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March 11, 2005

Lakshman One
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
V5A 1S6

Re: ENSC 440 Design Specifications for the Perfect Balance Temperature Controlled Mattress Pad

Dear Mr. One,

Attached will you will find ThermaCool's *Design Specifications for a Temperature Controlled Mattress Pad.* This document lists the design specifications for our ENSC 440 project.

We are currently designing and building a temperature controlled mattress pad which we have designated the Perfect Balance mattress pad. Once complete, the Perfect Balance mattress pad will provide an individual with a more comfortable sleeping environment by allowing the user to specify a pre-defined mattress pad temperature. Throughout the night, the system will automatically heat or cool the mattress pad in order to meet and maintain the user's desired temperature.

The enclosed design specifications serve as the blueprints with which the Perfect Balance mattress pad will be developed. It includes aspects such as hardware schematics, embedded software modules, and test plans. These specifications are essential to the successful operation of our product.

ThermaCool is composed of four fourth year Systems Engineering students. Team members include Slav Bienko, David Black, Sal Daswani, and Sean Pallister. Please feel free to contact us with any questions or comments regarding our project. We can be reached by telephone at 604-943-1418 or be e-mail at ensc440-thermacool@sfu.ca.

Sincerely,

David Black
Organization Department Head
ThermaCool Inc.

Enclosed: *The Design Specifications for a Temperature Controlled Mattress Pad*

ThermaCool Inc.

Design Specifications for a
Temperature Controlled Mattress Pad

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Submitted to: Lakshman One – ENSC 440
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EXECUTIVE SUMMARY

Often times, people have trouble falling asleep due to non-ideal sleeping conditions. Specifically, 20% of North Americans that have trouble sleeping say that uncomfortable sleeping temperatures prevent them from achieving a good night's rest [1]. While products such as heating blankets and mattress pads have been available on the market for many years, no consumer product has yet offered the ability to cool in addition to heat the user. This is all about to change with the advent of ThermaCool's Perfect Balance temperature controlled mattress pad.

The purpose of the Perfect Balance mattress pad is to ensure a consistent and comfortable sleeping temperature all throughout the night. Whether the night is too cold or too hot, the Perfect Balance mattress pad will automatically and discreetly heat up or cool down to maintain the user's pre-defined, desired sleeping temperature.

ThermaCool has proposed to develop the Perfect Balance temperature-controlled mattress pad in two phases. In the first phase, ThermaCool will be committed to developing a prototype product to demonstrate that such a temperature controlled mattress pad is realizable. This proof-of-concept phase will be completed by mid-April 2005. In the second phase, ThermaCool will investigate the potential for minimizing costs and rendering the product more usable. After completion of the second phase, ThermaCool will have a market-ready product.

Throughout the proof-of-concept phase, ThermaCool will be anticipating the needs of a next-generation temperature-controlled mattress pad that can be brought to market as a reliable, consumer-friendly product.

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1 INTRODUCTION

ThermaCool's Perfect Balance mattress pad will achieve a subtle yet effective solution for individuals seeking better comfort and control of their sleeping conditions. It will accomplish this task by circulating water, which has either been heated or cooled to a user's desired temperature, through a mattress pad. This document distinguished the specific design specifications for the Perfect Balance mattress pad that will allow it to accomplish this task. These design specifications have been developed for the proof-of-concept device, subject for completion in mid-April 2005.

1.1 Objective

This document describes the design specifications proposed by the engineers at ThermaCool for the Perfect Balance mattress pad. These design specifications will ensure that the operations of the Perfect Balance mattress pad will meet the requirements as described in the document *Functional Specifications for a Temperature Controlled Mattress Pad* [2]. Included are details pertaining to the hardware, firmware, software, and user interface. Also included is an exhaustive test plan, which will ensure the quality the Perfect Balance mattress pad.

Note that because we are in the prototype stage of development, the requirements described in the functional specifications document were developed on the side of leniency. It is expected that a great deal of knowledge will be gained while constructing the proof-of-concept device; hence, the final consumer product's functional requirements are subject to improvement. Any changes to the functional requirements will warrant changes to the design specifications, hence, this document is also subject to change.

For an overview of the Perfect Balance mattress pad and an introduction to the company members, please refer to the *Proposal for a Temperature Controlled Mattress Pad* document [3]. This document is available upon request from ThermaCool.

1.2 Intended Audience

This document is intended as a reference for ThermaCool design engineers and/or subcontract design engineers hired by ThermaCool, in order to ensure proper design and assembly of the various components that make up the Perfect Balance mattress pad. Additionally, this document may be referred to by project managers and quality assurance personnel to verify the integrity of the Perfect Balance mattress pad.

2 SYSTEM OVERVIEW

The Perfect Balance mattress pad will be composed of four main components: a control unit, a processing unit, a reservoir unit, and a mattress pad. Figure 1 shows the basic building blocks of the Perfect Balance mattress pad.

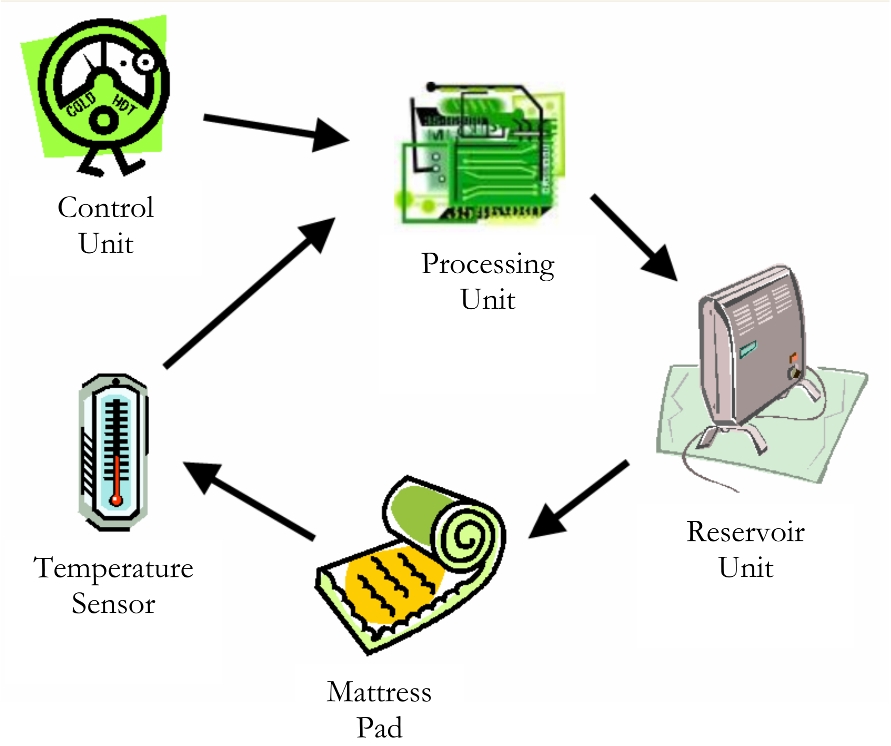

Figure 1 - The Perfect Balance Mattress Pad System Overview

A simple front panel control interface will allow the user to set the desired temperature of the mattress pad. Thermistors will be used as temperature sensors to monitor the surface temperate of the mattress pad and will relay this information to the processing unit. A microcontroller inside the processing unit will then compare this temperature to the desired temperature, as specified by the user. When a temperature difference is measured, the microcontroller will take the required actions and utilize proportional, integral, derivative (PID) control to either heat or cool thermoelectric (TEC) devices inside the reservoir unit. The temperature of these TEC devices will result in a temperature change in the water being pumped through the mattress pad. In this manner, the surface temperature of the mattress pad will be maintained at the desired temperature.

3 SYSTEM HARDWARE

In this section, the hardware components of the Perfect Balance mattress pad are discussed in detail. The main hardware components that make up the system are the mattress pad, the reservoir unit, the processing unit, and the control unit.

A block diagram outlining these major components is shown in Figure 2. The blue arrows represent the physical flow of current and the black arrows represent the signal flow. Ensuing diagram will display each of the blocks shown in Figure 2 in more detail.

