UNIVERSITY OF MAINE

ECE 403 DESIGN REPORT

Granny-Safe

A Smart Stove Top

Joshua Andrews, Electrical and Computer Engineer

Riley McKay, Electrical Engineer

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Abstract

This report describes the design, construction, and testing of a smart stove, that controls the temperature of a hot plate and includes an automatic shutoff feature. The project is powered by 120VAC mains which is stepped down to 5VDC. A full wave rectifier and DC-DC converter step down the supply to power to the rest of the project. The power supply was specified to output 5V $\pm 5\%$ at 500mA with less than 100mV ripple. A temperature sensor is used to read the temperature of the hot plate and outputs a voltage proportional to the temperature. The microcontroller processes the output of the temperature sensor and sends a signal to the hotplate controller based on the user-entered setpoint. The hotplate controller uses a triac (triode for alternating current) to control the power supplied to the hot plate. Controlled triggering of the triac allows only a portion of each half sine wave of mains power to be supplied to the hot plate, which is adjusted by the microcontroller, to maintain the temperature within $\pm 10°$F of the setpoint temperature. The microcontroller also outputs a signal to enable the alarm if the hot plate remains above 120°F for ten minutes. The project met all specifications and provided safe, precision temperature control of the hot plate.

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1 Introduction

This document describes the design, simulation, and construction of the Granny-Safe project. The Granny-Safe is a smart stove top that allows precision temperature control of a hot plate burner, while incorporating safety features including an audible and visual alarm when the hotplate has been left on for ten minutes. Power to the hot plate is disconnected if the alarm remains active for one minute, by means of an automatic shutoff feature. The Granny-Safe addresses the problem of hot plate dangers as well as accurate temperature control. Similar devices on the market today, such as the iGuardStove, are expensive and use motion sensors in the alarm process, which can be inconvenient. Granny-Safe is meant to be used for in home elderly care and for that reason the project was designed to be low cost, reliable, and easy to operate.

Project specifications are listed in the contract (Appendix A), and summarized here. The project had to meet the specifications in order to be successful. The contract requires a DC to DC voltage converter capable of supplying 5V$\pm$ 5% and at least 500mA with less than 100mV of ripple. The Granny-Safe must maintain a hot plate temperature within 10°F of the set temperature from 150°F to 400°F. Power to the hot plate must be controlled by a 5V input without the use of relays and must be capable of supplying 120VAC and a minimum of 5A. Lastly, the alarm timer is activated when the hotplate temperature exceeds 120°F and will sound if the reset button is not pressed within ten minutes.

In order to demonstrate that the Granny-Safe met specifications, a variety of methods were employed. Oscilloscopes from Barrows Hall were used to prove the power supply specifications, and a multimeter was used to prove the amperage supplied to the hotplate coil. The Adafruit MAX31865 PT100 RTD amplifier was used to confirm the temperature of the coil.

After the introduction of the project, the Granny-Safe is examined thoroughly in the sections below. Section 2 contains a high-level project overview, Section 3 contains an in-depth explanation on design choices. Section 4 details the results of the project, and Section 5 concludes the report.

2 Breakdown

The main goal of the Granny-Safe project was to provide precision temperature control with enhanced safety features for a hot plate burner. To best explain the functioning parts of the project, a high level block diagram is shown below in Figure 1. An explanation of the signal flow follows the diagram. Each block is then detailed with its inputs, outputs, and functionality in the system. The full schematic of the Granny-Safe is provided in Appendix B.

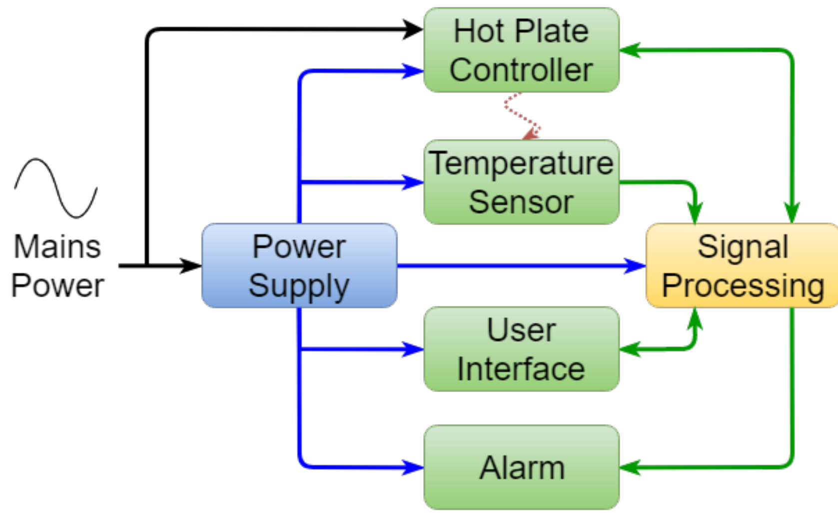

Figure 1: Functional block diagram of the Granny-Safe

As Figure 1 shows, the Granny-Safe is powered by mains power. The power supply then steps down the mains power to a level usable by the project. The hot plate controller is powered by mains and the power supply to regulate the power delivered to a hotplate. The temperature of the hot plate is measured by the temperature sensor and the output is sent to signal processing. Signal processing converts the signal into a temperature and compares it to the set-point entered through the user interface. Based on the comparison, the microcontroller sends a control signal to the hot plate controller to properly regulate the temperature. The user interface allows the user to view the temperature and enter a desired set-point temperature. When certain conditions are exceeded the alarm is triggered and emits an audible and visual alarm. If the alarm is not reset through the user interface, the hot plate controller will disconnect power to the hot plate.

2.1 Power Supply

The power supply in the Granny-Safe provides a 5VDC output capable of supplying at least 500mA, with no additional power sources other than 120VAC mains, to the rest of the project. The power supply uses a step down transformer and full wave rectifier to convert the AC source into a DC value. From there, a buck converter further drops and smooths the DC value to reach the final specified voltage and amperage levels.

2.2 Temperature Sensor

The temperature sensor consists of resistance temperature detector (RTD) to measure the temperature of the hot plate coil. The temperature sensor is powered by the power supply and utilizes an instrumentation amplifier to output a voltage that is proportional to the temperature. The output signal is sent to signal processing, which converts the voltage into a temperature. The temperature is displayed to the user and used to adjust the hot plate temperature as needed.

2.3 Signal Processing

The signal processing for Granny-Safe is provided by an Atmel Atmega328P-PU microcontroller. The microcontroller calculates the temperature based on the data received from the temperature sensor. It also processes and sends data to the user I/O as well as sends a control signal to the alarm circuitry to turn it on or off. The microprocessor takes the user entered setpoint, along with the temperature data and with the use of a proportional-integral-derivative (PID) controller, regulates the signal sent to the hot plate controller to then regulate the temperature of the hot plate.

2.4 Hot Plate Controller

The hot plate controller regulates the hotplate temperature. A zero sensing circuit is used to find the zero crossings of the AC power, at which, a pulse is sent to the microcontroller. The pulse allows an accurate starting point for the delay provided by the PID controller. The pulse sent by the zero sensing circuit is manipulated by the microcontroller by means of the PID controller, which alters the signal based on the differences between expected and actual values. Once the signal has been corrected based on expected and actual values, the triac (triode for altering current) circuit controls the flow of AC power to the hotplate through a BJT acting as an on/off gate. When a signal from the PID controller is sent to the triac, the gate opens and allows AC current to flow, therefore heating the hotplate. The previously described temperature sensor continuously sends the temperature values to the PID controller which keeps comparing the actual temperature to the desired setpoint and adjusts the flow as necessary to maintain the desired temperature.

2.5 User Interface

The user interface enables a user to interact with the hot plate controller. Through the user interface, the user can select at which temperature the hot plate will maintain by utilizing a keypad. The keypad allows the user to enter a set-point which is then displayed above the actual temperature on the LCD screen. If the alarm is activated, the keypad can be used to reset the alarm. A green LED indicates that a setpoint has been entered and a yellow LED indicates that alarm conditions have been met.

2.6 Alarm

The alarm informs the user that the hotplate has remained on for more than ten minutes. The alarm circuitry features a piezoelectric (PZ) speaker and red LED to serve as safety features for the Granny Safe project. The speaker and LED are connected to an input of the microcontroller. When the temperature sensor first records a temperature of 120 degrees Fahrenheit the alarm timer is enabled. After ten minutes the speaker and LED are activated. If the alarm is not reset within one minute, power will be disconnected to the hotplate, the alarm will turn off, and the setpoint will clear. Next each section of the project will be discussed.

3 Details

The design, analysis, theory and simulations conducted to complete the Granny-Safe are discussed in this section. Decisions were made based on previous knowledge and testing, and resulted in iterative revisions of the project until it met all specifications. The Granny-Safe's high level blocks, shown in Figure 1 are discussed, with each broken down into important sub-blocks and discussed at length. Included in Appendix C is a detailed parts list of all parts used in the Granny-Safe.

