Thermosyphon System Design

Senior Project Final Report

Team Members:
Ben Jordan
Nick Kipe
Tyler Thumma

Advisor:
Dr. Ressler

Abstract

The Themosyphon Design Project intended to verify or adjust, if necessary, the current mathematical model of a thermosyphon hot water heater collector by building and testing appropriate prototypes of the collector and comparing these tests with the mathematical model. In the process of constructing these prototypes, we were also able to make manufacturing recommendations for the construction of the collectors and create a materials cost list based on the materials we use to construct them. The Thermosyphon Team consisted of Ben Jordan, Nick Kipe and Tyler Thumma. The Collaboratory Energy Group sponsored this project, while Dr. Ressler and Brendon Earl were the advisors.

Table of Contents

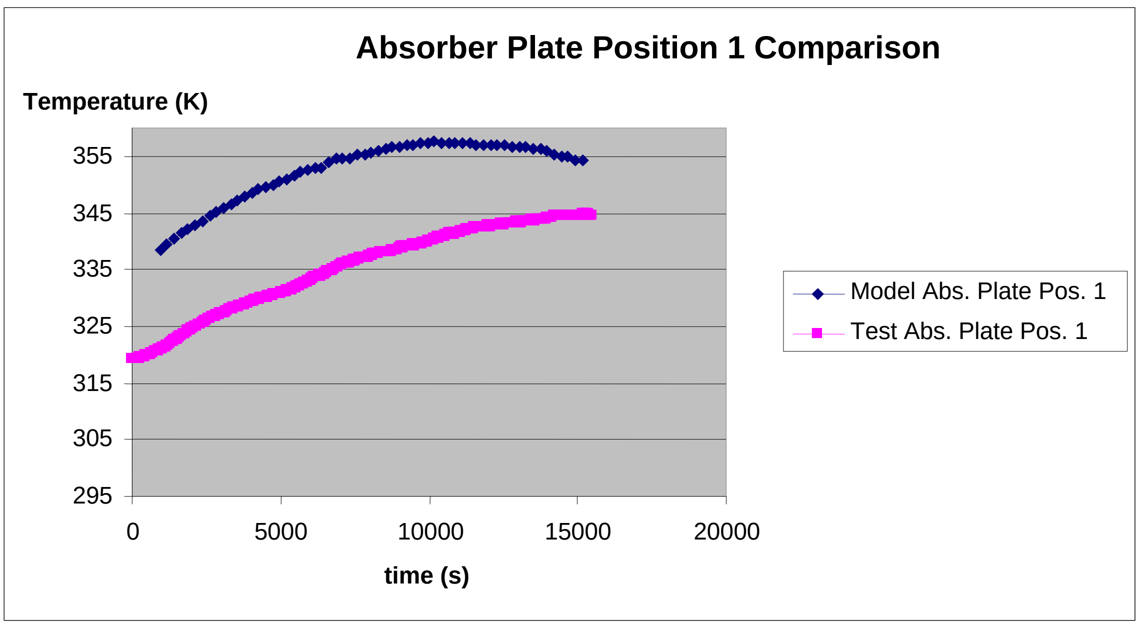
1 Introduction 4
2 Design Process 14
3 Implementation 19
4 Schedule 48
5 Budget 49
6 Conclusions 51
7 Recommendations for Future Work 53
Appendices 55

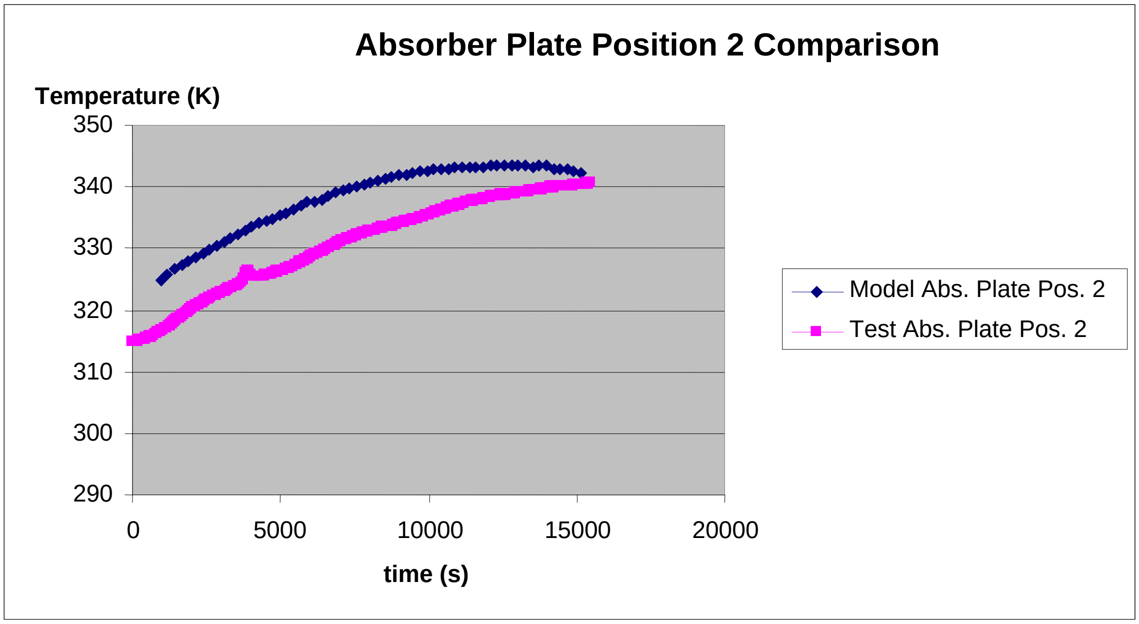
1 Introduction

1.1 Description

According to the Collaboratory website, the Thermosyphon Design Project "will result in a technique for designing and applying effective solar water heaters for specified applications." In the '04-'05 academic year a senior project team developed a mathematical model of a thermosyphon hot water heater using Microsoft Excel and a heat transfer analysis of each component of the thermosyphon system. The purpose of this model was to be able to optimize the variables of the thermosyphon system (such as pipe diameter, spacing and number of pipes) for the requirements of a particular application mathematically. In theory, this should significantly reduce engineering time by creating the ability to test different variable options in a computer program rather than in physical test models. This ability will theoretically reduce the cost to the customer by eliminating the need for multiple physical prototypes to be made and tested. This would allow regions of the world without sufficient economic or infrastructural means to have hot water without the use of electricity at a low cost. A more user-friendly version of the model could eventually be distributed to local businesses in the developing countries where, after initial training, it could be used over and over to develop thermosyphon systems for specific applications without the need for American assistance. The idea is that by training a few individuals within a geographic region with access to a computer to use the program, optimized designs can be created and used across that region. For this reason, the current user-unfriendly Excel model is being reprogrammed into a faster, more user-friendly program.