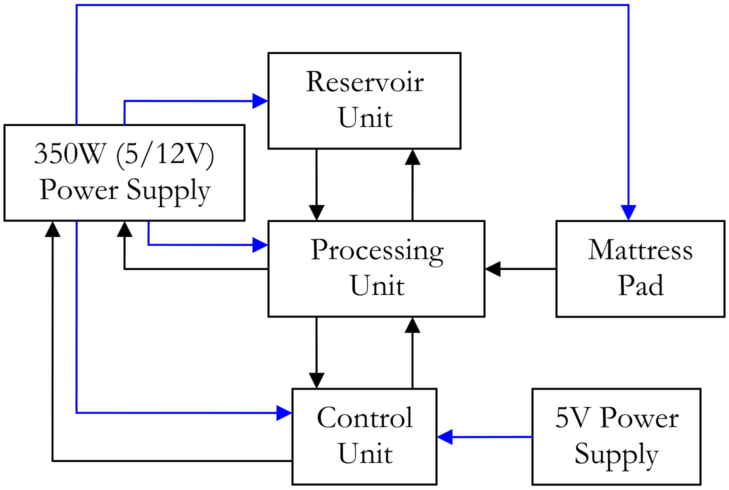

Figure 2 – A Block Diagram of the Entire System

3.1 The Mattress Pad

Shown in Figure 3 is a block diagram representing the hardware components involved with the mattress pad. A thermistor, powered by a 5V supply power supply, will measure the surface temperature of the mattress pad and relay this information to the processing unit.

Figure 3 – A Block Diagram of the Mattress Pad

3.1.1 Mattress Pad Layout

The mattress pad is produced by Gaymar Inc. It has been designed in such a way that water can flow through it without being cut off from pinching due to external pressure. This is achieved by way of small channels through which water can flow, interspersed with areas which direct the water through these channels. Pictured in Figure 4 is the Gaymar mattress pad design. The mattress pad measures 50.8cm by 149.9cm, which meets the size requirements of the Perfect Balance mattress pad. The arrows in Figure 4 represent the direction of flow of the water.

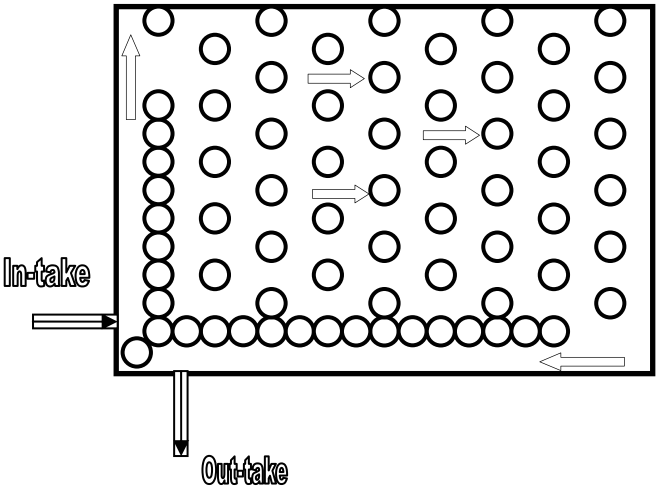

Figure 4 – The flow of water through the Mattress Pad

3.1.2 Mattress Pad Thermistor Circuit

During operation, it is essential that an accurate temperature be obtained from the surface of the mattress pad. This will ensure that the mattress pad surface temperature is always maintained at the desired level.

To accomplish this task, a thermistor will be used in a voltage divider circuit with a $10k\Omega$ resistor. The output voltage across the thermistor varies non-linearly with the temperature, and thus a simple subroutine has been written to linearize this voltage in relation to the ambient air temperature. Further details about this linearization process will be presented in Section 4.3.

The thermistor circuit is powered from a 5V line provided by the 350W power supply and will be located in the bottom right hand corner of the mattress pad. A circular piece of foil will be attached to the thermistor to obtain an average reading of the surface temperature of the mattress pad. The chosen thermistor is produced by BC Components, and has part number 232263383103. The choice for this thermistor was based on its small size, quick response time, and high stability.

3.2 The Reservoir Unit

The reservoir unit is composed of a heat exchanger, a pump, and insulated water reservoir. The heat exchanger uses TEC modules to either heat or cool the water that is passed through the mattress pad. A block diagram of the TEC driver circuit is shown in Figure 5. The insulated water reservoir encloses the pump, and holds the thermally treated water prior to it being circulated through the mattress pad. The insulation helps preserve the temperature of the thermally treated water. All of the aforementioned items will be enclosed in an aluminum casing.

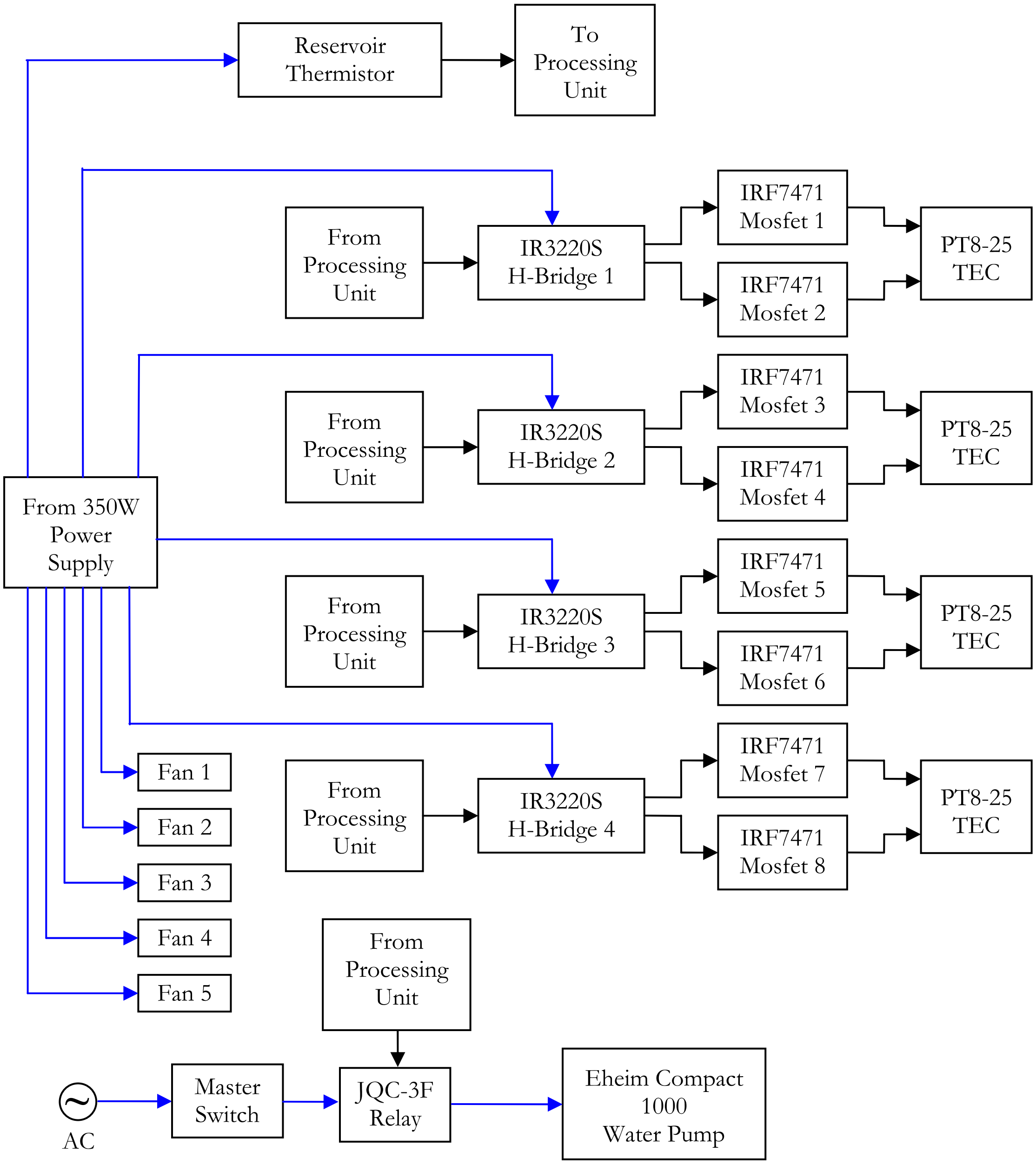

Figure 5 – A Block Diagram of the Reservoir Unit

3.2.1 Aluminum Enclosure

The reservoir's aluminum enclosure holds and protects all of the components of the reservoir unit. The enclosure will have three holes cut in it - two of the holes will be used to pass hoses from the mattress pad to the water unit, and one of the holes will be used to pass cables between the reservoir unit and the processor unit.

