Developing Positive Thermal Coefficient (PTC) Heaters for Solar Electric Cooking

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September 2022

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Abstract

Positive Thermal Coefficients, PTCs, are materials that abruptly change in resistance in response to changes in temperature. The purpose of this experiment is to explore the viability of using the switching type ceramic PTC thermistor as a replacement for current resistive heaters. These types of PTCs have a nonlinear change in resistance with increases in temperature. This device will be used as a temperature-controlling heating element intended to power an Insulated Solar Electric Cooker (ISEC). The ISEC is designed to cook meals throughout the day for impacted communities as an alternative cooking method that doesn’t require biofuel as an energy source and also reduces hazardous emissions. According to the World Health Organization, three billion people cook using biomass fuels and four million premature deaths are caused by household air pollution from inefficient cooking methods.[1] The goal of this technology is to reduce the environmental impact and health issues that arise from biomass cooking in enclosed areas such as households.

Introduction

ISEC is a multinational, non-profit organization pioneered by Cal Poly SLO students that aims to provide access to clean energy, in the form of solar-powered heated cookers, to individuals around the world. ISEC partners with globally diverse collaborators, who assemble and distribute the cookers for their respective communities. The Direct ISEC power usage is dependent on the resistance of the heater, the most common being a 100W solar panel with a 3Ω resistive heater, although higher power panels are also being used such as 200W and 400W. The solar panel is connected to an electrical heater that provides power to cookers as shown in Fig. 1.

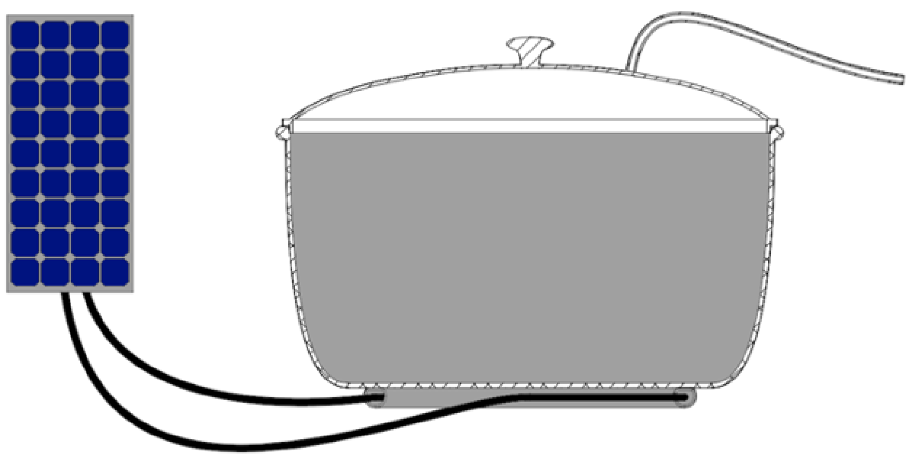


Fig. 1 shows a schematic of the Direct ISEC, not drawn to scale

Fig. 1 shows the solar panel leads connected to the heating element which is in thermal contact with the pot. To make cooking more convenient, a “nested pot” was added in order for the cook pot to be free of wires. The cook pot sits inside of the nested pot that has the heating element attached. This setup is displayed in Fig. 2.

Fig. 2 shows the nest pot that has the heating element fixed to the bottom (left) and the cook pot (right). The cook pot fits perfectly inside the nested pot with good thermal contact (right).

A key to making this technology work for impacted communities is making it affordable. Solar energy has proven to be an ideal solution, given their current cost trends and low maintenance. A low power solar panel in combination with the crucial surrounding insulation, results in an affordable method to attain high temperatures for cooking.

The 100W solar panel is found to provide 0.5 kWh of electricity over the course of a day, using 5 hours of optimal sunlight. Using this amount of energy, about 5 kg of water can be brought to a boil from room temperature in this 5 hour span. The calculation is shown below using the second half of equation 1. This means that in one hour, the ISEC can theoretically bring about 1 kg of water to a boil.[2]

$$E = P\Delta t = mc\Delta T \qquad (1)$$

$$E = (100W)(5hrs) = 500\,Wh = 0.5\,kWh$$

$$0.5\,kWh = 1800\,kJ = m(4.186\,\frac{J}{g\,C})(100^{\circ}C - 20^{\circ}C)$$

$$m = 5.4\,kg \qquad (with\ 5\ hours)$$

$$m = 1.1\,kg \qquad (in\ 1\ hour)$$

This provides a great method for boiling and simmering throughout the course of the day. The graph displayed in Fig. 3 shows that a 100 W solar panel has a manufacturing cost of $20 USD. With the decreasing cost of solar panels, the ISEC system demonstrates a desirable appropriate technology that can be adopted in many different communities.

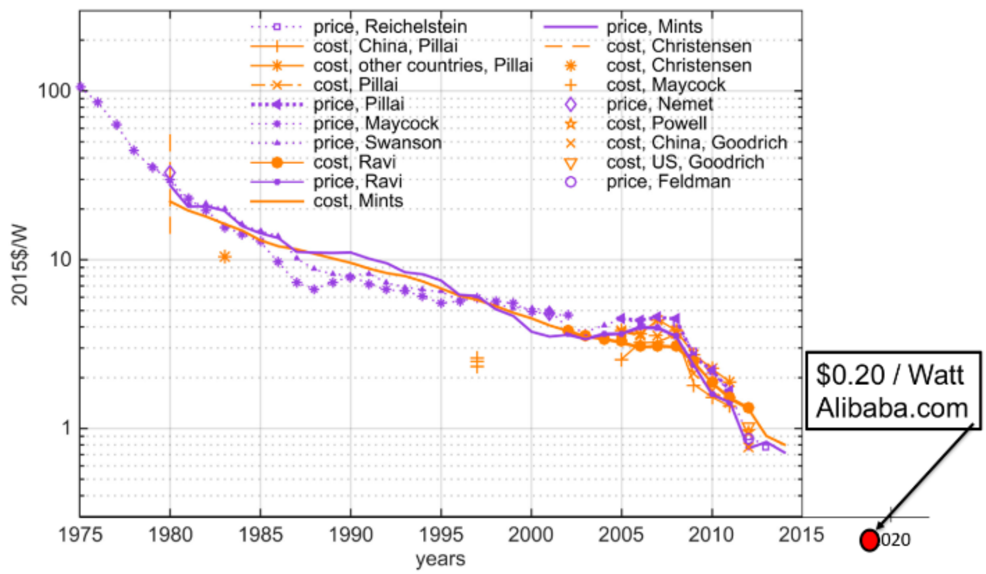


Fig. 3 shows a graph of the decreasing cost trends of solar panels ($/Watt)[12]

Research Background

The ISEC uses a variety of different heater types: resistive heating elements, nichrome wire, and diodes. The most common heating element is the resistive heater, an example of which is the range heater found on electric stoves. This heater is made of nichrome wire that is insulated with compressed magnesium-oxide powder. This is cut to yield resistance around 3.0Ω in order to optimize the extraction from the 100W provided by the 18V 6A solar panel. ISEC temperature is currently controlled by means of a thermal switch and thermal fuse which are necessary as safety precautions. The thermal switch behaves as a temperature control unit and opens the circuit at a temperature determined by the manufacturer, then closes the circuit at a lower temperature. The thermal fuse is used as a last resort to irreversibly open the circuit if the temperature reaches a thermal threshold by melting the metal inside the fuse, in this case 250℃. Generally, these are placed on the outside of the nested pot; far enough to let the heater heat up to a desired temperature. Fig.4 shows a picture of the thermal fuse and thermal switch.

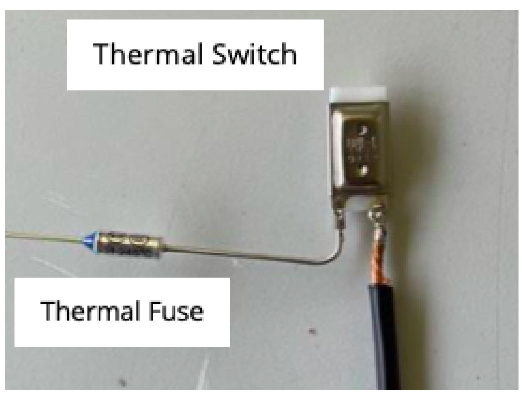


Fig. 4 shows the thermal fuse connected to the thermal switch

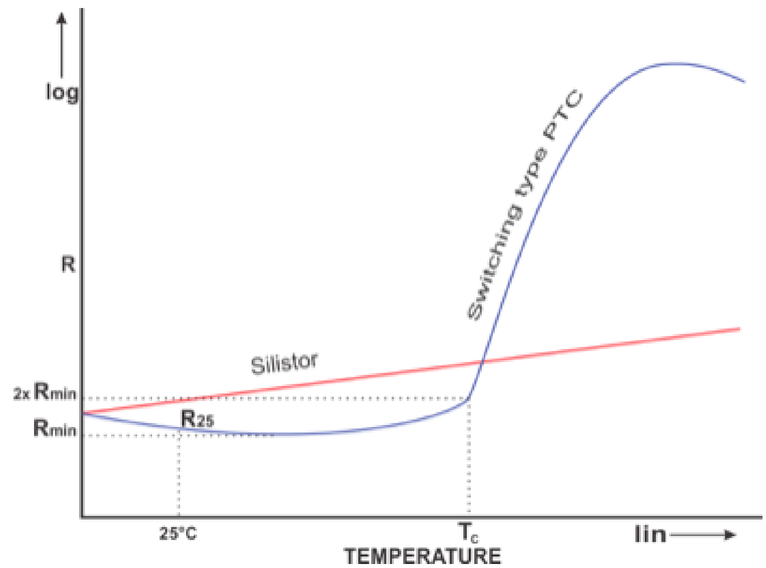
These components are inexpensive when purchased in large quantities, however are not always accessible to communities in rural areas. An appropriate technology like the ISEC should minimize the amount of imported equipment. Currently the composition of the heating element, thermal switch and thermal fuse creates the need to import more materials which makes the construction process more difficult. PTCs offer a solution by replacing all of the individual components needed for heat and safety mechanisms as one single component that performs as a self-regulating heater.