3.1 Power Supply

The purpose of the power supply is to convert mains power to a level usable by the project. It consists of a step down transformer, a full wave rectifier, and a buck converter. The Granny-Safe required a 5V power supply capable of providing at least 500mA of current. The conversion from 120VAC to 5VDC was a three step process. Firstly, a step down transformer was used to bring the 120VAC down to a more manageable 12VRMS. Second, a bridge rectifier was used to convert this 12VRMS into a usable DC voltage. Finally, a buck converter was used to further drop the voltage and to reach the required value. Further details about the bridge rectifier and buck converter will be discussed below.

3.1.1 Bridge Rectifier

The purpose of a bridge rectifier and transformer is to convert an AC signal into a low-voltage DC voltage. The transformer selected is a 10:1 transformer, dropping the AC voltage from 120VRMS to 12VRMS. The bridge rectifier uses four diodes to create a closed loop that has current paths for each half of the AC sine wave, with two pairs conducting current at a time while the other pair is in reverse bias.

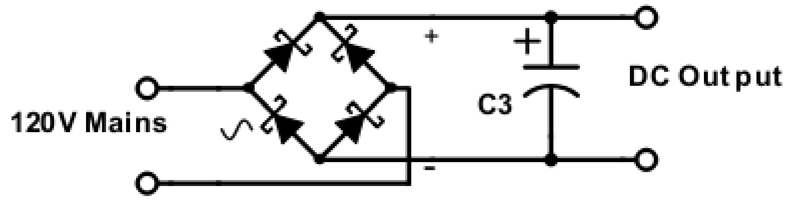

Figure 2: Bridge rectifier topology

As seen in the Figure 4, during the positive half of the sine wave current flows through D2 and D3. D3 provides a path to the buck converter load creating a loop with D2. D4 and D5 are reversed biased. During the negative half of the sine wave, D4 and D5 conduct current with the D2 and D3 are reverse biased. At this point, the rectified signal needs smoothing before it can be used as a DC voltage. The signal can then smoothed by using the capacitor C_3 to help maintain a constant voltage. After researching common bridge rectifier capacitor values, it was decided that values in the micro farad range would be sufficient for this application. Starting at 100μF, the output ripple of the rectifier was tested. By increasing each time by 100F, the ripple improved noticeably until approximately 400μF, then remained consistent for higher values tested. Due to availability of parts, a value of 470μF was chosen as the smoothing capacitor.

To implement the bridge rectifier, schottky diodes were used. Schottky diodes were selected due to their fast switching capabilities, low forward voltage, and adequately high breakdown voltage. In this case, the rectified voltage of 12V was significantly higher than the necessary 5V required, and therefore small losses through the diodes can be ignored. Although other diodes would have been sufficient, there was a negligible price difference between the chosen schottky diodes and other adequate, but not as highly rated diodes.

3.1.2 Buck Converter

Buck converters are a switching regulator used to control output voltages by switching on and off at a set duty cycle. They offer an efficient solution to voltage regulation compared to alternatives such as linear regulators or voltage dividers which lower the voltage by dissipating heat instead of increasing current. Figure 3 below depicts a simplified buck converter.

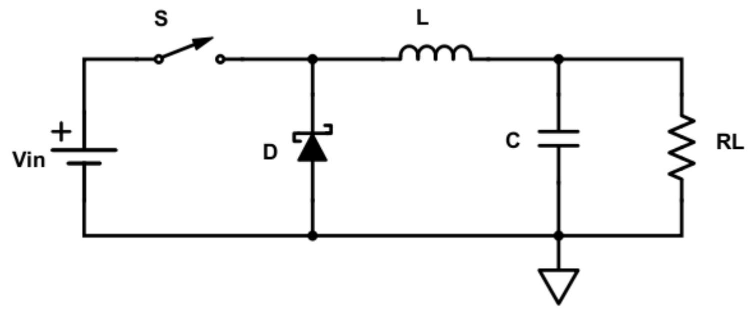

Figure 3: Buck converter topology

When the switch in a buck converter closes, current flows through the switch and the inductor, then through the parallel capacitor and load. Current across the inductor increases with time. The diode is reverse biased and therefore doesn't conduct current. When the switch is open, the capacitor discharges through the load. As this happens, the polarity of the inductor and diode changes. In response to the changing polarity, the inductor discharges current and therefore maintaining the current of the circuit. The diode is now forward biased, and provides a return path. Schottky diodes were selected for this application due to their fast switching capabilities coupled with low forward bias voltages. Low forward voltages and fast switching capabilities help improve the efficiency of the circuit. The fast switching capabilities help eliminate energy lost as the switch opens and closes. If there is any delay in switching between forward and reverse bias as the switch opens and closes, the current will be interrupted resulting in losses.

A TI simple switcher LM2576 was used as a buck converter chip. The LM2576 was selected due to its variable input range, adjustable voltage output, and smoothing qualities. The chip was capable of up to 2A of current, which met the contract specification that the power supply must supply must supply at least 500mA at 5VDC. During the design process, current was not expected to reach 1A. Although the exact current was unknown, 2A capability was thought to be a value that would be sufficiently large.

To find the necessary inductor values for the application, the duty cycle must be calculated first. The equation for the duty cycle of a buck converter is seen below in Equation 1.

$$D = (\frac{V_{\text{out}}}{V_{\text{in}}}) \tag{1}$$

With an input voltage of 17V and a desired output voltage of 5V, a duty cycle of 29% was calculated. With this value in mind, an inductor value is found by using Equation 2.

$$L_{\text{min}} = (\frac{T * V_{\text{out}}}{2 * I_{\text{out}}})(1 - D) \tag{2}$$

Using the duty cycle calculated above and knowing that the LM2576 switches at a frequency of 52KHz, the minimum inductor was calculated to be 210uH. Since the equation was for the minimum inductor value and knowing that standard inductors have up to a 10% variance, a value of 330μH was selected due to part availability.

For the capacitor values, the LM2576 datasheet [1] recommends a capacitor value of at least 470uμF. A 470μF capacitor was tested and resulted in a ripple that was close to the 100mV specification. Since 470μF was the minimum value, 100μF capacitors were added in parallel in an attempt to achieve a better value, but didn't yield a better result. The 100μF were added in parallel instead of using larger capacitors due to available components. After further research and consultation with professors, it was determined that bypass capacitors could be used to lower the ripple to an acceptable level. Referencing Figure 4, C9, C10, and C11 were added to eliminate noise. The values of bypass capacitors generally are a thousand times smaller than the original capacitors so to not interfere with other components. Since this was a general rule, three values of .1μF, 1nF, and 100pF were added to eliminate as much noise as possible.

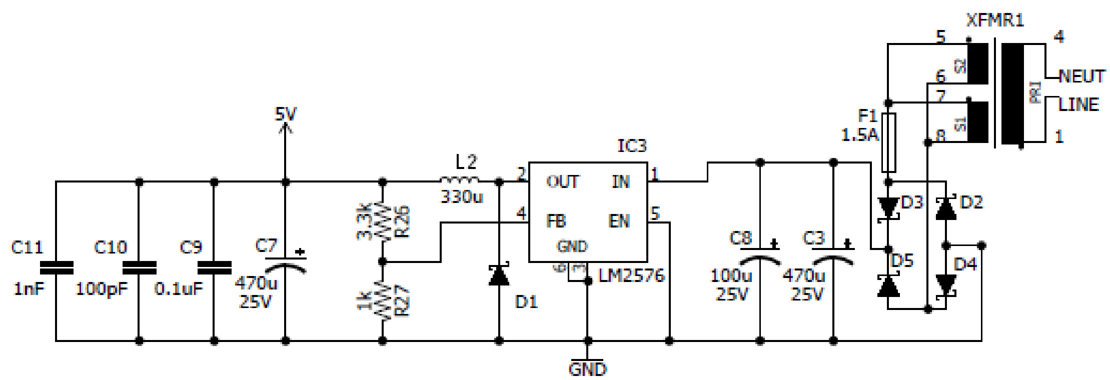

Figure 4: Power supply schematic

One of the main advantages of the LM2576 is the adjustable output voltage set by two resistor values, R_{26} and R_{27}. Resistors R_{26} and R_{27}can be seen in Figure 4. Using information provided by the LM2576, the resistor values can be calculated by using the following Equation 3.

$$V_{\text{out}} = 1.23 * (1 + \frac{R_{26}}{R_{27}}) \tag{3}$$

Referencing the equation above, a output voltage of 5V was desired. With this in mind, the ratio of R_{26} and R_{27} was calculated to be 3.06. Using resistors in the kΩ range, R_{26} was calculated to be

3kΩ and R_{27} was calculated to be 1kΩ. These values provided a voltage that was too low, so the value of R_{26} was increased to 3.3kΩ. The kΩ range was chosen because it was large enough so that parasitic resistances were negligible, but small enough to provide enough current to the feedback pin of the LM2576.

