum mass, the expectation would be that other materials with higher specific heat capacities (i.e., water, insulin, or vaccines) will hold their temperature for longer and not adjust to the changing conditions as quickly.

The average time to cool back down to 4 °C was the same for both test conditions. This makes sense given the very high thermal conductivity of aluminum, making it quick to change its temperature and thus, perform as if there were no mass. Altogether, it will be important to design per specific loadings in the refrigeration system, and it must be understood that the more thermal mass contained within the system, the more the system may have to utilize power and higher amounts of current to keep materials at the required temperatures.

Lastly, it must be noted that the refrigeration system did not utilize any more than 19.24 W of power at any one point during these tests, thus fulfilling the original design objective to stay under 20 W.

The data from this test can also be used to improve the Thermal-Electric model. Namely, the resistance of the TEC was fine-tuned, and the current efficiency of the system was adjusted. For this test, the TEC current source was adjusted to reflect the nature of the ON-OFF input voltage. A pulse wave drove the current source, with an initial delay set to match the time delay in the experimental test. This delay represents the amount of time the TEC was initially running at full current until the system reached the desired temperature. The duty cycle was also matched, setting the pulse current waveform to stay on for the same average percentage of time as the refrigeration system did in the test. The spice diagram in Figure 18 produces the temperature response shown in Figure 19, which resembles the experimental data shown in Figure 14 for the system with no additional aluminum mass.