PTC Background

The PTC thermistor is a resistor with a positive thermal coefficient, meaning its resistance increases with temperature. The PTC thermistor is made of doped polycrystalline ceramic and barium titanate.[11] Generally, ceramics make good insulating materials, which is why they need to be doped with materials that have higher valency to achieve lower resistance. Insulators have full valence bands, making it harder for electrons to move freely, whereas conductors have half-filled valency. Part of the barium titanate ions are replaced with the ions of higher valencies to obtain a specific number of free electrons which makes the ceramic PTC conductive.[13] As the temperature of the PTC increases, the atoms in the material vibrate much more vigorously which impedes the continuous flow of free electrons. Free electrons collide with the vibrating atoms which obstructs their flow and as a result decreases the electric current. With a decreased current and following the Ohm's law equation displayed in Eq. 2, the resistance must then increase.

$$V = IR \tag{2}$$

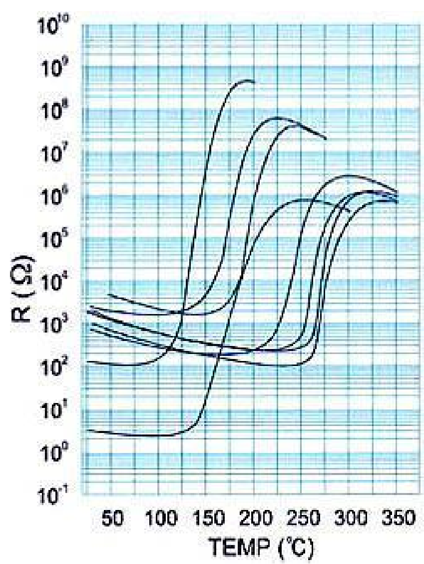
When power is applied to the PTC, the resistance initially decreases between 20 and 40 degrees Celsius, and then increases once its threshold temperature is reached. Once the threshold temperature is reached, the resistance of the PTC begins to increase rapidly, reducing the power being used and stabilizing at a constant temperature.[3] This temperature is known as the Curie Temperature or Curie Point, which represents the temperature at which the resistance of the PTC equals twice the minimum resistance (R_{min}).[4] A graph from the literature is displayed in Fig. 5 that demonstrates the PTC characteristics shown as the blue curve.



The resistance-temperature (R-T) characteristics of a PTC thermistor and a silistor

Fig. 5 displays RvT relationship of PTC thermistor and silistor[3]

Once the Curie Temperature is reached, T_c, the resistance begins to climb, which causes the current to decrease. The voltage output of the solar panel is limited and stays near constant, this reduces the PTC power output. A specialized ceramic PTC Thermistor Manufacturer, Sunlead Group, has shown the results of their PTC Resistance vs Temperature graphs on a logarithmic scale in Fig 6.



[5] *Fig. 6 shows the results of a manufacturers' measurements of their own PTC'*

Experiment

The performance and durability of PTCs were tested as a heater for the ISEC and a series of tests were conducted to either support or reject the PTC thermistor as a sufficient heating element for the ISEC. The experiment started with testing each of the PTC's temperature, current, and voltage, then graphing the relationship between resistance and temperature. Once understanding their behavior, the PTCs were tested in a few circuit variations to determine which variation produces the best results.

For the tests, a PTC rated for 24V and 220℃ and 5W-50W of power was used. The PTC is a ceramic material that is sheathed in an aluminum casing as seen in Figure 7.

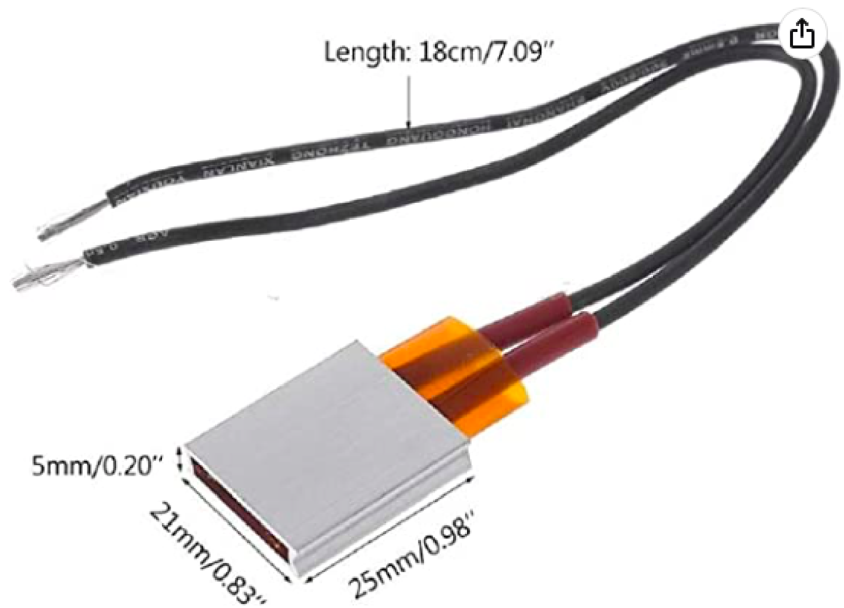


Fig. 7 shows a diagram of the PTC with its respected dimensions[5]

The PTC displayed in Fig. 7 was tested by connecting the leads to a power source and setting the limits of the power source to 18V and 6A to replicate the characteristics of a 100W solar panel. Since the resistance of the PTCs are always greater than 3Ω, the 6 Amp current limit was never invoked and the PTCs were under a constant voltage of 18 Volts. The PTC was insulated between layers of rockwool insulation to mimic the environment of an ISEC and was connected to shunt resistors. The resistance was calculated using Ohm's Law and by manually recording the voltage and current data.

The temperature was recorded using a thermocouple wire placed inside of the PTC between its two leads. The resistance and corresponding temperature data for one PTC is shown below in Fig. 8.

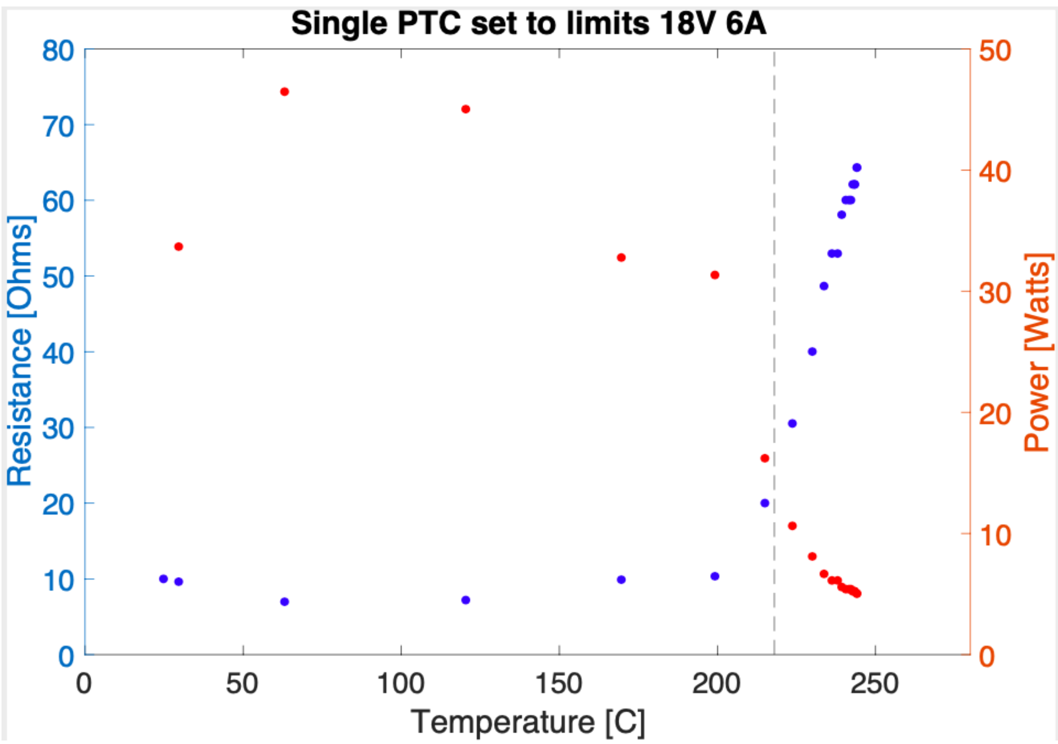


Fig. 7 indicates the relationship between the resistance and temperature of a single PTC as well as the Curie Point shown as the black dashed line. The Curie Point is equal to 220 C.

The results from testing a single PTC align with what was expected from the literature. The resistance should drop slightly in the beginning, but once it reaches the Curie Point the resistance rapidly increases. The Curie Point in this case is 220℃. After this point, the resistance increases, the power decreases and the temperature stabilizes at about 250℃.