In addition to the mathematical model, the '04-'05 team constructed a working water heater to test the accuracy of the model and developed some manufacturing techniques for construction of the water heaters. The thermosyphon collector specifically was tested by measuring the temperature at two locations on the absorber plate over time, and plotting these measured values against those calculated by the model at the same locations. The graphs of the temperatures at these two locations are shown below. The model's calculations were incorrect by too large of a margin in order to make the model entirely useful, so further analysis of the validity of the model was deemed necessary. Brendon Earl, the member of the '04-'05 team who wrote the Excel model of the system, is still involved in the Thermosyphon Design Project through the Collaboratory Energy Group. He is currently working with two computer science majors on the model programming. To complete this task, further testing and possible modifications were needed to make the model an accurate predictor of actual thermosyphon collector performance.





1.2 Literature Review

Since this is a follow up project, the previous group provided us with in-depth research of the different types of solar hot water heaters. Below is a selection that applies to our project.

"The collection of solar energy has numerous applications in various fields such as photovoltaics, HVAC, and water heating, to name a few. Of these, heating water is the most common solar thermal application in the developed world. The specific solar technology that we are interested in for this project is technology in the area of domestic solar hot water heating. After considering the current state of the art of this technology, we researched current, low-cost, appropriate applications of this technology in developing countries.

Commercially Available Solar Hot Water Systems

Commercial solar hot water units are manufactured in a wide variety of designs. The most prevalent are unglazed flat collectors. These relatively inefficient designs are used primarily for swimming pool heating, fish farming, or pre-heating for applications such as car washes. The most common design for domestic water heating is glazed flat-panel collectors, in either a passive or an active system. For cooler climates where freezing is a problem, closed-loop systems are often used while open-loop systems make solar hot water more affordable in warm climates. Another often used system is the integrated collector and storage (ICS) system, or batch collector. These systems combine storage and collection in a single unit and are affordable for climates where freezing is not a major concern. The most advanced commercially available residential hot water collector is the vacuum-tube collector. In this system, each pipe is contained inside a double-layer glass with a vacuum gap. The high insulation provided makes these systems very efficient but also quite pricey.

All of these collector types are sold in various configurations. Manufacturers provide either just the collector or offer complete systems with a storage tank. Many different designs are available and combinations of the systems exist, such as a batch tank with a flat panel collector that implements the thermosyphon circulation method. In most cases, the manufactured collectors use advanced glazings, coatings, and insulation to achieve higher efficiency and, in the case of batch units, to reduce heat loss at night. Costs for a system range between $1500 and $4000 depending on design and size. Some examples of commercially available collectors and systems follow:

The CopperHeart Integral Collector Storage (ICS) uses several large-diameter copper tubes to store water and absorb solar energy. The panel is relatively flat and uses glazed glass to achieve higher efficiency. The unit costs $2075 for a 25 ft^2 collector with 40 gallon capacity.

The SunSiphon system combines a flat-plate collector with a storage tank to produce a complete solar hot water system in on package. The system is closed-loop with anti-freeze circulating through the panel passively. Hot water is contained in an attached insulated tank. Prices range from \$2191 for a 25 ft^2 model with 40 gallon capacity to \$4138 for an 82 ft^2 collector with 116 gallons capacity.

A more typical system is the Cascade Drainback system that uses flat panels with a separate storage tank. A complete system costs \$2940 for a 40 ft^2 collector and 80 gallon tank or \$3715 for 80 ft^2 of collector area with an 80 gallon tank.

Another ICS system is the Progressive Tube Batch Water Heater, which uses copper tubes to contain and heat the water. Low-iron glass is used to collect radiation and the tank is insulated. A 24 ft^2, 30 gallon model costs \$1460 while a 32 ft^2 model with 5o gallon capacity costs \$1926.

Flat plate collectors are usually relatively similar in design, function, and cost. The Sun Earth collectors are used in several complete kits being sold and sell separately for \$494 for a 3′ x 8′ model to \$687 for a 4′ x 10′ model. The absorber plate is copper and features a selective black paint. The frame is aluminum with R-8 insulation. 5/32″ low iron glass is used as the glazing.

Low-cost, Appropriate Solar Hot Water Systems

Our project focuses on designing a solar hot water heater for TCZ. This specific design has not been done before; however, our research studies show that there have been similar solar projects. In our project a solar hot water heating system will utilize the available resources of southern Africa for sustainability of the technology, will be low cost to meet the needs of our client, and will be implemented in a tropical climate (Zimbabwe). While our research resulted in only a few matching projects, we found pertinent information from other projects that contained some design aspect that would be useful to our very specified application.

A company called Energy Tech Ltd has project goals that are very similar to our own. The following is quoted from their website:

EnergyTech Ltd will develop a solar water heating system for use in developing countries, with the emphasis on ease-of-use and low costs. In collaboration with

SolarSense of Swansea, EnergyTech Ltd are looking to develop a boxed package of materials, combined with instructions, for self-assemble solar water kits comprising of flexible and resistant piping. The kits will then be assembled using locally available materials and labor, thus bring down the cost to the customer dramatically. The idea is to provide a robust product which needs limited skills for application, and will therefore be of minimal cost without compromising the quality of materials used. This company's progress may provide useful information when designing for the specific system at TCZ.

