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Temperature Control of a Water Bath

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Abstract

A project investigating the design of a low-cost, accessible, open-source water bath for the heating of biological samples. This includes a literature review of current open-source scientific equipment, and the creation of a realistic specification for the water bath. The project determines whether the techniques found in other open-source projects can be applied to the design of a water bath. A flat plate mica heater is used to heat the water, and a PT1000 two-wire sensor is used to provide feedback to the control system. An investigation of how heat conducts through different materials is also made. The viability of the finished bath is assessed through the construction of graphs to show how the water in the bath heats up over time, with the final conclusion being that although the water bath does not meet the original specifications, this is due to extenuating safety factors, and not the design. Where experimental investigation is not possible, the results are modelled using equations and existing results.

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Contents

1 Introduction

Open Source Hardware is hardware with a publicly available design, so that anyone can modify, distribute, or study it. This allows other companies to make and sell hardware based on that design. This offers advantages including reducing costs through a competitive market, and faster innovation [1]. Although "open-source" is usually applied to simplistic electronics products with a DIY aspect, there has been a recent evolution towards non-electronic, more complex hardware projects [2]. However, the majority of options available still make use of electronics in some way.

Open Scientific Hardware (OSH) gives countries and institutions with limited funding access to free, open-source hardware for use in research and education. The current market is geared towards large laboratories with large budgets, leaving an uneven distribution of equipment availability around the globe. Although there are initiatives to make science more open and accessible, these are "mostly concentrated on issues that appear before and after experiments are performed: open access journals, open databases, and many other tools to increase reproducibility of science" [3].

OSH makes and releases designs and workarounds in many aspects of scientific equipment. These designs often include electronic components, either ones already available to the consumer such as smartphones, or ones which are easily purchasable, such as Arduino microcontrollers, or simple motors. One particularly expensive, and yet essential, piece of equipment is the scientific microscope. A step by step guide is accessible on the free Instructables website [4] on how to convert a smartphone into a digital microscope with up to 375x magnification. This is sufficient for inspecting cells and imaging blood samples for diagnostics.

Fig. 1. Using a smartphone microscope, taken from Instructables [4]

Another application example is animal testing, which has a requirement for automated feeders. These feeders need to dispense a set amount of food as a reward for completing certain tasks. For less than £200 it is possible to construct a

feeder that works with a variety of animal foods *[5]*. The design uses a stepper motor to dispense single food pellets. Stepper motors can be moved in very fine increments by sending specific pulses, created by a microcontroller. These pulses are similar to those used in servo motors. A servo motor would not be suitable here since it does not have 360 degrees of rotation: the design of the feeder requires a motor that makes a full rotation. A piezo electric sensor confirms correct operation. When the pellet compresses the sensor, it generates an electric charge which is picked up by the control hardware. Food is dispensed when prompted by a serial connection, this control loop is shown in

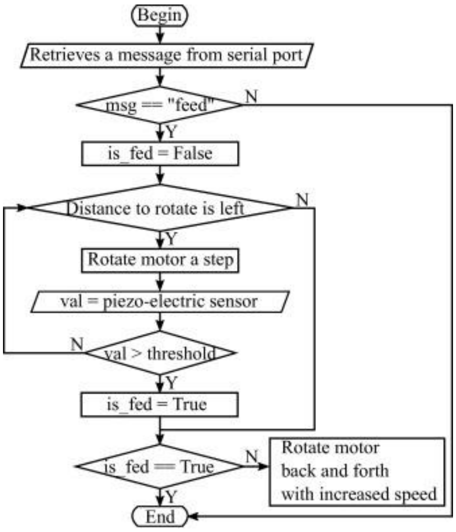

Fig. 2. Flowchart of the 'loop' section of the code controlling the feeder [5].

OSH also deals with heating applications. An open-source Polymerase Chain Reaction (PCR) thermocycler is available for under £500 [6], using a silicon heater mat with an adhesive backing stuck to an aluminium plate. This heater automates the temperature cycling needed to "amplify a single DNA molecule into millions of copies in a short time." [7]. By contrast, a commercial module used in this process can cost upwards of £4,500 [8], this is nine times more expensive, highlighting the relative affordability of OSH. The PCR thermocycler uses thermal paste to transfer heat effectively, and a heat-sync to minimise the heating of unwanted areas; specifically the enclosure, which is made of laser-cut wood, and is therefore susceptible to combustion [9].

Where a PCR thermocycler is an example of a complex use of heating in the lab, there are far more simple examples of heating instrumentation. Two of the most common types are hotplates and water baths.

Water baths are used to hold samples at a constant temperature, either to stimulate a reaction, or to simulate incubation by another organism. The baths used for biological enzymatic applications rarely need to go above 50°C, as any temperature greater than that will leave almost all enzymes denatured. The body's internal temperature is 37°C, and as such for many applications it is useful to be able to hold samples at this temperature. Water baths can be constructed with a large variety of add-ons such as magnetic stirrers or inbuilt test tube racks. The simplest models are 'containers of water that are heated' [10], these can be improved by adding thermometers and electronic controls, allowing a temperature to be set. Even these models have issues, mainly caused by convection, which can 'create non-uniform bath temperatures and, therefore, uneven heating' [10]. A solution to uneven heating is to replace the conventional water bath with a circulating bath, which stirs a container of liquid using an impeller or similar instrument. Shaking baths are also available which, as the name suggests, agitate the whole bath structure, rather than placing an agitator inside the water. These are really only suitable for applications where the sample to be heated has a secure lid. The cost of a small, non-circulating 200 Watt, water bath that relies solely on convection is around £450, an example is shown in Fig. 3 [11].

Fig. 3. A Commercial Water Bath [11].

Hot plates are used in student laboratories, not only because they are smaller than water baths, but also because they have a lower thermal inertia, and are therefore safer than water baths which can be hazardous if they spill or boil dry. Open-source examples of hot plates are also available, although the addition of a magnetic stirrer does add complexity [12]. Hot plates are also used in areas where contamination is an issue. Water baths sit at 37°C for extended periods of time while incubating samples, and even when maintained and cleaned properly, they can become a source of contamination [13]. Hot plates with magnetic stirrers can cost around £400 and have a power rating of around 500W [14]

The main goal for the project is to design a water bath in keeping with the style of OSH. The water bath should be cheaper than those already commercially available and should be able to be constructed by someone with access to a local makerspace, and a good level of computer literacy. In order to make the water bath useful, its target is to heat an amount of water (around 500ml: this keeps the size of the bath small, but still allows test tubes to be heated) up to a temperature that is higher than body temperature (50^{o}C). It should be able to heat water from a tap to the max temperature in around 15 minutes.

The bath should be powered from a normal 230V mains socket. Any laboratory without the resources to purchase a commercial water bath, almost certainly does not have access to a three-phase supply, or something similar which would be present in commercial laboratories.

It is far simpler to send a file electronically than it is to send it conventionally through postal services. Recent advancements in electronically aided distribution and manufacture have made this possible, and there is now a marked increase [15] in the use of rapid prototyping thanks to 3D printing and laser-cutting technologies. The project should make use of these advancements.

2 Methodology

This chapter starts with an outline of the main components of a water bath and explains the selection of components for the project. The heater element is discussed in section 2.1 followed by the sensor, casing, and control in subsequent sections. The chapter then describes the coding of the selected microcontroller, including the control of the selected heater based on input from the selected sensor.

2.1 Heater

When designing a water bath, careful consideration must be given to the type of heater used. The OpenPCR thermocycler uses a kapton resistive heater [6]. The time that a bath takes to heat up is dependent on the power rating of the heater being used. Using equation 1 it can be shown that a heater will need to have a power rating of around 100W to meet the specifications detailed above (being able to heat 500ml of water to 50°C in 15 minutes).

$$P = \frac{4.2 \times V \times \Delta T}{t} \qquad (1)$$

Most electric heaters are constructed from resistive wires, but a balance must be struck between high resistance (the aspect which generates the heat) and allowing current to flow. A heater with infinite resistance would, due to Ohm’s Law, have an infinitely small current flowing through it, therefore no heat would be produced. Nichrome wire has a resistivity of 100Ωm, compared to a normal copper wire, which has a resistivity of between 1.68Ωm and 1.72Ωm, depending on how it has been treated [16]. Nichrome is commonly used to create heating elements because it is stable at high temperatures and has a high melting temperature. It also is a good compromise between resistance and current flow [17].

A multitude of electric heaters is available, each with different benefits. A silicon heater pad has a working life of over ten years [18], and being adhesive and flexible, is very versatile. It is able to fit to curved, uneven, surfaces, and does not require traditional mechanical fasteners, such as screws, to remain in place. However, the only mats that have a suitable power rating (>100W) have a large footprint (100mm x 150mm), making them unsuitable for small applications.

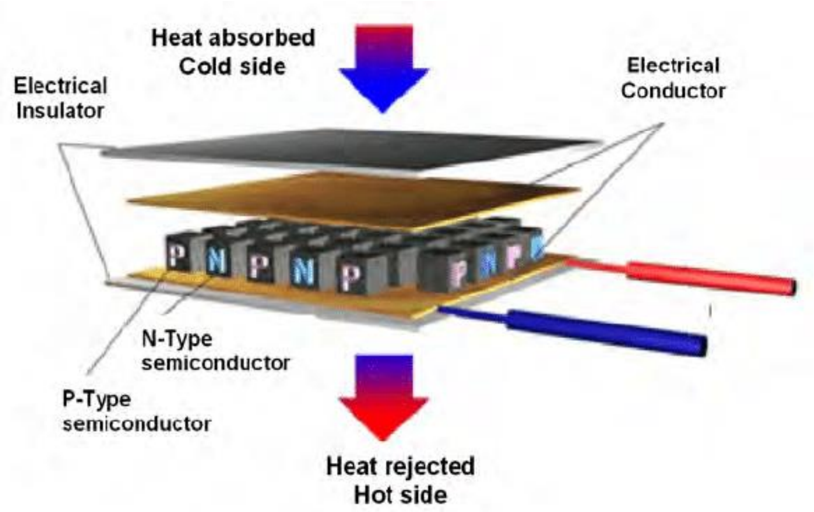

Fig. 4. Diagram of a Peltier module working as a refrigerator, taken from Heat Exchangers – Basic Design Applications [19].