Two more PTCs were tested, one of which burned out for undetermined reasons. The PTC seemed to behave with infinite resistance, as it was no longer drawing current when connected to the power supply, indicating an open in the circuit. This was a major concern regarding their implementations in the future due to reliability. In response, 12 more PTC heaters were ordered to conduct similar tests where the results can be found in Fig. 9.

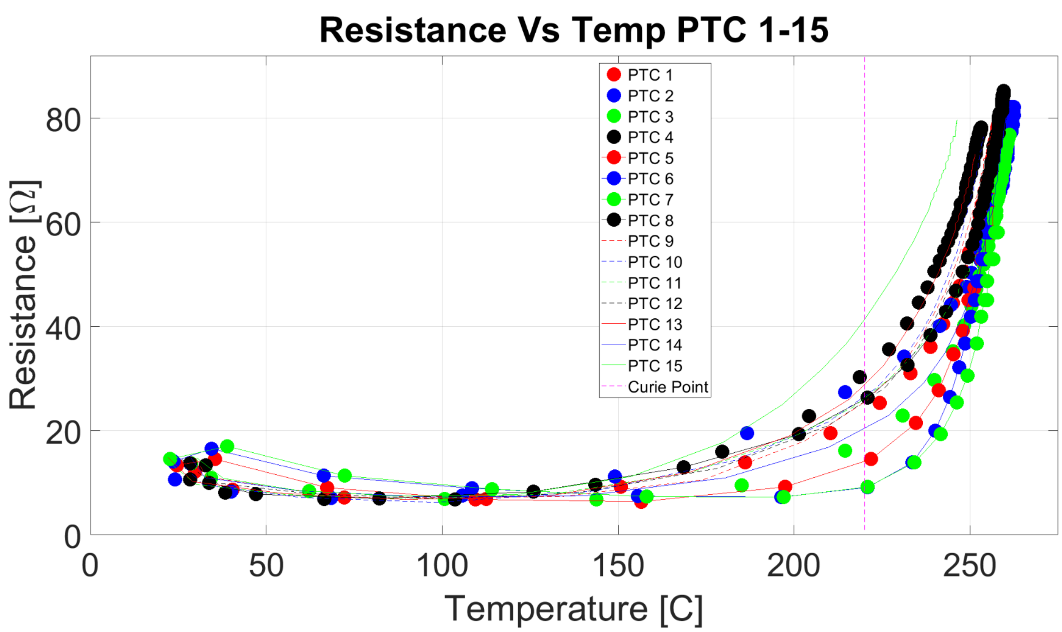


Fig. 9 Resistance vs. temperature graphs of 15 single PTCs with Curie Point 220 C measured using two reliable DMMs to get more accurate results.

The results from Fig. 9 show that each of the PTCs behave consistently, with some slight variations. A few of the PTCs increased in resistance before the Curie Point was reached. To understand the temperature variation displayed in Fig. 9, a verification test was done on one of the PTC heaters. The test involved three different thermocouples placed in the inside center between the two leads, on the inside between the ceramic and the aluminum sleeve, and on the aluminum sleeve of the PTC, while it was heating up to compare their temperatures. The locations can be seen in Fig. 10.

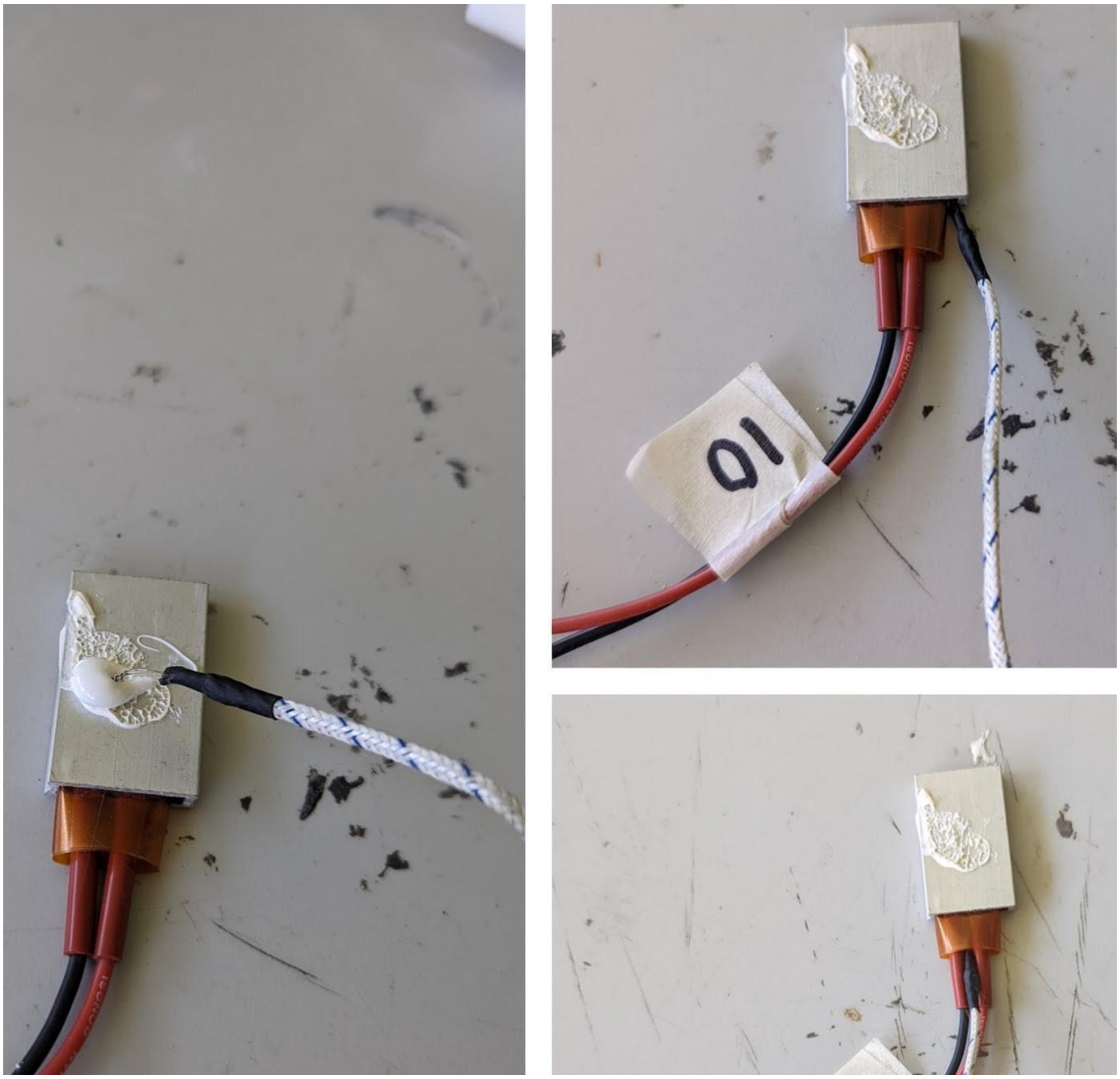


Fig. 10 the left image is where the thermocouple was attached to the aluminum sheathe, the top right is where the thermocouple is inserted into the inside side between the ceramic and the aluminum sheathe, and the bottom right image, where all of the experiments were tested from, is inside center between the two leads.

Fig. 11 demonstrates a difference of 40℃ between the outside of the PTC and inside center between the leads, as well as a 40℃ difference between the two leads and the side between the aluminum sheeting and the ceramic of the PTC. Therefore, the temperature of the PTC depends on where the thermocouple is placed.

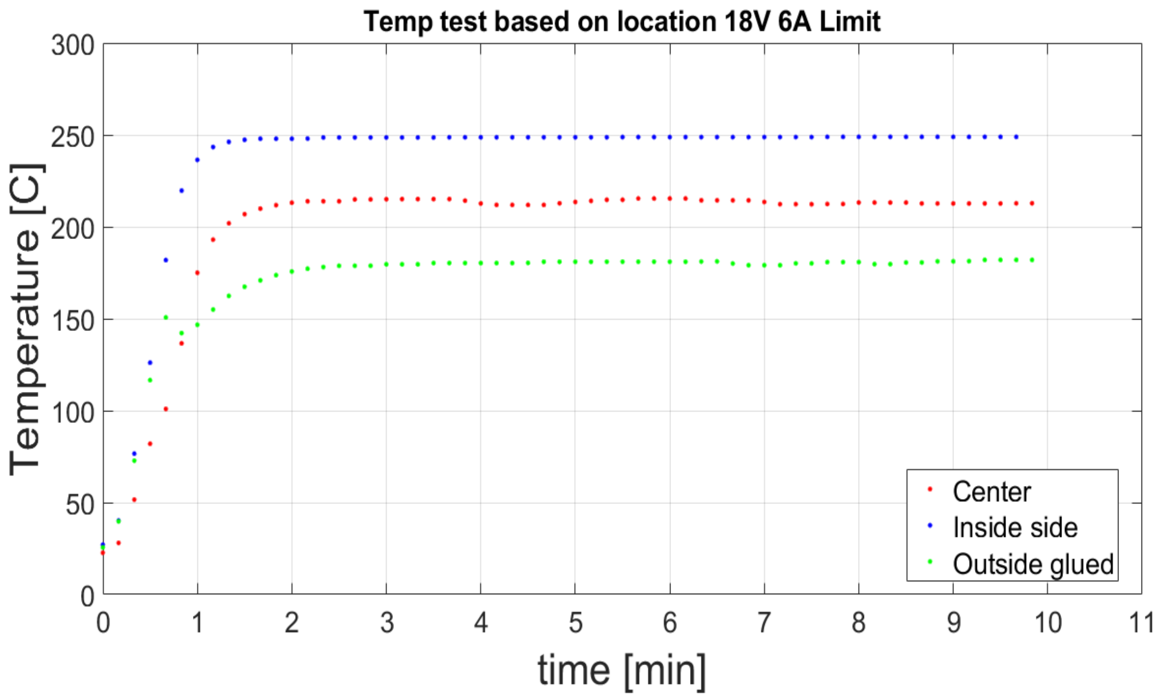


Fig. 11 shows the temperature variations in three different points of measurement on the PTC

However, the thermocouple was placed in the same position for each PTC test, which was between the two leads of each of the PTCs. Although it was at the same point, slight variation of location could result in variation of temperature reading. This could explain the discrepancy shown with PTC 15 in Fig. 9.