3.2.2 Heat Exchanger Unit

The heat exchange unit is composed of a milled piece of aluminum, four TEC modules, four PC fans, a heat sink, and interface circuitry. Channels are milled into the aluminum to facilitate water flow. As the water flows through the aluminum, TEC modules heat or cool the aluminum itself, which in turn heats and cools the water flowing through it. The heat sink and the PC fans are used to dissipate heat off the top of the TEC modules. The heat sink and TEC modules are bolted to the aluminum. Thermal grease is used between the heat sinks and the TEC modules, and between the TEC modules and the aluminum to further facilitate heat transfer.

3.2.2.1 Milled Aluminum

The piece of aluminum has surface dimensions of 23cm by 11cm, and is 0.95cm thick. A border of approximately 1.5cm encapsulated the milled channels, which are 0.8cm deep and 0.635cm wide. A total of eight channels running a length of 20cm from one side of the aluminum to the other have been milled. Figure 6 shows a diagram of the top view of the milled piece of aluminum. The outer border and 1.9cm un-milled island in the centre of the piece provided locations for bolts that will hold a 0.3mm thick cover on. The arrows represent the direction of water flow.

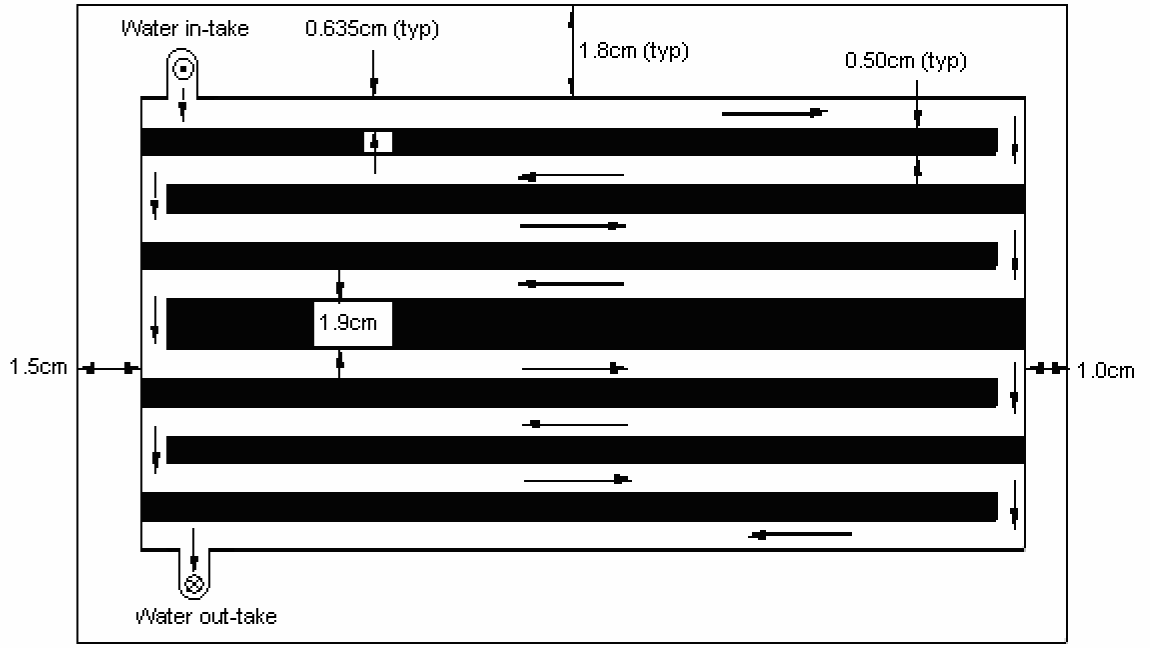

Figure 6 – The Milled Piece of Aluminum

3.2.2.2 TEC Modules

ThermaCool has decided to use TEC modules as the means to generate the cooling and heating of the mattress pad. Although the modules are referred to as thermoelectric coolers, they inherently generate heat as a result of their physical operation. While one side of the thermoelectric module is cooling, the other side will be heating and vice versa when the current supplied to the device is reversed. Their operation relies on the Peltier Effect which can be realized at the junction of a piece of either bismuth or iron wire and copper wire. A picture of a typical single-stage TEC module is shown in Figure 7, along with a diagram illustrating its operation.

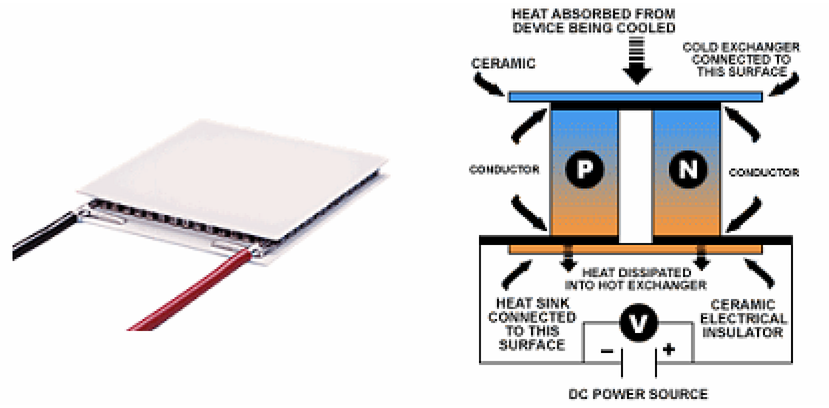

Figure 7 – (Left) Thermoelectric Cooler and (Right) Operation

Overall, TEC modules offer the advantage of no moving parts, no dangerous chemicals, and silent operation. Of course the fact that thermoelectric modules operate as dual-purpose devices with respect to their ability to either cool or heat is an added benefit.

We will utilize four PT8-25 TEC modules, which are produced by Melcor Thermoelectric. These modules were chosen because of their generous size of 4cm by 8cm, and their relatively inexpensive cost. Furthermore, they can tolerate a maximum voltage of 24V and a current of 8.5A. However, because of power restrictions the TEC modules will be powered with 12V and anywhere between 0A to 5A (based on a PWM, PID controlled wave). Thermal grease will be used between the modules and the milled piece of aluminum. These modules will be located as shown in Figure 8 (the hatched areas represent the TEC modules).

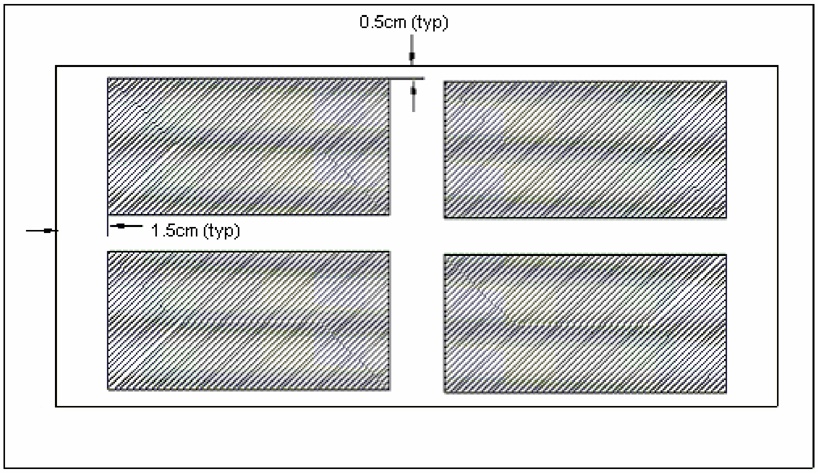

Figure 8 – The Orientation of the TEC Modules

3.2.2.3 Heat Sink and PC Fans

As previously mentioned, a heat sink is fastened to the TEC modules, with thermal grease used as a conducting medium. The heat sink is 22cm in length, 11.5cm in width, and 3cm in height, and is made of aluminum. The heat sink is fastened on top of the TEC modules by way of bolts through the milled piece of aluminum. Since the TEC modules are between the heat sink and the milled piece of aluminum, when the heat sink is fastened to the milled piece of aluminum, it applies pressure against the TEC modules. Thus, the heat sink is securely fastened to the TEC modules, and the TEC modules are securely fastened to the milled piece of aluminum. Furthermore, two PC fans, measuring 9.5cm along their diagonal are placed in such a manner that they blow air onto the side of the heat sink. These two fans have a maximum voltage and current rating of 0.22A and 12V. Another three PC fans, measuring 80mm along their diagonal are placed in such a manner so they suck air from the side of the heat sink. These three fans have a maximum voltage and current rating of 0.12A and 12V.
Therefore we have two larger fans blowing air into the aluminum enclosure and onto the heat sink, and three fans sucking air through the heat sink and out of the aluminum enclosure.

