# Solid State Thermoelectric Power Generation

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**Project Need:**

In many developing nations around the world, people still use indoor stove fires in order to cook their food. A lot of these residences do not have an adequate ventilation system to remove a lot of the poisonous gases that build up in their homes. Not only do indoor stove fires release dangerous chemicals such as carbon monoxide, it also reduces the oxygen levels in a room. Reducing the oxygen levels from 21% to 17% can cause impaired judgement, and at 9% can cause unconsciousness [1]. According to PBS, more than 2 million lives could be saved each year by finding a solution for the toxic gas generating indoor stove fires [2]. Additionally, the World Health Organization estimates that 1.6 million people die every year from diarrhoeal diseases (including cholera) attributable to lack of access to safe drinking water and basic sanitation and 90% of these are children under 5, mostly in developing countries [3]. Implementing a cook-top stove that can fix the water need for one family at a time can have a huge impact on today's society.

Figure 1: Indoor Cookstove

This problem could be solved by a simple product that takes the excess heat from the fire and turns it into electrical energy to power a ventilation system with a built in pasteurization device. A cost efficient device such as described could save over one million lives per year in the developing world.

**Introduction:**

The main application of the solid state thermal power generator, which is named Cool Stove (see Figure 2), is to create electrical power from an existing heat source, and use that energy to power a fan which will act as a ventilation system. This can be achieved through the use of thermoelectric chips, which require a hot and a cold side. A larger temperature differential between the sides of the chips results in a larger output voltage from the chips. The hot side will be provided by a heat source such as a fire stove, and the cold side will be a coolant such as water. Additionally, the water used as a coolant will enter the system at around room temperature, and leave at over 72 ºC. This exit temperature will allow the water to be pasteurized against Escherichia coli bacteria, as well as Vibrio cholerae, the bacteria that cause Cholera [4]. These two bacteria cause deadly waterborne diseases in developing countries.

Another application for the device is that it can be implemented in a community setting. The idea is that whoever uses Cool Stove would get paid for using it, because whenever someone uses it, the Cool Stove produces energy that can be sold back into the local micro-grid that serves the entire community.

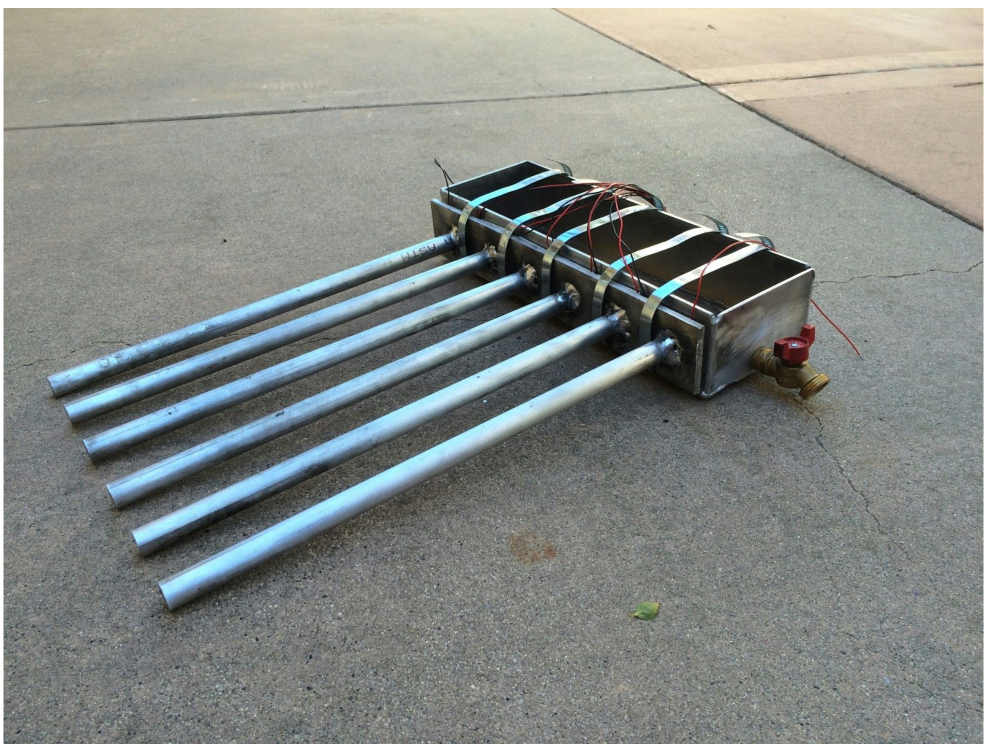


Figure 2: Cool Stove

Thermoelectric Chips

A thermoelectric generator chip, or TEG, can operate in two ways, that is with the Peltier effect or the Seebeck effect. The Peltier effect transforms electrical power into a temperature difference on the chip. This means that once side of the chip heats up, while the other side cools down. The Seebeck effect does the opposite, meaning that it generates electricity due to a temperature differential. In this application, the Seebeck effect will be utilized because the concept of the project is to generate electricity from heat. Both Figures 2 and 3 show a schematic of TEG's.

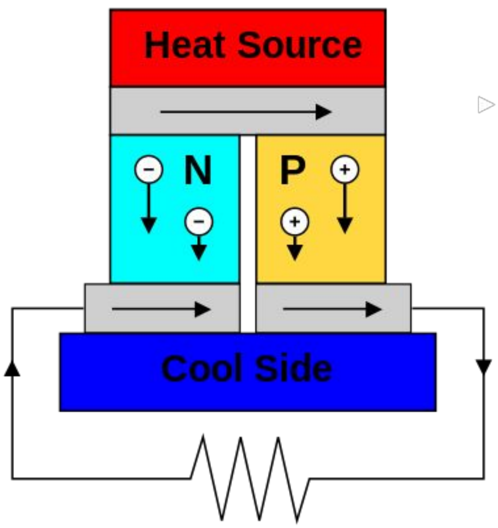



Figure 3: Schematic of Thermoelectric Chip

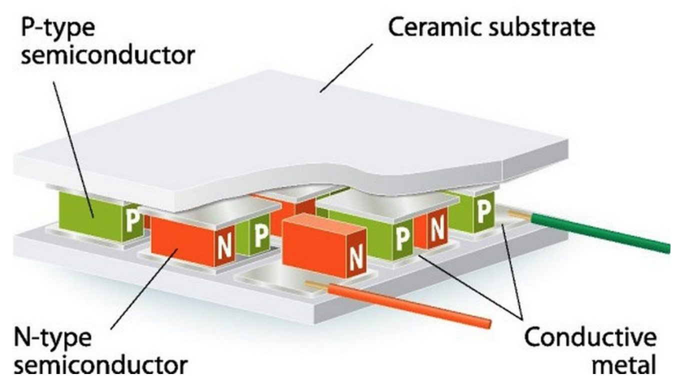



Figure 4: Inside a Thermoelectric Chip

Thermoelectric generators work on a basic principle that electrons can move easily through metals. Heating up one side of the chip increases the potential energy in the electrons causing them to move to the other (cool) side, and the flow of electrons creates an electric current. This effect was discovered by Thomas J. Seebeck, which this process is named after. Solids have charge carriers that facilitate the flow of electricity, these carriers are either n-type or p-type. The temperature differential then pushes the concentration of charge carriers across the chips, creating a change in voltage that can be measured [5].