3.2 Temperature Sensor

The purpose of the temperature sensor is to measure the temperature of the hot plate and supply the measured value to the microcontroller. A platinum 100Ω RTD was used in the temperature sensor circuit to respond to the temperature of the hotplate. A Wheatstone Bridge was used with the RTD to generate a voltage difference which is sent to an instrumentation amplifier. The instrumentation amplifier amplifies the small voltage difference to The RTD has to be capable of measuring 150°F to 400°F as well as be accurate in that range. The RTD was chosen due to its ability to operate in the specified range and is accurate within ±1.8°F up to 185°F. Further details about the instrumentation amplifier and Wheatstone Bridge are detailed below.

3.2.1 Wheatstone Bridge

The purpose of the Wheatstone Bridge is to determine the value of an unknown resistance. The advantages to using a Wheatstone Bridge are that it is low cost, simple, and accurate. The goal of the Wheatstone Bridge was to minimize power consumption while maintaining a high degree of accuracy in measurement. The Wheatstone Bridge, shown in Figure 5 acts as a simple two-part voltage divider, which serve as the inputs to the instrumentation amplifier.

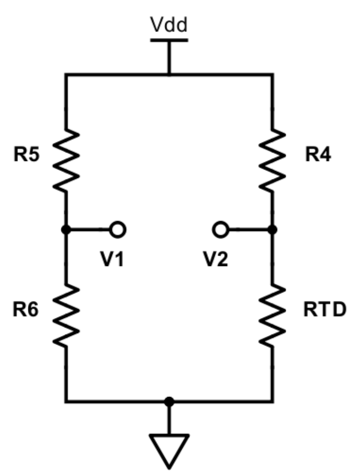

Figure 5: Wheatstone bridge topology

If the values for R_4, R_5, and R_6 are known, the resistance of the RTD and therefore temperature, can be calculated using simple voltage division. As the temperature increases, the thermal properties of the RTD cause the resistance to increase at a linear rate. The increase in resistance causes the voltage at V2 to increase. The voltage difference between V2 and V1 is found by using

$$\Delta V = V2 - V1 \tag{4}$$

where V2 changes due to the resistance change of the RTD.

At 32°F, the resistance of the RTD is 100Ω. The Granny Safe is not expected to operate below 32°F and because of this a 100Ω resistor was used for R_6. This ensures that ΔV remains positive while the Granny Safe is operating in order to allow for proper operation of the instrumentation amplifier discussed in the following section. A 1% tolerance resistor for R_6 was chosen to limit the error in the voltage difference. R_4 and R_5 limit current through each branch and are set equal to each other, at 2.4kΩ, for a maximum branch current of 2mA. The resistance of the RTD at a given temperature, in degrees Celsius, is found by using

$$R_{\text{RTD}} = R_0(1 + \alpha T) \tag{5}$$

where R_0 is the resistance of the RTD at 0°C and α is the resistance temperature coefficient for the RTD. The listed α for the Adafruit RTD was 0.00385Ω/°C. The contract specifies maintaining temperature from 150°F to 400°F, but in order to display temperatures above and below that range, the designed measurement range was chosen to be 32°F to 500°F (260°C). Since the resistance of the RTD at 32°F is known, Equation 5 was used to determine a resistance of 200Ω for the RTD at 500°F. From 32°F to 500°F, a shift of 100Ω in the RTD means that V2 will be 0V to 200mV. This voltage range will be used to calculate the gain required for the instrumentation amplifier which will calculate and amplify ΔV. With the design of the Wheatstone Bridge complete, discussion of the instrumentation amplifier follows.

3.2.2 Instrumentation Amplifier

The purpose of an instrumentation amplifier is to provide amplification to a test signal without the need for impedance matching. The design goal of the instrumentation amplifier is to utilize the full range of the microcontroller's ADC thus providing the most accurate temperature measurement. This goal is accomplished by use of input buffer amplifiers connected to the inputs of a difference amplifier. A three op-amp instrumentation amplifier configuration is shown in Figure 6.

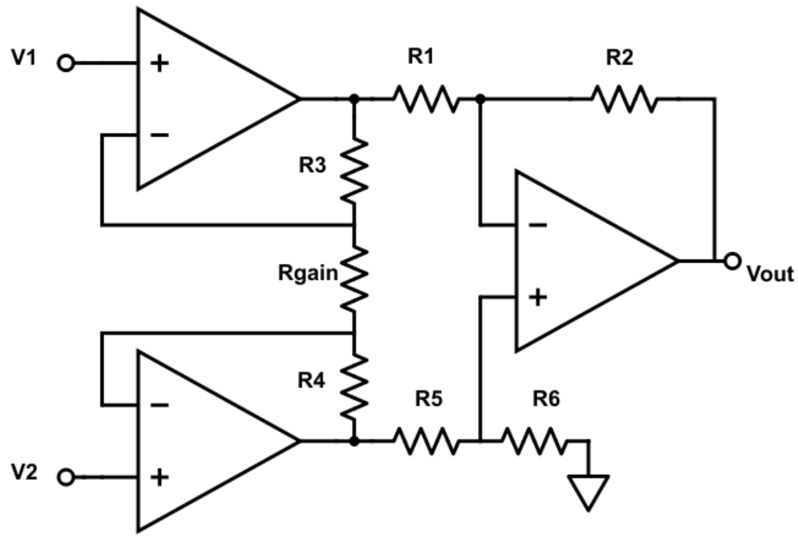

Figure 6: Op-Amp instrumentation amplifier topology.

To utilize the full range of the ADC, the output voltage of the instrumentation amplifier is required to range from 0V to 5V. Because the op-amps are connected to the 5V supply, the output will never fully reach 5V, causing the temperature measurement to be inaccurate. To overcome this inaccuracy, the higher temperature range was chosen to ensure the Granny-Safe's operating range was always accurately measured. Setting R_3 equal to R_4, R_1 equal to R_5, and R_2 equal to R_6 yields the following gain equation, taken from [2].

$$V_{\text{out}} = (1 + \frac{2R_3}{R_{\text{gain}}})(\frac{R_2}{R_1})(\Delta V) \tag{6}$$

Equation 6 was used to find the resistor values. V_{out} is desired to be 5V when ΔV is 0.2V yielding a gain of 25. The values of R_2 and R_1 were chosen to be 15kΩ and 3kΩ respectfully, along with an R_3 value of 20kΩ and an R_{gain} of 10kΩ, to reach the desired gain.

Since all resistors used in the instrumentation amplifier were $\pm 5\%$ tolerance, a way was needed to compensate for potential gain variations introduced by the resistor's tolerance range. A 10kΩ potentiometer was wired in series with a 5.1kΩ resistor, in place of the 10kΩ resistance value calculated for R_{gain} above, to provide that compensation. The potentiometer allows for manual calibration of the instrumentation amplifier output and was used to adjust the gain to the desired value of 25. The final schematic for the temperature sensor can be seen in Figure 7 below.

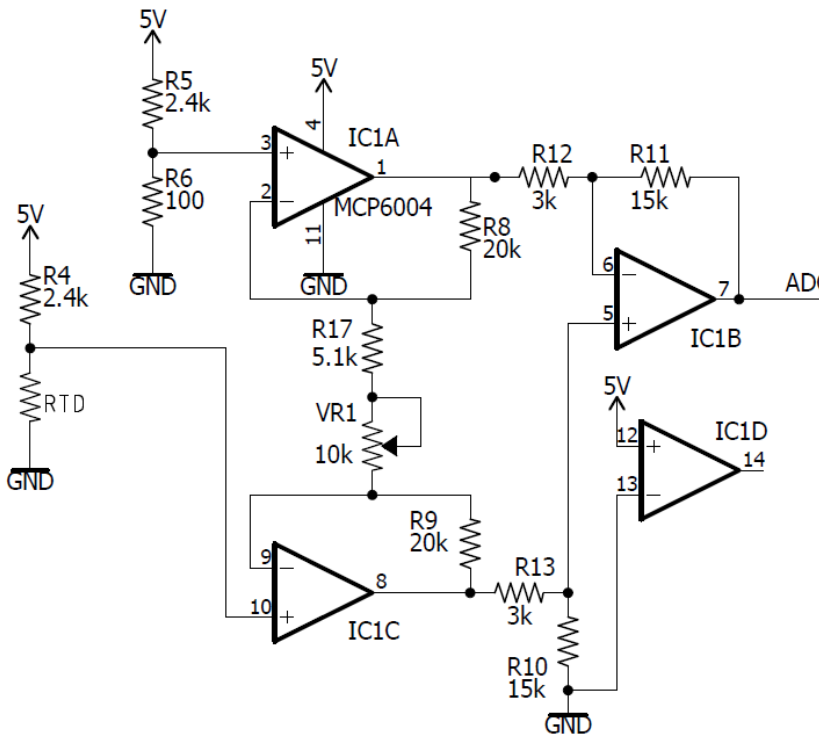

Figure 7: Temperature sensor schematic

Simulations confirmed the design and further details on processing the instrumentation amplifier output are found in the following section.