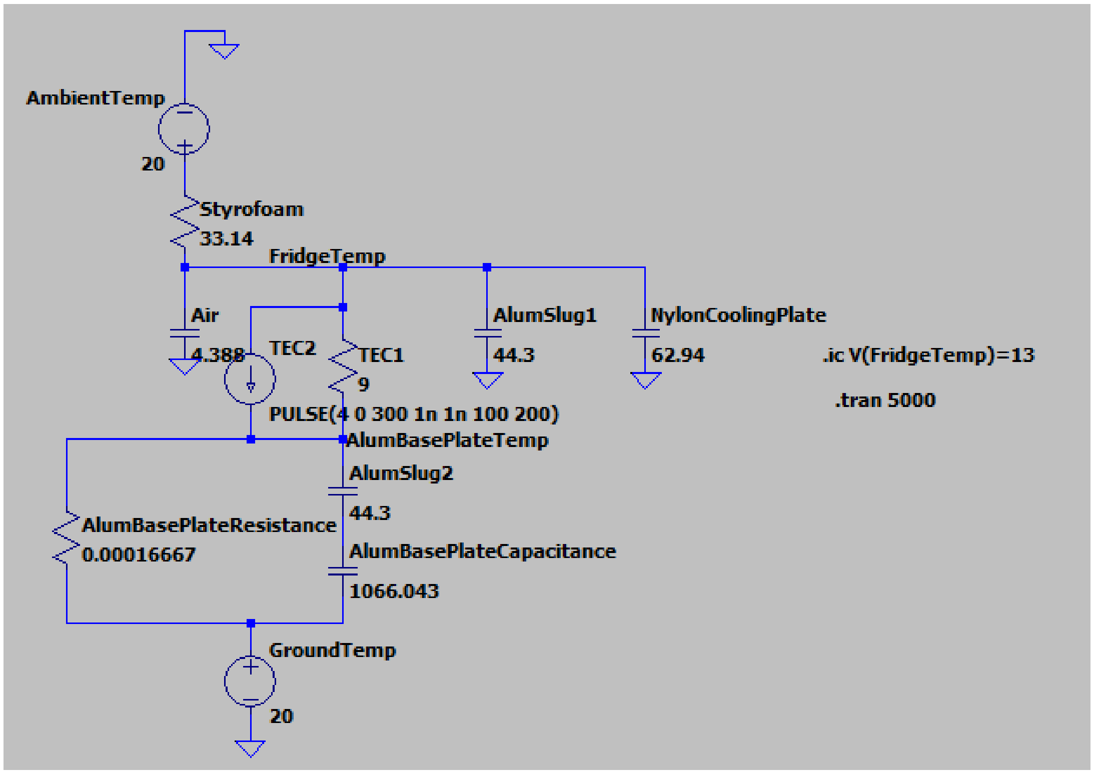

Figure 18: Updated Spice Diagram for On-Off Test

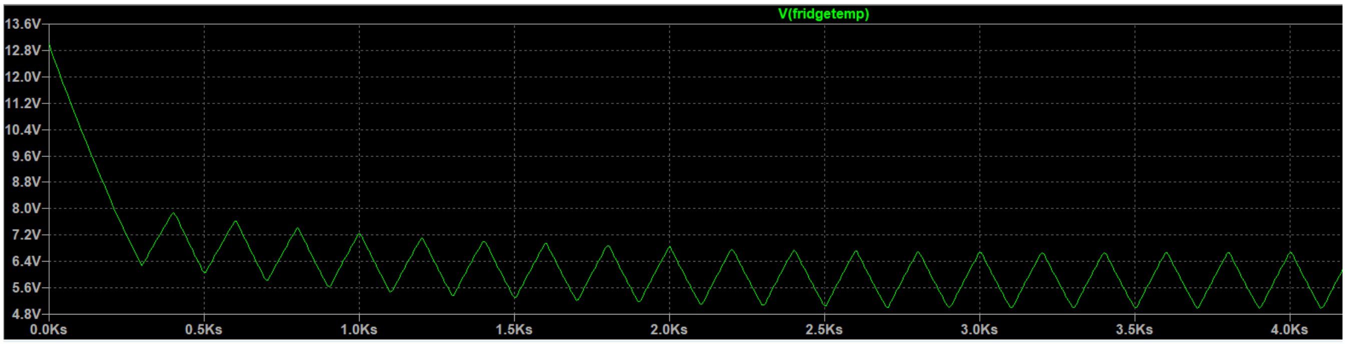

Figure 19: Temperature Response of the System according to the Thermal-Electric Model

In Figure 19, the Thermal-Electric model adequately reached the desired temperature in roughly the same time as the actual refrigeration system and then proceeded to hover around the 6 °C temperature mark, as the actual refrigeration system did in Figure 14.

Variable Current Test

One final method was tested for controlling the input voltage and current to the TEC. This involved varying the voltage and current as the temperature of the refrigeration system changed to maintain the temperature within the 2 to 8 °C window. The logic for the buck converter can be demonstrated in Table 4.

Instantaneous Temperature, *t* [C]	Input Voltage [V]	Input Current [A]	Supply Voltage [V]	Power [W]
if $t > 15$	10	1.5	13	19.5
if $t < 0$	0	0	13	0
if $t < 2$	1	0.01	13	0.132
if $t < 3$	2	0.01	13	0.132
if $t < 4$	3	0.061	13	0.792
if $t < 5$	4	0.2	13	2.64
if $t < 6$	5	0.37	13	4.81
if $t < 7$	6	0.58	13	7.54
if $t < 8$	7	0.89	13	11.57
if $t < 10$	8	1.21	13	15.73
if $t < 15$	9	1.5	13	19.5

Table 4: Variable Input Voltage/Current Logic

With this logic controlling the buck converter, the test was run for 1800 seconds (30 minutes), with the initial temperature of the refrigeration system at room temperature (approximately 23 °C). The results of the test can be seen in Figure 20.