## Heat Sinks

Heat Sinks are a crucial component in many electronic applications in today's world as they help to keep certain electronic components from overheating. Heat sinks are also a good way to regulate the amount of heat that flows into an electronic component, especially when the heat source puts out an irregular amount of heat such as a fire stove. Heat can be transferred in three main ways which are conduction, convection, and radiation. The effectiveness of a heat sink is related to the material, the amount of surface area, and the heat transfer coefficient. Instead of using traditional heat sinks that have many vertical fins to regulate heat flow, this device utilizes two methods of heat regulation that serve dual purposes. Since one of the applications of the project is to pasteurize water, an Aluminum water tank is used as a heat sink on the cool side of the chips. In addition, the hot side of the chips has a heat sink that is a series of Aluminum rods that transfer heat from the fire as well as provide a platform for the fire itself to be made on.

Figure 5: Example of a Traditional Heat Sink

## Water Pasteurization

Pasteurization is the process by which heat is used to kill pathogenic microbes. This process is named after French scientist Louis Pasteur, who in 1864 discovered that heating beer and wine killed bacteria and thus prolonged the life of the beverages [6]. Contrary to popular belief, water does not need to boil for it to be pasteurized. However, the effectiveness of pasteurization is directly related to temperature and time [4].

The World Health Organization approximates roughly 750 million people in the world lack safe drinking water, including 358 million people in the continent of Africa alone [7]. This leaves many children like the one in Figure 7 with no choice but to drink unclean water.

| Organism | Temperature (°C) | Inactivation time(s) | $Log_{10}$ reduction | Reference |
|---|---|---|---|---|
| **BACTERIA** | | | | |
| *Campylobacter* spp. | 60 | 300 | 3.9 log | D'Aoust et al. (1988) |
| | 63 | 300 | > 5 log | D'Aoust et al. (1988) |
| | 60 | 8.2 | Per log | Sörqvist (2003) |
| | 62 | 15 | 3.5–5 log | Juffs & Deeth (2007) |
| *Coxiella burnetii* | 79.4 | 25 | No survivors | Juffs & Deeth (2007) |
| *Escherichia coli* | 60 | 1 800 | 6 log | Moce-Llivina et al. (2003) |
| | 65 | < 2 | Per log | Spinks et al. (2006) |
| | 72 | 0.4 | Per log | Sörqvist et al. (2003) |
| *Escherichia coli* 0157 | 60 | 300 | 1.5 log | D'Aoust et al. (1988) |
| | 64.5 | 300 | > 5 log | D'Aoust et al. (1988) |
| | 65 | 3 | Per log | Spinks et al. (2006) |
| | 62 | 15 | < 1–5 log | Juffs & Deeth (2007) |
| *Enterococcus faecalis* | 65 | 7–19 | Per log | Spinks et al. (2006) |
| *Klebsiella pneumoniae* | 72 | 23 | Per log | Sörqvist (2003) |
| | 65 | < 2 | Per log | Spinks et al. (2006) |
| *Legionella pneumophila* | 58 | 360 | Per log | Dennis, Green & Jones (1984) |
| *Legionella* spp. | 80 | 18–42 | Per log | Stout, Best & Yu (1986) |
| *Mycobacterium paratuberculosis* | 72 | 15 | > 4 log | Juffs & Deeth (2007) |
| *Pseudomonas aeruginosa* | 65 | 5 | Per log | Spinks et al. (2006) |
| *Salmonella typhimurium* | 65 | < 2 | Per log | Spinks et al. (2006) |
| *Salmonella choleraesuis*[a] | 60 | 300 | Per log[b] | Moce-Llivina et al. (2003) |
| *Salmonella* spp. except *Salmonella seftenberg* | 72 | 0.1 | Per log | Sörqvist (2003) |
| *Salmonella seftenberg* | 60 | 340 | Per log | Sörqvist (2003) |
| *Serratia marcescens* | 65 | < 2 | Per log | Spinks et al. (2006) |
| *Shigella sonnei* | 65 | 3 | Per log | Spinks et al. (2006) |
| *Vibrio cholerae* | 55 | 22.5 | Per log | Johnston & Brown (2002) |
| | 70 | 120 | > 7 log | Johnston & Brown (2002) |
| *Yersinia enterocolitica* | 64.5 | 300 | > 5 log | D'Aoust et al. (1988) |
| | 72 | 0.5 | Per log | Sörqvist (2003) |

Figure 6: Thermal Inactivation of Bacteria

Figure 7: Polluted Drinking Water

The effectiveness of pasteurization is measured by factors of 10 or a base 10 logarithmic scale. For example, a 1 log reduction indicates that 90% of microbes have been killed. A 5 log reduction indicates that 99.999% of microbes have been killed [6]. In order to target Escherichia coli , Escherichia coli 0157 and Vibrio cholerae bacterium in one step, a pasteurization temperature and time must be selected that effectively kills each of the three bacteria. This can be done using information from the World Health Organization in Figure 6. By selecting the highest temperature, and the longest inactivation time for each of the three bacteria, one can make a plan for killing them in one step. A minimum temperature of 72 degrees Celsius paired with a minimum inactivation time of 120 seconds will ensure a 7 log or greater reduction of Escherichia coli , Escherichia coli 0157 and Vibrio cholerae bacteria, should they all be present in the same water container.