3.3 Signal Processing

The signal processing in the Granny Safe is performed by an Atmel Atmega328P-PU microcontroller. This microcontroller is responsible for computing the temperature, handling the user interface, and controlling the hot plate temperature by means of a PID controller. The microcontroller was programmed by the the Arduino Uno R3. The two main components of the signal processing of the Granny-Safe are the microcontroller and the PID controller. The microcontroller also handles the processing of the user interface and alarm components. More details about the microcontroller and PID controller will be discussed next.

3.3.1 Microcontroller

The microcontroller supplies the ”brains” to the Granny-Safe. It is responsible for processing all of the signals through the project. The microcontroller receives inputs from the user interface, as well as the zero-sensing circuit. The microcontroller also supplies power to the LED's and audio alarms when necessary.

The microcontroller used is the Atmel Atmega328P-PU, chosen due to its ample documentation, 10-bit ADC, and due to its many GPIO ports. The 10-bit ADC allows for adequately accurate conversion of the voltage from the temperature sensor. The microcontroller also features i2c connections which are utilized by the LCD and, by using the Arduino Uno R3, an easy IDE environment to develop code for and flash the microcontroller. As the Uno R3 board would not be used in the Granny-Safe project, an external 16MHz crystal oscillator was connected to the XTAL pins of the Atmega328P-PU with two 22pF capacitors connected to those pins and ground as shown in Appendix B. A 10K pull-up resistor on the reset pin and connections for the TX/RX pins allowed flashing of the microcontroller, without removing from the Granny Safe PCB, via the Arduino Uno R3.

The 10-bit ADC featured by the microcontroller allows for 1024 digital levels between 0 and 5V. Since 0V corresponds to 32°F and 5V corresponds to 500°F the temperature conversion result has a 0.457°F resolution. The resolution and the affect it has on temperature accuracy will be discussed in the results section.

3.3.2 PID Controller

The purpose of the proportional integral derivative controller, otherwise known as the PID controller, is to regulate when the triac gate is energized, and therefore to control the amount of power going to the hotplate. The PID library provided by Arduino allowed for much easier development of the PID algorithm and was used in the Granny Safe. The PID function compares the measured temperature to the desired setpoint temperature and returns a response based on the the PID parameters and the temperature difference.

The PID in the Granny Safe outputs a delay which the hotplate controller discussed later in the report uses. The delay is used to control when in the mains supply half cycle to energize the hotplate. This allows only a portion of each mains half wave to flow to the hotplate. A longer delay corresponds to less power delivered to the hotplate while a short delay equals more power to the hotplate. The microcontroller uses the most recent zero crossing as a starting point for the delay. Figure 8 shows how the delay corresponds to the the hotplate voltage.

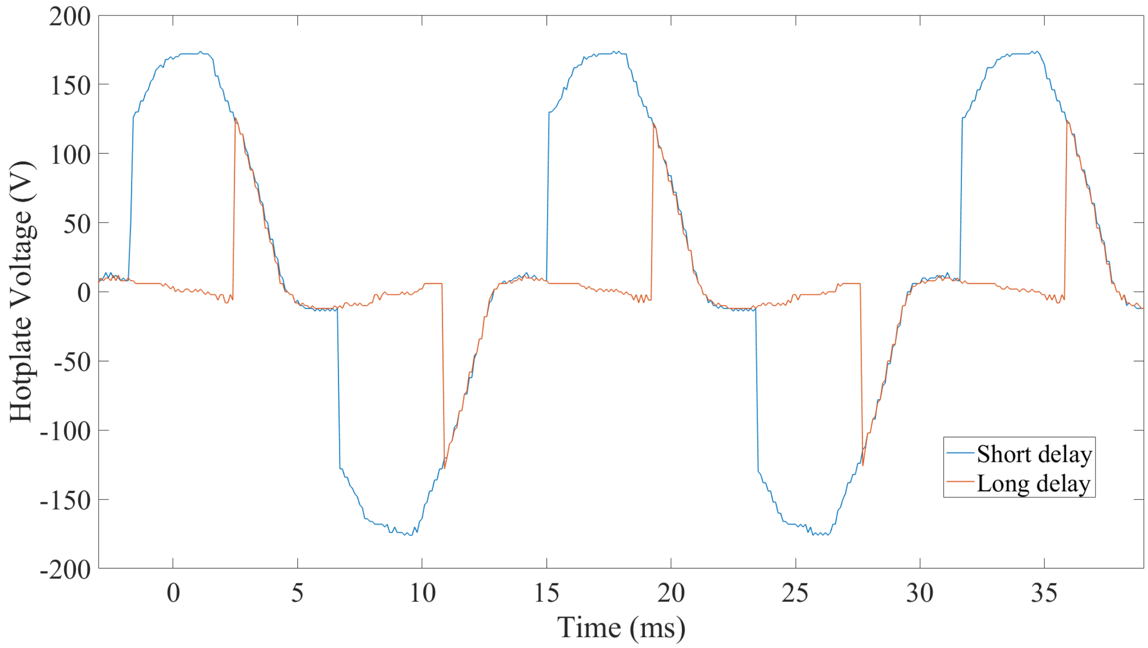

Figure 8: PID delay versus hotplate voltage

As the figure above shows, the delay causes a chopping effect on the beginning of each half wave. To ensure the delay never exceeded the period of the mains half wave, 8.33ms, the PID output was limited. The limited range corresponds to a low of 30μs, to account for fall time of zero sense pulse, and a high of 8.15ms, which prevents inadvertent delaying into the next half wave. The triac controller, and how the PID is used in conjuction with it is explain in more detail in the next section.

3.4 Hot Plate Controller

The purpose of the hot plate controller is to regulate the amount of power delivered to the hot plate. Regulating the power of the hot plate provides a means of controlling the temperature of the hot plate and allows for disconnecting power completely to the hot plate. Regulation is provided through the use of a zero sensing circuit and a triac control circuit and are discussed in the following subsections.

3.4.1 Zero-Sensing

The purpose of the zero-sensing circuit is to provide a pulse to the microcontroller for every zero crossing of mains power. This pulse is sent as an input to the microcontroller to be used in the PID controller discussed earlier in this report.

The zero-sensing circuit is operated like a comparator, with one signal constantly being zero volts and the other being the sinusoidal AC mains power. Figure 9 below shows the zero-sense schematic.

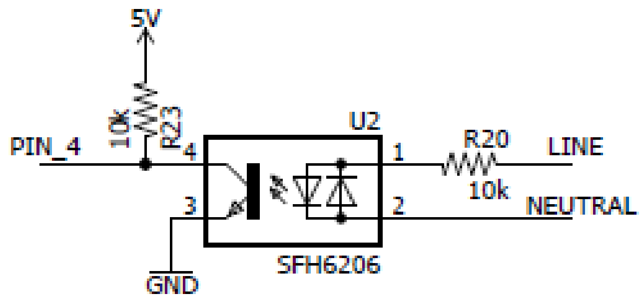

Figure 9: Zero-Sense schematic

The resistor R20 was was set to 10kΩ in order to limit the current flow through the LEDs in the SHF6206 optocoupler to a maximum of 17mA. The value of 17mA ensured proper operation of the LEDs with minimal power. By maintaining the current draw low, power consumption can be minimized and the usable life of the LEDs extended. On the DC side of the optocoupler R23 limits the current flow through the photo-transistor when it is triggered. The 10kΩ value also allows for a sharp 5V pulse to been seen at PIN 4 of the microcontroller.

When the mains supply voltage gets close to 0V, either on the positive or negative half wave, the active LED in the optocoupler turns off. With no light to trigger the photo-transistor, also in the optocoupler, it turns off and 5VDC is seen at PIN 4 of the microcontroller. When the mains voltage moves further from 0V, an LED is energized which triggers the photo-transistor and allows current to flow to ground via the transistor. As a result only the V_{ce} of the phototransistor, at 0.2V, is seen at PIN 4.

The sine wave changes polarity twice every period, and with a frequency of 60Hz, 120 pulses per second are sent to the microcontroller. These pulses, approximately one every 8.33ms, can be seen in Figure 10.