Peltier modules use a p-n junction to generate heat. This makes use of the Peltier effect, discovered in 1834 by Jean Peltier. As electrons move from the n-type material to the p-type material they drop to a lower energy state, releasing energy (in this case heat) into the surrounding area. How much heat is transferred is given by the Peltier coefficient π which is calculated using Equation 2. ΔQ_{ab} is the change in heat between two points, and I is the current passed through the material.

$$\pi_{ab}(T) = \frac{\Delta Q_{ab}}{I} \qquad (2)$$

When electrons move in the opposite direction, they move up into a higher energy state, absorbing energy. For this reason, Peltier modules have both a hot and cold area, and therefore would only be suitable for this application if the water were pumped over the hot portion of the module. For full submersion, as is required in a non-circulating bath, the Peltier heater would heat and cool the water equally, rendering it ineffective.

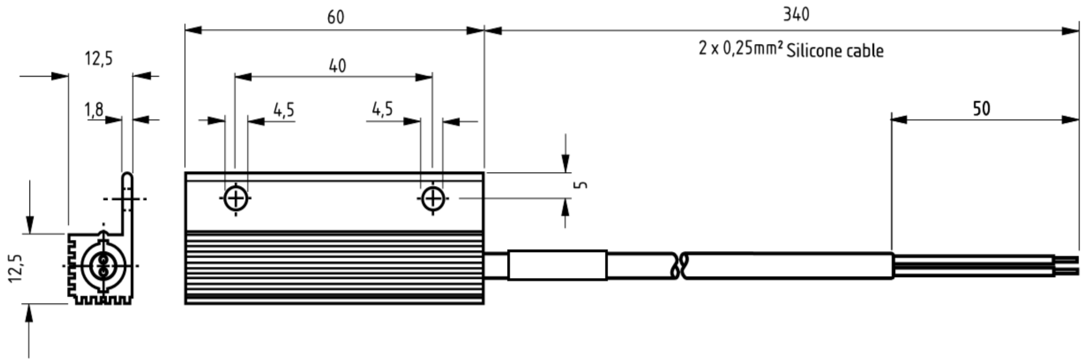

Fig. 5. Diagram of an Enclosure Heating Element (distances in mm), taken from RS Components Ltd [20].

Table 1. Enclosure Heating Element Power Ratings, taken from RS Components Ltd. [18] .

Art. No.	Power (approx) at 20°C	Surface temperature (approx)
01602.0-00	8W *	150 °C
01602.0-04	3W *	75 °C
01602.0-05	3W **	85 °C
01609.0-00	10W *	155 °C
01609.0-01	5W **	120 °C
01610.0-00	13W *	170 °C
01610.0-01	10W **	150 °C
01610.0-04	3W *	68 °C
01610.0-05	4W **	75 °C
01610.0-06	7W *	110 °C
01610.0-07	8W **	110 °C

Enclosure heating elements are another option, since they are fully submersible, removing the need to conduct the heat through the walls of the water bath. Although usually used to protect vulnerable areas (such as computer servers) against condensation [21] they could also be repurposed to heat liquids directly. Unfortunately, although the element's size is small enough to be discrete when in the bath (Fig. 5), there does not exist a model with a large enough power rating (>100W) to heat water sufficiently quickly (Table 1). Furthermore, a submersible heater would be in danger of being directly in contact with a sample tube, transferring more heat than is required to the tube, rather than allowing the water to heat the sample evenly.

Flat plate mica heaters are "used when heat is needed on a flat surface, but when it is impractical to bore a hole in the plate" [22], this makes them highly desirable for a water bath as drilling a hole, without sealing it, would be detrimental to the bath's operation. They are also low-cost and have a high-power output [22] for a relatively small footprint (60mmx60mm) . For these reasons, a flat plate mica heater (RS Stock Number 790-4827 [22]) was chosen for the project.

2.2 Sensor

The other major component of a water bath is the temperature sensor. Without the temperature sensor there would be no way to determine when the required temperature had been reached. There are two different types of temperature sensor; the first is a thermistor, which can have either a Positive Temperature Coefficient (PTC), or a Negative Temperature Coefficient. (NTC). NTC thermistors decrease in resistance as temperature increases, they are the most common type of thermistor [23], whereas a PTC thermistor increases in resistance as the temperature increases. Thermistors do not have a suitable range of temperatures for which they are accurate [23]. For this reason, they cannot be used to sense the temperature of the water bath.

The second type is a Platinum resistance Temperature (PT) sensor. These have a greater range of temperatures for which they are responsive, and always increase in resistance with temperature [24]. PT sensors have a set resistance at 0°C, either 100Ω or 1000Ω, hence the two varieties of PT sensor, PT100 and PT1000. This set resistance then increases as the temperature increases above 0°C.

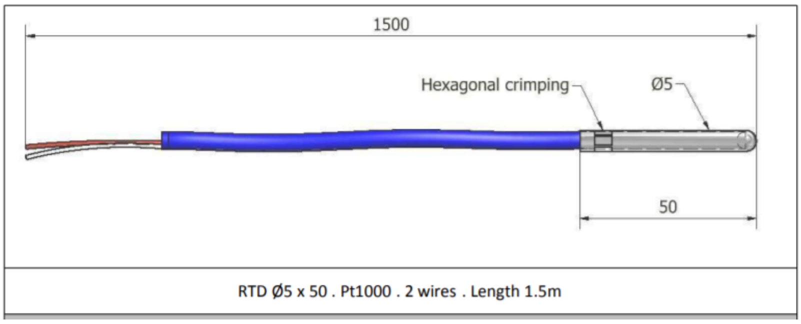

Fig. 6. A PT1000 Sensor, dimensions in mm, taken from RS Components [25].

PT sensors come in three different configurations; two-, three-, and four-wire. The conclusion reached by Inst Tools [26] is that two-wire sensors only work when the leads connected to them are short (< 30 metres), and when they are held in an environment with a constant temperature (because of the effect these factors have on the resistance of the metal in the wire). So long as the leads are short (< 30 metres), and held at a constant temperature, they should perform just as well as three-wire sensors. The third wire is a grounding wire which eliminates the lead wire resistance effect. If the effect is not present, then the third wire is not required. The lead wire resistance effect occurs because of the differences between copper and platinum when it comes to resistance changing with temperature, the longer the wire, the more the effect is visible. A four-wire configuration can be discounted immediately as being too expensive and complex for this application. Four-wire configurations are only used for precise (0.5°C [27]) temperature control in industry. Because of the PTs increased range of sensitivity in comparison to a thermistor, and because the wires connected to the sensor are short, and are held at a constant temperature, the decision was taken to use a two-wire PT1000 sensor (RS Stock No. 869-8399 [25]) . The OpenPCR Thermocycler uses a thermistor directly embedded inside the block which receives heat. It is secured using a ‘thermally conductive and yet electrically insulating epoxy’ [6]. The Thermocycler is controlled using an Arduino Uno, and displays its status using a 4x20 character LCD.

2.3 Control

Most water baths use a microcontroller to monitor the user’s inputs, to display the current temperature, and to control the heating of the water. The Arduino IDE (Integrated Development Environment) has a wide range of support materials and libraries available [28]. For a project that is designed to be universally accessible, a universally used language such as Arduino is very suitable. The Arduino Mega has 54 digital I/O pins, 16 analogue inputs, and hardware based on the ATmega2560 [29]. This means it can export data to an LCD screen, and receive multiple inputs, and still have ports left over for expansion. The analogue inputs can accurately measure an incoming voltage which can then be used to measure the temperature of the water in the bath. The project uses an Arduino Mega [29].

The project work started by placing the PT1000 sensor in a potential divider (
Fig. 7) with a 1kΩ resistor, and then measuring the output voltage in relation to the known input voltage, it is then possible to convert voltage to resistance using equation 3. From there resistance is converted to temperature using lookup tables provided with the sensor [30].

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2} \qquad (3)$$

Using a resistor with a similar resistance to the sensor will improve the accuracy, since there will be a greater change in voltage for a given change in resistance.

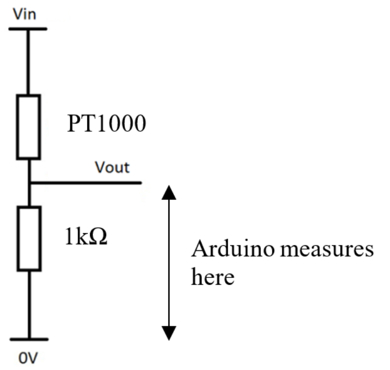

Fig. 7. A Circuit Diagram of the Potential Divider Circuit

The control for the heater is based on a simple hysteresis controller. While the required temperature has not been reached, the heater is turned on. Once the water is at the pre-set temperature the heater is turned off. After the temperature decreases (because of heat loss to the surroundings), the heater is turned back on.

The rest of the code for the control of the water bath is shown in Appendix B and consists of five functions. *setup()* handles the administration of pin assignments and variable construction. *calculateResistance()* takes the input voltage from the PT1000 potential divider and converts it into a resistance using Equation 3. *temperatureConvert()* takes that resistance and uses equations constructed in MATLAB (Appendix C) to convert it to a temperature. The MATLAB equations remove the need for the PT1000 lookup table (Appendix A) (which takes up memory on the Arduino), and instead convert the table values into sets of linear equations. These equations can then be used to change a resistance value into a temperature reading. *getTemperature()* is the function that handles all user inputs and is only called on the first iteration of the code. The whole *getTemperature()* function runs inside a 'while' loop which is constantly checking whether the 'confirm' button has been pressed. The same result could be achieved using interrupts, but this method makes the code more readable. So long as the 'confirm' button isn't pressed, the user can adjust the required temperature using the 'increase' and 'decrease' buttons. Pressing these buttons changes a variable which in turn is broadcast to the serial monitor, and the LCD screen, shown in Fig. 8 .