## Electronic Components

In order to make the project more autonomous and easy to use, several electronic components can be added to simplify the project. This however comes at a cost of not only monetary value, but also in the sense that these parts require electricity. The idea currently is to have two different models, one with electronic components and one without. The one without would just require the attention of whoever is operating the stove, while the model with electronic components could be fully autonomous. A list of different electronic components and its use is given below:

Arduino UNO: The Arduino Uno is a microcontroller that has an ATmega328 processor, along with a development board that contains 14 digital inputs/outputs, and  6 analog inputs. The plan is to use this microcontroller in order to manage and maintain the control flow of the system that will be built. The function of the Arduino Uno is to control temperature sensors, output data to the LCD display, and operate servos (that control the valves).

Servos: A servo motor is a small motor that has been designed to rotate or push parts of a machine with great precision. This can be used in order to open or close certain valves in the pasteurization system.

TMP-36: The TMP-36 is a temperature sensor that has a specified temperature range from negative forty degrees Celsius to 125 degrees Celsius. This temperature sensor is ideal to use in the project because it is easy to use with the Arduino and it can help allow the microcontroller know when the water temperature has reached a pasteurization levels.

Piezo Beep: The piezo beep is a piezoelectric buzzer that emits a sound (beep). This could be implemented to let the user know that the water has reached pasteurization temperature.

Liquid Crystal Display: An LCD could be used to not only monitor the temperature of the water, but also the temperature of the chips making sure that they do not overheat. The LCD would essentially act as a serial monitor for the Arduino microprocessor.

## **Initial Designs**

Our design needs to incorporate three main parts: a water tank, thermoelectric chips, and a ventilation system. If all three of these main goals can be met, the system will be able to pasteurize water, as well as create energy to power a ventilation system in the homes of those living in the developing world. The team has decided on several different design aspects as well as design constraints.

### Design Considerations

The main aspect of the project is to create energy, this is done through creating a reliable temperature difference across the chips. This allows for steady power generation meaning that the fans will run at an output level that is suitable for the amount of air that needs to be displaced. Another big aspect of the project is to pasteurize water. Since one side of the chip needs to be cool, this is an ideal place to set the water. Heat will slowly flow from the hot to the cold side allowing water to be pasteurized once it hits a certain temperature. Another important aspect to think about is that the system should not interfere with the use of the stove fire for those who use it to cook food.

### Design Constraints

The most important design constraint is that the device has to be rugged and durable. Since it will be implemented in communities in the developing world, it will be hard to get replacement parts so it is crucial that it does not break down. Another important constraint is the cost of the product. Dr. Robert Van Buskirk, who has been working in Africa for over 20 years to provide cost effective electricity to rural communities estimates that the justifiable cost for a power generating product in a community is $3/Wh/day, meaning that if the product runs at 15 Watts for 10 hours per day, a justifiable cost would be $450. Another design constraint is that the chips do not burn out because that would basically leave the product useless, especially since replacement parts will be hard to find. Lastly it is important to keep in mind that the product needs to withstand very high temperatures and needs to be made out of materials that can do that.

### Preliminary Designs

After some initial research has been done several different preliminary designs were created. The team basically looked into two main ways the heat from the fire could be transferred to the chips, creating power as well as pasteurizing water. The main difference between the two designs is how they transfer heat from the fire to the chips.

Design 1:

The first design can be seen in figure 8. Whatever needs to be cooked would be placed on stove plate. The TEG chips are located in between the green heat sinks and the yellow pasteurization box. The heat sinks underneath the chips should allow for a regulated heat flow to the hot side of the chips. The cool side of the chips would be in contact with the water purification box which is filled with unclean water that is being pasteurized. The two water tanks are part of the purification system. The top tank holds unclean water, while the bottom tank holds clean water. Once the water in the yellow box reaches a certain temperature, it is emptied out into the clean tank, and refilled with dirty water from the unclean tank. This process then repeats over and over all while generating electricity from the thermoelectric generator chips.

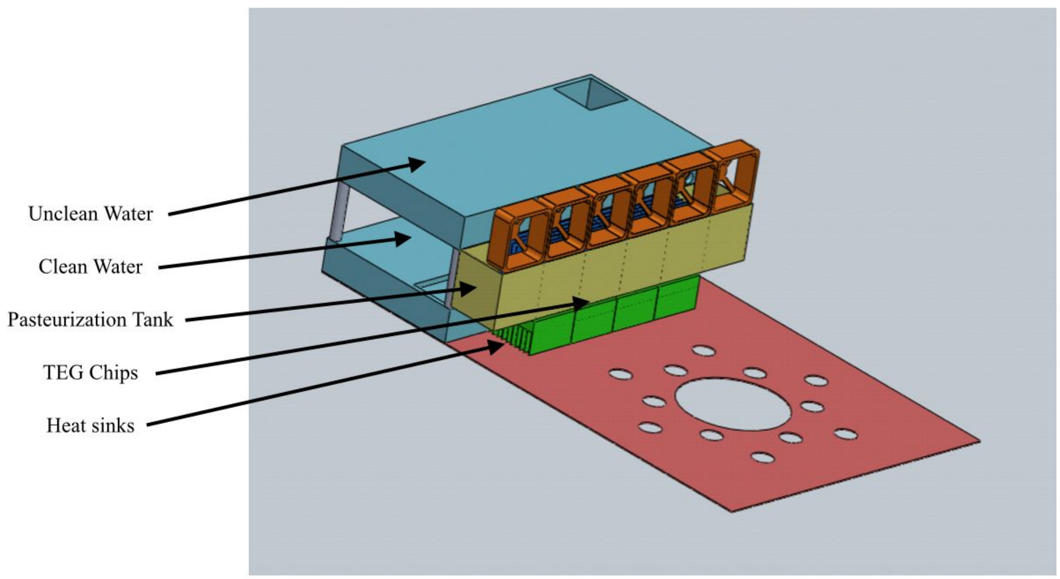
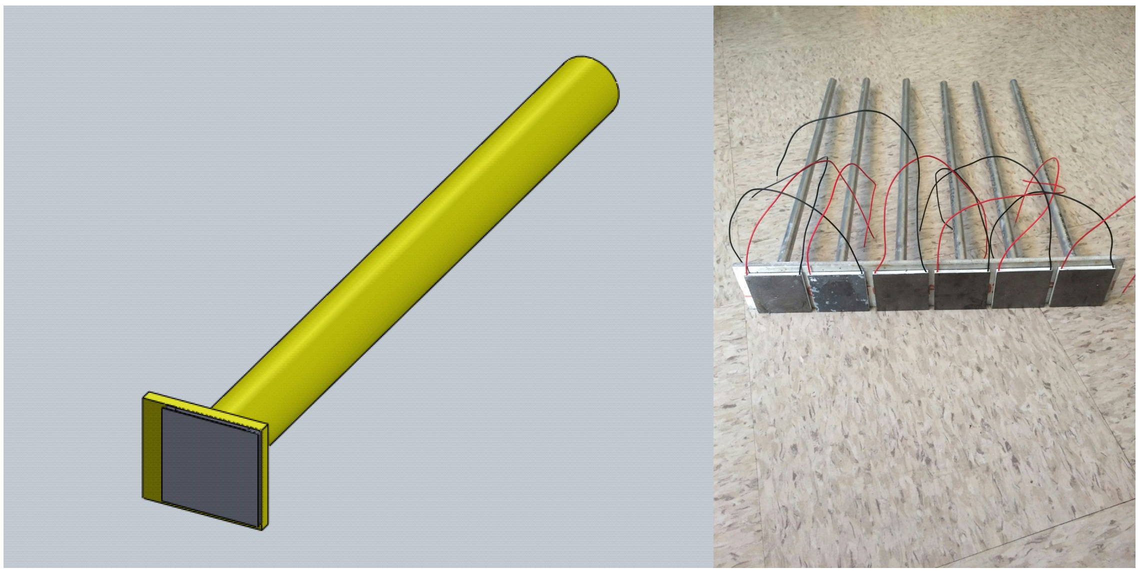