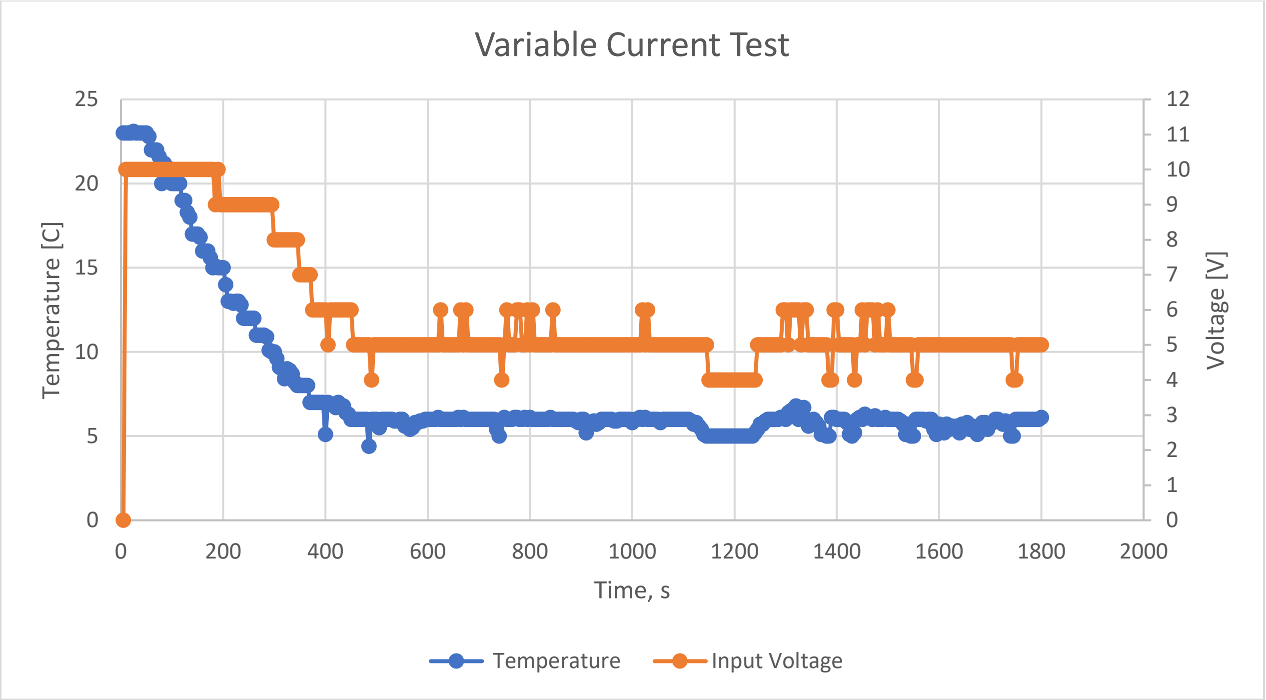

Figure 20: Variable Current Test

As can be seen in Figure 20, after approximately 450 seconds (around 7 minutes), the temperature of the refrigeration system settled at around 6 °C and stayed in that range for most of the test. It also never drifted outside the 8 °C range after initially settling into a steady condition.

The most important analysis to draw from this test is its energy consumption. After settling in around 6 °C at the 7-minute mark, the input voltage averaged 5 V, equating to an input current of 0.37 A to the TEC. With a supply voltage of 13 V, this results in a power consumption of 4.81 W. This indicates that the refrigeration system would utilize approximately 115 Wh daily. This is almost half the energy consumption of both the ON-OFF and Constant Current control methods, making it the most energy-efficient. Table 5 draws this comparison from the three tests.

Control Method	**Estimated Daily Energy Consumption**
Constant Current	230 Wh

On-Off	270 Wh
Variable Current	115 Wh

Table 5: Control Method Energy Consumption Comparison

PREDICTING SYSTEM BEHAVIOR

With the Thermal-Electric Model more closely reflecting the actual system behavior, it can be better utilized to predict the performance of the refrigeration system with varying contents inside the fridge. As an illustration, utilizing the On-Off Thermal Electric network, an estimate of system performance can be made. As an example of this capability, a model was created estimating the thermal mass of placing a few pounds of vaccines, mostly filled with liquids with values similar to the specific heat capacity of water and enclosed in a vial made mostly of glass. A few pounds of vaccines are approximated to have a thermal mass of 1000 Farads.

As shown in Figures 21 and 22, the addition of this larger thermal mass changes the performance of the system. It now does not bring the temperature into range as fast and is failing to reach the desired range promptly.