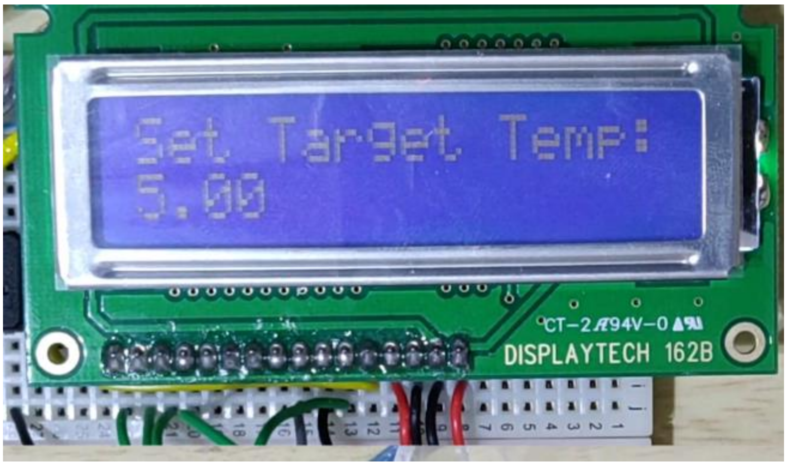

Fig. 8. The User's Current Requested Temperature Displayed on the LCD Screen

Once the ‘confirm’ button is pressed, the final chosen value of the variable is passed back to the main code block, and the function exits. *loop()* can be considered as the main code block. This code loops continuously and calls all the other functions. It first reads the resistance of the PT1000, then converts that resistance to a temperature. This temperature is displayed on the LCD, along with the target temperature. These two temperatures are then compared. If the measured temperature is lower than the target temperature, the relay controlling the heater is turned on. If the measured temperature is higher than the target temperature, the relay is turned off. This is basic, discontinuous hysteresis, or ‘bang-bang’ control [31].

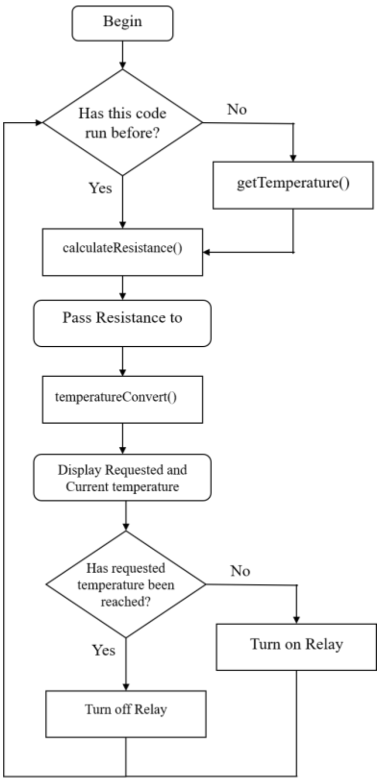

Fig. 9. A Flowchart of the Code Controlling the Water Bath

2.4 Casing

The casing for the bath must be waterproof, and yet portable, it must also be able to transfer heat, because of the many requirements for the casing material, a combination of materials will be used.

Because of the need to transfer heat through the casing of the bath, a metal plate must be added into the base. For the construction of the bath, the only advantage of 3D printing over laser-cutting would be its guaranteed waterproofing. To add a metal plate, a hole must be added in the bottom of the bath, removing any advantages gained by 3D printing parts. While a single piece of 3D-printed plastic is more durable than individual pieces of laser-cut acrylic; 3D printing still takes longer than laser cutting, which can be completed in a matter of minutes. Both methods are usually accessible in a local makerspace. For these reasons, there is no reason to 3D print the enclosure, and so the enclosure of the bath is constructed from pieces of laser-cut acrylic, attached together using a chemical bonding agent (Fig. 10).

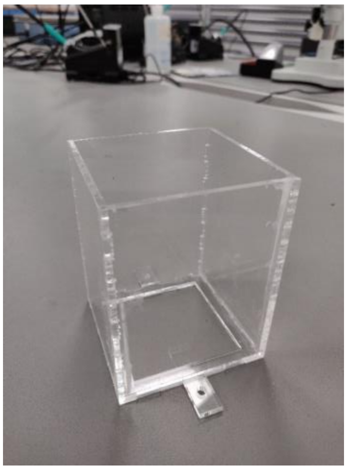

Fig. 10. The bath casing, without the metal base plate. 80mmx80mmx105mm

The metal which will be used to seal the base of the bath, and to conduct the heat into the water, must be able to withstand constant contact with water without corroding and must be able to conduct heat well. In addition to these two practical requirements, the cost of the metal must be considered, not to mention its workability. A soft, malleable metal would not be a good choice if it were required to provide structural support. Table 2 shows the thermal conductivities of some metals.

Table 2. The Thermal Conductivity (k) of Various Metals) [32].

Metal	k
Silver	4.29
Copper	4.01
Aluminium	2.37
Copper Brass	1.11
Iron	0.73
Carbon Steel	0.51
Stainless Steel	0.16

From Table 2, it can be concluded that the heating plate should be made of silver, copper, or aluminium. Silver can be immediately discounted because of its cost. A 250mm^2 sheet of 0.9mm copper costs £21.98 [33], whereas the same size and thickness of aluminium costs just £7.47 [34]. Therefore, despite its inferior heat conducting ability, in keeping with the accessible nature of the project, 2mm aluminium plate will be used for the base of the bath, 2mm plate was chosen because of its relative abundance in makerspaces, demonstrated by its presence in the B59 workshop at the university.

3 Results and Discussion

This chapter covers the methods used to construct the bath, and the measurements taken to assess its quality. Section 3.1 details the casing construction, and the delivery of power to the heater. Section 3.2 gives the results taken for a dry heater powered with 60V, the results for tests involving water and at lower voltages follow.

3.1 Water Bath Construction

When the whole system was put together; the acrylic was bonded using the Anglosol 1200 solvent [35] to fuse the plastic together, creating a watertight seal. The metal plate was then bonded to the bottom of the bath enclosure using a two-part epoxy. The bath section was attached to the base of the enclosure using two bolts which passed through the protruding tabs shown on opposite sides of the bath in Fig. 10. These bolts were also used to sandwich the mica heater into the gap between the metal plate and the top of the lower enclosure. When the bolts are tight, the heater is in contact with the metal plate and transfers heat to it.

The circuit containing the temperature sensor was soldered to stripboard, as was the circuit containing the relay which controls the mains supply going to the heater. This is enclosed in a separate box for safety (Fig. 11). This box is enclosed on both sides by waterproof wire lug nuts and all of the wires coming in and out are screwed into fixings which are in turn soldered into the stripboard. This reduces the chance of the live wire touching either neutral or earth and causing a short circuit or damaging a component.

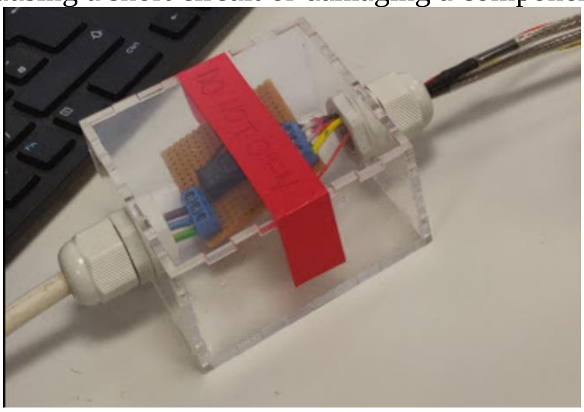

Fig. 11. The relay box, isolating any wires carrying mains voltage.

As the container which encloses the heater is predominantly acrylic, which has a melting point of 160°C [36], it is not possible to send a voltage of 230V to the heater. A voltage that high will generate the heater's maximum power, which raises its surface temperature to 260°C [22], and will melt the casing. The solution to this problem is to send less than the full 230V AC (Alternating Current) to the heater. To accomplish this, an autotransformer, or Variac is used. Shown below in Fig. 12, the Variac consists of a single winding as opposed to the normal two and is therefore used where AC voltages must be quickly varied without changing the input voltage.

Fig. 12. A Variac autotransformer set to output 60V AC.

3.2 Dry Plate Measurements (60V)

Through careful consultation with laboratory technicians and persons responsible for project safety, it was decided that 60V was the maximum voltage allowed to be passed to the mica heater. This, as shown in Fig. 13, means that the heater can reach a maximum temperature of 57°C. Fig. 13 shows the average (taken from 3 repeats which are shown in Fig. 14) heating curve of a dry metal plate at 60V AC. All measurements in this project were taken at 30 second intervals.

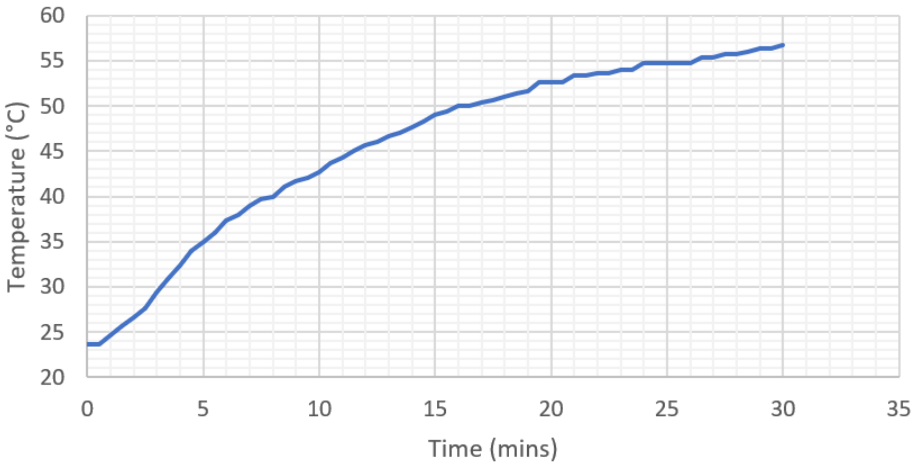

Fig. 13. An average of temperature vs. time for a dry plate at 60V AC, taken from 3 repeats.

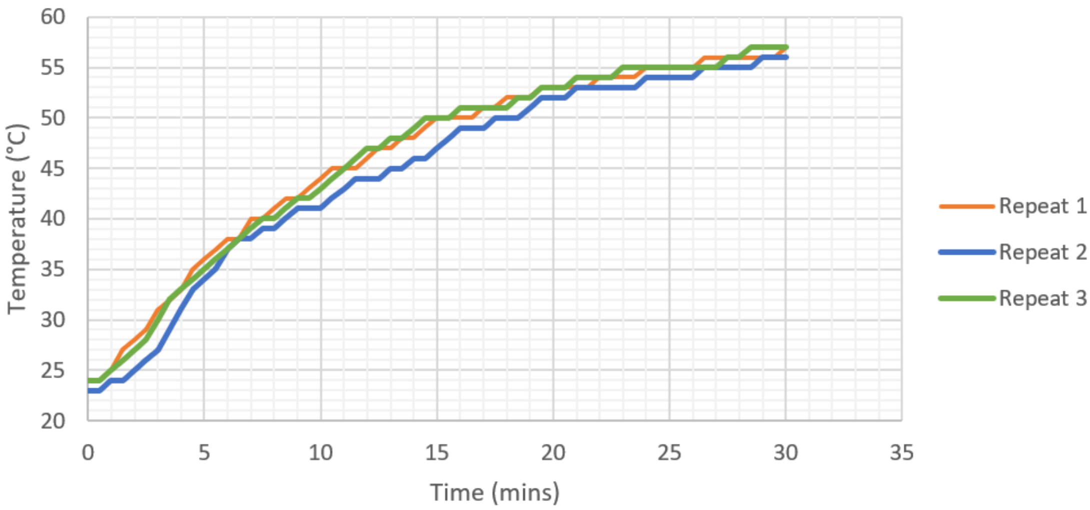

Fig. 14. All measurements taken to produce Fig. 13.