3.2.2.4 TEC Drivers

The TECs require a very large current input and they can cool or heat depending on the direction of current flow, so we had to find a way to supply that current need and control it as well. The solution we came up with was to use the circuit shown below in Figure 9. The main components of the circuit consist of an International Rectifier IR3220S H-Bridge and two International Rectifier IRF7471 Power Mosfets. The IR3220S H-Bridge will not function as a full H-Bridge on its own, for it only consists of two high side mosfets, hence the need for the two IRF7471 power mosfets to make up the full H-Bridge with two high side and two low side mosfets.

The IR3220S H-Bridge can output 6A continuously without a heat sink, and it has programmable in-rush Pulse Width Modulation (PWM). The IRF7471 power mosfet has a V_{DSS} of 40V, an $R_{DS(ON)}$ of 13mΩ maximum, which is very low, and a drain current of 10A. Seeing as we will not be using more than 5A on the TECs, these specs are quite good for our application.

Combining the two IRF7471s (the two low side mosfets) with the single IR3220S (the two high side mosfets), we obtain a full H-Bridge. So, each of the two TEC lead wires would be connected between the drain of a low side mosfet and the source of a high side mosfet. By using an H-Bridge we can control the direction of current flow, by controlling which mosfet is turned on. If high side mosfet 1 and low side mosfet 2 conduct, then current flows in one direction, but when high side mosfet 2 and low side mosfet 1 conduct, then current flows in the other direction. Since the TEC is connected at the junction of each of the low side and high side mosfets, the direction of current flow (negative or positive current) to the TEC can be controlled.

In order to control the full H-Bridge, the microcontroller will send a digital signal to the IR3220S IN1 and IN2 pins, and a PWM signal to the IR3220S SS pin. With a high signal to

IN1 and a low signal to IN2, the full H-Bridge will operate in forward rotation (positive current to the TEC), whereas a low signal to IN1 and a high signal to IN2 results in a reverse rotation (negative current to the TEC). Also, by controlling the PWM signal sent to the SS pin of the IR3220S, we control the magnitude of the current output to the TEC. So, by using the circuit depicted in Figure 9, we can control the current flowing into the TEC (anywhere between -5A to 5A).

Figure 9 displays the schematic for the TEC driver schematic, which will be converted into a PCB. The dark circles are actually mounting pads, and we require mounting pads because the microcontroller sends control signals to the IRF7471 through wires, and the TEC has built in lead wires. So, all those wires need to have room to be mounted on the PCB after it is fabricated. However, most of the mounting pads will be used to have one large ground plane on the reverse side of the PCB. There will be a TEC driver circuit for each of the four TECs.

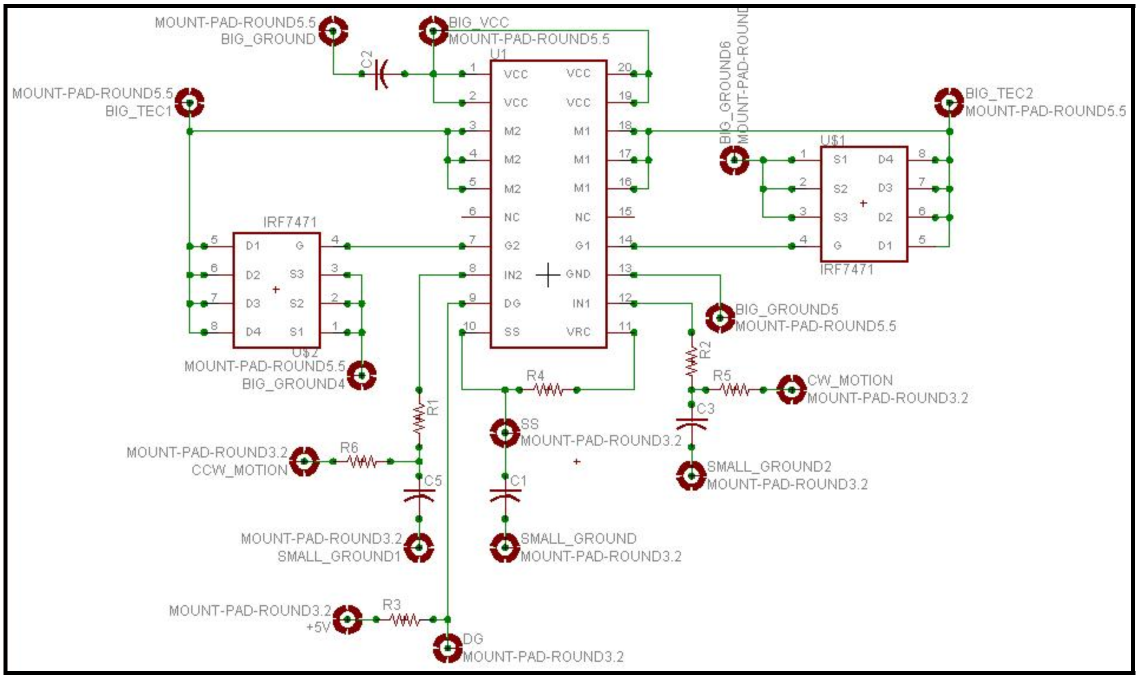

Figure 9 – TEC Driver Circuit Schematic

3.2.3 Water Reservoir

The water reservoir consists of a watertight container (acting as a reservoir) insulated with Styrofoam. Located inside the watertight container is a pump, which will be used to circulate water throughout the system. In addition, a thermistor circuit will measure the temperature of the water contained in the watertight container. The 5V line from the 350W power supply will be used to power the thermistor circuit, whose output will be communicated to the processing unit. A 120V AC power source wall socket will be used to power the pump. Furthermore, a relay, controlled by the control unit, will have to be latched before a connection to the pump can be made. In addition, a master switch will have to be turned on for any power to reach the pump. One and a half liters of water will be continually circulated throughout the entire system by the pump.

3.2.3.1 Watertight Container and Styrofoam Insulation

A plastic Tupperware container will be used to hold the thermally treated water. This container will be 14cm wide, 14cm long and 11.25cm high. The Tupperware container will be equipped with a tight-fitting, watertight lid. Furthermore, this container will be insulated with firm Styrofoam. This will act to either keep the water cool if it is cooler than the ambient air temperature, or warm if it is hotter than the ambient air temperature. The insulating Styrofoam will be 1.5cm thick, and will be placed between the Tupperware container and the reservoir aluminum enclosure. There will be a Styrofoam top which will be glued to the lid of the aluminum enclosure.

3.2.3.2 Pump

An Eheim compact 1000 water pump will be used to circulate water throughout the system. This pump has a maximum flow rate of 16L/min; however, we will be operating it at 0.8 L/min to ensure optimal heat transfer. The pump has base dimensions of 7.6cm by 5.3cm and is 9.4cm high. Furthermore, the pump will be fastened to the bottom of the Tupperware container using suction cups.