The Immediate Technology Development Group claims that the thermosyphon design is most widely used solar water heating design by developing countries due to its simplicity and reliability. This technology uses no electricity, however it requires a tank elevated above the panels. One example of its success occurred during an energy crisis in Kosovo in 2001 when forty thermosyphon solar hot water heaters were locally constructed and installed at Gjakova hospital. These low-cost energy savers not only provided hot water, but also provided jobs for those in Kosovo undergoing difficult times.

Batch solar water heaters are appropriate possibilities for developing countries as they are inexpensive, simple and require no electricity. The simplicity of this design makes it the most easily attainable solar water heating system. Also, in tropical climates (i.e. Zimbabwe) freezing is not an issue.

The unglazed solar water heaters, while extremely inexpensive, are not very effective. In fact, application of this technology is mainly used for heating swimming pools. This technology has been used to preheat water to reduce the power output of electrical hot water heaters." [1]

---

[1] Dunkle, Earl, et al. *Solar Hot Water Heating for the Developing World*. May 9 2005. Pg. 5-7.

In addition to understanding the process the '04-'05 group went through in choosing the type of solar water heater to use for their design, we also had to understand the details of the theoretical model they developed of the thermosyphon solar collector. We accomplished this research primarily through meetings with Brendon Earl throughout the fall semester.

The theoretical model of the solar collector uses the finite element heat transfer analysis method to evaluate the heat transferred from solar energy incident on the face of the panel to the water flowing through the parallel pipes. The absorber plate is first broken into symmetrical sections of pipe, each with a bend at each end which connects them to the next parallel pipe in the system or the panel input or output in the cases of the first and last pipe, respectively. Each of these pipes is then modeled as a straight pipe. Because of symmetry about the center of each pipe, an adiabatic heat transfer condition is assumed across this central axis, and only half of each pipe is modeled in the finite element model. This half of a pipe is modeled as being connected to a piece of absorber plate on one side only with a width equal to half the distance between the two pipes. This edge is also adiabatic because of a similar symmetry condition. This is all illustrated in Figure 1 of Appendix II. Heat transfer through the top and the bottom edges of the plate (into the wooden frame) are also neglected because they are assumed to be small relative to the heat transfer by conduction through the plate into the pipe and the heat lost to the environment from the top surface of the absorber plate and through the insulation underneath. This heat loss is modeled by an array of thermal resistances in series and in parallel which represent each mode of heat loss from the collector (See Figure 2 of Appendix 2). From the top of the absorber plate, heat is lost by convection to the air gap between the absorber plate and the first glazing (or simply to the ambient air if no glazing is present). From the first air gap, heat is conducted through the first layer of glazing and convected into the next air gap (or to the ambient air if only one layer of glazing is present). From here, heat is conducted through the last layer of glazing and convects to the ambient air from the top surface. Radiant energy is also emitted from each of these surfaces to their surroundings. With each layer of thermal resistance, the amount of heat lost to the environment is reduced, resulting in more heat transferred to the water in the pipe. From the bottom surface of the absorber plate, heat is conducted through the insulation and then through the wood on the bottom of the collector, and finally convected to the air below the collector. Radiant energy is also emitted from this surface to the surroundings. All of these paths of heat transfer are analyzed in a separate section of the theoretical model to determine the total heat lost to the environment. This total heat loss is combined into a single effective heat loss coefficient which is used in the analysis of the heat transfer of the absorber plate, pipe and water themselves. The absorber plate itself is modeled with a number of finite elements, with the temperature in each element given by the equation

$$T_{xy} = \frac{I \cdot A_{xy} + \frac{k_{abs} \cdot A_x}{L_x}(T_{x-1} + T_{x+1}) + \frac{k_{abs} \cdot A_y}{L_y}(T_{y-1} + T_{y+1}) + U_{col} \cdot A_{xy} \cdot T_{amb}}{2\left(\frac{k_{abs} \cdot A_x}{L_x}\right) + 2\left(\frac{k_{abs} \cdot A_y}{L_y}\right) + U_{col} \cdot A_{xy}}, \text{ where}$$

T_{xy} = temperature at element (x,y)

I = solar insolation

A_{xy} = area of finite element (x,y)

k_{abs} = absorber plate thermal conductivity

A_x = area for conduction in x-direction (perpendicular area to x)

L_x = length for conduction in x-direction

T_{x-1} = temperature of element (x-1,y)

T_{x+1} = temperature of element (x+1,y)

A_y = area for conduction in y-direction (perpendicular area to y)

L_y = length for conduction in y-direction

T_{y-1} = temperature at element (x,y-1)

T_{y+1} = temperature at element (x,y+1)

U_{col} = effective collector heat loss coefficient

T_{amb} = ambient temperature

The derivation of this formula is shown in Figure 3 of Appendix 2. The last column of finite elements of the absorber plate provides the thermal connection to the pipe, which is modeled as the next column of finite elements which are half the width of the plate finite elements. Heat transfer occurs across an equivalent resistance of the solder and pipe connection. This resistance is given by the equation

$$R_{eq} = \frac{1}{4}\pi D \Big/ k_{pipe} \cdot \Delta y \cdot c_{sp} + t_{solder} \Big/ k_{solder} \cdot \Delta y \cdot \frac{w_{solder}}{2}, \text{ where}$$

D = pipe outer diameter

k_{pipe} = pipe thermal conductivity

Δy = y-direction finite element length

c_{sp} = circumferential length of solder on pipe

$$= \sqrt{(t_{solder})^2 + (w_{solder})^2}$$

t_{solder} = average thickness of solder

k_{solder} = solder thermal conductivity

w_{solder} = width of solder along absorber plate

This equation was developed by Brendon and involves a number of simplifications and assumptions. From the pipe finite element, heat is transferred into the last column, which models the water flowing through half of the pipe. A partial finite element array in 2D and 3D can be see in Figure 4 if Appendix 2.