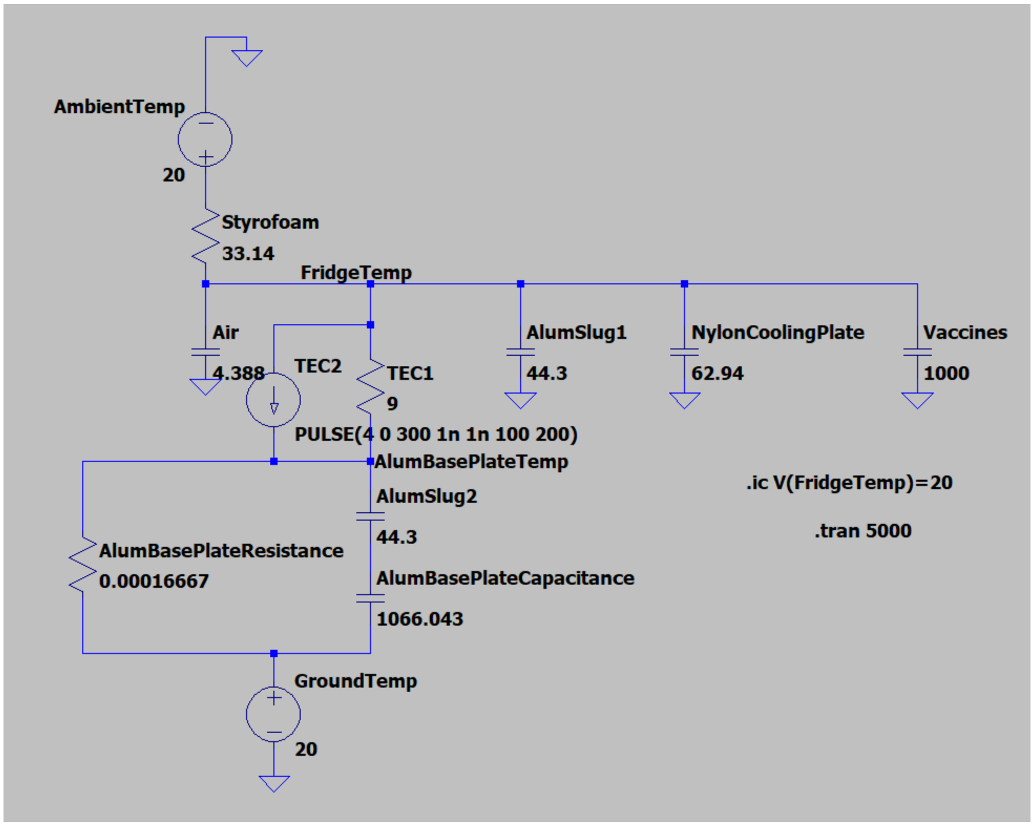

Figure 21: Thermal-Electric Model with Vaccine Load Estimate

Figure 22: Refrigeration System Temperature with Vaccine Load

Due to its inability to reach the necessary temperature, the model can be adjusted to now allow the current to run at max for a longer time before eventually turning on and off cyclically. This was done to ensure that the power usage of the system does not exceed 20 W since the magnitude of the current did not need to be increased. The duty cycle is also held constant (roughly 50%) such that the long-term performance utilizes the same daily energy consumption as the system with no mass.

In Figures 23 and 24, the time that the current is held constant is increased to 5000s (roughly an hour and a half). By increasing the amount of time the current is initially running at full, the refrigeration system now meets the temperature requirements.