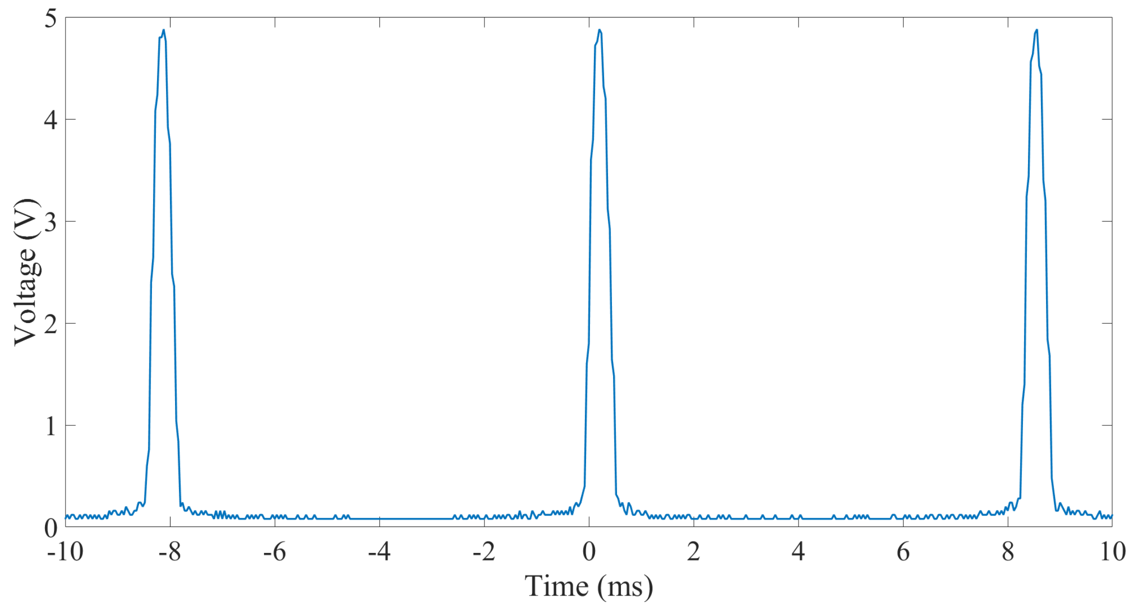

Figure 10: Zero-sensing circuit output

The zero sensing pulse signal shown above is used by microcontroller discussed in Section 3.3.1. Based on the delay generated by the PID algorithm, the microcontroller uses the zero sense signal as a starting point for the delay. When the delay expires the microprocessor sends a signal to control the triac and is discussed in the next section.

3.4.2 Triac Controller

The purpose of the triode for alternating current, or triac, is to control the flow of AC power to the hotplate. The AC power that flows to the hotplate is responsible for heating the coils and allowing the hotplate to reach the desired temperature. The more power that flows to the hotplate is proportional to the temperature. Therefore, a zero-sensing circuit was used with the triac controller to vary the amount of power going to the hotplate. A zero sensing circuit paired with a triac current gate was used to control the power to the hot plate, and thus the temperature. Similarly to the zero-sensing circuit, the triac controller utilizes optical isolation between mains power and 5VDC as shown in Figure 11.

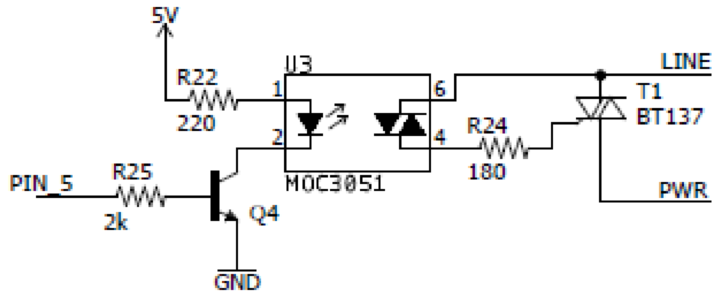

Figure 11: Triac controller schematic

The resistor on the base of Q4, R_{25}, limits the maximum gate current to 2.15mA due to the 0.7V V_{be} drop of Q4. This limits the output current the microcontroller needs to supply on PIN 5 and helps to protect the pin from damage due to excessive current draw. A logical control signal is sent by the microcontroller to the triac controller via PIN 5. The control signal is based on the zero sensing output and the delay from the PID algorithm, which will be detailed later in the section.

The MOC3051 optoisolator shown Figure 11 consists of an LED and a triac. When PIN 5 is high, Q4 is saturated and allows current to flow through the LED and thus illuminates it. When the LED is illuminated, the optoisolator triac allows current to be seen at the gate of the hotplate controller triac. The current seen at the gate activates the triac and allows current to flow through it and supplies power to the hotplate via the PWR connection.

In order to find the required value for R_{24}, Equation 7 was used and taken from [4].

$$R_{22} = \frac{V_{\text{p}} AC\ line}{I_{\text{TSM}}} \tag{7}$$

The peak voltage of the mains supply is 170V and the peak non-repetitive surge current, I_{TSM}, limit of 1A is also taken from [4]. This provides a value of 170Ω for R_{22}. Since 170Ω is not a standard value, the nearest highest standard resistor value of 180Ω was chosen for R_{22}. The resistance was chosen higher than the calculated value to ensure that the 1A I_{TSM} limit is not exceeded.

When the microcontroller sends a signal to activate the triac, based on the PID output delay and zero sensing signal, power is immediately to the hotplate through the triac. This allows the mains supply to be partially chopped off before it is sent to the hotplate, as seen in Figure 12 below.

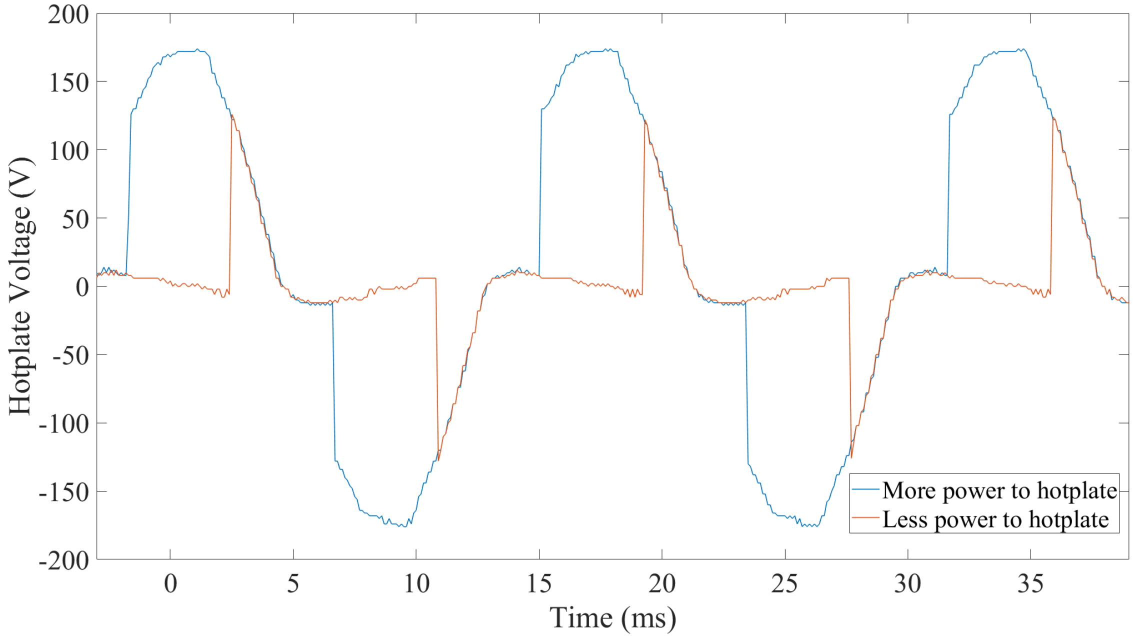

Figure 12: PID delay versus hotplate voltage

Based upon the PID delay output, the triac is triggered either earlier or later in the half cycle of mains to regulate the hotplate temperature. A shorter delay means more power is delivered to the hotplate and the temperature increases, while a longer delay results in less power and temperature decreases. The triac acts as an open when no gate current is applied and therefore the mains supply is not delivered to the htplate during the delay.

3.5 User Interface and Alarm Activation

Audible and visual alarms are used as safety features for the Granny-Safe, as well as user inputs and outputs to allow the user to monitor and control the temperature of the hotplate. The user input is a 3 x 4 keypad. When the user inputs a setpoint, the setpoint is displayed on the LCD along with the current temperature of the hotplate. Once a setpoint is entered, the green LED is turned on. When the temperature exceeds 120 degrees, the yellow LED turns on. This warns that the hot plate is hot to the touch. After the hot plate has been on for 10 minutes, the red LED and audio alarm turns on. If the user does not press the reset button within one minute, power will be cut off to the hot plate. With all project components discussed in detail, the next section will analyze the results.