1.3 Solution

Our project's primary goal was to begin the thorough analysis of the theoretical model by comparing it with actual thermosyphon system performance. In order to do that, we had to first completely understand how the model works and what assumptions and simplifications Brendon Earl used. Our project focused on one sub-system of the entire thermosyphon system: the solar collector. In this sub-system, solar energy is transmitted to an absorber plate through glass pane(s) or glazing(s), and then transferred through the absorber plate and into the water pipes, which contain the water being heated. Not all of the solar energy incident on the collector is absorbed, as some is reflected away or lost by convection to the surrounding air. After researching the analysis done on this system to understand its model, we developed the following objectives for our project:

1. Get model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a single pipe and controlled temperature boundary condition.
2. Get model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a single pipe and known insolation.
3. Get model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a pipe array and known insolation.
4. Identify any limits to system parameters that cause model temperatures to fall outside the expected range of uncertainty of experimental temperature results.
5. Identify manufacturing lessons learned during construction of test prototype collectors.
6. Identify a set of available materials and costs for U.S. manufacturing of parallel pipe flat collectors.

These objectives would be met by constructing test prototypes to confirm or reject the way in which the system was modeled. The first test prototypes consisted of extremely simplified components of the system which allowed us to test the most basic assumptions made in the model analysis and was intended to verify the conduction heat transfer analysis only by eliminating the variable of insolation (solar radiation). The second test was then designed to verify the modeling of this added variable of insolation by using the same simple prototypes from the first test, but placing them in the sun in an enclosure similar to those used for actual thermosyphon solar collectors. A final test intended to verify a more complex array of pipes against the model's simplified single-pipe analysis, while maintaining the variable of insolation. By using this method of graduated test complexity, we could verify the most basic elements of the model first, before moving on to the complex analysis of the entire collector. Throughout all of these tests, we chose to vary the parameters of pipe diameter, pipe length and pipe spacing, which were determined to be the most important variables as a result of discussions with Brendon Earl. Through the use of multiple tests under different conditions, we also were able to vary the parameters of insolation, ambient temperature, and flow rate. In addition to the verification of the model, building test prototypes gave us the ability to document any manufacturing issues we encountered and tips for construction of the collectors. These suggestions will aid in the future development of manufacturing techniques for these kinds of collectors which will also be included in the final program. In addition, we documented the material costs of the collectors we built for use in future cost analyses of different collector designs in the program.

2 Design Process

Our design process began by choosing what part of the thermosyphon system model we wanted to verify with experimental results. The two most significant sub-systems of the system in terms of modeling it were the tank and the collector. Many significant and uncertain assumptions were made in the modeling of both of these systems, so substantial research was needed for both. We chose to focus on the collector sub-system because we felt this was the most important piece of the system because it is where the heat is actually transferred from the sun to the water itself. From the analysis of the thermosyphon prototype built in '04-'05, the collector panel had the greatest variation between theoretical and actual temperatures. It is also the most complex system, and therefore would derive the greatest benefit from an entire senior project being devoted to it. The other systems may be able to be studied by individuals or by members of the collaboratory group because of their relative simplicity. We also chose the collector because it would allow for the most in-depth hands-on construction, which we felt would be a rewarding aspect of a senior project.

Once we selected the collector as our system to analyze, there were many alternative paths we could have taken to test it. One approach could have been to simply build an entire prototype of the collector from the start, and attempt to compare the experimental results obtained from this prototype with the much simpler theoretical model. We instead chose an approach of starting simple and building in complexity because this would allow us to verify the most basic assumptions first before moving to more complex ones. We believed it would have been difficult to identify discrepancies between the prototype and the theoretical model if the prototype contained all the variables of the actual system. We also had to decide on a few parameters to vary among many potential ones. We chose to vary the parameters of the pipes themselves (diameter, length) and the absorber plate width, because Brendon felt these were the most influential parameters to the model performance.

The next step in our design process was planning the actual tests we would run and the prototypes we would need to build in order to run the tests. The first series of test prototypes of the collector were designed almost exactly as they were assumed to be simplified in the theoretical model: as single straight pipes soldered to an absorber plate. Since we were unable to use half of a pipe with water flowing through it to simulate the adiabatic condition discussed previously, we essentially mirrored the theoretical modeled half of a pipe and half an absorber plate width on one side onto itself so that we have a whole pipe with half of an absorber plate width on each side of the pipe with the pipe centered on the absorber plate (See Figure 5 of Appendix 2). This first test design does not evaluate the assumptions made by assuming straight pipes all with equal inlet and outlet temperatures, but it will show us how accurately the model simulates this simple situation once we analyze the results. The first test was designed to apply a known (measured) temperature along the vertical edges of the absorber plate in a controlled environment and with a known water inlet temperature and flow rate through the pipe. As the pipe is heated along this edge, the temperature variation along this edge and at various locations throughout the absorber plate, as well as the output water temperature were measured over time until the system reached steady-state. We could then verify the method in which heat transfer through the plate and into the water was modeled by inputting the measured edge temperature variation into the program, then comparing the measured temperature values throughout the absorber plate and at the water outlet to those given by the simulation when we input all the parameters of our test setup.

The first test consisted of four separate prototypes in which the pipe diameter, pipe length, and absorber plate thickness are varied to prove the model correlates to experimental results for a range of these parameters. They consisted only of an absorber plate with a pipe soldered on one side and then covered on that side with insulation. By removing the extra components like the wooden frame and glazings, as well as the complex variable of insolation, these parameters can be eliminated from the model so that only conduction through the plate and convection and radiation from the plate can be analyzed and verified. The final design of each of these prototypes can be seen in Figure 6 of Appendix 2.