As a result, the final assembled system (Fig. 15) does not meet the original specifications detailed at the end of section one. It was decided to continue with taking measurements at different voltages for both the bare heater, and the constructed and filled bath. This was due to the increased complications that would be introduced in order to test the bath safely at full voltages, such as the need for a metal casing, and a moulded plastic inner layer to hold the water,

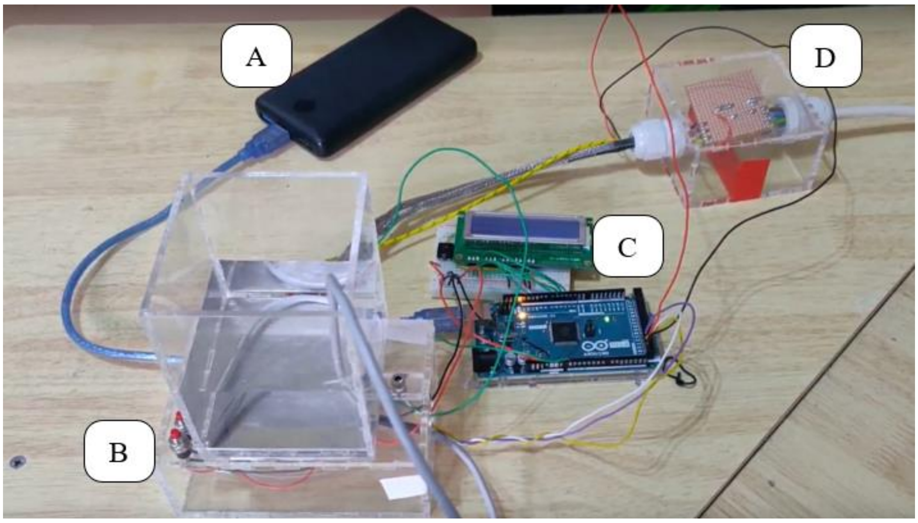

Fig. 15. The system constructed and operational. A: Power Supply. B: Water bath with sensor. C: Arduino and LCD. D: Heater Relay.

From the graphs shown above in Fig. 13 and Fig. 14 we can see that the temperature of the metal plate with no water present initially rises linearly (between zero and five minutes) with time. This quickly becomes a curve as the temperature increases, this is due to heat lost to the surroundings, and a decreased temperature gradient between the metal plate and the mica heater. This can be demonstrated using Equation 4

$$Q = \left(\frac{k}{s}\right) A(T_1 - T_2) \qquad (4)$$

Where Q is heat transfer, k is the thermal conductivity of the material, s is the material thickness, A is the area of heat transfer, and T_1 and T_2 are the two temperatures used to calculate the temperature gradient in the material. All elements are measured in their standard SI units. As the temperature gradient decreases, the heat transfer also decreases, since all other aspects of Equation 4 are constant. This means that as the metal plate approaches the maximum temperature of the heater, the heat transfer becomes slower, and heat loss to the surrounding becomes a larger problem. These factors combined contribute to a slower heating time, and as a result the curves shown above in Fig. 13 and Fig. 14 decrease in gradient as they increase in temperature.

Fig. 16 shows the experimental set-up for measuring the dry plate temperature. An external thermistor-based temperature sensor (A) was used as the PT1000 sensor was unable to measure the temperature of the plate accurately because of its bulky waterproof collar.

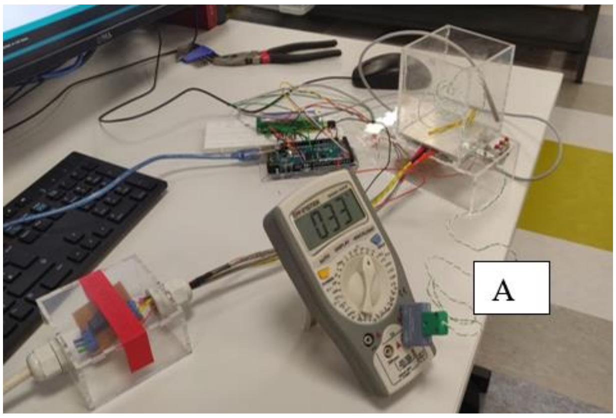

Fig. 16. The experimental set up for measuring the dry plate. An external temperature sensor (A) was taped to the plate because the PT1000 sensor was not able to measure the dry plate temperature accurately.

3.3 Measurements for 0.12 Litres of Water (60V)

Fig. 17 and Fig. 18 show the graphs of temperature vs. time for the bath when it contained 0.12 litres of water. The sensor does not touch the plate in these tests. A volume of 0.12 litres was originally intended to act purely as a benchmark, and as a test to investigate the approximate time to heat the full bath. However, the early closure of the B16 laboratory caused by the COVID-19 pandemic did not allow for a full test of the bath, and therefore results taken for this volume of water are the only ones available for analysis.

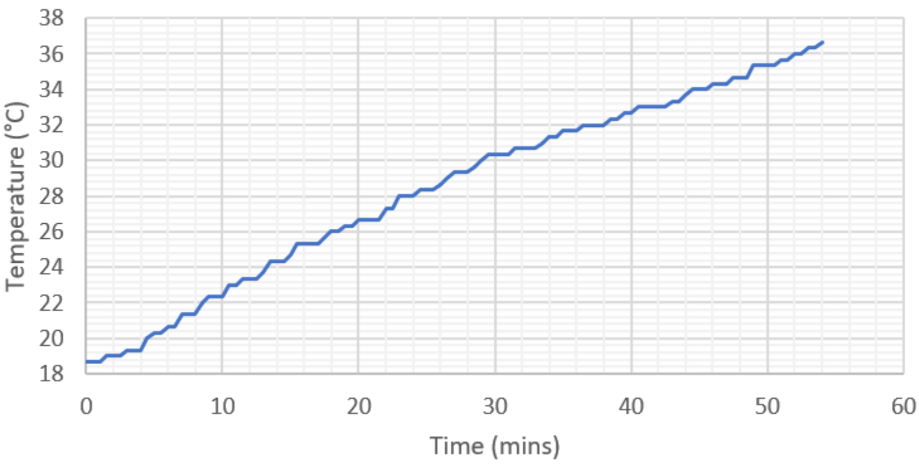

Fig. 17. An average of temperature vs. time for 0.12 litres of water at 60V AC, taken from 3 repeats.

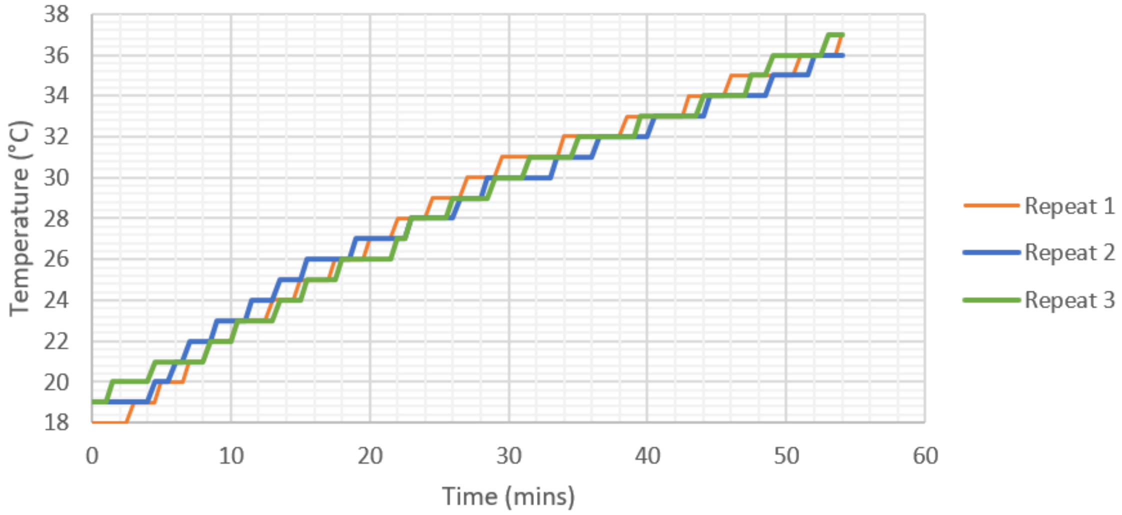

Fig. 18. All measurements taken to produce Fig. 17.

In the same amount of time as for the dry test, the bath only increased to approximately half of the temperature change achieved when measuring the dry metal plate. This is due not only to a change in thermal resistance (k in Equation 4) but also to an increase in thermal inertia. Thermal inertia is 'the degree of slowness with which the temperature of a body approaches that of its surroundings' [37] and it is why water baths can be considered less safe than hot-plates. Once a water bath is up to temperature, it will remain at that temperature (if turned off) for longer than a hot plate would in identical conditions.

Although the bath takes longer to heat when it contains water, the resulting heating curve is more linear, indicating the heating is more stable. However, the addition of water also increases the opportunity for heat loss, both through the walls of the bath, and from the surface of the water into the air.

Table 3 below shows a direct comparison between the dry and wet measurements at 60V. The maximum temperature reached with the water was not the maximum possible temperature, but rather the maximum temperature reachable in an hour.

Table 3. A Comparison of wet and dry heating at 60V AC, recorded for up to an hour.

	60V AC, Dry Plate	60V AC, 0.12 litres of water
Maximum Temperature Reached	57°C	37°C
Time Taken to Reach Max Temp	30 mins	54 mins

The initial plan for results measurement was to vary both the volume of water in the bath and the voltage supplied to the heater by the Variac autotransformer. However, due to the closure of the B16 project lab, not all these measurements were completed. Table 4 shows both the intended measurements, and those which were actually produced before the closure.

Table 4. The impact of B16 Closure on the number of measurements made in the laboratory.