Figure 8: SolidWorks Model of Design 1

Design 2:
The second design differs from the first design mainly in how the heat is transferred from the fire to the thermoelectric generators. Instead of placing the chips on top of the fire, the chips are placed on the side of the fire. The heat is being collected from the fire through the use of a metallic rod seen in Figure 9 which acts like a heat sink. The chip is then placed between this rod and a water tank which will be pasteurized from the excess heat that flows to the hot side of the chips. In Figure 10 a whole array of six rods and six chips can be seen.



Figures 9 & 10: SolidWorks Model and Physical Model of TEG Chip with Metallic Rod

## **Initial Testing of the Chips**

### Temperature Control

Throughout the testing of the thermoelectric chips, one of the main issues was the inability to accurately control the temperature of the hot plate. Although the setting on the hot plate would not change, the temperature could vary in magnitude sometimes more than 100 degrees Celsius. With the use of a J-KEM Scientific temperature controller, the temperature of the hot plate was much better regulated. This allowed for more precise control over the experiments carried out, and it also prevented the thermoelectric chips from burning out. Although the temperature controller is nice to have in a lab environment, it is important to remember that the actual heat source will vary in temperature and that is something that the product will need to be able to handle.

Figure 11: J-KEM Scientific Temperature Controller

In addition to the temperature controller, different methods were attempted to try and regulate the heat flow to the chips such as, putting the chips directly on the hot plate, aluminum insulation, copper insulation, and thermal paste. Aluminum insulation worked well to prevent the cool side of the chip heating up too much, which helps to keep the temperature differential as high as possible. Thermal paste also worked well to increase the thermal conductivity between the chips and whatever component they were attached to (hot plate, heat sink, etc..). From those results it was clear that insulation as well as thermal paste should be used in the final prototype in order to maximize the amount of power generated from the thermoelectric generators.

<u>First Working Prototype</u>

After initial testing, a functioning prototype was built which met most of the design considerations. Not only was it able to power a ventilation system, but it also pasteurized water over the course of 150 minutes (2.5 hours). The setup used two TEG chips in order to create energy from the heat. Two copper heat sinks were also used to dissipate heat on both sides of the chips. This allows for a more uniform heat flux through the chips. The hot plate was regulated using the J-KEM scientific temperature controller, and the temperature of the chips and the water were monitored using a Fluke K-type thermocouple. The “unclean” water was held in a bucket which was placed on top of the chips. The idea is that the cooler water will help keep the top sides of the TEG chips cool, while simultaneously heating up due to the excess heat from the hot plate and the TEG chips. This system was then hooked up to two 12V fans which acted as the ventilation system. It is important to note that the 12V fans can operate at a lower voltage. The overall results were successful as the TEG chips generated enough energy to power one of the two 12V fans for over 2 hours, sometimes even powering both of them. The results are shown below in a table 1 and figure 12.

| Time [min] | Temp. of Water [ºC] | Voltage (Open Circuit) [V] |
| --- | --- | --- |
| 0 | 23 | 5.3 |
| 90 | 54.3 | 6.7 |
| 120 | 65.3 | 5.9 |
| 150 | 70.6 | 5.6 |
| 156 | 73.6 | 6.8 |