The next test was designed to re-use these first prototypes, but more accurately simulate the way in which heat is transferred to the absorber plate. Instead of applying a known temperature at the edges of the plate, the plate was exposed to a known (measured) solar insolation on its top surface (see Figure 7 of Appendix 2). Also, the prototypes were contained in a wooden frame and covered with a sheet of glass to simulate an actual collector panel and to enhance heat transfer to the water so a more significant temperature increase could be achieved. The design of this enclosure can be seen in Figure 8 of Appendix 2. Like the first test, this test measured the temperatures throughout the absorber plate as well as the water inlet and outlet temperatures and flow rate. This test added the need to measure the velocity of the ambient air to which heat is convecting, and the solar energy incident on the surface of the absorber plate. Having established that the conduction, radiation and convection were accurately modeled in the first test, this test allowed us to analyze the accuracy with which the insolation heat transfer is modeled. It also analyzed how accurately the model simulates heat influx from the top surface rather than through the sides.

The final test design included a new and more complex prototype design, in which an entire collector was made with four parallel pipes. The final design also was placed in a wooden frame with a layer of glass and was again exposed to a known solar insolation on its top surface (see Figure 9 of Appendix 2). Since we know that the heat transfer from the sun to the water is correctly modeled from the previous test, this final test was developed to analyze the assumptions made with regard to the interactions of multiple parallel pipes in a collector. The final design of the third test collector panel and enclosure can be seen in Figure 10 of Appendix 2.

During our design process, we developed the following test specifications based on our objectives:

The theoretical model will do the following:

1. Determine the output water temperature and absorber plate surface temperatures throughout the collector within the expected range of uncertainty.
2. Take minimal explanation (less than 5 minutes) and be easy to use.
3. Comprehensively manage all of the possible input variables (between 8-12 different variables).

Test Prototype Specifications

Flow Rate	$1x10^{-7} < Q < 1x10^{-5}$ m^3/s
Input Water Temperature	$15 < T_i < 25$°C
Pipe Material	Copper
Absorber Plate Material	Copper
Pipe Diameter	0.25 in < D < 1 in
Pipe Spacing (Absorber Plate Width)	10 cm < δ < 30 cm
Pipe Length	0.5 m < L< 2.0 m
Glass Thickness	0.125 in < t < 0.25 in
Applied Plate Boundary Temperature	400°C < T_s < 600°C
Incident Insolation	700 W/m^2 < I < 1000 W/m^2
Insulation R-value	R-13 or better

Other Specifications:

1. The purchasing of materials for construction of test prototypes will provide a list of typical material costs for collector panel construction.
2. The construction of test prototypes will provide a list of manufacturing instructions and lessons for collector panel construction.
3. This project will determine any limits to the parameters of pipe length, pipe diameter, and pipe spacing.

Having designed the test method, each of the specific test setups, all of the collector panel prototypes and enclosures, and the test specifications, we were finished with our design process.

3 Implementation

3.1 Construction

The majority of the construction of our test prototypes and their enclosures was fairly simple. The design of our first two test prototypes required only a soldered connection between a straight pipe and a flat strip of absorber plate, and fittings to be soldered to the ends of each pipe for the connection to the water source. The construction of the first prototypes was completed at Dickinson College's maintenance shop. Construction began by cutting each of the pipes to their desired lengths. The copper flashing was measured and marked to the required sizes of the absorber plates' widths and lengths, and then the absorber plates were cut with snips. The centerline of each absorber plate was marked where the pipe was to be soldered, then this centerline was cleaned with sandpaper before applying flux. The pipes were also sanded and fluxed in the same manner along the surface to be soldered to the absorber plate. The pipe was then placed along the centerline of the plate and clamped into place. The edges of the plate were also clamped down using long steel bars to reduced possible warping when the heat of the soldering torch was applied. The soldering process started at one end of the pipe by concentrating the heat of the torch directly on the contact area between the plate and the pipe. This heat was applied on the back side of the pipe, while the solder was touched to the opposite side so it would flow toward the heat once it melted. The heat and solder were slowly moved down the length of the pipe so that a bead of solder was created between the pipe and the plate, establishing a good thermal and structural bond. After the soldering the pipe to the plate, the fittings were soldered to the end of each pipe.

After constructing the prototypes for the first two tests, these prototypes had to be prepared for the first test. First we had to connect the thermocouples to the top of the absorber plate along the edge where the temperature was applied, as well as at various locations throughout the middle of the absorber plate. This was done using a high conductivity paste and high temperature tape. The other ends of these thermocouples were inserted into the various channels of the board we used to collect data. We then cut insulation to the required length and width in order to place it underneath the pipe. This simulates the design of the actual collector panel, which uses insulation to reduce the heat lost from the bottom surface of the absorber plate and from the pipe itself. The first test also required the construction of the wooden boards which supported the test prototypes as well as insulated the pipe from the direct heat from the Bunsen burners. These were simply scrap boards from the engineering shop, which we stood on end and nailed 2x4 scraps to so they would be stable. These boards were clamped close together to allow enough absorber plate overhanging on each side to contact the burner flame without catching the wood on fire. The water inlet fitting was connected to the faucet using a ½" hose, and the outlet was connected to a short piece of hose which was bent up to cause the pipe to be filled with water. A thermocouple wire was inserted into this outlet hose to measure the outlet temperature of the water and therefore the temperature change.

The second test required the construction of an enclosure to hold a layer of insulation and a panel of glass, between which each of the four test prototypes could be placed for testing. This construction was completed at Dickinson College's maintenance shop. First, scrap pieces of wood were cut to the desired lengths and widths for the sides and bottom of the testing enclosure. A groove was cut into the pieces to be used for the sides of the enclosure to hold the panel of glass. A hole was drilled in each end piece to allow for insertion of both ends of the pipe. The bottom of the enclosure was secured to three of the sides with wood glue and nails, while the fourth side (end piece) was only screwed in to the two adjacent sides to allow for quick removal so that the test prototypes could be changed out. A piece of insulation was cut to the inside dimensions of the enclosure and placed in the bottom. Finally, the glass panel was slid into place and the end piece was secured temporarily for transportation.

The prototypes themselves had to be modified slightly for the second test by painting their top surfaces black to enhance solar absorption. They were each cleaned and prepared for paint with paint thinner, and then coated with two layers of flat black spray paint. When it came time for each test two prototype to be tested, it was inserted into the test enclosure and then thermocouples were placed at five locations on the surface. The thermocouple wires were secured with thermal tape and aluminum duct tape to maintain a strong bond to the absorber plate surface. Once each prototype was prepared, the glass panel was slid into place over the prototype and the end piece was secured in place for testing.