The temperatures the PTCs reach under these conditions, range from 230℃ to 250℃; this deviation in temperature represents a percent error of 8% and can be considered a fair portrayal of the PTCs' behavior. The PTCs' behavior on average shows they behave consistently, all reaching near the same resistance of about 65Ω at 250℃.

Testing of the circuits

The setup consisted of the PTC's attached to the bottom surface of an aluminum pot using RTB glue (Fig. 13). One of the leads for each of the PTCs was connected in series with their own shunt resistor connecting them all to the common. Figure 12 is the electrical diagram for the connections and Figure 13 shows the connections in practice. Figure 14 shows the abundance of insulation used to simulate its working conditions.

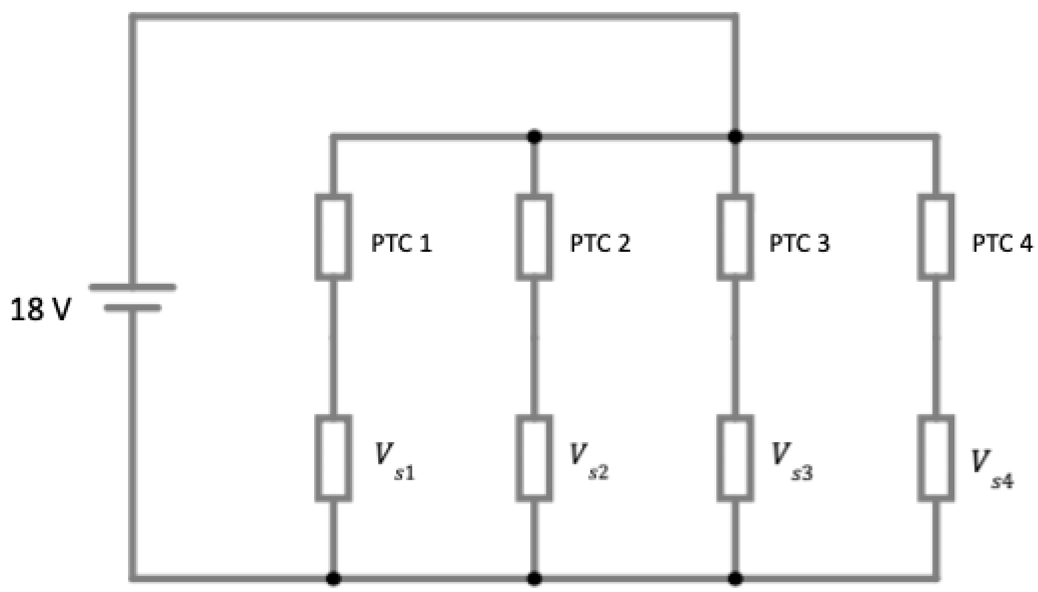


Fig. 12 shows the circuit diagram of four PTCs in parallel, these voltages were read by an Arduino

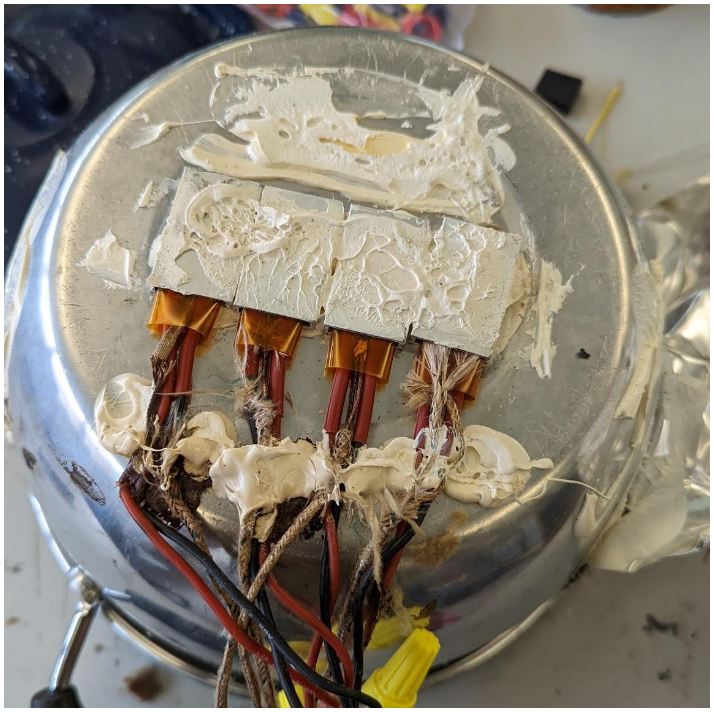


Fig. 13 shows the PTCs connected to a shunt resistor by use of an electrical nut, and the thermocouples are on the inside center of the PTC.

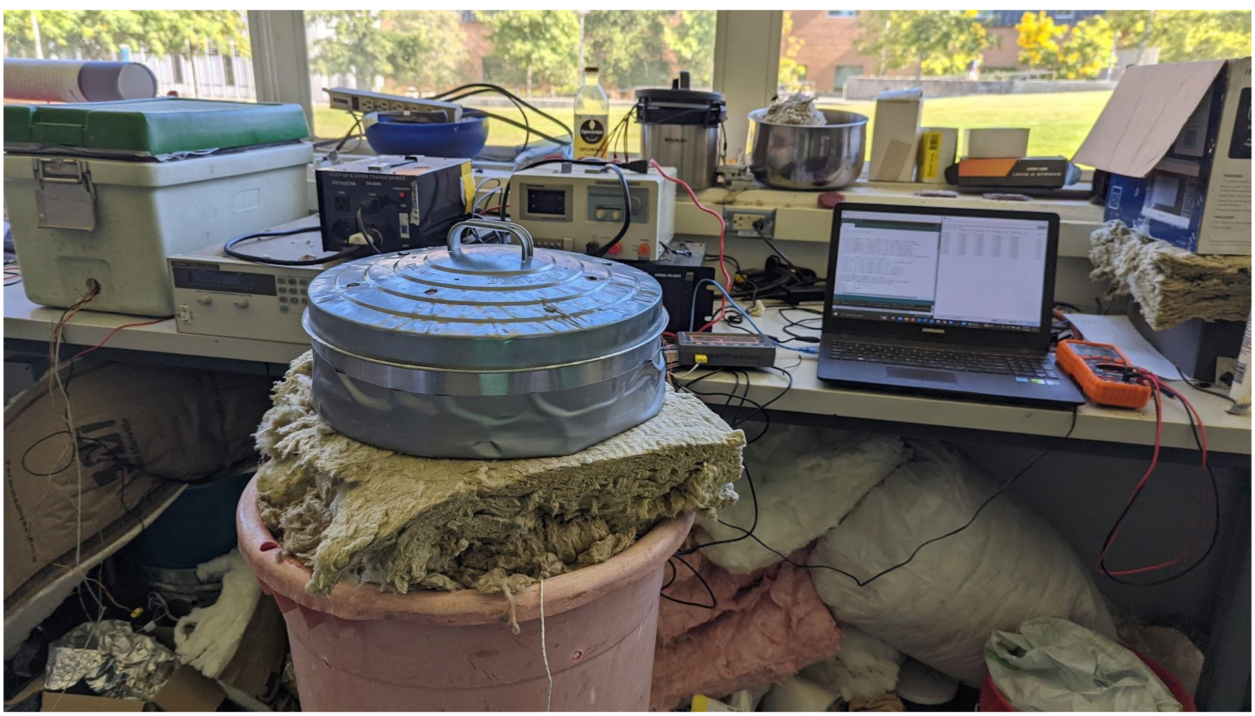


Fig. 14 is the setup used to measure and monitor the results of the Arduino including a DMM to reference measurements to.

The voltage across the shunt resistors (R ~ 0.18Ω) was recorded via an Arduino, code available in Appendix I, and the current was calculated by using Equation 2, Ohm's law. The voltage across the PTC was determined using Kirchoff's loop rule. The voltage drop across each of the shunt resistors was subtracted from the voltage applied, measured with a DMM, to calculate the voltage across the PTCs. Using these two variables, the resistance of the PTCs was determined using Equation 2 and dividing the voltage across the PTC by the current in each parallel path. The Arduino needs to be calibrated each run and needs time to stabilize, the time of which varies with each microcontroller. The Arduino measurements were normalized by periodically taking measurements of voltage with a DMM. The Arduino data were then adjusted to match the DMM measurements as shown in Fig. 15.