Table 1: Temperature and Open Circuit Voltage of Experiment

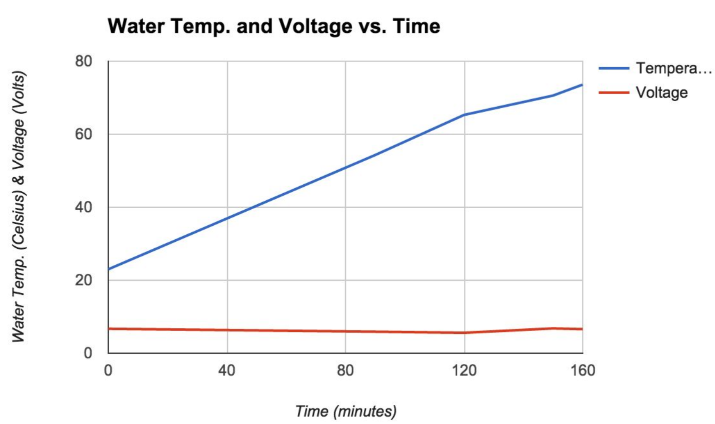



Figure 12: Open Circuit Voltage and Temperature vs. Time

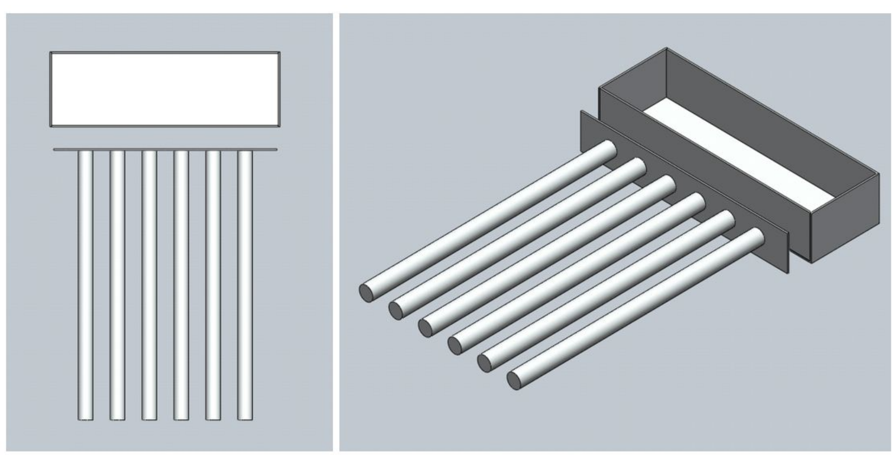
Two important things to note from the results are that about 2L of water was pasteurized in the process, and the TEG chips were able to generate a more or less constant voltage over the course of 150 minutes. Even when the temperature of the water increased up to over 72ºC, the voltage generated stayed around 6V. The TEG chips were connected in series, with each chip generating on average a voltage of about 3V. The water temperature also stayed above 72ºC for over five minutes, which means it is pasteurized making it much safer to drink than before. An average human should consume about 2L of water per day, which is how much was pasteurized in this experiment.

Figure 13: Set-up of the Working Prototype

One major change that the final product will have compared to this initial test is a fully automated process. This will bring a lot of new challenges especially because a lot the electronic components will require additional power which the TEG chips will also have to generate.

**<u>Prototype</u>**

The initial prototype utilizes the design with the horizontal rod as a way to transfer the heat from the fire to the chips. There is a container on the backside of the chips to hold water for pasteurization and cooling of the chips. The main problem that arises while using this design is the heat control for the chips. With the chips held in place using clasps and open to the environment (fire) there needs to be a way to make sure the flames would not go directly to chips and eventually burn them. To fix this spark proof insulation that is rated up to 537ºC was used. This initial prototype is meant to test the feasibility of the systems that would be implemented. In the final design there would be two more holding containers for the water, one holding unclean water and another holding clean water. This initial prototype is meant to test the feasibility of the systems that would be implemented. In the final design there would be two more holding containers for the water, one holding unclean water and another holding clean water.



Figures 14 & 15: SolidWorks Models of the Prototype

Proper air flow rate

In order to make the living environment safe, a certain amount of air needs to be removed. This is measured in cubic feet per minute (CFM). There are three different ways to calculate the minimum required amount of CFM to make a kitchen environment safe. The first method is to initially determine how much heat the fire generates and from that it can be found how many CFM the fans need to output to remove the proper amount of air. The Home Ventilation Institute recommends to divide the BTU rating by 100, and that will then be the required CFM. A stove fire puts out around 50,000 BTU meaning that the minimum required CFM is 500. Another method is using the range size. If the stove is located on a wall, add 100 CFM for every foot between the stove and the vent. If the stove is located on an island, add 150 CFM for every foot between the stove and the vent. It is anticipated that the stove will be placed on a wall with a distance between the stove and the fans of about two to three feet. This will result in a necessary CFM of 200-300 CFM. The final way to calculate the CFM is through the size of the kitchen. Unfortunately these sizes vary a lot and the information is unavailable to us. The equation however is to divide the volume by four since it is recommended to vent a kitchen about 15 times per hour. Based off the three different methods, the most CFM the system needs to handle will be about 500 CFM [8].

The 12-Volt fan that the system will incorporate does not have any ratings in terms of CFM so a test was conducted to see how much flow rate the fan produces at different voltage levels. To do this, an anemometer was used to measure the wind speed of the fan at different levels, and by knowing the area of the fan output the flow rate could easily be calculated. The results can be seen in Figure 16.

| Voltage | CFM |
|---|---|
| 4 | 37.21 |
| 5 | 50.26 |
| 6 | 57.75 |
| 7 | 69.10 |
| 8 | 81.43 |
| 9 | 89.88 |
| 10 | 100.27 |
| 11 | 112.35 |
| 12 | 121.29 |

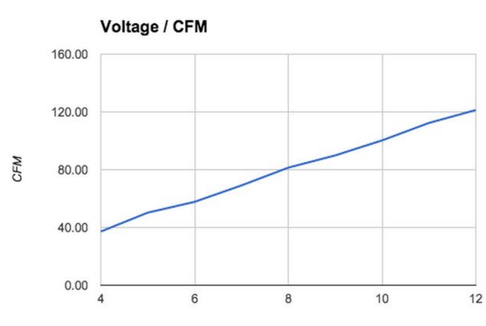



Figure 16: CFM of 12-V Fan Depending on Voltage

Since it is not anticipated that the system will run at 12-Volts the entire time, a lower voltage reading was picked. The picked voltage was 10, meaning that each fan would output around 100 CFM. This means that the system will require a total of five fans.

Heat Transfer

In order to maximize the energy produced from the TEG chips, the amount of heat transfer in the prototype needs to be calculated. It can be found on the specifications sheet (Table 7) that the heat flow rate across the chips is around 325 Watts. Ideally this will be the heat energy that should reach the hot side of the chips, however exceeding it could be dangerous as the chips could break because of it. The prototype allows is for a lot of customization in terms of how close it is to the fire, and the distance from the heated rods to the chips. The main equation needed for these calculations is shown in equation 1.

$$q = \frac{kA(\Delta T)}{L}$$

Equation 1: Conduction

The amount of heat transfer is q [W/m], k [W/m*K] is the thermal conductivity coefficient, A [m^2] is the cross sectional area of the rod, T is the change in temperature from the fire to the chip, and L [m] is the length of which the heat has to travel from the fire to the chips. Four different designs were considered in terms of how to place the prototype over the fire as well as two different metals. The metals were aluminum and copper. Copper is a much more effective metal when it comes to heat transfer, however it is also more expensive. Since the required amount of heat transfer can be reached with aluminum (see below), aluminum was chosen over copper because of the difference in price. Two different models were taken into account, one with a 0.5 inch diameter, and one with a 0.75 inch diameter. The distance from the fire to the chip can be adjusted from 0.095 meters to 0.15 meters. This results in four different variations with each having a different amount of heat transfer which can be seen in Table 2.

| Diameter [in] | Distance [in] | Heat Transfer [W] |
|---|---|---|
| 0.75 | 2 | 283.65 |
| 0.75 | 4 | 177.28 |
| 0.5 | 2 | 126.26 |
| 0.5 | 4 | 28.85 |