The third test required the construction of a new pipe array and absorber plate prototype as well as a new enclosure. The pipe array was constructed first, in a manner similar to the single pipe prototypes for the first two tests. First, the long, vertical pipes were cut to length and the ends were sanded to prepare them for soldering. Then the short, horizontal pipes were cut to their appropriate lengths to allow for the correct pipe spacing, and the ends were sanded. The entire pipe array was assembled to ensure correct fitment before soldering. Each piece was then removed, fluxed, and then reassembled to be soldered. The entire array was soldered together by heating each joint at a time with a torch and applying solder wire until it flowed into the joint. All of this soldering was done on a table so the array would remain flat. Once the soldered array had cooled, it was positioned on the copper flashing which would become the absorber plate. The position was marked, and then all connecting surfaces between the pipe array and the absorber plate were cleaned, sanded and fluxed in preparation for solder. The pipe array was then placed back in position on the absorber plate and clamped down using long vice grips. The edges of the absorber plate were also clamped to the table using long steel bars and vice grips to reduce the warping during soldering. Each pipe was then soldered to the plate by heating one side and applying the solder wire to the other side to allow the solder to flow into the connection. The heat and solder were moved simultaneously down the length of each pipe until all of the pipes were completely soldered to the plate. Once the assembly cooled, the surfaces were cleaned from flux residue. The top surface of the absorber plate was cleaned with paint thinner and coated with flat black spray paint.

Next, the enclosure was constructed in a manner similar to the second test enclosure. The bottom of the enclosure was constructed first by cutting pieces of particleboard to the required lengths and widths. The side and end pieces were all ripped to the appropriate width and length, and then a groove was cut for both the glass and the absorber plate to slide into. The two ends and one side piece were secured to each other and to the bottom with wood glue and nails. A hole was cut in each of the side pieces to allow for insertion of the inlet and outlet pipes. A piece of insulation was cut to the dimensions of the enclosure and placed inside. Next, the absorber plate and pipe assembly was slid into its groove. Thermocouples were secured to the top surface and on the surface of one of the pipes with thermal tape and aluminum duct tape. Each tape connection was also spray painted flat black so that uniform absorption would occur on the surface. Finally, the glass panel was slid into place above the absorber plate and the side of the enclosure was secured with screws so it could be removed if necessary. Photographs from the construction of the third test collector panel and enclosure can be seen in Figure 15 of Appendix 2. This completed the construction for our project.

3.2 Operation

The operation of our project involved two major components: running the tests to collect data and inputting this data into the program to analyze it. The first test was completed in the fall semester. In this first test, we heated the edges of the prototypes' absorber plates with 3 Bunsen burners on each side. Each pipe and the bottom surface of each plate were insulated with a layer of R-13 insulation to simulate the actual insulation that would be present on a thermosyphon collector. To protect the actual pipes from direct heat from the Bunsen burners, we placed a wooden block between the Bunsen burners and pipes on each side. This was important because we wanted only to test conduction from the plate to the pipe. While testing, we improvised with these wooden blocks. To provide more room on the outside edges of the plates, we clamped the two wooden blocks together, which allowed us to place the burners directly under the edges of the plate without getting the flames too close to the wood. This process took some trial and error to get the proper alignment. Because the absorber plate for the ¼ inch pipe was so narrow, we were unable to use this prototype for the first test because there was not enough absorber plate beyond the wooden blocks to touch the flame to. We placed 14 thermocouples throughout the top surface of the plate to create a representative array of temperatures, as well as one thermocouple in the end of the pipe to measure the output water temperature. These T-type thermocouples were then connected to the National Instruments data collection equipment which interfaced with a computer to automatically collect the temperature data for our test. We measured the input water temperature by collecting some of the water from the tap and then measuring the temperature with a thermometer. The flow rate was measured by collecting the water in a graduated cylinder over a measured amount of time, and using the volume collected over the time to determine the flow rate. The ambient air temperature was measured using a thermometer.

In addition to these inputs, certain parameters of our prototypes had to be measured to input into the program. The pipe length was equal to the length of our absorber plate as it was designed. The absorber plate width (pipe spacing) was measured as the actual width of the plate which was insulated underneath. We could not use the whole width of the absorber plate in the program because the edges were not insulated and therefore did not have the same heat loss coefficient as the insulated section. The pipe inner and outer diameters were determined from copper pipe specifications, but were verified with calipers. The absorber plate thickness was measured at multiple locations with calipers. The width and average thickness of the solder were also measured with calipers at multiple locations along the connection of each pipe to its absorber plate to find an average. In addition to these measured parameters, we used the thermal conductivity of the pipe, plate and solder which the previous senior project group had researched and found because our materials were the same.

After inserting each of these inputs and parameters into the program, an appropriate method of analyzing it needed to be determined. Since our applied temperature boundary condition consisted of three hot spots where the Bunsen burners were on each side of the prototype, we decided to estimate the temperatures of these hot spots based on the measured temperature values throughout the absorber plate. The location of each hot spot and measured spot were marked on the Excel program with red letters and highlights, respectively. Initial temperature guesses were placed in each hot spot cell, replacing the original formulas for these cells with this constant temperature value. The program was then solved, and the resulting water and absorber plate temperatures were compared to the experimental values. Then each of the temperature guesses was modified and the program was resolved until the program's temperatures matched the experimental temperatures. Our first solution method was to assume the modeling of the absorber plate conductivity was correct by matching the theoretical and experimental absorber plate temperatures as closely as possible and then comparing the output water temperatures. Our other solution method was to assume the modeling of the heat transfer into the water was correct by matching the theoretical and experimental water temperatures as closely as possible and then comparing the absorber plate temperatures. The results for each of these tests can be seen below.