4 Results

Once the hardware and software had been developed, testing confirmed that that all contract specifications were met. Mains AC power was used as the power input to the circuit. The buck converter achieved the 5V specification, and provided 500mA of current with less than 100mV ripple voltage. The temperature sensor was able to be accurate within 10 degrees of the temperature setpoint between 150 and 400 degrees. The Granny Safe was able to control 120 VAC and was capable of supplying 5A to the hotplate. A Rigol DS1102E oscilloscope was used to confirm the results. The power supply results will be discussed first, followed by the temperature sensor and temperature control. Finally, the results of the triac current conditions will be discussed.

4.1 Power Supply

The goal of the power supply was to create a 5V DC output from 120VAC. The testing of the power supply consisted of ensuring that the buck converter was able to supply the 5V with at least 500mA of current while keeping the ripple within the 100mA specification.

The first specification that had to be met was that the output voltage had to be 5V$\pm$ 5%. The range of voltages could have been between 4.75 and 5.25V. As seen in Figure 13, the red and blue lines represent the upper and lower bounds of the contract respectively.

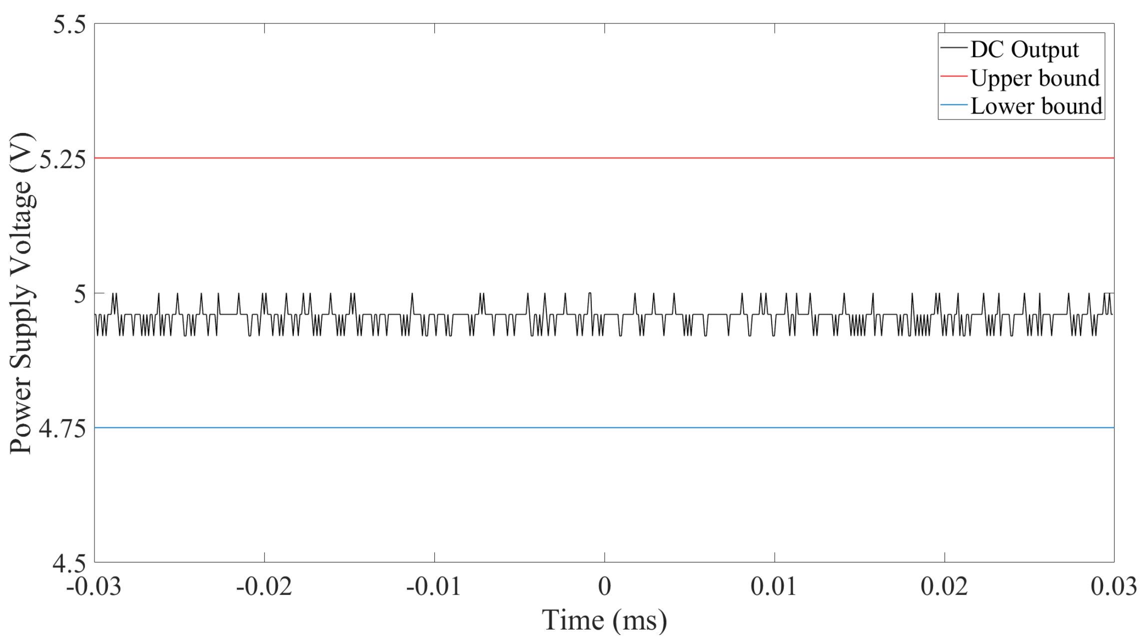

Figure 13: Power supply voltage output with contractual bounds

As proved by Figure 13, the project is well within specification with a measured voltage of 4.96V.

The next step was to prove the current specification. In order to prove that the buck converter was capable of supplying the specified 500mA, the voltage was measured across a 10 Watt, 9.1 Ω power resistor. Ohm's law was applied by dividing the measured voltage drop of the resistor by the resistor value to calculate the current. Since the voltage across the 9.1Ω resistor was 4.98V, the buck converter was supplying 549mA, which exceeds the specification.

The final power supply result was the ripple on the 5V output. The ripple was measured by taking the AC value of the signal. The results are seen below in Figure 14.

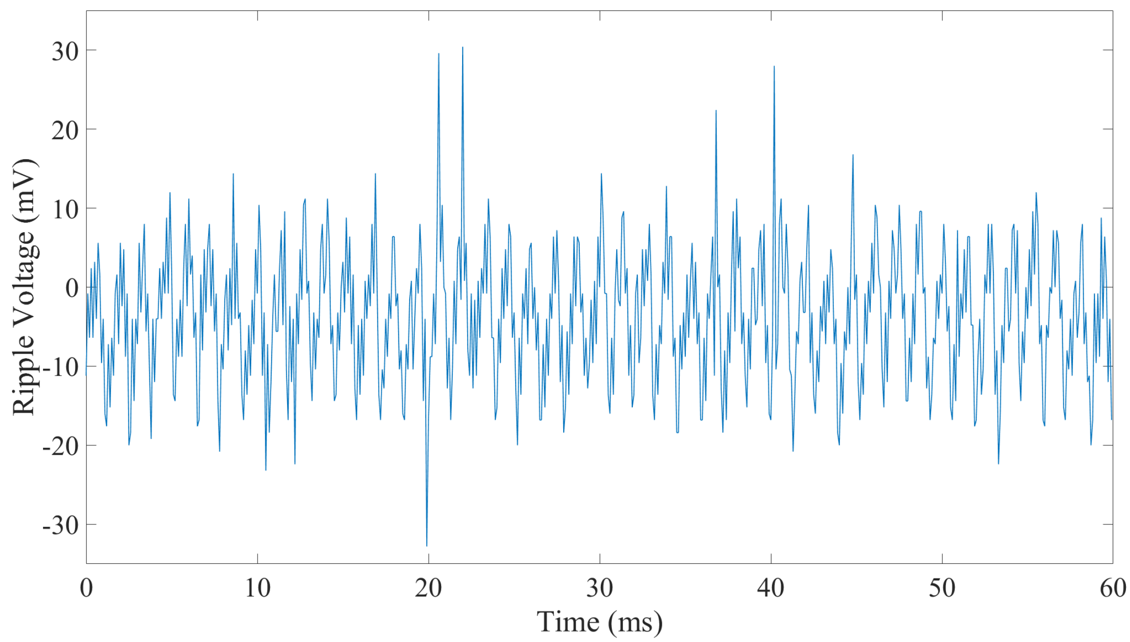

Figure 14: Voltage ripple measured across 9.1Ω resistor

As proved by the test measurements and figure above, the Granny-Safe met or exceeded all specifications for the power supply. The peak to peak ripple was 61mV, which is well within the 100mV specification.

4.2 Temperature Sensor

The temperature sensor was specified to maintain temperature within 10 degrees of a setpoint between 150 and 400 degrees. To verify this specification, an Adafruit temperature sensor was used. The purpose of the Adafruit temperature sensor was to verify that the designed temperature sensor was reading the correct temperatures. Figure 15 displays the measured vs. actual temperature for values between 150 and 400 degrees.

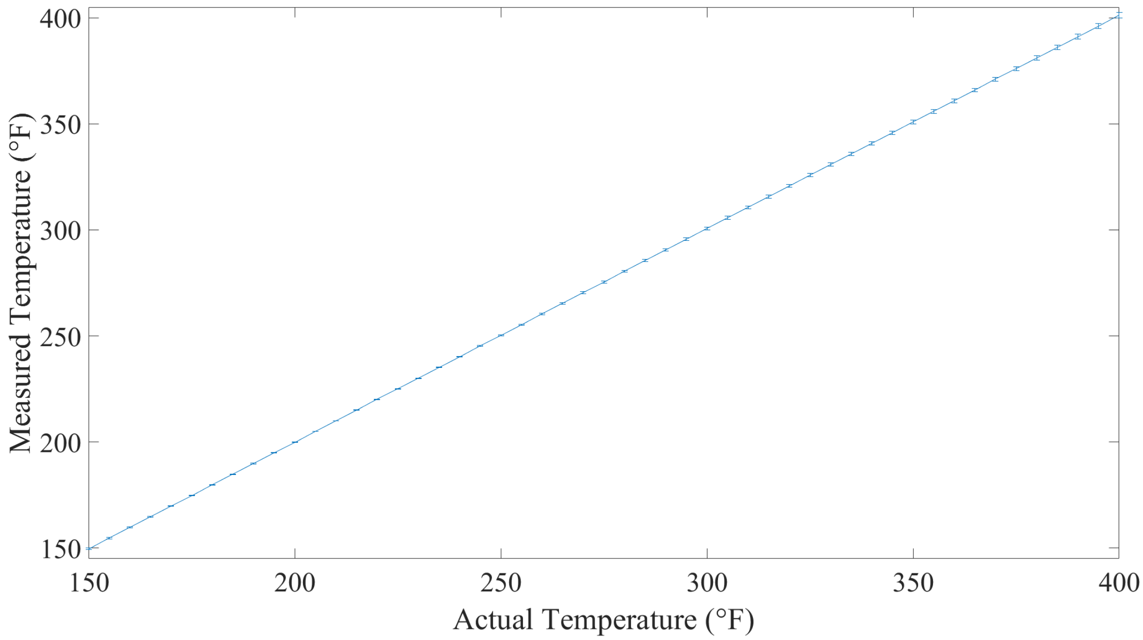

Figure 15: Comparison of measured temperature versus actual temperature

As seen in the figure above, the measured temperature was very close to the actual temperature, well within the limits of ± 10 degrees. The temperature sensor was often within a few degrees of the actual temperature for the whole measurement span. Variations between the two temperatures can be explained by physical variations of the placement of the hotplate probes. Although the probes are as close as possible to each other, there is no guarantee that the actual coil maintains a constant temperature along its length, and it was reasonable to assume a one or two degree variance. Despite this possible variance, it was determined that the method of measurement was the most accurate method available.