Table 2: Amount of Heat Transfer Depending on Configuration

Materials

The material that was used to build the prototype was Aluminum T6 6061. One main reason for that is that it is a fairly cheap metal, with adequate thermal conductivity determined by the constant k in equation 1. Although Copper has a higher thermal conductivity coefficient, meaning that it transfers more heat, it is also more expensive. T6 6061 has a yield strength of 241 MPa which is more than enough for this application. It is also worth noting that the price of TEG1-12611-8.0 thermoelectric generator chips decreases when purchased in bulk. In Table 3 a Bill of Materials that was used to create the prototype is shown.

| Part | # Required | Dimensions [in] | Price [$ USD] |
|---|---|---|---|
| TEG1-12611-8.0 | 6 | 56 mm x 56 mm | 420.00 |
| Rods | 6 | Dia = 0.75 | 12.00 |
| Rod Connector | 1 | 15.5 x 2.5 | 3.00 |
| Aluminum box | 1 | 16x5x3 | 10.00 |
| Cpu thermal paste | 1 | | 8.99 |
| Metal Ties | 5 | | 10.90 |
| Fiberglass insulation | 1 | 18x5 | 10.00 |
| Valve | 1 | 0.5 | 4.00 |
| | | Total | 478.89 |

Table 3: Bill of Materials

Testing of Prototype

Initially, it had planned to use the device as a cook-stove top. The Aluminum bars would rest above the fire and through conduction would draw heat to the Thermoelectric Generator Chips. Initial testing yielded around 1V, a note about this is that the fire was poorly built and kept going out. The data from that experiment is shown in Table 4.

| Time (minutes) | Temp chips (C) | Temp water (C) | Open Circuit Voltage (Volts) | Short Circuit Current (Amps) | Power (Watts) |
|---|---|---|---|---|---|
| 1 | 28.9 | 34.8 | 0.142 | 0.018 | 0.002556 |
| 5 | 37.6 | 34.9 | 1.842 | 0.245 | 0.45129 |
| 10 | 48.2 | 35.5 | 2.721 | 0.35 | 0.95235 |
| 15 | 51.7 | 36.9 | 2.889 | 0.355 | 1.025595 |
| 20 | 52.4 | 38.2 | 2.419 | 0.3 | 0.7257 |
| 25 | 51.6 | 38.8 | 1.876 | 0.22 | 0.41272 |
| 30 | 50.8 | 39.3 | 1.422 | 0.16 | 0.22752 |
| 35 | 49.7 | 38.3 | 1.212 | 0.14 | 0.16968 |
| 40 | 49 | 39.3 | 0.944 | 0.106 | 0.100064 |

Table 4: Initial Test Results with Prototype

After reconsidering the heat transfer calculations it was also found that the device could be placed deeper into the fire and operate at a higher efficiency. In Figure 17 it can be seen how the device can be used as a cook-stove top.

Figure 17: Initial Testing of Prototype

In the next test, the device was placed six inches closer to the fire, meaning that the rods would heat up more creating a bigger temperature drop across the chips, thus a higher voltage. The improved setup can be seen in Figure 18.

Figure 18: New Setup with Rods Closer to Fire

This new setup resulted in much better results. The max voltage was recorded at 4.497 Volts and the max current was recorded at 0.57 Amps. This results in a max power of 2.56 Watts which is a major improvement compared to the last test. These Results can be seen in Table 5.

| Time (minutes) | Temp chips (C) | Temp water (C) | Open Circuit Voltage (Volts) | Short Circuit Current (Amps) | Power (Watts) |
|---|---|---|---|---|---|
| 0 | 19.4 | 25.1 | 0.132 | 0.012 | .002 |
| 5 | 28.6 | 26.0 | 1.60 | 0.220 | .352 |
| 10 | 31.7 | 27.6 | 1.89 | 0.230 | .435 |
| 15 | 38.9 | 29.4 | 3.34 | 0.460 | 1.53 |
| 20 | 45.9 | 31.4 | 4.40 | 0.526 | 2.31 |
| **25** | **49.6** | **33.8** | **4.50** | **0.570** | **2.56** |
| 30 | 53.0 | 36.0 | 4.44 | 0.540 | 2.39 |
| 35 | 55.2 | 39.1 | 3.98 | 0.421 | 1.67 |

Table 5: Reconfigured Experiment Setup

**Maximum Power Transfer**

To obtain maximum power transfer to a load, the internal resistance of the system and the load must be equal. From the data sheet below it can be seen that the matched load resistance is 1.8Ω, with 6 chips total this leads to a total internal resistance of 10.8Ω. To make sure that the internal resistance is known, the following circuit diagram was used to measure the open circuit voltage and the voltage across a known load when attached. This allowed the internal resistance to be calculated with equation 2.

$$Vab = Voc \star \frac{Rl}{Rl + Rint}$$

Equation 2: Voltage Division

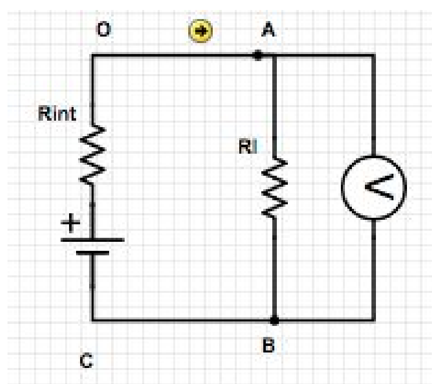



Figure 19: Voltage Divider Circuit

The above equation is a simple voltage divider between to two resistors in the system. The data taken and calculated is given in table 6.

| | |
|---|---|
| $V_{oc}$ (V) | 12.24 |
| V ab (V) | 9.94 |
| $R_L$ (Ω) | 50 |
| $R_{int}$ (Ω) | 11.569 |
| P (W) | 3.237 |

Table 6: Tabulated Data for Maximum Power Transfer

| | |
|---|---|
| Hot Side Temperature (℃) | 300 |
| Cold Side Temperature (℃) | 30 |
| Open Circuit Voltage (V) | 9.5 |
| Matched Load Resistance (ohms) | 1.8 |
| Matched load output voltage (V) | 4.8 |
| Matched load output current (A) | 2.7 |
| Matched load output power (W) | 13.0 |
| Heat flow across the module(W) | ≈ 325 |
| Heat flow density($Wcm^{-2}$) | ≈ 10.4 |
| AC Resistance(ohms) Measured under 27℃ at 1000Hz | 0.7~1.0 |

Table 7: Specifications of TEG chips

The power is calculated using the equation $P=I^2R$. For this matched load the power is at maximum and the efficiency will be 50%. A main reason to maximize power over increasing efficiency is because of the lack of resistors that are able to handle such high powers, while doing this test many resistors were burnt to get an accurate reading of $V_{AB}$.