Test 1: ½ Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	295.37		
Effective Collector Heat Loss Coefficient (W/m^2*K)	16.93		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	297.104		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.24835E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4351		
Pipe Spacing - Vertical Array (m)	0.1016		
Pipe Inner Diameter - Vertical Array (m)	0.0144526		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	323.372528	325.975	5.166451
Absorber Plate Position 3 (K)	309.0254289	309.805	2.163947
Absorber Plate Position 4 (K)	315.2140668	316.906	4.007984
Absorber Plate Position 5 (K)	352.3810948	366.326	17.56704
Absorber Plate Position 6 (K)	339.9979126	337.956	3.047726
Absorber Plate Position 7 (K)	309.3438563	308.226	3.075778
Absorber Plate Position 8 (K)	323.9278665	323.491	0.857814
Absorber Plate Position 9 (K)	332.1605259	328.323	6.486633
Absorber Plate Position 10 (K)	349.9259998	341.536	10.90659
Absorber Plate Position 11 (K)	307.3972785	304.94	7.143817
Absorber Plate Position 12 (K)	317.2429417	314.198	6.882322
Absorber Plate Position 13 (K)	321.7372754	322.534	1.634734
Absorber Plate Position 14 (K)	342.0889352	339.128	4.285687
Output Water (K)	316.2637935	318.328	4.77121

Test 1: ¾ Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	295.37		
Effective Collector Heat Loss Coefficient (W/m^2*K)	16.93		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	297.104		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.24835E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4351		
Pipe Spacing - Vertical Array (m)	0.1016		
Pipe Inner Diameter - Vertical Array (m)	0.0144526		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	329.6221191	325.975	6.441156
Absorber Plate Position 3 (K)	311.4816641	309.805	4.357047
Absorber Plate Position 4 (K)	318.2969533	316.906	3.070744
Absorber Plate Position 5 (K)	354.8282672	366.326	14.05105
Absorber Plate Position 6 (K)	340.7509279	337.956	4.125298
Absorber Plate Position 7 (K)	310.8320611	308.226	6.888499
Absorber Plate Position 8 (K)	328.6940264	323.491	9.342162
Absorber Plate Position 9 (K)	333.9699245	328.323	9.26182
Absorber Plate Position 10 (K)	352.4911845	341.536	13.78163
Absorber Plate Position 11 (K)	309.6807532	304.94	12.92436
Absorber Plate Position 12 (K)	318.3475626	314.198	9.150575
Absorber Plate Position 13 (K)	323.2058655	322.534	1.338221
Absorber Plate Position 14 (K)	352.837014	339.128	17.17125
Output Water (K)	318.2931262	318.328	0.076996

Test 1: ¾ Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	294.67		
Effective Collector Heat Loss Coefficient (W/m^2*K)	24.37		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	292.78		

Volumetric Flow Rate - Array Pipe (m^3/s)	8.56667E-07		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.2192		
Pipe Spacing - Vertical Array (m)	0.12065		
Pipe Inner Diameter - Vertical Array (m)	0.0205994		
Pipe Outer Diameter - Vertical Array (m)	0.022225		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.00635		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	324.7820549	329.998	10.07288
Absorber Plate Position 3 (K)	444.3504377	420.456	13.94478
Absorber Plate Position 4 (K)	360.6623266	365.449	5.460354
Absorber Plate Position 5 (K)	329.2074569	334.326	9.10652
Absorber Plate Position 6 (K)	337.3880331	339.803	3.750645
Absorber Plate Position 7 (K)	308.109763	312.404	12.23089
Absorber Plate Position 8 (K)	309.6727692	310.029	0.971377
Absorber Plate Position 9 (K)	332.6427481	336.464	6.406901
Absorber Plate Position 10 (K)	N/A	N/A	N/A
Absorber Plate Position 11 (K)	336.9507343	334.589	3.693053
Absorber Plate Position 12 (K)	359.2827926	344.59	17.02865
Absorber Plate Position 13 (K)	335.0810934	346.71	18.7318
Absorber Plate Position 14 (K)	344.3871896	337.772	9.266634
Output Water (K)	325.8663556	330.482	8.730779

Test 1: ¾ Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	294.67		
Effective Collector Heat Loss Coefficient (W/m^2*K)	24.37		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	292.78		
Volumetric Flow Rate - Array Pipe (m^3/s)	8.56667E-07		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.2192		
Pipe Spacing - Vertical Array (m)	0.12065		
Pipe Inner Diameter - Vertical Array (m)	0.0205994		
Pipe Outer Diameter - Vertical Array (m)	0.022225		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		

Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.00635		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	324.8334888	329.998	9.963657
Absorber Plate Position 3 (K)	445.0366544	420.456	14.28803
Absorber Plate Position 4 (K)	380.9126114	365.449	14.32975
Absorber Plate Position 5 (K)	334.4736685	334.326	0.240214
Absorber Plate Position 6 (K)	342.2961252	339.803	3.597784
Absorber Plate Position 7 (K)	308.8310579	312.404	9.971634
Absorber Plate Position 8 (K)	312.6165993	310.029	6.531604
Absorber Plate Position 9 (K)	340.941363	336.464	6.59004
Absorber Plate Position 10 (K)	N/A	N/A	N/A
Absorber Plate Position 11 (K)	340.021438	334.589	8.105523
Absorber Plate Position 12 (K)	359.2705243	344.59	17.01685
Absorber Plate Position 13 (K)	337.1217883	346.71	14.95313
Absorber Plate Position 14 (K)	351.5122177	337.772	17.50074
Output Water (K)	330.4563405	330.482	0.044659

Test 1: 1 Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	295.37		
Effective Collector Heat Loss Coefficient (W/m^2*K)	13.35		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	298.012		
Volumetric Flow Rate - Array Pipe (m^3/s)	2.61324E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4732		
Pipe Spacing - Vertical Array (m)	0.12065		
Pipe Inner Diameter - Vertical Array (m)	0.02616		
Pipe Outer Diameter - Vertical Array (m)	0.0287		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	392.3		
Thermal Conductivity - Array Pipe (W/m*K)	392.3		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.012598		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	363.1002096	374.269	12.39596
Absorber Plate Position 3 (K)	324.7223695	325.665	1.822481
Absorber Plate Position 4 (K)	337.2765003	330.77	10.12267