4.3 Temperature Control

The contract states that the Granny-Safe must maintain temperature within 10 degrees of a setpoint between 150 and 400 degrees. To prove that this specification was met, the graph below recorded the highest and lowest temperatures recorded throughout the measurement span. The results of this measurement can be seen below in Figure 16.

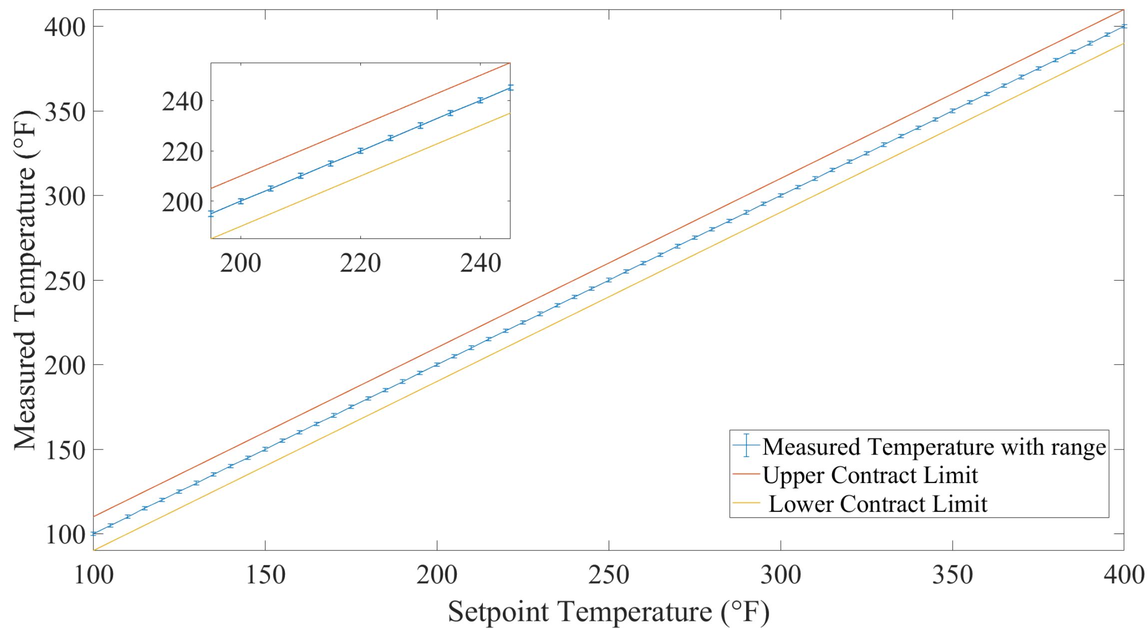

Figure 16: Minimum and maximum measured steady state temperature

As seen above in Figure 16, the Granny-Safe remains within specification throughout the range of temperatures. The measured temperatures are very close to the setpoint within the first 250 degrees. After that, there is more variance in the temperature, although the measured values are still well within spec. This variance can be explained in two ways. The first possible reason for the variance in the higher temperatures can be explained by the performance of the RTD. It is presumed that the resistance of the RTD functions linearly with temperature. However, the RTD is not completely linear for the higher temperatures, which can account for some fluctuation. The second possible explanation for the high end variance can be explained by the PID controller not being as precise when the temperature increases rapidly due to the properties of derivation and integration.

4.4 Triac Current Conditions

The contract stated that the project must be able to supply at least 5A of current at 120VAC to the hotplate. To prove that the project meets the specification, a Klein CL1000 multimeter was used. After several tests, the triac routinely provided 5.86A to the hotplate at max output. With all results analyzed and specification met, the following section concludes the report.

5 Conclusion

The project was successful and met all specifications listed in the project contract. The design, testing, and results of the Granny-Safe were discussed. The complete project consisted of a PCB, keypad, LCD, RTD, and a hot plate. Various changes were made throughout the design process in order to meet specifications while still ensuring safety. Operating instructions are provided in Appendix E. The Granny-Safe provides a low cost and safe solution to maintaining the temperature of a hot plate. It excels due to its use of a triac to regulate power and its consistent alarm condition.

References

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[2] A.S. Sedra, K.C. Smith, Microelectronic Circuits, Oxford University Press, New York, New York, pp. 76-80, 2010.

[3] ”SFH620A, SFH6206 Data Sheet” 2015 - Vishay Electronics. [Online]. Available:
http://www.vishay.com/docs/83675/sfh620a.pdf

[4] ”MOC3051M, MOC3052M Random-Phase Triac Driver Optocoupler” 2015 - Fairchild. [Online]. Available: https://www.fairchildsemi.com/datasheets/MO/MOC3051M.pdf

Appendices

A Project Contract

Smart Stove Project "Granny-Safe"

Members
Josh Andrews, Electrical Engineering
Riley McKay, Electrical Engineering

Description
This device is designed to create a product which uses a temperature sensor to monitor and control a hot plate burner. The product will feature time and temperature settings, where the user will be able to control the temperature of the hot plate within ±10°F of a set temperature . Also featured would be a setting that turns the power to the burner off if the burner was left on for a set period of time. The device will also include the exclusion of relays, instead opting to use discrete components to control the hot plate burner. The project will also be comprised of a micro-controller and alarm circuitry. The main components will be powered by 5VDC, which will be obtained by utilizing an AC-DC and DC-DC converter from the wall outlet.

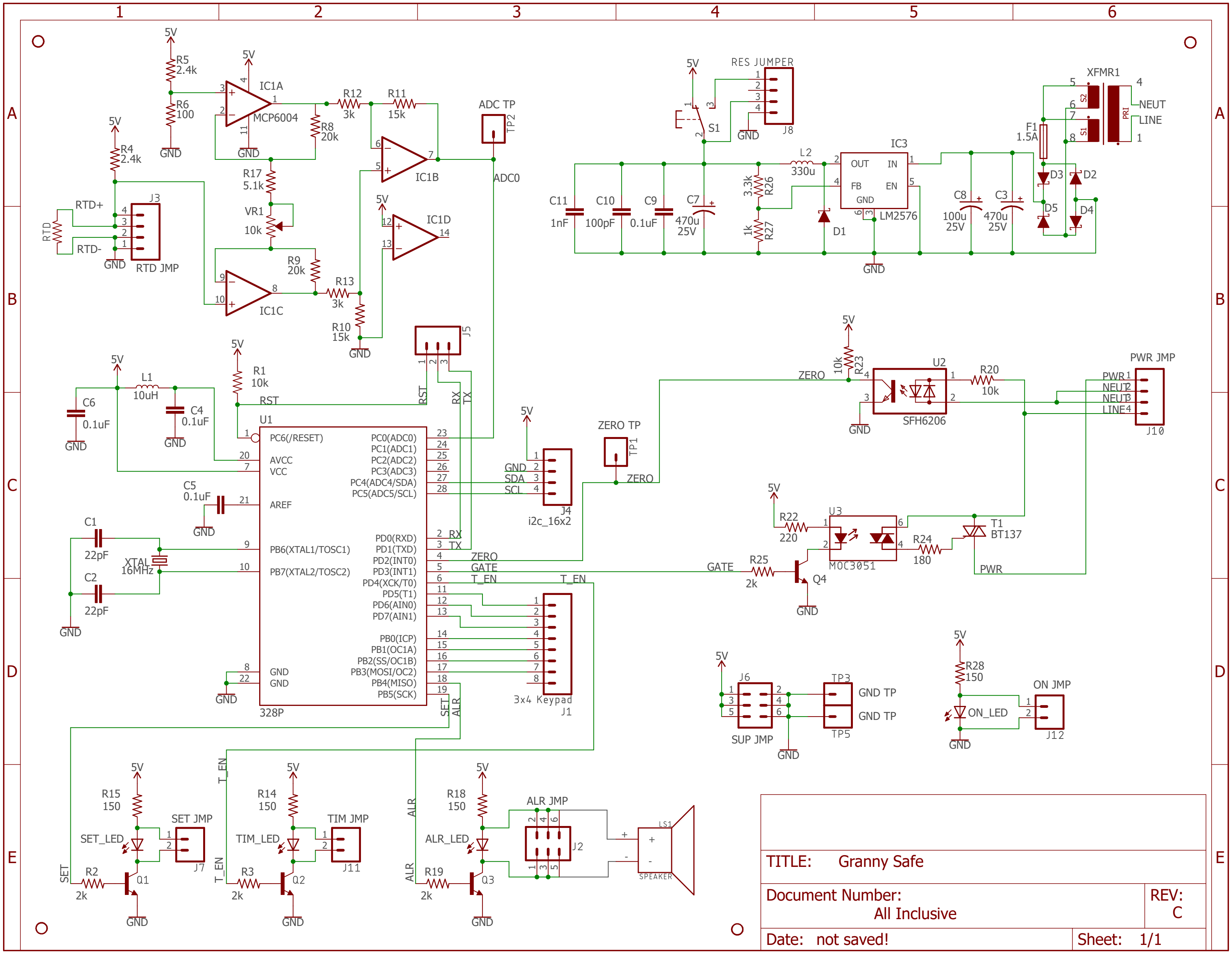
Inputs
- Temperature sensor data
- Temperature control knob/keypad
- DC voltage
- Pushbutton