**Final Results**

For the finished product, two more modifications were made for the final test. First, the aluminum rods were increased in size from 0.5 to 0.75 inches for additional heat transfer. Also the bricks that held up the base of the aluminum rods were decreased in size, that way less heat is lost as the heat travels from the rods to the thermoelectric chips. The results with this final test setup were very impressive with a max power of 18.85 Watts. The setup and data can be seen below in Table 6 and Figure 17. Additionally the system was able to pasteurize 3.93 Liters over the course of 100 minutes.

| Time (minutes) | Temp chips (C) | Temp water (C) | Open Circuit Voltage (Volts) | Short Circuit Current (Amps) | Power (Watts) |
|---|---|---|---|---|---|
| 1 | 24.5 | 27.6 | 0.127 | 0.013 | 0.002 |
| 5 | 42.8 | 27.4 | 1.659 | 0.229 | 0.380 |
| 10 | 46.3 | 28.4 | 2.128 | 0.301 | 0.641 |
| 15 | 70.3 | 28.7 | 5.130 | 0.700 | 3.591 |
| 20 | 82.0 | 30.3 | 6.257 | 0.820 | 5.130 |
| 25 | 82.8 | 33.0 | 6.212 | 0.838 | 5.205 |
| 30 | 93.7 | 34.7 | 7.030 | 0.910 | 6.397 |
| 35 | 105.3 | 37.3 | 8.240 | 1.060 | 8.734 |
| 40 | 121.4 | 41.4 | 9.550 | 1.200 | 11.46 |
| 45 | 126.2 | 45.2 | 10.01 | 1.210 | 12.11 |
| 50 | 129.5 | 49.5 | 10.03 | 1.227 | 12.31 |
| 55 | 146.2 | 52.7 | 11.92 | 1.347 | 16.06 |
| 60 | 150.4 | 55.9 | 12.59 | 1.420 | 17.88 |
| 65 | 156.7 | 61.1 | 12.52 | 1.324 | 16.58 |
| 70 | 168.6 | 65.4 | 12.62 | 1.360 | 17.16 |
| 75 | 170.1 | 67.0 | 12.30 | 1.310 | 16.11 |
| 80 | 166.2 | 69.5 | 11.63 | 1.252 | 14.56 |
| 85 | 161.5 | 68.8 | 10.99 | 1.310 | 14.40 |
| 90 | 179.9 | 69.4 | 12.24 | 1.340 | 16.40 |
| 95 | 184.7 | 70.0 | 13.00 | 1.450 | 18.85 |
| 100 | 185.3 | 72.0 | 13.08 | 1.349 | 17.64 |

Table 8: Data of Final Design Test

What is really significant about the final results is that not only was a large amount of power produced, the Cool Stove was able to produce over 10 Watts for over an hour. Even while the cool side of the chips increased all the way up to pasteurization temperature, the chips were still able to produce enough power to maintain way above 10 Watts. In Figures 22 and 23 the results from two separate tests can clearly be seen. After around 30 minutes in both trials, the voltage remained more or less the same while the temperature of the water steadily increased.