Measurement Type	Results:	Repeats:
Dry Plate, 60V AC	Yes	Yes
Dry Plate, 40V AC	Yes	Yes
Dry Plate, 20V AC	No	N/A
0.12 litres of water, 60V AC	Yes	Yes
0.12 litres of water, 40V AC	Yes	Yes
0.12 litres of water 20V AC	No	N/A
0.5 litres of water, 60V AC	No	N/A
0.5 litres of water, 40V AC	No	N/A
0.5 litres of water, 20V AC	No	N/A
Dry Plate, 40V AC, raised to 60V AC after max temperature is reached	Yes	No
0.12 litres of water, 40V AC, raised to 60V AC after max temperature is reached	No	N/A
0.5 litres of water, 40V AC, raised to 60V AC after max temperature is reached	No	N/A

3.4 Dry Plate Measurements (40V)

It is still possible to compare the results for 60V and 40V. Below, in Fig. 19 and Fig. 20, are the plots of temperature vs. time for the dry aluminium plate at 40V AC.

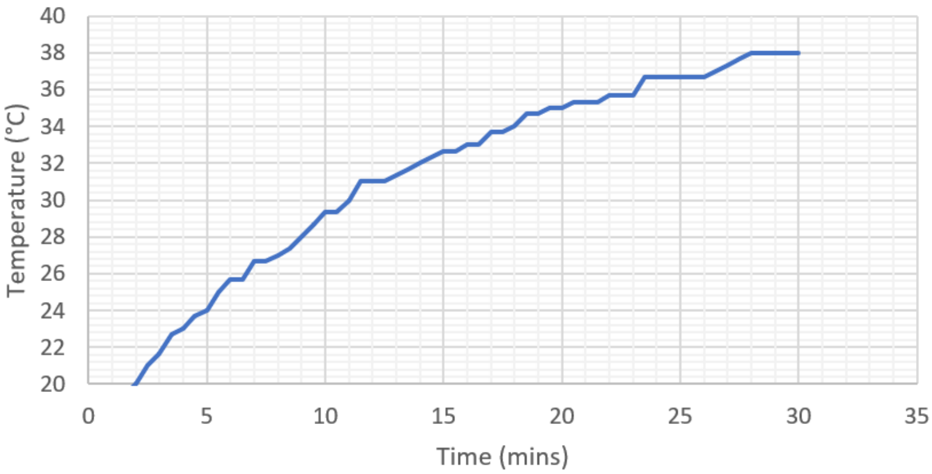

Fig. 19. An average of temperature vs. time for a dry plate at 40V AC, taken from 3 repeats.

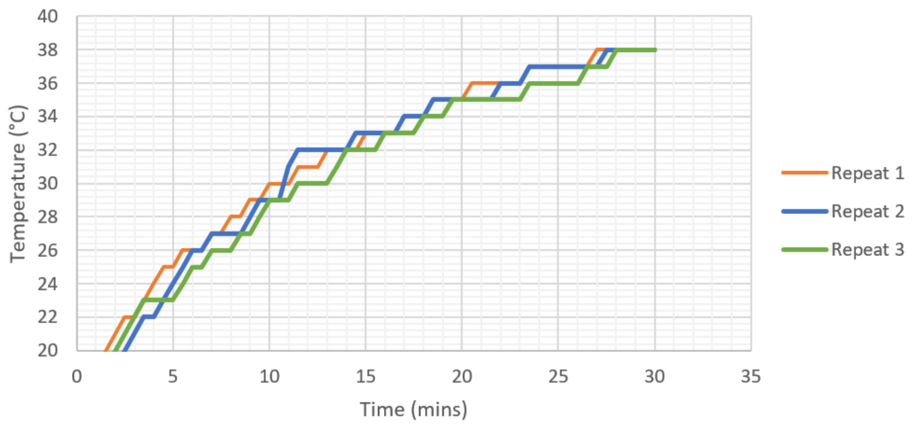

Fig. 20. All measurements taken to produce Fig. 19.

In Fig. 19, it is possible to see that the max temperature had been reached at 28 minutes. The graph has clearly plateaued. This is consistent with the results found for 60V in Fig. 13**.** An input of 60V gives an output temperature of around 60°C, and an input of 40V gives an output of around 40°C. This linear relationship clearly continues up to higher voltages, as the specification for the heater lists its maximum temperature as 260°C with an input voltage of 230V AC [22]. Fig. 21 shows a combination of Fig. 13 and Fig. 19. It compares the average temperature vs. time curve at 60V with the curve at 40V.

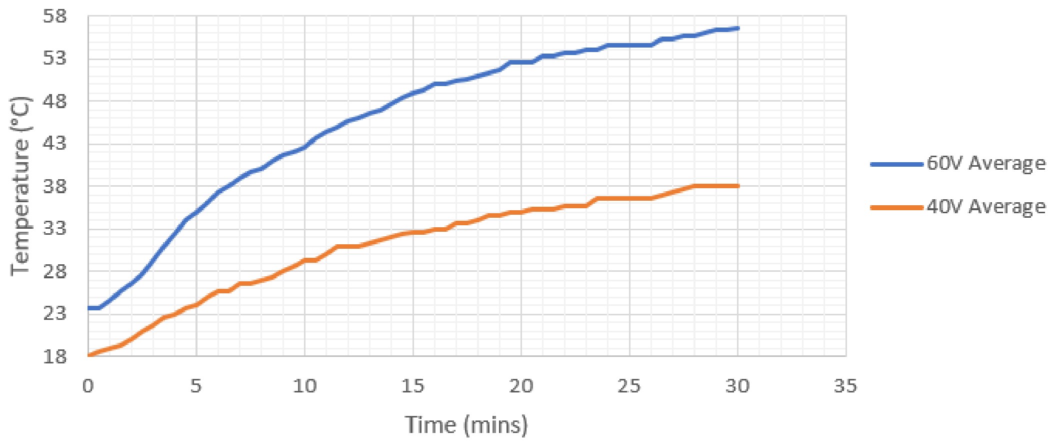

Fig. 21. A comparison of heating curves for 60V and 40V measurements.

The two curves are indicative of what is expected by looking at Equation 4. The increased heat present at 60V provides a faster heat transfer at the start, hence it initially has a steeper gradient than the 40V line. However, once the temperature of the plate approaches that of the heater, the temperature gradient between the two materials is reduced, and so heat is transferred more slowly. This is demonstrated by the decrease in gradient of both lines on the graph as they approach 30 minutes. For one of the repeats taken to achieve Fig. 19, once the maximum temperature was perceived to have been reached, the Variac autotransformer was adjusted so it would supply 60V to the heater. The resulting curve is shown below in Fig. 22. It should be noted that this is a single result, no repeats or averages have been taken.

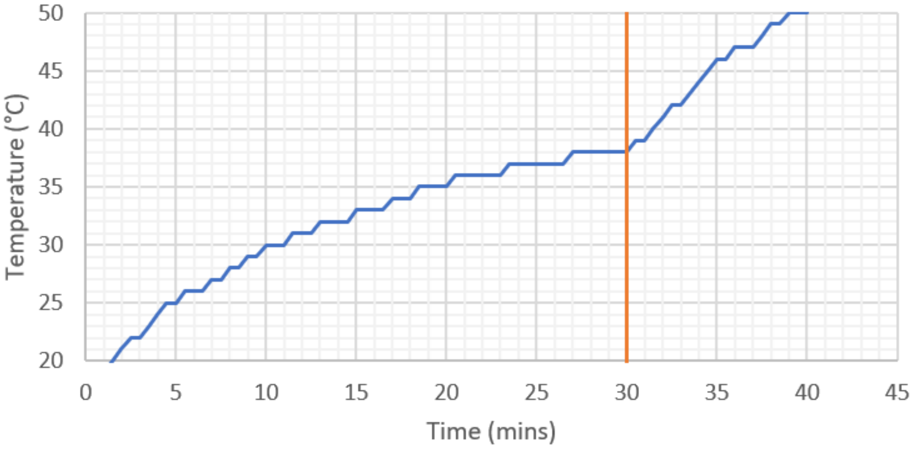

Fig. 22. Temperature vs. time at 40V, increasing to 60V after the vertical line.

This curve once again demonstrates Equation 4. The input voltage was immediately increased by 20V at 30 minutes, and as a result the heat transfer was increased from,

$$Q = \left(\frac{2.37}{2 \times 10^{-3}}\right)(72 \times 10^{-3})^2(40 - 38) = 12.28W$$

to,

$$Q = \left(\frac{2.37}{2 \times 10^{-3}}\right)(72 \times 10^{-3})^2(60 - 38) = 135.15W$$

This increase in Q underpins the clear increase in gradient of the graph at the 30-minute point.

3.5 Measurements for 0.12 Litres of Water (40V)

The problems encountered with increased thermal inertia can again be seen in Fig. 23 and Fig. 24 below.

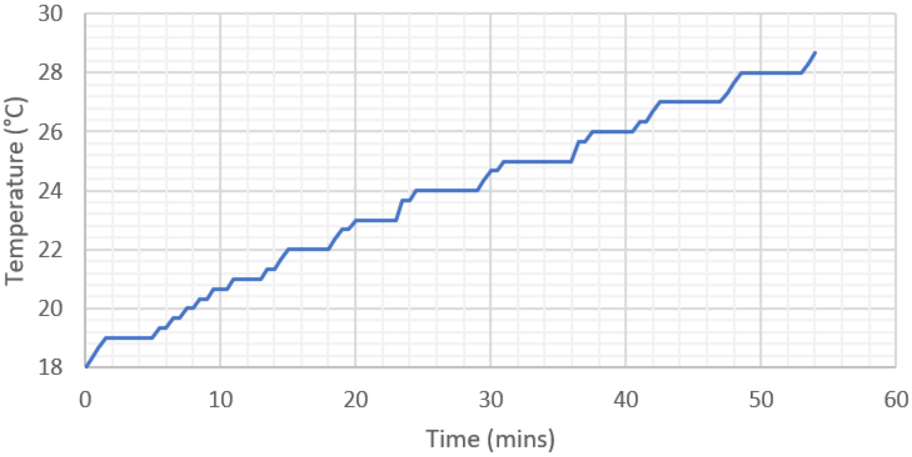

Fig. 23. An average of temperature vs. time for 0.12 litres of water at 40V, taken from 3 repeats.