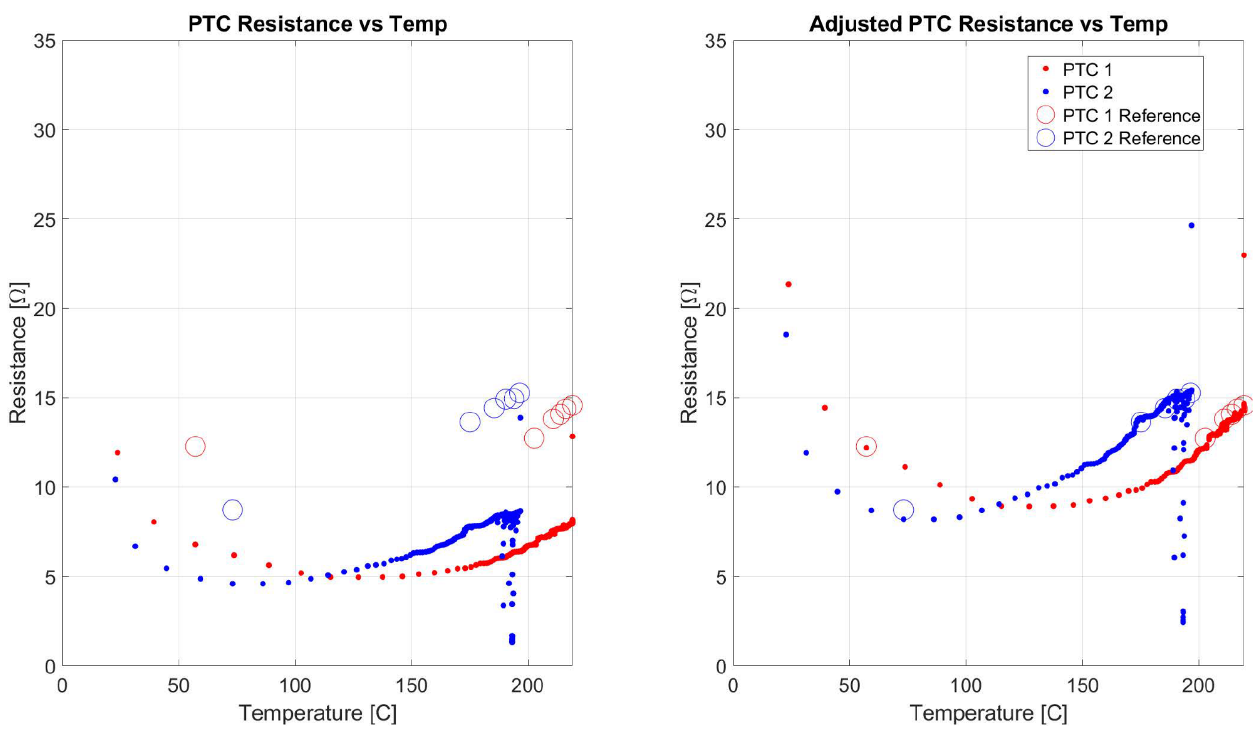


Fig. 15 shows the accuracy of the measurements taken by the Arduino before and after calibration.

PTC Circuit Testing

In order to test the PTCs under operating conditions, three tests were conducted:

1. Four PTCs in Series in Parallel
2. Two PTCs in Parallel
3. Two Series PTCs in Parallel

To determine whether the PTC heater is an appropriate alternative to the resistive heating element of the current ISEC, The power production was measured by bringing 1 kg of water to a boil, 100 W should boil 1 kg of water in about an hour. The power supply was used once again to mimic the properties of a solar panel by setting the output limits to 18V and 6A for each of these tests.

1. Four PTCs in Parallel:

One of the more promising variations was the four in parallel, the diagram of which can be seen in Fig. 12.

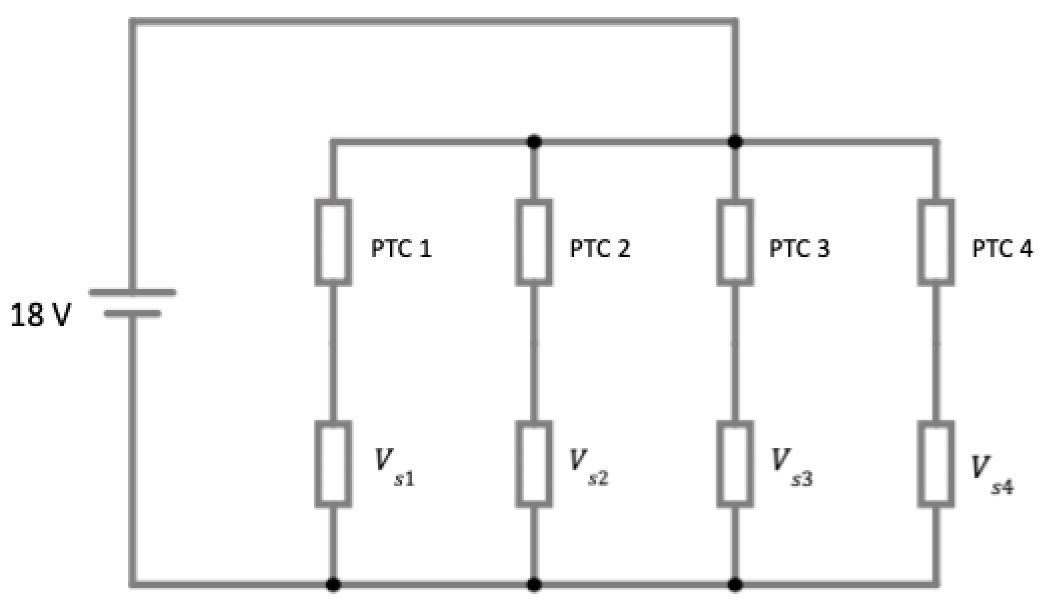


Fig. 12 shows the circuit diagram of four PTCs in parallel with their respected shunt resistor

The PTC ISEC started with a small amount of water, approximately 300g, that started to boil after around 25 min, and completely evaporated at 50 min (Fig. 16).

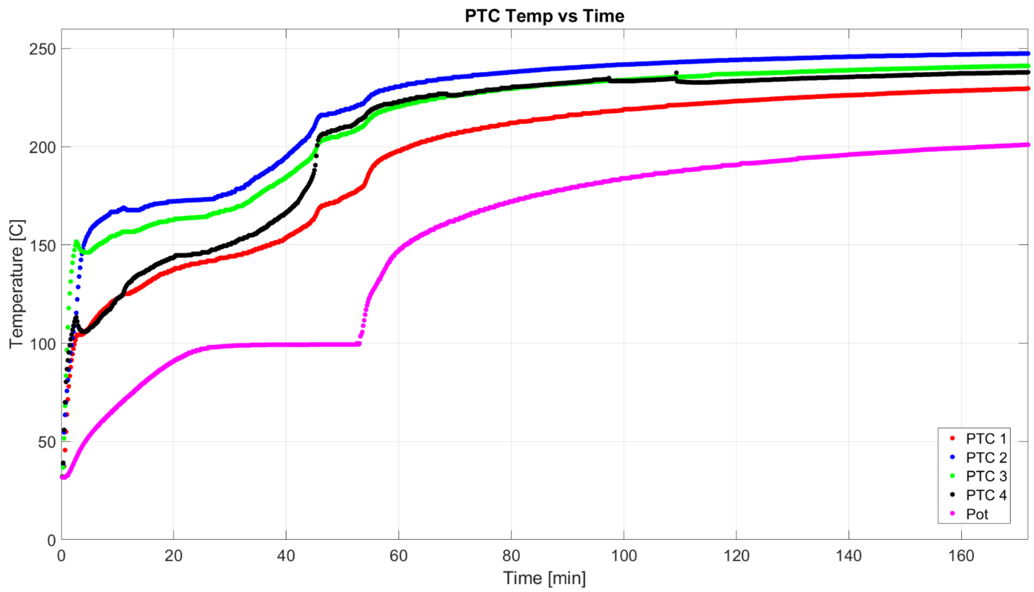


Fig. 16 shows the temperature data of four PTC heaters in parallel

$$P = \frac{mc\Delta T}{t} \quad (3)$$

A thermocouple was attached on each of the PTCs in between the leads and an additional one in the pot to measure the temperature of the water. The time during which the water boiled can be seen at the plateau along the water curve. When the water completely evaporated, the temperature increased.

The test was done an additional time except with 1 kg of water inside the aluminum pot seen in Fig 17.

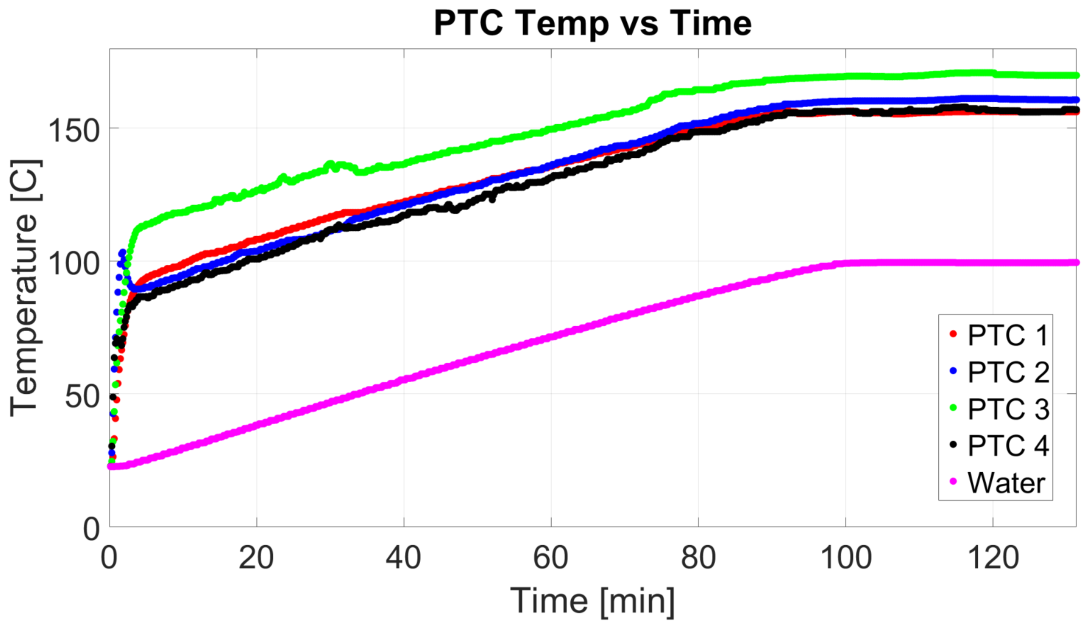


Fig. 17 shows the temperature data of the four PTCs and 1 kg of water

The water was brought to a boil after 1.5 hrs of heating, corresponding to an average thermal flow to the water of 81W, calculated from Equation 3, from the PTC heaters.