Figure 20: Improved Setup with Bigger Rods and Smaller Bricks

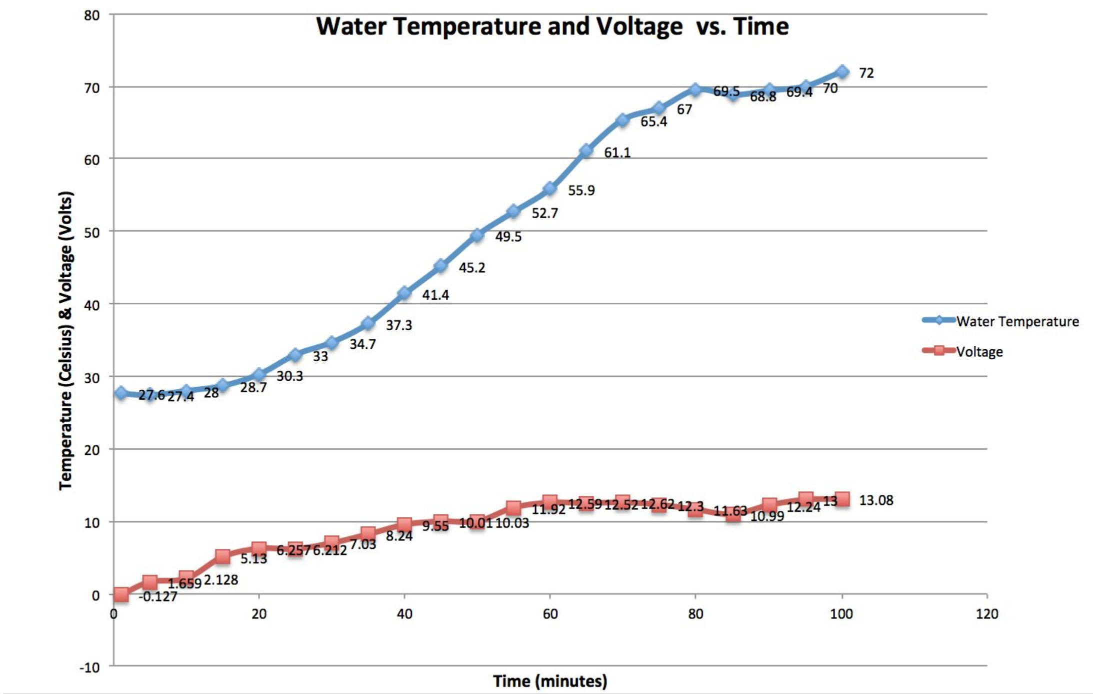



Figure 21: Temperature and Open Circuit Voltage vs. Time

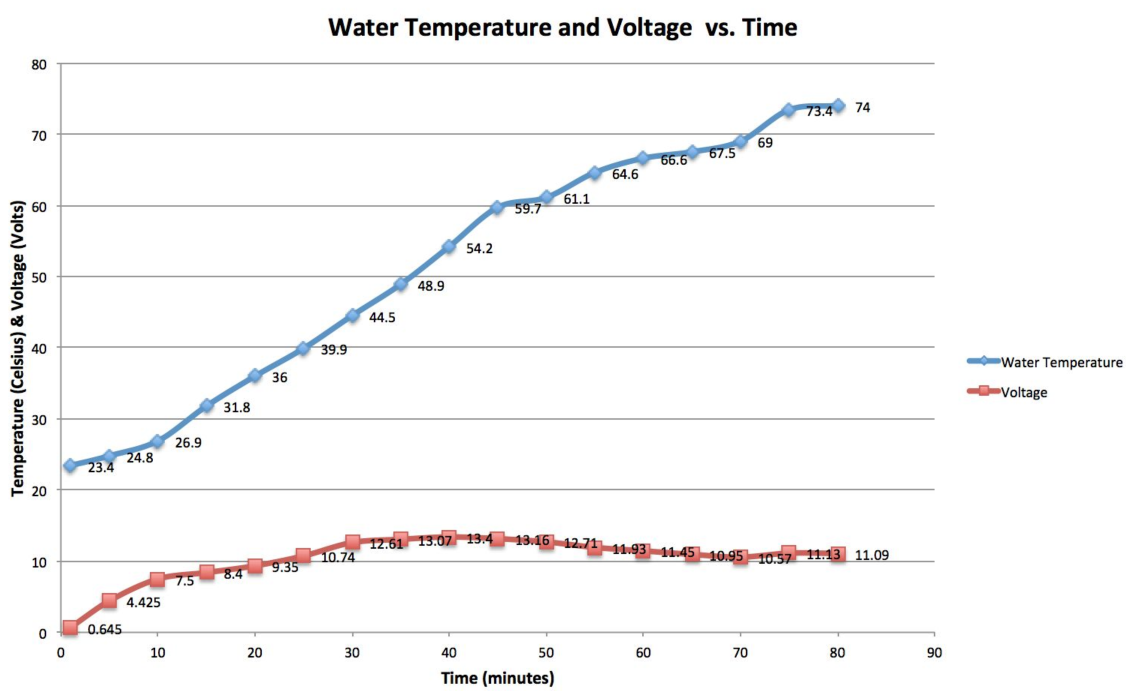



Figure 22: Temperature and Open Circuit Voltage vs. Time

## **Improvements for Future**

Improvements can always be made, one area that can be modified is making the entire product automated. This means that the water pasteurization system would be controlled 100% by the Arduino microprocessor, and through a system of valves, TMP-36 temperature sensors, and servo motors, the user would only have to get the fire started and nothing else.

Preferably the system would also include a battery charger, allowing it to create power that can be used at a later time. Giving all households that implement this system access to a 12V battery charging system would be crucial in providing power to more homes in the third world. If possible it would be ideal to combine this project with the micro-grid project where the surplus energy would be put back into the grid allowing for much more returns over just charging a 12V battery.

# **Appendix**

## Informational Sources

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## Image Sources

Figure 3: “Thermoelectric generator diagram” *wikipedia.org*. Wikipedia, 2015. JPEG file. Web. 12 Aug. 2015. <https://upload.wikimedia.org/wikipedia/commons/thumb/8/8b/Thermoelectric_Generator_Diagram.svg/2000px-Thermoelectric_Generator_Diagram.svg.png>.

Figure 4: “Thermoelectric Module.” *cleantechnica.com*. Sustainable Enterprises Media, 2014. JPEG file. Web. 10 Aug. 2015. <http://cleantechnica.com/2014/06/13/gmz-teg-module-successfully-generates-200w-engine-heat>.

Figure 5: “Do it yourself Trade.” *diytrade.com*. DIYSite, 2015. JPEG file. Web. 11 Aug. 2015. <http://img.diytrade.com/cdimg/450778/2512149/0/1154335266/Extruded_Heat_Sink.jpg>.

Figure 7: “The Clean Water Crisis.” *thinglink.com.* ThingLink, 2015. JPEG file. Web. 10 Aug. 2015. <http://www.thinglink.com/scene/459030840748277762>.

Table 7: “Specifications TEG Module TEG1-12611-8.0 .” *thermoelectric-generator.com.* FasterReach - Wordpress Development Toronto, 2014. PDF file. Web. 22 Jul. 2015. <http://thermoelectric-generator.com/wp-content/uploads/2014/04/SpecTEG1-12611-8.0Thermoelectric-generator.pdf>.

# Arduino Code

countfunctiontest

```
#include <Servo.h>
#include<Arduino.h>  //maybe not the right library

Servo myservo;     //Servo object 1
Servo myservo2;    //Servo object 2
float celTemp = 0.0;  //initially set the temperature to 0. This should be a global variable
int sensorPin = 0; //TMP36 Pin Variable
int count = 0;
//The setup function. Happens on reset or when power first given to Arduino
void setup()
{
  Serial.begin(9600);  //to view results, open the serial monitor. console log will be posted there. effective for reading temperature
  myservo.attach(2);   //servo set to digital pin 2
  myservo2.attach(3);  //servo set to digital pin 3
}


//The loop function. This goes on forever
void loop()
{
    openValve1();
    delay(10000);                          //ten second delay to keep the valve open.
    closeValve1();
    float celTemp = tmpRead();
    while(count<10)
    {
      celTemp = tmpRead();
      if(celTemp > 70)
      {
        count++;
        Serial.print("COUNT HAS JUST INCREASED");  //in order to avoid temperature sensor errors

      }
      delay(500);
    }
    count=0;
    openValve2();
    delay(10000);                        //another ten second delay
    closeValve2();
}
```

```
void openValve1()                            //The funciton to open valve 1
{
  int pos = 0;
  for(pos = 0; pos < 90; pos += 1)
  {
    myservo.write(pos);
    delay(10);
  }
}

void openValve2()                             //The function to open valve 2
{
  int pos2 = 90;
  for(pos2 = 90; pos2 >= 0; pos2 -= 1)
  {
    myservo2.write(pos2);
    delay(10);
  }
}

void closeValve1()                            //The function to close valve 1
{
  int pos=90;
  for(pos = 90; pos>=1; pos-=1)
  {
    myservo.write(pos);
    delay(10);
  }
}

void closeValve2()                             //The function to close valve 2
{
  int pos2=0

  ;
  for(pos2 = 0; pos2<90; pos2+=1)
  {
    myservo2.write(pos2);
    delay(10);
  }
}


//The function for tmp36 to read temperature
float tmpRead()
{
  int reading = analogRead(sensorPin);                        //gets the voltage
  float voltage = reading * 5.0;                              //convert reading to voltage
  voltage /= 1024.0;
  float temperatureC= (voltage -0.5)*100;                     //convert to degrees C
  Serial.print(temperatureC); Serial.println(" degrees C");   //print it out in the serial monitor
  return temperatureC;
}
```