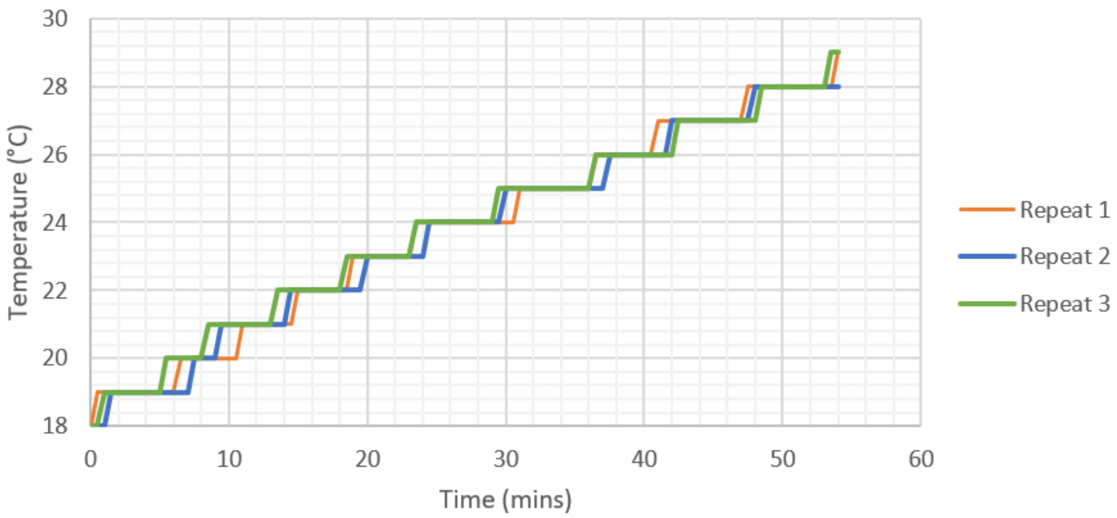

Fig. 24. All measurements taken to produce Fig. 23.

In 54 minutes, the temperature did not reach the minimum required temperature of 37°C. Therefore, 40V is not enough power to heat even a small amount of water. As can be seen in the comparison between 60V and 40V (Fig. 25), although the 60V average did eventually reach a useful temperature, a hotter plate (with more than 60V available to power it), would have heated the water much more effectively.

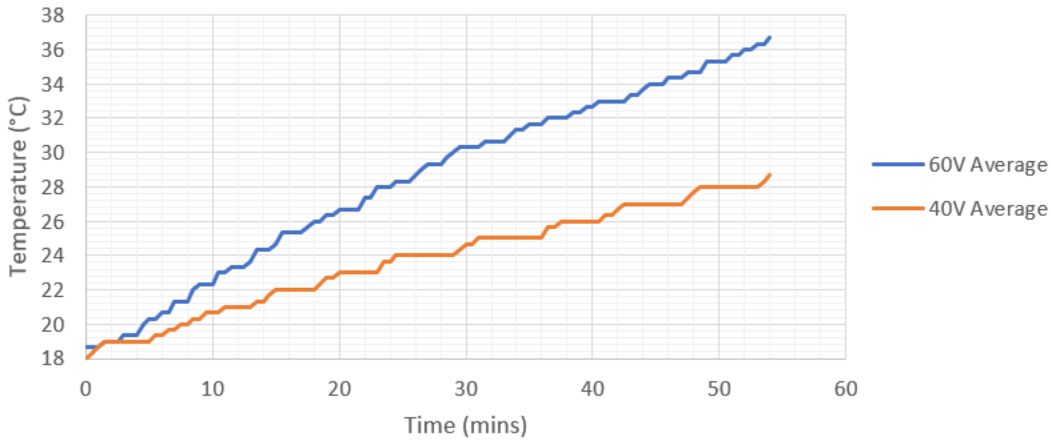

Fig. 25. A comparison of averages taken for 0.12 litres of water at 60V and 40V

Using the results taken for 60V, and Equation 1, the efficiency of the heat transfer between the heater and the water can be estimated. There are many sources of loss; heat lost from the water surface, through the bath walls, and into the enclosure holding the heater. Using Equation 1 the power transferred to the water at 60V can be calculated.

$$P = \frac{4.2 \times 0.12 \times (36.67 - 18.67)}{54 \times 60}$$

$$P = 2.8 \times 10^{-3}\ kW$$

$$P = 2.8\ W$$

2.8 W is a small amount of power. The mica heater has a power rating of 100W, at 230V, so with only 60V available, it follows that the adjusted power rating would be 26W:

$$P = \frac{60}{230} \times 100 = 26.1\,W\ (3\ significant\ figures)$$

Therefore, the percentage of power available from the heater that is transferred to the heater is:

$$P_{transferred} = \frac{2.8}{26.1} \times 100 = 10.7\%\ (3. s. f.)$$

It can then be extrapolated from this that with a full 100W available, the heater would transfer 10.7W to the water. For 0.12 litres of water, at full voltage, the time taken to heat from 18°C to 37°C is calculated below using a rearranged version of Equation 1.

$$t = \frac{4.2\ \times\ V \times \Delta\mathrm{T}}{P}$$

$$t = \frac{4.2\ \times\ 0.12 \times (37 - 18)}{10.7 \times 10^{-3}}$$

$$t = 891\ secs$$

$$t = 14\ mins\ 52\ secs$$

This model shows that for 0.12 litres of water, the water bath heats up to 37°C in a time that is within the original specifications. The next step would be to model the behaviour of the bath for the full 500ml of water, using results taken in the lab. However, since the early closure of the B16 labs removed the opportunity to take the required measurements, this will not be possible and the data that had been collected before has had to suffice.

Instead, using the 40V results for 0.12 litres of water and using Equation 1, the method used above will be repeated to obtain a second estimate for the time taken to heat 0.12 litres of water at full power.

$$P = \frac{4.2\ \times\ 0.12\ \times (28.67 - 18)}{54 \times 60}$$

$$P = 1.66 \times 10^{-3}\ kW\ (3\ s. f.)$$

$$P = 1.66\ W$$

As expected, with a smaller temperature change in the same time, a lower amount of power has been transferred.

$$P = \frac{40}{230} \times 100 = 17.4\,W\ (3.s.f.)$$

With a total of 17.4 Watts available, around 16 Watts of power is being lost to the surroundings.

$$P_{transferred} = \frac{1.66}{17.4} \times 100 = 9.55\%\ (3.s.f.)$$

Again, with a full 100W, 9.55% of 100 (9.55) Watts will be transferred.

$$t = \frac{4.2\ \times\ V \times \Delta\mathrm{T}}{P}$$

$$t = \frac{4.2\ \times\ 0.12 \times (37 - 18)}{9.55 \times 10^{-3}}$$

$$t =\ 1002\ secs$$

$$t = 16\ mins\ 43\ secs$$

Using the results from 40V, the modelled extrapolation predicts that the heater would take over 16 minutes to reach 37°C, slightly outside the pre-set specifications. The result is also different to the one found using the 60V data. This is due to the increased effect of heat loss on a lower power heater. This increased heat loss factor is then transferred up through the model until it affects the results for a predicted 230V heater. This increased effect of heat loss will also affect the 60V data, and therefore it is probable that the model is over-estimating the time required to heat the water, and in fact a full test at 230V would reveal a heating time of less than the predicted 14 minutes and 52 seconds.

4 Conclusions

A water bath was assembled from laser cut acrylic, a flat plate mica heater [22], and a PT1000 sensor [25]. Heat versus time data was obtained in the absence and presence of water. With water, the temperature increased from 19°C to 37°C in 57 minutes. This was outside the original specifications; however, this is due to the limitations of the heating element, specifically its requirement for unsafe levels of AC voltages (above 60V). In hindsight, given a wider range of more specialist suppliers, it may have been possible to find a more suitable heating element, such as one powered by DC voltage.

The total cost of hardware (Appendix D) shows that this bath is over four times cheaper than other baths [11] and, by creating the bath using only tools available in the university's workshops it can be concluded that maintaining the accessible and open-source nature of the project was a success. Many other conclusions can also be drawn from this experience, as well as multiple ideas for how to improve the design.

Given more time, including the time lost during the B16 lab closure, there are some very obvious ways in which to improve the system, the first of which is to add insulation. Currently, around 10% of the heat from the heater is transferred into the water, the remaining 90% is lost to the casing. 50% of the total heat is produced on the 'wrong side' of the heater, meaning it is absorbed by the bottom of the enclosure. The remaining 40% is lost to the walls of the bath, and then into the surroundings. A layer of insulation around the walls of the bath would not only reduce this heat loss, but would in turn stabilise the bath temperature, less heat loss means a more consistent temperature. As well as insulation around the bath walls, a reflective surface placed between the bottom of the heater and the enclosure would help to reflect heat back up into the water. A simple piece of aluminium foil would accomplish this and would only add a small cost to the project. Lining all the walls of the bath with aluminium foil would also help since the insulating foil is resistant to corrosion and degradation in water

To improve the connection between the mica heater and the metal plate, the gap between them can be filled with thermal paste. This paste is most commonly used in computer temperature management, and facilitates the transfer of heat between two materials by filling any air gaps which could act as thermal insulation. It is not only thermally conductive but is usually electrically insulating [38]. The electrical insulation will add another layer of protection should the heater become charged with a high voltage due to a fault elsewhere in the system.

The most obvious improvement that can be made is to change the construction material. Acrylic- or in fact any plastic- is unsuitable for a heater this powerful, therefore the bath would have to be constructed using a metal. However, a metal bath is no longer in keeping with the open-source nature of the project. The tools required, such as welders, are not as easy to use as laser cutters. Outside of a university laboratory however, a voltage higher than 60V may be used, providing the heater does not exceed the melting point of the acrylic. This increase in voltage, along with the other improvements detailed in this section, should create a water bath which is inside the original specifications.

The control of the bath is also not ideal, the ‘bang-bang’ control is clunky and basic. A far more elegant control system would be to use a Pulse Width Modulated (PWM) signal. This uses a fast switching signal to turn the relay on and off quickly, reducing the average heat produced by the heater. This does create a clicking sound, which could be eliminated using a solid-state relay [39]. This improvement would have been tested, had there been more laboratory time available.

It should be noted that many of the challenges and issues encountered in this project were encountered because of the requirement that it remain in keeping with the ethos of the Open Scientific Hardware scheme. Any manufacturing technique considered too specialist was out of scope, and although the Variac autotransformer is not a common piece of equipment, its use was mandated for safety reasons during testing. A lower power heater would negate this requirement. Perhaps a compromise between a 100W mica heater and an 8W one can be found. The difficulties encountered in the project may suggest why there are no open-source water baths in any OSH literature.

The Journal of Chemical Education [40] talks about the possibility of using culinary sous vide immersion circulators (Fig. 26) as low-cost water bath alternatives: simply attach the device to any container and it will maintain a constant temperature. However, these are bulky and necessitate large bath volumes.