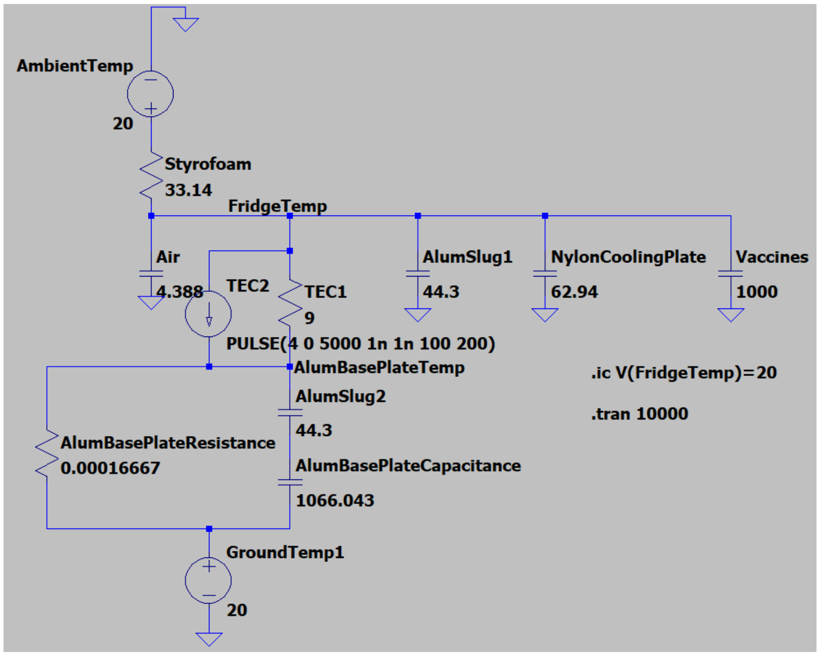

Figure 23: Updated Thermal-Electric Model with Vaccine Load Estimate

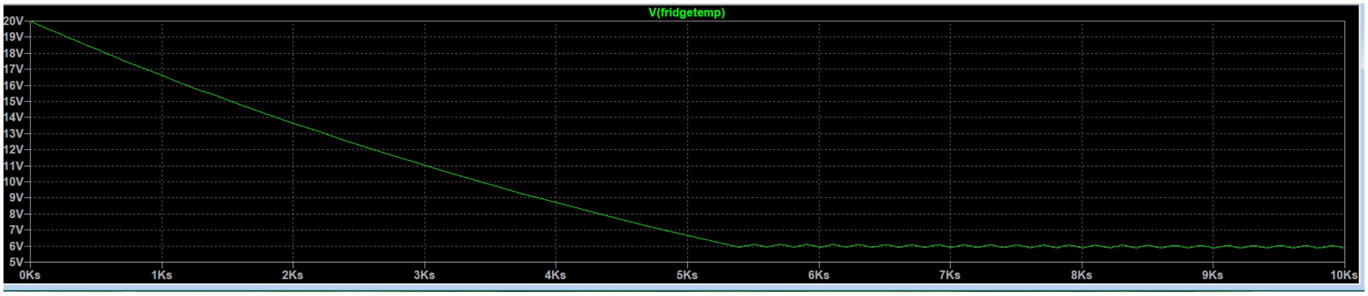

Figure 24: Updated Refrigeration System Temperature with Vaccine Load

In practice, vaccines would most likely be placed into the refrigeration compartment already at the proper temperature, and the system will probably have been on at the moment such occurred. Additionally, the actual performance of the refrigeration system may look very different. At the very least, it can be concluded by that to cool objects stored in the refrigeration system, more energy consumption is going to be needed on the front end. While the exact value of energy consumption may differ significantly from what the model suggests, as more tests like this are run, the Thermal-Electric model can be further refined until it becomes highly accurate at predicting such numerical quantities.

NEXT STEPS

The results of this research indicate that the concept of using thermoelectric technology with low-power consumption is an effective solution to the need for refrigeration in rural Nicaraguan villages. While a few working prototypes of this design concept have been created, it is not yet ready to be utilized on-site. The most important next steps to be taken are outlined in the bullet points below.

1) Further communication must be made with the local technicians on how to best manufacture the system with local resources. This will most likely look like drafting current manufacturing plans, a bill of materials, and traveling to the site with the current prototype. With this information, the technicians can utilize their knowledge and resources to fabricate the system in a way that is most efficient for them, while also getting a gauge on what components will need to be imported.
2) Electrical components need to be integrated from an Arduino® circuit board to a smaller breadboard. Placement of this within the system would most likely be between the outer sheet metal casing and the Styrofoam insulation, but exact plans for this have not yet been made.
3) Additional testing with the current prototype must be completed. This includes testing the temperature performance of the refrigeration system whenever the lid is off, as well as monitoring the temperature of various objects when placed inside the refrigeration compartment.
4) Field-testing with the final working prototype should be conducted. There are bound to be testing conditions within the villages that may change the experimental data. This will

also be necessary to determine the finalized wiring from the solar cell to the refrigeration system itself.

5) As further tests are run, the Thermal-Electric model can continue to be updated and refined to reflect actual system behavior more closely.

CONCLUSIONS

- Thermoelectric technology can be utilized at low power to cool a properly insulated refrigeration system.
- Conduction served as the best form of heat transfer for the refrigeration system, due to the high power that would be needed to create a convection air cooling system.
- Material thermal characteristics, when properly understood, are the most important elements to system design when the transfer of heat must take place. Proper understanding and use of materials will allow for heat to travel in the desired manner.
- The Thermal-Electric model can be an important digital tool for characterizing a system's thermal performance. Once a reliable model can be drawn, it can be used to predict system behavior and assess the mechanical areas for improvement.

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