Voltages were recorded across each shunt resistor to calculate the current, which was used to calculate the resistance of each PTC. The resistance and temperature relationship is shown below in Fig 18.

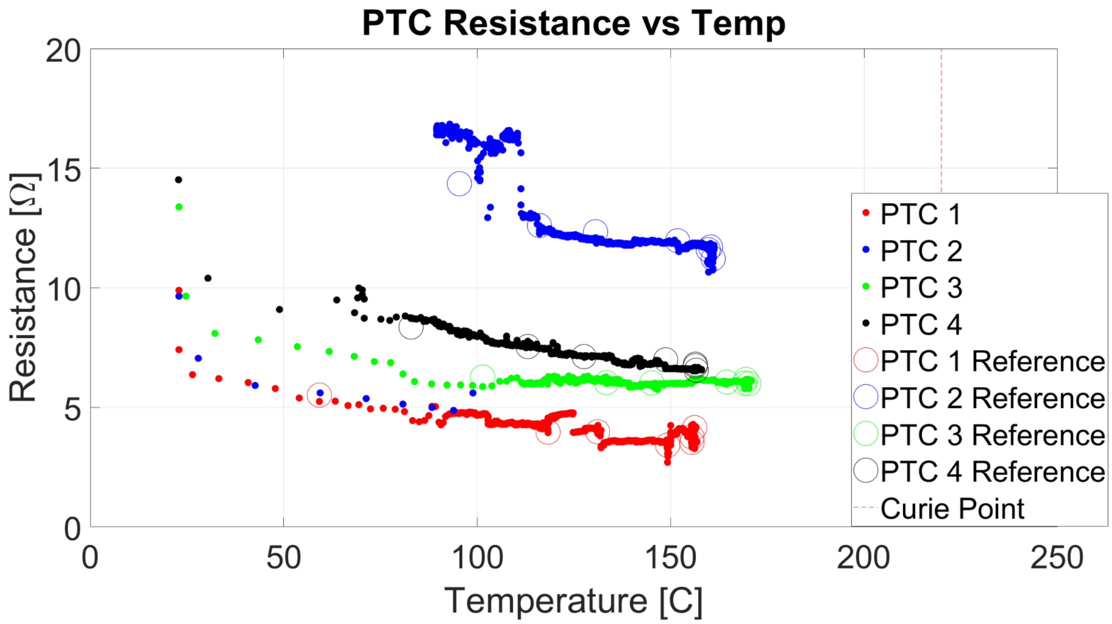


Fig. 18 shows the Resistance vs Temperature data for the four PTCs in parallel bringing 1kg of water to boil.

The PTCs behaved as expected, by decreasing resistance in the beginning of heating. Due to the water in the pot, the temperature of the PTCs never reaches past 200℃. The PTCs are in good thermal contact with the pot, heating the water, and therefore never reach the Curie Point. Since they never reach the Curie Point, the resistance does not increase as indicated in Figures 7 and 8, but is consistent with the resistance vs time graph in Figure 8. Manually taking DMM measurements often perturbed the Arduino readings, resulting in transitory spikes as shown in Fig. 18.

The spikes are likely due to the low voltages and small changes in the wire, which is significant because the voltage across the shunt resistors is approximately 0.1V. The total voltage is approximately 18V and the small changes in the shunts voltage result in changes in the current through each circuit which compounds the problem.

To determine the power efficiency of the PTCs, the power graph is shown in Fig. 18. The power of each PTC climbs in the beginning and then levels off.

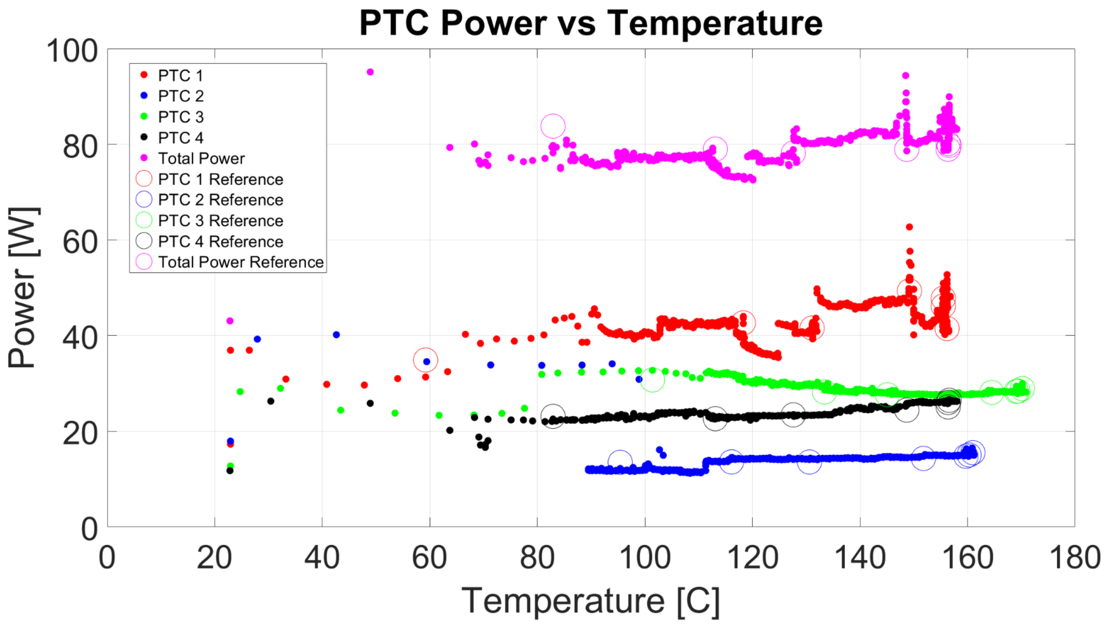


Fig. 19 shows the power output of each of the PTC heaters, as well as the perturbations from manual measurements likely due to disturbances in the shunt voltage when measuring with a DMM.

2. Two PTCs in Parallel

Two PTCs in parallel with one another were tested with 1kg of water. The data measurements were taken with the same methodology as the four in parallel. However, instead of four, two shunt resistors were used to measure the voltage and calculate the current using Ohm's Law. The circuit diagram is shown below in Fig. 20.

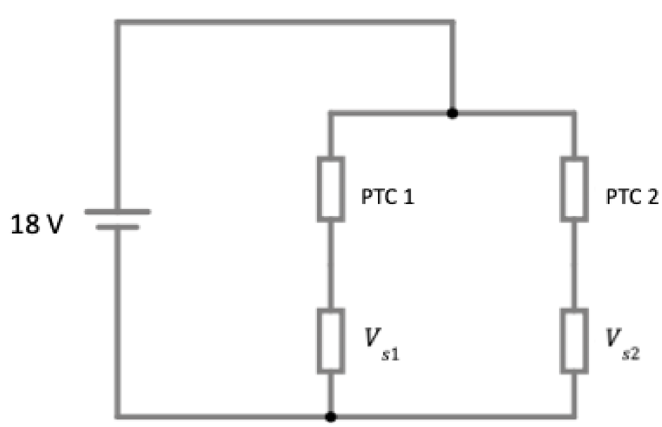


Fig. 20 shows the circuit diagram of two PTCs in parallel

The power of the two PTC heaters is displayed in Fig. 21. The power consumption of the PTCs stabilizes as temperature increases. The power output of the PTCs in this configuration is not as high when compared to other circuit testing. Therefore, having exclusively two PTCs in parallel is not a recommended option.