Fig. 26. A culinary sous-vide machine

Using the progress made during this project; enclosure design, component selection, heater control, and user interaction, coupled with the ideas presented regarding immersion circulators, a purpose-built open source small-scale water bath is a possibility in the near future.

Word Count: 6835 from Introduction to Conclusion (checked in MS Word)

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Appendix A. PT1000 Lookup Table

Temp (°C)	0	1	2	3	4	5	6	7	8	9
-70	723.30	719.30	715.30	711.30	707.30	703.30	699.30	695.30	691.30	687.30
-60	763.30	759.30	755.30	751.30	747.30	743.30	739.30	735.30	731.30	727.30
-50	803.10	799.10	795.10	791.10	787.20	783.20	779.20	775.20	771.20	767.30
-40	842.70	838.70	834.80	830.80	826.90	822.90	818.90	815.00	811.00	807.00
-30	882.20	878.30	874.30	870.40	866.40	862.50	858.50	854.60	850.60	846.70
-20	921.60	917.70	913.70	909.80	905.90	901.90	898.00	894.00	890.10	886.20
-10	960.90	956.90	953.00	949.10	945.20	941.20	937.30	933.40	929.50	925.50
0	1000.00	996.10	992.20	988.30	984.40	980.40	976.50	972.60	968.70	964.80
	0	1	2	3	4	5	6	7	8	9
0	1000.00	1003.90	1007.80	1011.70	1015.60	1019.50	1023.40	1027.30	1031.20	1035.10
10	1039.00	1042.90	1046.80	1050.70	1054.60	1058.50	1062.40	1066.30	1070.20	1074.00
20	1077.90	1081.80	1085.70	1089.60	1093.50	1097.30	1101.20	1105.10	1109.00	1112.90
30	1116.70	1120.60	1124.50	1128.30	1132.20	1136.10	1140.00	1143.80	1147.70	1151.50
40	1155.40	1159.30	1163.10	1167.00	1170.80	1174.70	1178.60	1182.40	1186.30	1190.10
50	1194.00	1197.80	1201.70	1205.50	1209.40	1213.20	1217.10	1220.90	1224.70	1228.60
60	1232.40	1236.30	1240.10	1243.90	1247.80	1251.60	1255.40	1259.30	1263.10	1266.90
70	1270.80	1274.60	1278.40	1282.20	1286.10	1289.90	1293.70	1297.50	1301.30	1305.20
80	1309.00	1312.80	1316.60	1320.40	1324.20	1328.00	1331.80	1335.70	1339.50	1343.30
90	1347.10	1350.90	1354.70	1358.50	1362.30	1366.10	1369.90	1373.70	1377.50	1381.30
100	1385.10	1388.80	1392.60	1396.40	1400.20	1404.00	1407.80	1411.60	1415.40	1419.10
110	1422.90	1426.70	1430.50	1434.30	1438.00	1441.80	1445.60	1449.40	1453.10	1456.90
120	1460.70	1464.40	1468.20	1472.00	1475.70	1479.50	1483.30	1487.00	1490.80	1494.60
130	1498.30	1502.10	1505.80	1509.60	1513.30	1517.10	1520.80	1524.60	1528.30	1532.10
140	1535.80	1539.60	1543.30	1547.10	1550.80	1554.60	1558.30	1562.00	1565.80	1569.50
150	1573.30	1577.00	1580.70	1584.50	1588.20	1591.90	1595.60	1599.40	1603.10	1606.80
160	1610.50	1614.30	1618.00	1621.70	1625.40	1629.10	1632.90	1636.60	1640.30	1644.00
170	1647.70	1651.40	1655.10	1658.90	1662.60	1666.30	1670.00	1673.70	1677.40	1681.10
180	1684.80	1688.50	1692.20	1695.90	1699.60	1703.30	1707.00	1710.70	1714.30	1718.00
190	1721.70	1725.40	1729.10	1732.80	1736.50	1740.20	1743.80	1747.50	1751.20	1754.90
200	1758.60	1762.20	1765.90	1769.60	1773.30	1776.90	1780.60	1784.30	1787.90	1791.60
210	1795.30	1798.90	1802.60	1806.30	1809.90	1813.60	1817.20	1820.90	1824.60	1828.20
220	1831.90	1835.50	1839.20	1842.80	1846.50	1850.10	1853.80	1857.40	1861.10	1864.70
230	1868.40	1872.00	1875.60	1879.30	1882.90	1886.60	1890.20	1893.80	1897.50	1901.10
240	1904.70	1908.40	1912.00	1915.60	1919.20	1922.90	1926.50	1930.10	1933.70	1937.40
250	1941.00	1944.60	1948.20	1951.80	1955.50	1959.10	1962.70	1966.30	1969.90	1973.50
260	1977.10	1980.70	1984.30	1987.90	1991.50	1995.10	1998.70	2002.30	2005.90	2009.50
270	2013.10	2016.70	2020.30	2023.90	2027.50	2031.10	2034.70	2038.30	2041.90	2045.50
280	2049.00	2052.60	2056.20	2059.80	2063.40	2067.00	2070.50	2074.10	2077.70	2081.30
290	2084.80	2088.40	2092.00	2095.60	2099.10	2102.70	2106.30	2109.80	2113.40	2117.00
300	2120.50	2124.10	2127.60	2131.20	2134.80	2138.30	2141.90	2145.40	2149.00	2152.50
310	2156.10	2159.60	2163.20	2166.70	2170.30	2173.80	2177.40	2180.90	2184.40	2188.00
320	2191.50	2195.10	2198.60	2202.10	2205.70	2209.20	2212.70	2216.30	2219.80	2223.30
330	2226.80	2230.40	2233.90	2237.40	2240.90	2244.50	2248.00	2251.50	2255.00	2258.50
340	2262.10	2265.60	2269.10	2272.60	2276.10	2279.60	2283.10	2286.60	2290.20	2293.70
350	2297.20	2300.70	2304.20	2307.70	2311.20	2314.70	2318.20	2321.70	2325.20	2328.70
360	2332.10	2335.60	2339.10	2342.60	2346.10	2349.60	2353.10	2356.60	2360.00	2363.50
370	2367.00	2370.50	2374.00	2377.40	2380.90	2384.40	2387.90	2391.30	2394.80	2398.30
380	2401.80	2405.20	2408.70	2412.20	2415.60	2419.10	2422.60	2426.00	2429.50	2432.90
390	2436.40	2439.90	2443.30	2446.80	2450.20	2453.70	2457.10	2460.60	2464.00	2467.50
400	2470.90	2474.40	2477.80	2481.30	2484.70	2488.10	2491.60	2495.00	2498.50	2501.90
410	2505.30	2508.80	2512.20	2515.60	2519.10	2522.50	2525.90	2529.30	2532.80	2536.20
420	2539.60	2543.00	2546.50	2549.90	2553.30	2556.70	2560.10	2563.50	2567.00	2570.40
430	2573.80	2577.20	2580.60	2584.00	2587.40	2590.80	2594.20	2597.60	2601.00	2604.40
440	2607.80	2611.20	2614.60	2618.00	2621.40	2624.80	2628.20	2631.60	2635.00	2638.40
450	2641.80	2645.20	2648.60	2652.00	2655.30	2658.70	2662.10	2665.50	2668.90	2672.20
460	2675.60	2679.00	2682.40	2685.70	2689.10	2692.50	2695.90	2699.20	2702.60	2706.00
470	2709.30	2712.70	2716.10	2719.40	2722.80	2726.10	2729.50	2732.90	2736.20	2739.60
480	2742.90	2746.30	2749.60	2753.00	2756.30	2759.70	2763.00	2766.40	2769.70	2773.10
490	2776.40	2779.80	2783.10	2786.40	2789.80	2793.10	2796.40	2799.80	2803.10	2806.40
500	2809.80	2813.10	2816.40	2819.80	2823.10	2826.40	2829.70	2833.10	2836.40	2839.70