Outputs
- LCD display
- Hotplate controller signal
- Alarm (speaker and LED)

Specifications
-DC to DC voltage converter 5V ± 5% with less than 100mV ripple supplying at least 500mA.
-No relays, 5V DC input controlling 120V AC and at least 5A.
-Alarm timer enabled when temperature exceeds 120°F, Alarm sounds after 10 minutes, and alarm deactivates if hotplate is turned off or reset if reset button pressed.
-Maintain hot plate temperature within ±10°F of set temperature between 150℉ and 400℉, measured in middle of second hotplate coil.

Name: __________________________ __________________________
Signature: __________________________ __________________________
Date: __________________________ __________________________

B Schematic



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Sheet: 1/1
U1 328P
IC1A MCP6004
IC1B
IC1C
IC1D
IC3 LM2576
U2 SFH6206
U3 MOC3051
T1 BT137
XFMR1
F1 1.5A
L1 10uH
L2 330u
XTAL 16MHz
RTD JMP
RES JUMPER
PWR JMP
SUP JMP
ON JMP
ALR JMP
SET JMP
TIM JMP
ADC TP
ZERO TP
GND TP
i2c_16x2
3x4 Keypad
SET_LED
TIM_LED
ALR_LED
ON_LED
SPEAKER
NEUT
LINE

C Parts List

Part	Vendor	Quantity	Part Number	Description	Price	Extended
Alarm Speaker	DigiKey	1	102-1554-ND	SPEAKER 8OHM 100MW TOP PORT 89DB	$3.14	$3.14
Temperatre Sensor	DigiKey	1	1528-2090-ND	PLATINUM RTD SENSOR - PT100 - 3	$11.95	$11.95
Transformer	DigiKey	1	595-1180-ND	XFRMR LAMINATED 20VA THRU HOLE	$11.99	$11.99
Currernt Limiting Fuse	DigiKey	10	507-1849-1-ND	FUSE 2A 350V RADIAL	$0.32	$3.15
Clock Crystal	DigiKey	6	X1104-ND	CRYSTAL 16.000312MHZ 18PF T/H	$0.69	$4.14
Zero Sensing	DigiKey	3	MOC3051M-ND	OPTOISOLATOR 4.17KV TRIAC 6DIP	$1.07	$3.21
Zero Sensing Surface	DigiKey	3	MOC3051SR2MCT	OPTOISOLATOR 4.17KV TRIAC 6SMD	$1.35	$4.05
Triac	DigiKey	5	1740-1028-ND	TRIAC SENS GATE 600V 8A TO220AB	$0.66	$3.30
Triac Surface	DigiKey	5	1740-1034-1-ND	TRIAC SENS GATE 600V 8A DPAK	$0.68	$3.40
Buck Chip	DigiKey	5	576-1045-ND	IC REG BUCK ADJ 3A TO220-5	$1.88	$9.40
Buck Chip Surface	DigiKey	2	576-1539-1-ND	IC REG BUCK ADJ 3A TO263-5	$1.96	$3.92
Opto Isolator	DigiKey	5	SFH620A-3-ND	OPTOISOLATOR 5.3KV TRANS 4-DIP	$0.92	$4.60
Op Amp	DigiKey	10	MCP6004-I/SL-ND	IC OPAMP GP 1MHZ RRO 14SOIC	$0.46	$4.60
Resistor	DigiKey	20	311-100HRCT-ND	RES SMD 100 OHM 1% 1/10W 0603	$0.02	$0.30
Terminal Connector	DigiKey	5	732-10955-ND	TERM BLOCK 2POS SIDE ENTRY 5MM	$0.38	$1.90
Slotted Terminal Connector	DigiKey	20	36-1040-ND	TERM TEST POINT SLOTTED .118"	$0.18	$3.60
Surface Mount Inductor	DigiKey	10	535-11587-1-ND	FIXED IND 10UH 3MA 2.55 OHM SMD	$0.10	$0.96
Capacitor	DigiKey	25	311-1088-1-ND	CAP CER 0.1UF 16V X7R 0603	$0.02	$0.53
Capacitor	DigiKey	10	1276-2096-1-ND	CAP CER 0.056UF 50V X7R 0603	$0.08	$0.79
Capacitor	DigiKey	10	490-6421-1-ND	CAP CER 0.56UF 10V X7R 0603	$0.15	$1.47
Diode Surface Mount	DigiKey	10	1655-1360-1-ND	DIODE GEN PURP 75V 250MA SOD123	$0.13	$1.25
Diode Through hole	DigiKey	10	SR306-TPMSCT-N	Diode Schottky 60V 3A Through Hole DO-201AD	$0.42	$4.20
Buck Chip surface mount	DigiKey	2	296-46303-1-ND	IC REG BUCK ADJ 2A SYNC 16HTSSOP	$4.30	$8.60
Inductor	DigiKey	2	732-7149-ND	FIXED IND 10UH 4.6A 23 MOHM TH	$1.87	$3.74
Schottky Diode Surface Mount	DigiKey	10	SK36A-LTPMSCT-	Diode Schottky 60V 3A Surface Mount DO-214AC (SMA)	$0.60	$6.00
Surface Mount Inductor	DigiKey	5	SRR1280-331K	FIXED IND 330UH 1.1A 600 MOHM	$1.06	$5.30
Power Resistor	DigiKey	2	SQP10AJB-9R1	RES 9.1 OHM 10W 5% AXIAL	$0.64	$1.28
Capacitor Through Hole	DigiKey	10	25YXJ220M6.3X1	CAP ALUM 220UF 20% 25V RADIAL	$0.19	$1.93
Potentiometer Surface Mount	DigiKey	10	TC33X-2-103E	TRIMMER 10K OHM 0.1W SMD	$0.12	$1.20
Potentiometer Through Hole	DigiKey	10	1-1623849-0	TRIMMER 10K OHM 0.5W TH	$0.27	$2.70
Ceramic Capacitors	DigiKey	20	MR045A682EAA	Various capacitors for buck converter	$0.03	$0.67
Atmel ATmega328p	DigiKey	1	ATMEGA328PB-A	Microcontroller	$1.38	$1.38
LCD Display	DigiKey	1	NHD-12232KZ-N	Information display	$12.50	$12.50
Solid State Relay	DigiKey	1	CLA233CT-ND	Test purposes only	$1.20	$1.20
Triac	DigiKey	1	F7290-ND	Hotplate controller component	$3.13	$3.13
Arduino Uno R3	In possession	1	\\\	Used to program microcontroller	$3.95	$3.95
Hot Plate	In possession	1	\\\	Main Part	$12.95	$12.95
Temperature Sensor	In possession	1	\\\	Temperature sensor	$4.99	$4.99
PCB Board	In possession	1	\\\	Implementing project	$1.20	$1.20
Keypad	In possession	1	\\\	User interface	$4.59	$4.59

D Operating Instructions

To operate device

1.) Ensure the RTD is attached to hot plate and both are plugged into device.

2.) Plug device into 120V wall outlet, the blue LED should illuminate.

3.) Enter a setpoint temperature between 100°F and 400°F and press button to enter. The green LED should illuminate.

4.) When temperature exceeds 120°F, the yellow LED will illuminate, indicating the alarm timer is activated.

5.) After ten minutes the alarm with activate. To reset the timer and silence the alarm, press the * button.

7.) If the alarm is not reset within one minute, the hot plate will turn off, the setpoint will clear, and the screen will display ”ALARM”.