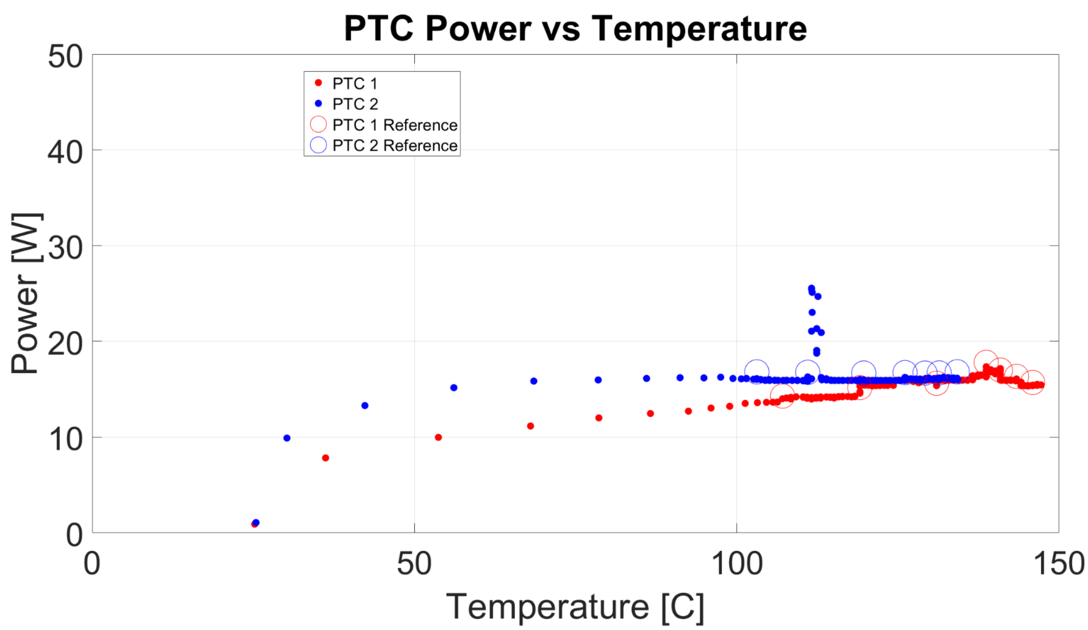


Fig. 21 shows the power and temperature relationship, Power calculated from the voltage measured using an Arduino and the known resistance of the shunts.

3. Two Series PTCs in Parallel

Two PTCs were connected in series and put in parallel with another set of series PTCs (Fig. 22). The results of the experiment can be seen in Fig. 23 and 24.

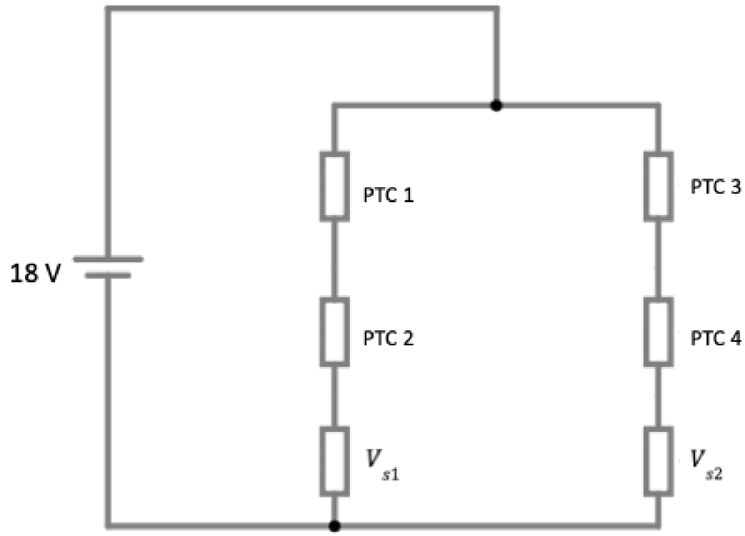


Fig. 22 shows the circuit diagram of two series PTCs in parallel with another set of series PTCs

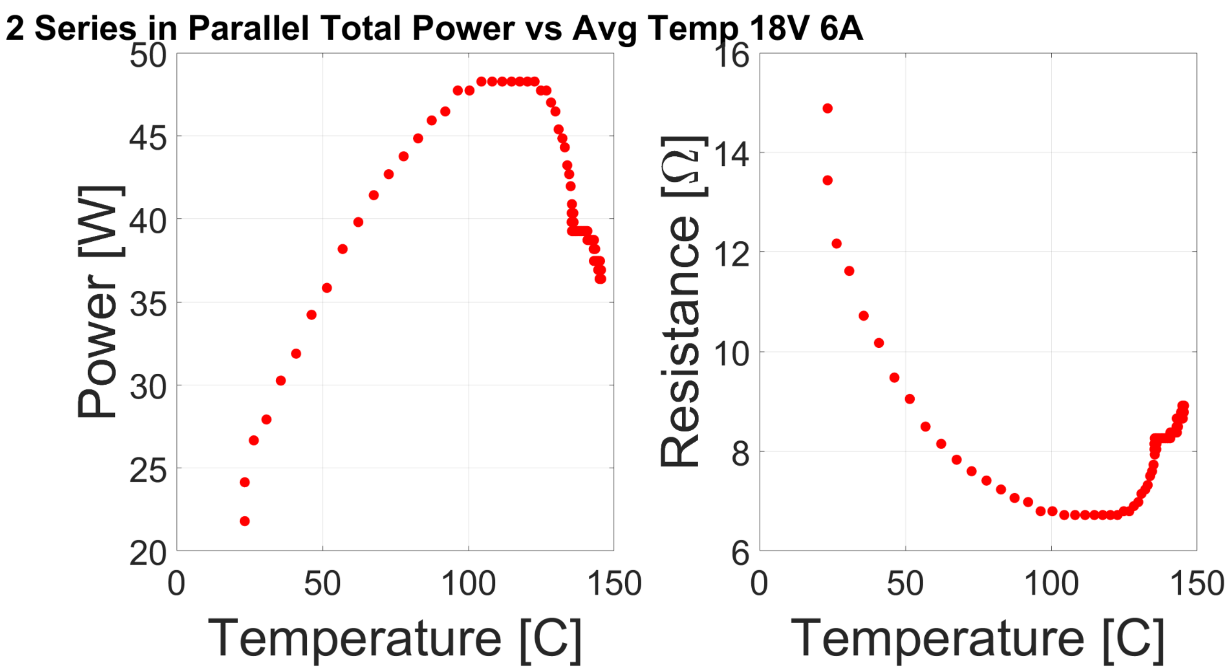


Fig. 23 shows the power and resistance curves of a low temperature PTC with respect to the temperature of the load measured via the power source.

As the temperature increases the resistance for each of the PTC's increases.

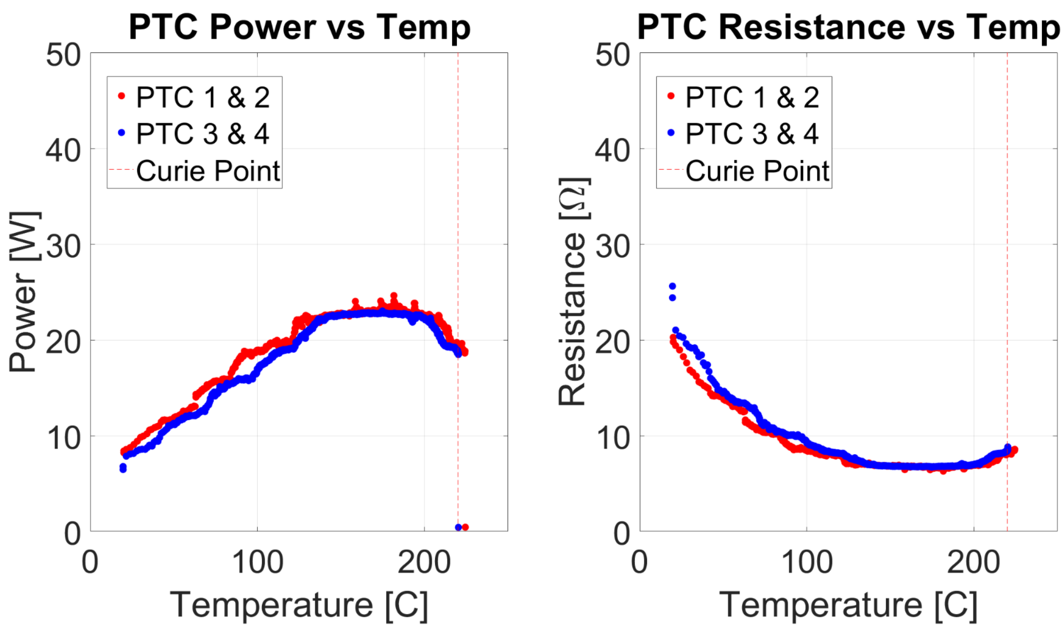


Fig. 24 shows the power and resistance curves of a high temperature PTC with respect to the temperature of the load. PTCs 1 and 2 were in series and parallel to the series of 3 and 4. The voltage drop and current were calculated for each series and their temperature data were averaged.

The PTCs decrease their power consumption as the temperature passes the Curie temperature where the resistance begins to increase. The PTC maintains a set power consumption once it reaches its maximum resistance at a high temperature, approximately 250 ℃. This keeps the PTCs at that temperature until power is removed.

Discussion

Our findings indicate PTC heaters are a viable alternative to other direct DC heaters, if not preferential, as they consist of only one part for heating and safeguards. By measuring the electrical resistance and exploring different circuit configurations, the 50W PTCs have boiled 1kg of water in 1.5 hours. The four PTCs in parallel used and transferred 81W of thermal power. Out of the 16 PTCs tested, there was only one failure experienced at the beginning of testing.

Not only are PTCs effective heaters, but they also keep ISEC cookers affordable. PTC heaters are fairly cheap, on Alibaba the cost of the PTCs used in this study ranged from $1.20 USD per unit for an order less than 2000. For orders greater than 2000, the cost drops significantly to $0.50 USD per unit.[7] Whereas the Bimetal thermal switches used in prior experiments cost $1.21 USD per unit for orders of 1000 to 9999 and the thermal switches of the same range that were used cost between $0.08 to $0.09 USD per unit for a minimum order of 1000 units.[8] For orders of 1000 units, PTC's are cheaper by about $90 USD, or $0.10 USD difference per unit, and for orders of 2000, or more the price difference increases to $1580 USD, or an $0.80 USD difference per unit. The most successful circuit configuration was the four in parallel. The price difference is $22 USD for orders of 1000 and for orders greater than 2000, $397 USD just for the safeguard. Replacing the heating element increases the price difference substantially.