3.2.3.3 Reservoir Thermistor Circuit

A thermistor circuit identical to that described Section 3.1.2. will be used to measure the temperature of the water contained inside the watertight container. The purpose of this temperature sensor will be to provide an early warning system of any water temperatures that fall outside of our predefined safe limit of 10°C and 40°C.

3.3 The Relays

There are two relays in the system, one is a latching relay (Nais DS2Y-SL2), and the other is a standard relay (Soke JQC-3F). The DS2Y-SL2 relay is triggered by either the on/off switch, or the microcontroller. This relay is used to make a jumper connection on the 350W power supply, which is used to allow the power supply to accept current. The DS2Y-SL2 relay is triggered by an input of 5V, and is rated for 0.3A/125VAC. The JQC-3F relay will be controlled solely by the microcontroller, and is used to allow current to pass to the pump. The JQC-3F relay is triggered by an input of 5V, and it is rated for 10A/125VAC.

3.4 The Master Switch

A Light Country R19A-2 switch is used as the master switch in the system. This switch allows the passage of current from the wall outlet to the 350W power supply and the 5V power supply. It is a simple flip switch that will allow the user switch on and off power to the system. The master switch has to be in the *ON* position in order for the on/off button to work, or any other part of the system to work for that matter. The Master switch can also be used as an emergency off button as well. The Master switch will be located on the processing unit.

3.5 The Processing Unit

The processing unit is used as a means to delegate commands to the display driver, the reservoir unit, and the relays based on inputs from the control unit and the mattress pad. A basic block diagram of the interactions of these components is shown in Figure 10. At the heart of the system is a microcontroller, which controls the operations of each individual component in the system. This is a key component of the Perfect Balance sleep system, without a microcontroller, all other components of the system are useless. After considering the complexity of our control system and the nature of our inputs and outputs, we selected the Microchip PIC18F458 8-bit microcontroller. We chose the PIC18F458 due to its low-cost, large I/O pin count, Serial Peripheral Interface (SPI), Pulse-Width-Modulation (PWM) port and on-board EEPROM.

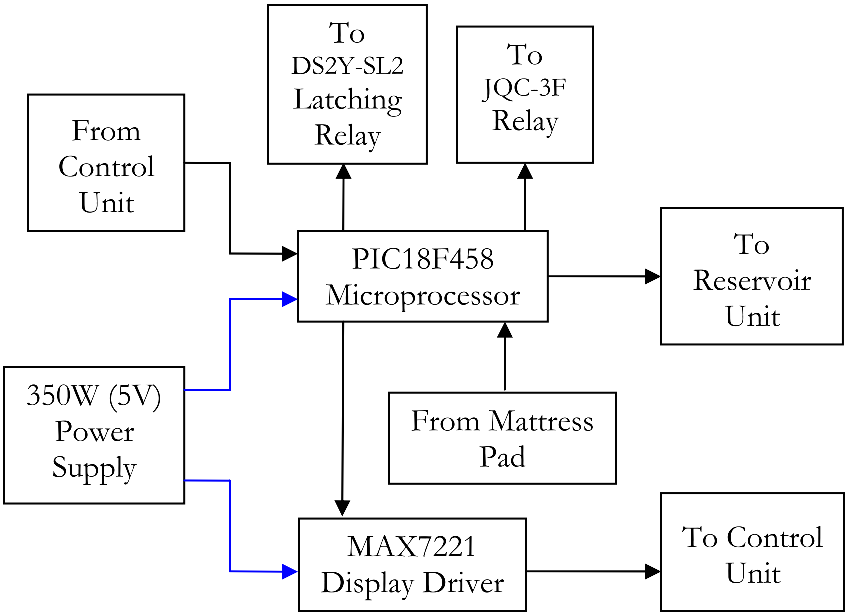

Figure 10 – A Block Diagram of the Processing Unit

3.6 The Control Unit

Interaction with the user will be achieved through the control unit. The control unit simply consists of four momentary switches, which will be used as input buttons to power the system on and off, toggle between actual and desired mattress pad temperatures, and increase and decrease the desired mattress pad temperature. The 5V power supply will power the control unit's Power button while the 350W power supply will power the Display Mode button as well as the Increase and Decrease desired temperature buttons. The principal means of communication between the system and the user is accomplished through the use of a 4-digit, 8-segment LED display. With a 4-digit display, it is possible to present the user with temperature readings accurate to three significant digits and include a "C" or "F" character in the fourth digit position to represent whether the displayed value is in degrees Celsius or degrees Fahrenheit, respectively. Because we wanted a display that would be easy-to-read for an individual in bed without glasses or without light, we decided to use the Lumex LDQ-N512RI common cathode LED display. The LDQ-N512RI features large14.22mm high digits with green LED segments. In order to drive our LED display, we could have used the PIC18F458; however, in order to conserve I/O pins and processing power on our microcontroller for other system tasks, we decided to employ the use of a slave microcontroller to drive the display. We found the Maxim MAX7221 common cathode LED display driver to be the ideal device for this application. By using a 3-wire Serial Peripheral Interface, we were able to connect the PIC18F458 microcontroller to the MAX7221 display driver such that simple and quick write commands for the display could be sent to the MAX7221 for interpretation. A more in-depth look at the SPI communication between the microcontroller and display driver is presented in Section 4.1.

3.7 The 350W Power Supply

The TEC modules are power hungry devices, and require a constant and stable supply of current for efficient operation. Because of their reliable track record and high quality, an Enermax 350W PC power supply has been chosen. This power supply is powered from a 120V AC socket, and will only be active when the master switch is in the *ON* position and the DS2Y-SL2 relay of the control unit is latched. The 5V and the 12V outputs from the PC power supply will be used to power all electrical components of the Perfect Balance mattress pad, except for the on/off button. Figure 11 shows the various connections to the 350W power supply.

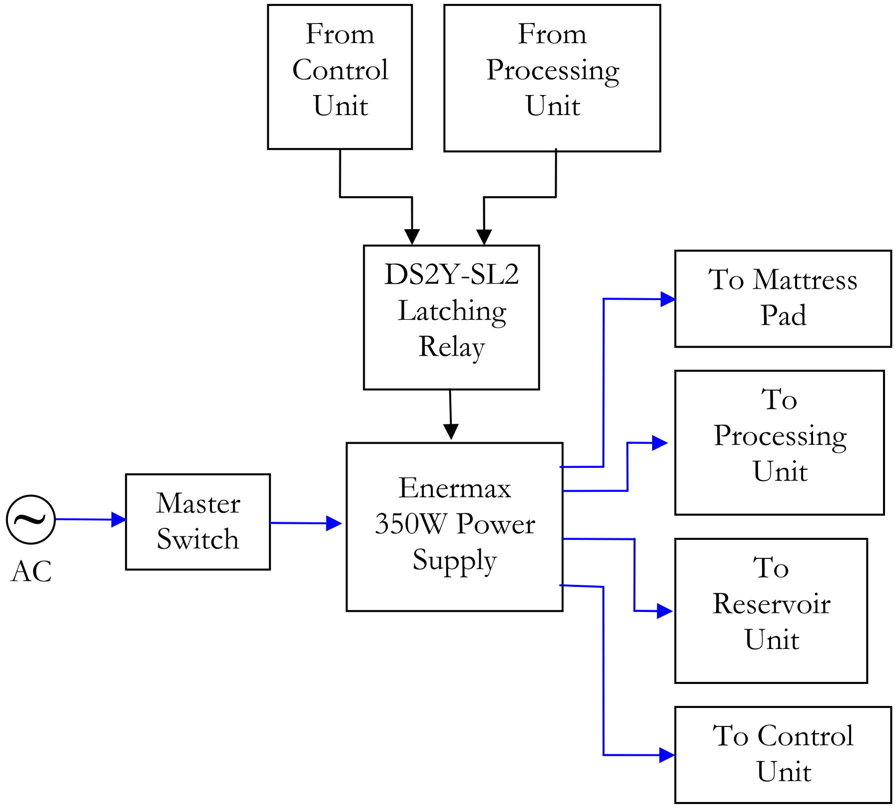

Figure 11 – A Block Diagram of the 350W Power Supply

3.8 The 5V Power Supply

The 5V power supply is used to power the on/off button of the control unit. The heart of this power supply is a MagnaQuest 5V transformer. This power supply is powered from a 120V AC socket, and will only be active when the master switch is in the *ON* position.