Appendix B. Arduino Code

```
#include <LiquidCrystal.h>
//Using a 1Kohm resistor because the closer the known resistor is to the measured one, the
//lower the error
int analogPin = 0; //defining Pin0 as the analogPin
int relayPin = 52;//defining Pin52 as the relay+Pin
int rightButton = 50;//defining Pin50 as the right communication button
int centreButton = 48;//defining Pin48 as the centre communication button
int leftButton = 46;//defining Pin46 as the left communication button
int raw = 0; //initialising a variable to store the raw input from Pin0
int Vin = 5; //setting Vin as 5V, if we had used the 3.3V pin, this would be set to 3.3
float Vout = 0; //initialising a high precision variable to hold the result of the voltage calculation
float currentTemperature = 0; //initialising the variable that wil store our output temperature
float R1 = 995; //setting the value of the constant resisitor. Since the one we have used is 1KOhm,
//the value is set to 995 (the value measured by an external Ohmmeter)
float R2 = 0; //initialising our output
float buffer = 0; //initialising a variable to perform a similar function to 'Ans' on a calculator
float userTemperature = 0; //initialising the variable to recieve the inputted temperature

// initialize the lcd library with the numbers of the interface pins
LiquidCrystal lcd(12, 11, 4, 5, 6, 7); //(rs,enable,D4,D5,D6,D7)

void setup() //this code runs once, and is mostly admininstrative
{
  lcd.begin(16, 2 ); // set up the LCD's number of columns and rows:
  Serial.begin(9600);//Open Serial for debugging
  pinMode(relayPin, OUTPUT); // Defines the relay's pin as an output
  pinMode(leftButton, INPUT);// Defines this button pin as an input
  pinMode(centreButton, INPUT);// Defines this button pin as an input
  pinMode(rightButton, INPUT);// Defines this button pin as an input
  digitalWrite(relayPin, LOW);//Safety Feature. The first action taken
  //by the program is to turn off the heater.
}
float calculateResistance () //Function to calculate the resistance of the PT1000
{
  raw = analogRead(analogPin); //Take a reading of the voltage coming into Pin0,
  //since it is an analog pin,it can measure continuous values for voltage, rather than just ON of OFF
  //The analog reading comes in as a 10-bit representation of the voltage, it will need converting later

  if (raw) //Only broadcasts a resistance reading if there is a connection
  {
    buffer = raw * Vin; //Multiply the reading by the known input voltage
    Vout = (buffer) / 1024.0; //Divide that answer by 1024 to convert from the 10-bit
    //representation we got from Pin0
    buffer = (Vin / Vout) - 1; //Divide Vin by Vout and subtract 1 because of the rearrangement of the
    //potential divider equation used here to calculate the value of the unknown resisitor
    R2 = R1 * buffer; //Calculate R2 by multiplying R1 by the 'Ans'
    return R2; //Function outputs the value of the unknown resistor
  }
  else //If there is no PT1000 connected
  {
    while (1)
    { //Print this message to both the serial monitor, and the lcd
      Serial.println("Sensor Error, check connections and try again");
      lcd.autoscroll();
      lcd.print("Sensor Error, check connections and try again");

    }
  }
}
```

```
float temperatureConvert (float R) //Function to convert the resistance into temperature
{
  //using equations calculated in MATLAB, calculate temperature from the measured resistance.

  if (1000 < R <= 1039) // 0 - 10 degrees
  {
    currentTemperature = (0.2564 * R) - 256.4103;
  }
  else if (1039 < R <= 1077.9) // 10 - 20 degrees
  {
    currentTemperature = (0.2569 * R) - 256.9747;
  }
  else if (1077.9 < R <= 1116.7) // 20 - 30 degrees
  {
    currentTemperature = (0.2576 * R) - 257.6846;
  }
  else if (1116.7 < R <= 1155.4) // 30 - 40 degrees
  {
    currentTemperature = (0.2585 * R) - 258.695;
  }
  else if (1155.4 < R <= 1194) // 40 - 50 degrees
  {
    currentTemperature = (0.2592 * R) - 259.4684;
  }
  else if (1194 < R <= 1232.4) // 50 - 60 degrees
  {
    currentTemperature = (0.2602 * R) - 260.7140;
  }
  return currentTemperature;
}
float getTemperature ()// A function to allow the user to input their required temperature
{ //All LCD communications are also sent to the serial interface
  Serial.print("Current Set Temperature is:");
  Serial.println(userTemperature);
  //lcd.clear();
  lcd.print("Set Target Temp:");
  lcd.setCursor(0, 1); //Move to the 2nd Line
  delay(500);
  lcd.print(userTemperature); //Print the temperature currently set by the user
  lcd.setCursor(0, 0); //Move to the 1st line
  delay (500);

  while (digitalRead(centreButton) == LOW) //While the confirm button hasn't been pressed
  {
    while ((digitalRead(centreButton) == LOW) && (digitalRead(rightButton) == LOW) && (digitalRead(leftButton) == LOW))
    {
      //While there are no buttons pressed, do nothing
    }
    if (digitalRead(leftButton) == HIGH) //If the decrease button has been pressed
    {
      userTemperature = userTemperature - 1; //Decrease required temperature
      Serial.print("Current Set Temperature is:");
      Serial.println(userTemperature); //Print the value on the same line
      lcd.clear();
      lcd.print("Set Target Temp:");
      lcd.setCursor(0, 1);
      delay(10);
      lcd.print(userTemperature);
      lcd.setCursor(0, 0);
      delay (300);
    }
```

```
    else if (digitalRead(rightButton) == HIGH) //If the increase button is pressed
    {
      userTemperature = userTemperature + 1; //increase required temperature

      Serial.print("Current Set Temperature is:");
      Serial.println(userTemperature); //Print the value on the same linelcd.clear();
      lcd.print("Set Target Temp:");
      lcd.setCursor(0, 1);
      delay(10);
      lcd.print(userTemperature);
      lcd.setCursor(0, 0);
      delay (300);
    }
    else //if the centre 'confirm' button is pressed
    {
      delay(50); //Wait
    }
    //Then exit the function, and pass the selected temperature to the program.


  }

  return userTemperature;
}


void loop() //this code loops continously.

{
  if (userTemperature == 0) //If the loop is on its first iteration
  {
    getTemperature(); //Call the function to ask the user to input a temperature
  }
  calculateResistance(); //Call the function that converts pin0 Voltage to R2 Value

  temperatureConvert(R2); //Pass the value of R2 to the program that converts into temperature
  Serial.print("Target Temp:");
  Serial.println(userTemperature);
  Serial.print("Current Temp: ");
  Serial.println(currentTemperature);

  lcd.clear();
  lcd.print("Target Temp:");
  lcd.setCursor(0, 1);
  lcd.print(userTemperature);
  delay(2000);
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Current Temp: ");
  lcd.setCursor(0, 1);
  lcd.print(currentTemperature);
  lcd.setCursor(0, 0);

  if (userTemperature > currentTemperature) //Simple Bang Bang Hysteresis Control
  {
    digitalWrite(relayPin, HIGH);
  }
  if (userTemperature < currentTemperature)
  {
    digitalWrite(relayPin, LOW);
  }
  delay(2000);
}
```

Appendix C. MATLAB Code

TemperatureEquationFinder.m

```
%Create 2 arrays per 10 degree section with points at 1 degree intervals

x1=[1000,1003.9,1007.8,1011.7,1015.6,1019.5,1023.4,1027.3,1031.2,1035.1,1039];
y1=[0,1,2,3,4,5,6,7,8,9,10];
x2=[1039,1042.9,1046.8,1050.7,1054.6,1058.5,1062.4,1066.3,1070.2,1074,1077.9];
y2=[10,11,12,13,14,15,16,17,18,19,20];
x3=[1077.9,1081.8,1085.7,1089.6,1093.5,1097.3,1101.2,1105.1,1109,1112.9,1116.7];
y3=[20,21,22,23,24,25,26,27,28,29,30];
x4=[1116.7,1120.6,1124.5,1128.3,1132.2,1136.1,1140,1143.8,1147.7,1151.5,1155.4];
y4=[30,31,32,33,34,35,36,37,38,39,40];
x5=[1155.4,1159.3,1163.1,1167,1170.8,1174.7,1178.6,1182.4,1186.3,1190.1,1194.00];
y5=[40,41,42,43,44,45,46,47,48,49,50];
x6=[1194,1197.8,1201.7,1205.5,1209.4,1213.2,1217.1,1220.9,1224.7,1228.6,1232.4];
y6=[50,51,52,53,54,55,56,57,58,59,60];

%Plot all data points individually, vs. a line of best fit from 0 to 60
%degrees C
X =[x1,x2,x3,x4,x5,x6];
Y =[y1,y2,y3,y4,y5,y6];
xA=[1000,1232.4];
yA=[0,60];
figure(1)
plot (X,Y)
hold on
plot(xA,yA);
hold off
%Plot the datapoints to check all are correct
figure(2)
plot (x1,y1)
hold on
plot(x2,y2)
plot(x3,y3);
plot(x4,y4);
plot(x5,y5);
plot(x6,y6);
hold off

%Produce linear equation coefficients for the 10 degree data groups
p1 = polyfit(x1,y1,1)
p2 = polyfit(x2,y2,1)
p3 = polyfit(x3,y3,1)
p4 = polyfit(x4,y4,1)
p5 = polyfit(x5,y5,1)
p6 = polyfit(x6,y6,1)
```

Appendix D. Hardware Costs

Description	Quantity	Sub-Total
KNITTER-SWITCH Single Pole Single Throw (SPST) Momentary Miniature Push Button Switch, 7.4 (Dia.)mm, Panel Mount, 250V	3	£11.77
Displaytech 162B-CC-BC-3LP Alphanumeric LCD Display, White on Black, 2 Rows by 16 Characters, Transflective	1	£8.30
Omron G6E SPDT Non-Latching Relay PCB Mount, 3V dc Coil, 3A	1	£5.29
Panasonic SPDT Non-Latching Relay PCB Mount, 5V dc Coil, 5A	1	£1.49
Arduino Mega 2560 Rev3 MCU Development Board A000067	1	£35.23
Mica Heater, 60 x 60 mm, 100 W	1	£28.12
RS PRO 2 wire PT1000 Sensor, -20°C min +100°C max, 50mm Probe Length x 5mm Probe Diameter	1	£10.82
	Total	£101.03

Appendix E. Data Archive Contents

```
| | | +---Data Archive
| | | +---CAD
| | | | | ArduinoMega.SLDPRT
| | | | | BathAssembly.SLDASM
| | | | | BathBase.SLDPRT
| | | | | BathBaseSpacer.SLDPRT
| | | | | BathHousingAssemby.SLDASM
| | | | | BathWall.SLDPRT
| | | | | HousingAssembly.SLDASM
| | | | | HousingBase.SLDPRT
| | | | | HousingLongSide.SLDPRT
| | | | | HousingShortSide.SLDPRT
| | | | | HousingShortSideRemovable.SLDPRT
| | | | | HousingTop.SLDPRT
| | | | | MetalPlate.SLDPRT
| | | | | Thumbs.db
| | | | +---60Vbox
| | | | |     60Vbase.DXF
| | | | |     60Vbase.SLDPRT
| | | | |     60Vgrommetside.DXF
| | | | |     60Vgrommetside.SLDPRT
| | | | |     60Vside.DXF
| | | | |     60Vside.SLDPRT
| | | | |     Assem1.SLDASM
| | | | \---LaserCutting
| | | |         BathBase.DXF
| | | |         BathBaseSpacer.DXF
| | | |         BathWall.DXF
| | | |         HousingBase.DXF
| | | |         HousingLongSide.DXF
| | | |         HousingShortSide.DXF
| | | |         HousingShortSideRemovable.DXF
| | | |         HousingTop.DXF
| | | +---Code
| | | | +---Arduino
| | | | | +---LCD_Test
| | | | | | |     LCD_Test.ino
| | | | | +---V1simpleOhmmeter
| | | | | | |     V1simpleOhmmeter.ino
| | | | | +---V2introduceFunctions
| | | | | | |     V2introduceFunctions.ino
| | | | | +---V3inputTemperature
| | | | | | |     V3inputTemperature.ino
| | | | | +---V4addRelay
| | | | | | |     V4addRelay.ino
| | | | | +---V5addButtons
| | | | | | |     V5addButtons.ino
| | | | | +---V6addPWM
| | | | | | |     V6addPWM.ino
| | | | | +---V6buttonImprovements
| | | | | | |     V6buttonImprovements.ino
| | | | | +---V7addLCD
| | | | | | |     V7addLCD.ino
| | | | | +---V8debugLCD
| | | | | | |     V8debugLCD.ino
| | | | | \---V8dserialAndLCD
| | | | |         hs_err_pid7268.log
| | | | |         V8dserialAndLCD.ino|
| | | | \---MATLAB
| | | |         TemperatureEquationFinder.m
| | | \---Heating Data
| | |         Heating Curves Data No Graphs.xlsx
| | |         Heating Curves Data With Graphs.xlsx
| | |         Heating Curves Data.xlsx
```