The cost of a regular heating element from [10]Alibaba is $4.80 USD per unit for orders of 1000 or more. Using the same comparative process for orders of 2000 or more, the cost difference is approximately $0.60 USD per unit. The cost difference of solely the heater is $1200 USD for orders of 2000 or more. In total, the cost difference as a replacement for safeguards and heating element is approximately $1600 USD.

Some problems that the PTCs face are that they don't get very hot and don't produce power when they do get hot. It is important that they are in good thermal contact with the thermal load. Regular resistors still heat up when they aren't connected and continue to heat up past a safe temperature, which is why they needed the safeguards, and will lose the same amount of power at a high temperature. PTCs seem to also have a large degree of variation overall with their mean resistance before their Curie point being 59.4±20.5Ω, which has a standard deviation of 35%. The mean of the PTCs prior to the Curie point have a greater variation, with the mean resistance being 15.7Ω. The average resistance at the Curie Point is 29.6±8.8Ω, about a 30% variation.

Conclusion and Outlook

Overall PTCs are a preferred alternative to other direct DC heaters under some conditions, but are inadvisable for thermal storage as they cannot provide significant amounts of power above 200 ℃. They are cheaper, have simpler safeguards, have fewer parts, and facilitate simpler assembly. The drawbacks are that PTCs are more selective of resistance, which is why they don't convert power as efficiently as a properly chosen resistor; this can be fixed by using a Buck Converter. PTCs require good thermal contact with the load, and need to be checked before use. Going forward, testing the PTC heaters upon arrival is recommended to determine their durability as well as the reliability from manufacturers.

References

[1]World Health Organization. Household Air Pollution and Health. 2022 https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

[2]Crofton, Jack. Insulation and Structural Support for Solar Electric Cooking. 2021 https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1216&context=ph yssp

[3]EE Power. PTC Thermistor. https://eepower.com/resistor-guide/resistor-types/ptc-thermistor/#

[4]Ohizumi. Technical terms of PTC thermistors. https://www.ohizumi-mfg.jp/english/product/technote2.html

[5]Sunlead Group. Ceramic PTC Thermistors: General Heating Applications. http://www.sunlead.com.tw/p1.htm

[6]EPCOS. PTC Thermistors: General Technical Information. February 2012 https://www.tdk-electronics.tdk.com/download/531162/d78540dfe0589d2bd90cabef477c90b9/pdf-general-technical-information.pdf

[7]Bestol. 2pcs PTC Heating Elements AC DC 24V 220 Degree Consistent Temperature Ceramic Thermostatic. https://www.amazon.com/dp/B07VCKB6S1?psc=1&ref=ppx_yo2ov_dt_b_product_details

[8]Allibaba. 2 Pcs Ptc Heaters Heating Element Hair Dryer Accessories Curlers Heater 80/120/220 Degrees Celsius 12V Air Heater https://www.alibaba.com/product-detail/2-Pcs-Ptc-Heaters-Heating-Element_1600186407876.html?spm=a2700.galleryofferlist.normal_offer.d_image.73525d2aTqH7pp

[9]Allibaba. 10A 250V 240C Thermal fuse for household appliances
https://www.alibaba.com/product-detail/10A-250V-240C-Thermal-fuse-for_1600440770390.html?spm=a2700.galleryofferlist.normal_offer.d_image.78da6456qUbRrk

[10]Alibaba. Yuling Brand OEM ODM Customize Burner Heating Element Replaces WB30M2 8" Stove Surface Element
https://www.alibaba.com/product-detail/Element-Stove-Yuling-Brand-OEM-ODM_60072115379.html?spm=a2700.7735675.normal_offer.d_image.4a9223acXzhrSz&s=p

[11]TDK. PTC Thermistors: General Technical Information.
https://www.tdk-electronics.tdk.com/download/531162/d78540dfe0589d2bd90cabef477c90b9/pdf-general-technical-information.pdf

[12]Kavlak, et al. Evaluating the causes of cost reduction in photovoltaic modules. 2018.
https://www.sciencedirect.com/science/article/abs/pii/S0301421518305196?via%3Dihub

[13]I.W. Chen. Dielectric and Ferroelectric Ceramics: Interfaces
https://www.sciencedirect.com/topics/engineering/polycrystalline-ceramic

Appendix

Code:

```
/*
uno: calibrate ADC inputs
*/

const int repeats = 1000; // number of times to repeat the measurement
long int sum = 0; // a running total of the measurements for that channel

#define VOLTAGE1 A0 //Assigns the analog pins to whichever Voltage you are trying to
record
#define VOLTAGE2 A1
#define VOLTAGE3 A2
#define VOLTAGE4 A3
#define VP A5

double t = 10000; // Time for Arduinos is counted in miliseconds
// to match our data loggers it was set to 10 seconds.

double tiMe = t/1000; // Variable name used for counting the number of seconds after
each cycle

double PS = 0; // Initially set the values of the power source and other pins to 0
double V1 = 0;
double V2 = 0;
double V3 = 0;
double V4 = 0;

#include <SPI.h> // Include the library for the shield attachment to the Arduino
#include <SD.h> // Include the library to write to an SD card
File record; // Name of the file all data will be put into set as a .csv file

void setup() {
  Serial.begin(9600); // Initialize the Serial monitor to view the recordings directly
  while (!Serial) {
    ; // wait for the serial port to connect. Needed for native USB port only
  }
```

```
  if (!SD.begin(4)) {
    Serial.println("initialization failed!"); // If the SD card doesn't work or isn't present
    //stops the code
    while (1);
  }

  // This section is for labeling purposes for the Serial Monitor
  Serial.println("initialization done."); // If the SD card does work and is inserted

  // Opens the file and allows the Arduino to write to it
  record = SD.open("record.csv", FILE_WRITE);

// Display the labeling on the Serial monitor
  Serial.print("Voltage 1 [V]"); Serial.print("\t"); Serial.print("Voltage 2 [V]");
Serial.print("\t");
  Serial.print("Voltage 3 [V]"); Serial.print("\t"); Serial.print("Voltage 4 [V]");
Serial.print("\t");
  Serial.print("Power Source [V]"); Serial.print("\t");
  Serial.println("Time [s]");
  Serial.println("________________________________________");

  // This section is for labeling purposes on the file
  record.print("Voltage 1 [V]"); record.print(","); record.print("Voltage 2 [V]");
record.print(",");
  record.print("Voltage 3 [V]"); record.print(","); record.print("Voltage 4 [V]");
record.print(",");
  record.print("Power Source [V]"); record.print(",");
  record.println("Time [s]");
  record.close(); //closes the file

// Uses the 5V supplied to the Arduino from the connection as the reference
  analogReference(DEFAULT);
// NB use "EXTERNAL" only if using an external reference
}

// take measurements and print result
void loop() {
  // Sets the values of our measurements to zero each run
  PS = 0;
  V1 = 0;
```

```
  V2 = 0;
  V3 = 0;
  V4 = 0;

  record = SD.open("record.csv", FILE_WRITE); // Opens the file again to write on it

  if (record) {

    readvoltage(); // Local function used for collecting the data

    // Displays the values on the Serial Monitor
    Serial.print(V1, 6); Serial.print("\t");  Serial.print(V2, 6); Serial.print("\t");
    Serial.print(V3, 6); Serial.print("\t");  Serial.print(V4, 6); Serial.print("\t");
    Serial.print(PS, 6); Serial.print("\t"); Serial.print("\t");

    // records the values to the file RECORD
    record.print(V1, 6); record.print(","); record.print(V2, 6); record.print(",");
    record.print(V3, 6); record.print(","); record.print(V4, 6); record.print(",");
    record.print(PS, 6); record.print(",");
    record.println(tiMe);
    record.close(); // closes the file for another run
  } else {
    // if the file didn't open, print an error:
    Serial.println("error opening record.csv");
  }
  tiMe = tiMe + t/1000; / /increases the time to show the increase
}

void readvoltage() {

  // Sets new variables for measuring to zero
  double sumV1 = 0;
  double sumV2 = 0;
  double sumV3 = 0;
  double sumV4 = 0;
  double sumPS = 0;
  double aveV1 = 0;
  double aveV2 = 0;
  double aveV3 = 0;
  double aveV4 = 0;
```

```
  double avePS = 0;

  // A for loop to do multiple readings for finding the mean of the results
  for (int j = 0; j < repeats; j++) {
    sumV1 += (analogRead(VOLTAGE1));
    sumV2 += (analogRead(VOLTAGE2));
    sumV3 += (analogRead(VOLTAGE3));
    sumV4 += (analogRead(VOLTAGE4));
    sumPS += (analogRead(VP));
    delay(8); // choose a short delay that does not add to 20msec.
  }

  aveV1 = sumV1/repeats; // calculates the average results
  aveV2 = sumV2/repeats;
  aveV3 = sumV3/repeats;
  aveV4 = sumV4/repeats;
  avePS = (sumPS/repeats);

  V1 = (aveV1/100); // Assigns the averaged values to use in the main code
  V2 = (aveV2/100);
  V3 = (aveV3/100);
  V4 = (aveV4/100);
  PS = (avePS/100);
}
```