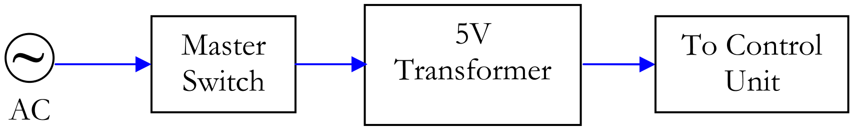

Figure 12 – A Block Diagram of the 5V Power Supply

4 SYSTEM FIRMWARE

For our microcontroller to perform all the tasks and calculations that are essential to the successful operation of the Perfect Balance sleep system, we had to embed software into its flash program memory. Such embedded software is often termed firmware due to its implementation into an integrated circuit chip's Read Only Memory (ROM) and inability to be later modified by an end user. With the PIC18F458, there are two principal means of creating such firmware. Specifically, one can create the embedded software using the low-level assembly language (machine code) or using the higher-level C programming language. In the beginning, ThermaCool intended to develop all firmware using assembly language due to the relative simplicity of the Perfect Balance sleep system. However, it was later on discovered that a key equation for linearizing the non-linear voltage values generated by our temperature-sensing thermistor circuits required the use of several complex mathematical functions available only with the math library within the C programming language. At this point, we chose to begin development of the firmware using version 2.40 of Microchip's MPLAB C18 compiler within version 7.01 of the MPLAB® Integrated Development Environment (IDE).

Our firmware is comprised of four main software modules. There is the LED display driver module, the control unit interface module, the temperature-sensing circuit module and the TEC driver module. In this section we elaborate on the importance of each of these modules and provide an understanding of their interaction with the microcontroller.

4.1 LED Display Driver

In order for the microcontroller to communicate with the MAX7221 display driver, it was necessary to utilize the SPI ports on the PIC18F458. SPI enables the serial communication of data between two devices using only 4-wires. Because the microcontroller was only required to send write commands to the display driver rather than send *and* receive commands, only 3-wires were required for the interconnection of the two devices. The exact circuit used to establish communication between the microcontroller and the display driver is shown in Figure 13. Also seen in the aforementioned figured is the interconnection of wires between the MAX7221 display driver and the LDQ-N512RI LED display.

Write commands are sent from the microcontroller to the MAX7221 display driver in two bytes (16 bits of information). The first byte is used to specify the address of the register to which the following second byte of data will be stored. These two bytes of serial data are sent out of the Serial Data Out (SDO) port of the microcontroller and arrive at the Data In (DIN) port of the MAX7221. Each bit of information contained within these bytes is clocked into the MAX7221 on the rising edge of the Serial Clock (SCK) signal which is output to the Clock (CLK) input of the display driver. Each transmission of a write command (two bytes) must occur while the Chip Select (CS/) signal to the display driver is low. Once the transmission of the serial data is complete, the CS/ signal is sent high to latch the data into the MAX7221.

In order to display the "C" or "F" character to denote ºC or ºF respectively, it was required of us to operate the MAX7221 device in its no-decode mode of operation. Otherwise, the MAX7221 would be run in its B-decode mode of operation which would only display Code B Fonts to the display, which includes the characters 0-9 and letters E, L, H and P.

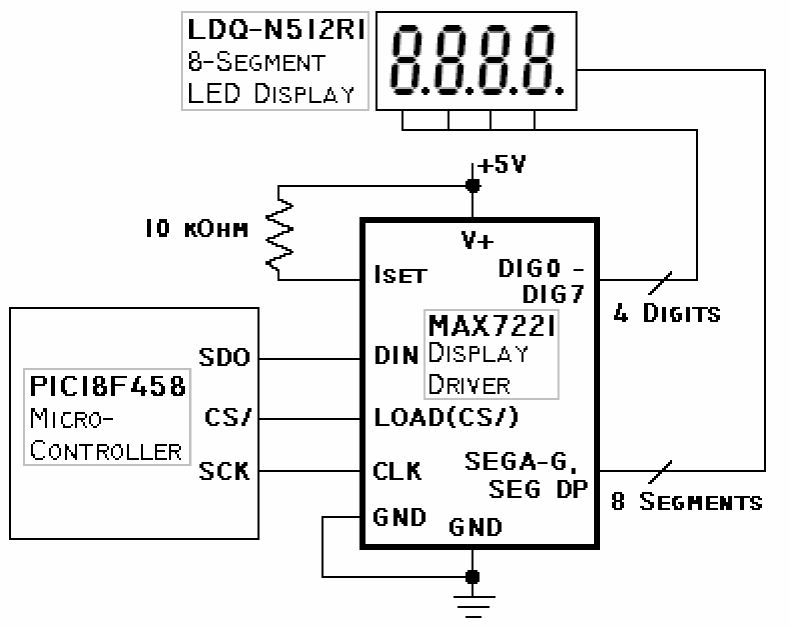

Figure 13 – Interconnection of the Microcontroller, Display Driver and LED Display

4.2 Control Unit Interface

The control unit interface accepts user input in the form of button presses. In order to use these button presses to perform various tasks, the microcontroller must be setup such that it can recognize when a button has been pressed, and what button has been pressed. This task of "button press detection" can be accomplished through the use of microcontroller interrupts. Specifically, the PIC18F458 features an "Interrupt-On-Change" capability on PORT B pins 4 through 7. Therefore, each of the Power, Select, Warm and Cool buttons is connected to one of the four Interrupt-On-Change capable pins in order to detect user input. In this manner, when any of the four interface buttons are pressed, a digital high signal of 5V will be observed at one of the PORTB<4:7> pins. When the microcontroller realizes this 5V signal, it will set a PORTB-specific interrupt flag (the RBIF bit) at which point the main program will be redirected to an interrupt routine to investigate which button was just pressed. In order to determine which button has been pressed, the microcontroller will compare a set of global shadow variables containing the last know state of pins at PORTB<4:7> to those currently observed. After the pin state comparison is complete, it is known which button has been pressed, and the program can proceed to carry out the appropriate control subroutine.

The below table shows the association of the user input buttons with the PORTB Interrupt-On-Change pins, and their resulting actions.

Table 1 – Description of User Input Interrupts

Interface Button	PORTB Pin	Resulting Action
Power Button	RB4 (digital I/O)	Send a 5V "Kill" command to the 350W power supply via latching relay and shutdown microcontroller to effectively turn all relays and system OFF
Select Button	RB5 (digital I/O)	If the interface is currently displaying the Actual Temperature, then divert power from the "Actual Temp." to the "Desired Temp." LED and display the Desired Temperature. Otherwise, if the interface is currently displaying the Desired Temperature, then divert power from the "Desired Temp." to the "Actual Temp." and display the Actual Temperature of the mattress pad
Warm Button	RB6 (digital I/O)	If the interface is currently displaying the Desired Temperature, then increment the desired temperature global program variable by 0.5, and write the updated value to the LED display. Otherwise, if the interface is currently displaying the Actual Temperature, then simply divert power from the "Actual Temp." to the "Desired Temp." LED and display the existing desired temperature value (subsequent Warm Button presses will then increment the value)
Cool Button	RB7 (digital I/O)	If the interface is currently displaying the Desired Temperature, then decrement the desired temperature global program variable by 0.5, and write the updated value to the LED display. Otherwise, if the interface is currently displaying the Actual Temperature, then simply divert power from the "Actual Temp." to the "Desired Temp." LED and display the existing desired temperature value (subsequent Cool Button presses will then decrement the value)

4.3 Temperature-Sensing

As was first mentioned in Section 3.1.2, the output of the temperature-sensing, thermistor voltage divider circuits is non-linear. However, in order to execute an accurate system response (warm or cool the mattress pad) with proper magnitude and direction over a wide range of temperatures, linear data must be used. Fortunately, there exists a linearizing equation named the Steinhart-Hart equation which can be used to linearize the non-linear thermistor resistance values. This linearizing equation is as follows,

$$\frac{1}{T} = A + B\ln(R) + C(\ln(R))^3, \tag{1}$$

where R is in Ω, and T is in °K. The constants A, B, and C are obtained from experimental measurements of resistance at three different temperatures, and were found to be 1.1378E-3, 2.327E-4, and 9.612E-8 respectively. The equation gives the reciprocal of absolute temperature as a function of the resistance of a thermistor, and allows for calculation of the temperature of a thermistor from the measured resistance [4].

Therefore, the simple algorithm used for measuring the thermistor temperature after reading in the output voltage, v_{out}, of the thermistor circuit using the microcontroller's on-board 10-bit Analog to Digital Convert (ADC) is as follows:

1) **Convert the ADC Value**
   Using one of the ADC analog input ports (any of pins <0:7> on PORTA, however we will use RA0 for the mattress pad and RA1 for the reservoir thermistor circuits) and using $v_{ref+} = v_{dd}$ = 5V and $v_{ref-} = v_{ss}$ = 0V, read in a 10-bit digital value from the ADC corresponding to v_{out} as output by the voltage-divider circuit. Take this value and convert it to a decimal float value as follows for use in the voltage-divider equation circuit,

   $$v_{out} = \frac{v_{adc} 5}{1024}. \qquad (2)$$

   Notice that we have multiplied the ADC value, v_{adc}, by 5V since this is our analog voltage input range, and divided by 1024 since this is our ADC bit resolution.

2) **Determine Thermistor Resistance, *R*:**
   Considering the above v_{adc} value to have been derived from a voltage-divider circuit with a 10kΩ resistor in series with a 10kΩ thermistor at 25°C, and measuring v_{adc} as the voltage drop across the thermistor with respect to ground, we can determine the thermistor resistance as,

   $$R = \frac{v_{out} R_s}{5 - v_{out}}, \qquad (3)$$

   where R_s is the approximate value of the 10kΩ series resistor, and 5V is being supplied to the voltage-divider circuit.

3) **Determine Thermistor Temperature, *T*:**
   Using the above value of *R* in Equation 1, we can solve for the thermistor temperature, *T*, in °K. A padding value of 273 is added to the *T* value in order to convert it into °C.

After this process is complete, the thermistor temperature is stored into a global program variable associated with either the mattress pad or reservoir temperature.

4.4 PWM Control of TEC Drivers

Once the mattress pad temperature is determined by following the process outlined in the above section, it can be compared against the user's desired mattress pad temperature and subsequently, a control decision can be made to either increase or decrease the temperature of the mattress pad. There are two possible outcomes of this comparison:

1) If result of $T_{actual} - T_{desired} \geq 0$, then decrease the mattress pad temperature, else
2) If result of $T_{actual} - T_{desired} < 0$, then increase the mattress pad temperature.

Of course, decreasing the temperature would imply the need to enable the cooling mode of the TECs, whereas, increasing the temperature would imply the need to enable the heating mode of the TECs. The cooling and heating modes of operation for the TECs will correspond to opposite directions of current flow, as shown in the below table.

Table 2 – TEC Mode of Operation and Associated Current Flow

TEC Mode of Operation	Direction of Current Flow
Cooling	Forward
Heating	Reverse

Therefore, in order to reverse the direction and of current flow through the TECs, we require the use of H-Bridge circuits, as were described in Section 3.2.2.4. Specifically, we have chosen the International Rectifier IR3220S H-Bridge circuits, due to their ability to source a large 6A of continuous current with low heat dissipation. The H-Bridge can be, and in our case is, used such that the direction of current flow is specified using two digital input signals and the corresponding current magnitude is specified by altering the duty cycle of a square wave using PWM. This being said, the H-Bridge circuits that drive the TECs are controlled by only 3 control signals that are output from the microcontroller. The necessary interconnections between the microcontroller and the H-bridges are tabulated below.

Table 3 – Microcontroller Output and H-Bridge Input Interconnections and Function

Microcontroller Output	H-Bridge Input	Function
RD0 (digital I/O)	IN1	When IN1 is high and IN2 is low, flow current forward through H-Bridge circuit
RD1 (digital I/O)	IN2	When IN2 is high and IN1 is low, flow current backwards through H-Bridge circuit
P1A (PWM O/P A @ RD4) (Pulse Width Modulation Output)	SS	Increase the duty cycle of the PWM waveform to increase the magnitude of current flow through the H-Bridge circuit, or decrease the duty cycle of the PWM waveform to decrease the magnitude of current flow through the H-Bridge circuit

Using the above microcontroller signal definitions and ganging control lines them together to control all four H-Bridge circuits to drive all four TECs, we are able to use the PWM module within the PIC18F458 to very accurately cool and heat the mattress pad.

5 SYSTEM INTERFACE

The human interface for the Perfect Balance mattress pad entails a simple, yet effective design. A SolidWorks model of the system interface is shown below in Figure 144.

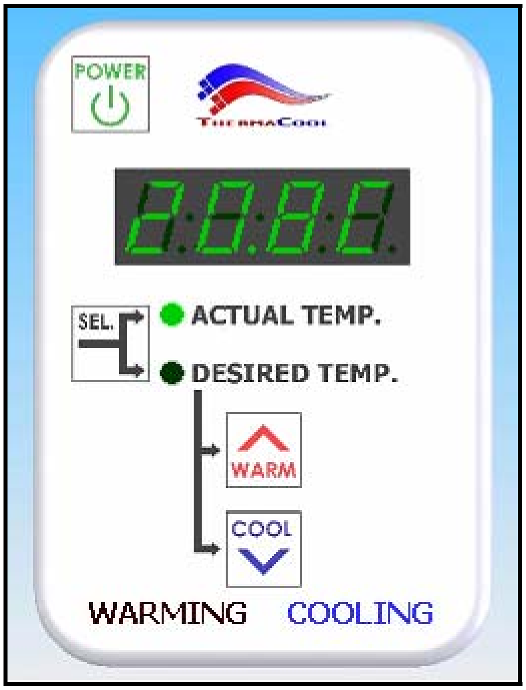

Figure 14 – Interface for the Perfect Balance mattress pad

Using only four buttons, the user can easily control the Perfect Balance mattress pad system and change the mattress pad temperature. The four buttons that make up the interface are all momentary switches, and are listed and defined in the table below.

Table 4 – Description of User Input Buttons

Control Unit Button	Description	Button Function
POWER	Power button	Toggles the system between its On and Off states
SEL.	Mode Select button	Toggles the display between showing the Actual Temperature and the Desired Temperature
WARM	Increase temperature button	Increases the temperature of the mattress pad by 0.5ºC
COOL	Decrease temperature button	Decreases the temperature of the mattress pad by 0.5ºC

In order to explain the interconnection of these buttons into the rest of the Perfect Balance mattress pad system, we have included the functional block diagram as seen below in Figure 15.

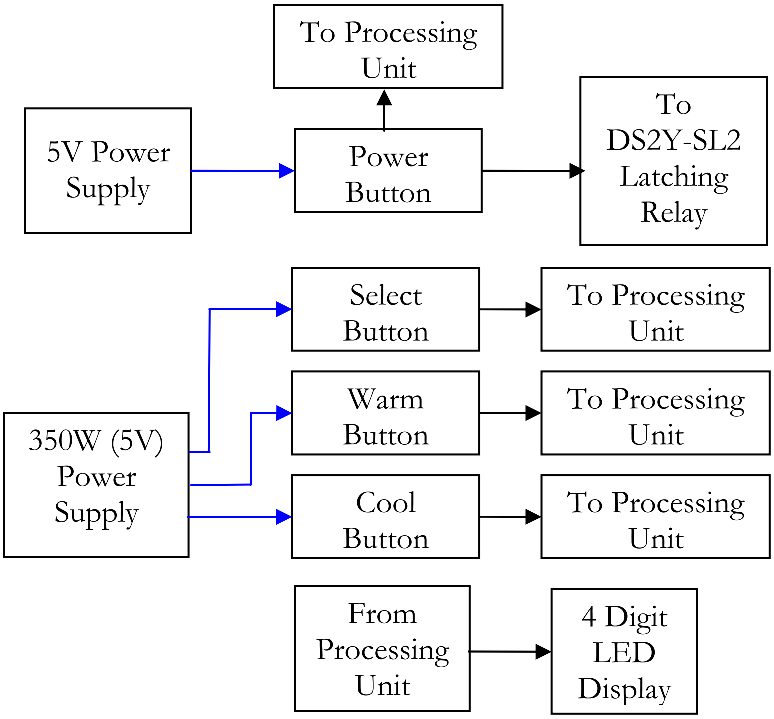

Figure 15 – A Block Diagram of the Control Unit

From the above block diagram, we see that there are two power supplies involved. Specifically, there is the 5V power supply which is always supplying 5V to the Power Button so long as the Master Power Switch of the processing unit is in the *ON* position. The 350W power supply on the other hand, is only supplying 5V to the Select, Warm and Cool buttons if the microcontroller is *ON*. To better understand the reasoning behind this approach we consider the following three scenarios:

1) **Master Switch is *OFF*:**
   Neither the 5V nor the 350W power supplies are on, and therefore none of the buttons are operational.

2) **Master Switch is *ON* and Microcontroller is *OFF*:**
   The 5V power supply is on, and the Power button is operational. In this case, if the Power button is depressed, 5V will be sent to the latching relay which will then close the circuit connection to turn the 350W power supply on.

3) **Master Switch is *ON* and Microcontroller is *ON*:**
   The 5V and the 350W power supplies are on, and all buttons are fully operational. If the user depresses any of the Select, Warm or Cool buttons, a 5V signal will be sent to the microcontroller to issue the associated command. If the user depresses the Power button, then 5V will be sent to the microcontroller in order to issue a

subsequent kill command (5V signal) to the latching relay, thus turning *OFF* the 350W power supply.

Visual cues to the user include a 4-digit, 8-segment LED display, Actual and Desired Temp. Display Mode LEDs, and Warming and Cooling status indicators as described in Table 5 below.

Table 5 – Description of Visual Cues

Control Unit Visual Cue	Description	Visual Cue Function
(No Name) *LED Display*	Temperature Display	Display to the user the Actual or Desired Temperature in either °C or °F
ACTUAL TEMP.	Display Mode Indicator	Inform the user that the interface is displaying the Actual Temperature if LED is illuminated
DESIRED TEMP.	Display Mode Indicator	Inform the user that the interface is displaying the Desired Temperature if LED is illuminated
WARMING	System Status Indicator	Inform the user that the system is currently increasing the temperature of the mattress pad
COOLING	System Status Indicator	Inform the user that the system is currently decreasing the temperature of the mattress pad

The purpose of the 8-segment LED display is to provide a means of informing the user of the actual temperature of the mattress pad, as well as to provide the user with a means of intuitively changing the desired mattress pad temperature. The "Actual Temp." and "Desired Temp." display mode LEDs are present to inform the user what temperature reading the LED display is currently displaying. Only one display mode LED will be illuminated at any given time. Finally, we have the "Warming" and "Cooling" system status indicators to inform the user of whether the mattress pad temperature is being increased or decreased, respectively. The system status indicators consist of backlit, transparent labels that will be red for the "Warming" label and blue for the "Cooling" label when illuminated. Of course only one system status label will be illuminated at any given time.

With this description in mind, we can see that in Figure 14 the control unit is displaying the actual temperature of the mattress pad as 20.8°C and the temperature of the mattress pad is currently being decreased.

6 TESTPLAN

Each major section of the design of the Perfect Balance mattress pad will be independently tested. This will make discovering sources of any errors easier, and will ensure that all components are operating efficiently.

6.1 Hardware Testplan

6.1.1 The ICs, Switches, Relays and Thermistor Circuits

To test the functionality of the PIC18 microcontroller, H-bridges, MOSFETs, relays, switches, thermistor circuits, and LED display drivers, a two stage test will be used.

6.1.1.1 Component Connection Verification

The first stage of the hardware test plan consists of verifying the component connections of the various pieces of hardware.

6.1.1.2 The Integrated Circuits (ICs), Switches and Relays

To test the PIC microcontroller, H-bridges, MOSFETs, LED display drivers, relays and switches we must do the following:

1. Verify connection of all IC pins to breadboard or PCB
2. Verify component connections match schematics

Once the component connections are verified, a second check (see Section 6.1.2) will be used to ensure hardware functionality.

6.1.1.3 The Thermistor Circuits

The thermistor circuits, which each consist of a 10kΩ resistor and a thermistor will be tested in the following manner:

1. Verify the connection of all leads to the breadboard
2. Verify all resistor values are within 5% of nominal

Once the component connections are verified, a second check (see Section 6.1.2) will be used to ensure hardware functionality

6.1.1.4 DC Power Verification

After the first step is complete, a second step will be used for all the hardware to ensure functionality:

1. Apply DC voltages across all power nodes
2. Ensure correct voltages at output nodes (note that in the case of the PIC microcontroller, this step will be completed after initializing the I/O ports)

6.1.2 The TEC Modules

Each of the four TEC modules will be tested in the following way:

1. Mount TEC module being tested on 3.2mm piece of aluminum
2. Mount heat sinks on top of TEC module being tested
3. Ensure there is adequate airflow by using an air meter
4. Supply current to the TEC module being tested
5. Use a surface mount TEC to measure the change in temperature
6. Reverse the direction of the current to the TEC module being tested
7. Use a surface mount TEC to measure the change in temperature

By completing this testplan, we will be able to see how efficiently the TEC modules heat and cool.

6.1.3 The 350W Power Supply

The 350W power supply was obtained from Enermax. It will be tested to ensure that it supplies the correct power (either 5V or 12V) when given 120V AC.

6.1.4 The Pump

The pump must be tested to ensure that it functions at an adequate flow rate. This will be done in the following way:

1. Submerge the pump in water
2. Attach a hose from the output of the pump to a container
3. Start the pump
4. Measure the volume of water in the container after one minute

6.2 Software Testplan

6.2.1 The Interrupts

Software interrupts allow for the detection of button toggles, and therefore, are imperative for the proper operation of the user interface. To ensure that interrupts function correctly, we will test each button for the required functionality, and determine that minimum lag is present.

For example, if we are testing the power button, we would perform the following tests:

1. Leave the master switch off and press the power button -> nothing should happen
2. Turn the master switch on and press the power button -> the system should power on and the display should light up
3. Ensure that the lag time between button depression and system response is not too long

6.2.2 The PWM

The PWM wave generation is essential for providing the TECs with proper power. To test the PWM generation, we will perform the following steps:

1. Program the microcontroller to execute a PWM wave of minimum frequency
2. Observe the resulting waveform with an oscilloscope and verify its integrity
3. Program the microcontroller to execute a PWM wave of maximum frequency
4. Observe the resulting waveform with an oscilloscope and verify its integrity

6.2.3 The SPI

The SPI is used to send commands from the microcontroller to the LED display driver. To ensure that the SPI is working correctly, the following test procedure will be carried out:

1. Program the microcontroller to communicate with the LED display driver via SPI
2. Attach an LED display to the display driver
3. Power the system and ensure the desired characters are displayed

7 CONCLUSION

The design specifications shown in this document outline the methods by which the major components of the Perfect Balance mattress pad will be constructed. ThermaCool is committed to using the most efficient design methods for construction of its product, and our team is continually focused on improving existing design ideas. Therefore, while the majority of these specifications are absolute, a minority are subject to change upon construction of the marketable version of the Perfect Balance mattress pad. Adequate testing will ensure that product components meet or exceed industry standards. By following these design guidelines, ThermaCool is confident that the Perfect Balance mattress pad will meet all functional specifications previously outlined.

8 SOURCES AND REFERENCES

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[4] Mastascusa, E. "Temperature Sensor – The Thermistor," March 2005, http://www.facstaff.bucknell.edu/mastascu/eLessonsHTML/Sensors/TempR.html

[5] Microchip, "PIC18FXX8 Data Sheet," March 2005, http://ww1.microchip.com/downloads/en/DeviceDoc/41159d.pdf