Absorber Plate Position 5 (K)	316.3697121	317.383	2.336395
Absorber Plate Position 6 (K)	330.8255654	339.191	14.46667
Absorber Plate Position 7 (K)	324.4472039	337.163	24.7162
Absorber Plate Position 8 (K)	391.6482482	404.522	10.85035
Absorber Plate Position 9 (K)	357.4088706	359.04	1.932415
Absorber Plate Position 10 (K)	335.5194864	343.491	N/A
Absorber Plate Position 11 (K)	313.0680363	311.293	4.430056
Absorber Plate Position 12 (K)	324.5805709	322.28	4.46015
Absorber Plate Position 13 (K)	376.3493615	366.685	9.351157
Absorber Plate Position 14 (K)	337.9315663	327.149	16.60605
Output Water (K)	316.1671873	315.749	0.968762

Test 1: 1 Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	295.37		
Effective Collector Heat Loss Coefficient (W/m^2*K)	13.35		
Incident Insolation (W/m^2)	0		
Temperature - Panel Input (K)	298.012		
Volumetric Flow Rate - Array Pipe (m^3/s)	2.61324E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4732		
Pipe Spacing - Vertical Array (m)	0.12065		
Pipe Inner Diameter - Vertical Array (m)	0.02616		
Pipe Outer Diameter - Vertical Array (m)	0.0287		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	392.3		
Thermal Conductivity - Array Pipe (W/m*K)	392.3		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.012598		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 2 (K)	362.0955897	374.269	13.66331
Absorber Plate Position 3 (K)	320.9961842	325.665	9.727473
Absorber Plate Position 4 (K)	336.1281979	330.77	8.487804
Absorber Plate Position 5 (K)	315.0436981	317.383	5.563978
Absorber Plate Position 6 (K)	331.5101844	339.191	13.12731
Absorber Plate Position 7 (K)	328.0787821	337.163	16.49313
Absorber Plate Position 8 (K)	375.9842318	404.522	27.71081
Absorber Plate Position 9 (K)	357.9005195	359.04	1.342136
Absorber Plate Position 10 (K)	334.3736691	343.491	N/A
Absorber Plate Position 11 (K)	313.8313118	311.293	6.216581
Absorber Plate Position 12 (K)	323.1838497	322.28	1.801077
Absorber Plate Position 13 (K)	363.3613817	366.685	3.67814

Absorber Plate Position 14 (K)	338.7644647	327.149	17.66222
Ouput Water (K)	315.7353058	315.749	0.032044

Photographs of the first test, as well as the transient temperature data can be seen in Figure 11 and Figure 12 of Appendix 2, respectively.

The second test was completed in the Spring Semester with each of the four prototypes from the first test with the addition of an enclosure and the sun being used to heat the panels instead of the Bunsen burners. First, each prototype was inserted in the test enclosure on top of the insulation. Five thermocouples were secured to the top surface of each prototype with high temperature tape and heat sink compound. This was further secured with aluminum duct tape because of a problem we encountered with the high temperature tape peeling off when exposed to the sun. Like the first test, an additional thermocouple wire was inserted into the output end of the pipe to measure the output water temperature. The glass panel was slid into place over the absorber plate and the enclosure was closed up. The enclosure and panel was then placed into the sun at an angle which provided the most direct solar energy incident on its surface. For the second test, the thermocouples were measured with hand-held thermocouple meters periodically over time until the temperatures reached steady state. These final temperatures were then recorded. We chose this method of measurement because it eliminated significant setup time by not having to hook up all of the data acquisition equipment. Since the program only needs the steady-state temperatures, the transient data obtained with this equipment was simply unnecessary. The input water temperature was measured at the faucet with a thermocouple, and the ambient air temperature was measured with a thermometer. The flow rate was measured just like the first test by collecting a known volume of water in a graduated cylinder over a known amount of time. The solar insolation was measured with a hand-held solar energy meter, held perpendicular to the surface of the absorber plate. All of the other parameters remained the same from the first test, except the absorber plate width (pipe spacing) was now equal to the entire absorber plate width unlike the first test.

Analysis of the second test was completed in a similar manner to the first test, but instead of estimating hot temperature spots until the absorber plate or water temperatures matched, the effective collector heat loss coefficient was adjusted until the temperatures matched. Again, one solution set assumed the modeling of the heat transfer into and throughout the absorber plate was correct by matching the experimental and theoretical absorber plate temperatures. This solution was accomplished by allowing another part of the program to estimate the effective collector heat loss coefficient as an initial guess, and then adjusting its value until the experimental and theoretical absorber plate temperatures matched as closely as possible. This solution was intended to test the assumptions made in modeling the heat transfer into the water. The other solution set assumed modeling of the heat transfer into the water was correct by modifying the loss coefficient until the experimental and theoretical output water temperatures matched. This solution was intended to determine how close the absorber plate temperatures would match if the water was correct.

One major problem we encountered with the analysis of this test occurred because the flow rate for two of the prototypes (¼ inch and ¾ inch) was measured at the faucet after disconnecting the hose and pipe, while the other two prototype flow rates were measured from the actual output of the pipe. This was a problem because there was a very significant difference between the flow rates when measured between these two locations. As we measured later, the flow rate at the faucet was between 200 and 400 percent of the flow rate coming out of the pipe. This is because after the hose and pipe are disconnected, the flow is no longer restricted by the various losses associated them and can therefore flow faster. Because of this incorrect flow measurement for the ¼ and ¾ inch pipes, the actual flow rate out of the pipe was estimated based on flow measurements taken later, but since this was only an estimate these tests are not completely valid.

The results of each of the second tests can be seen below.

Test 2: ¼ Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	290.8		
Effective Collector Heat Loss Coefficient (W/m^2*K)	12.00		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	295		
Volumetric Flow Rate - Array Pipe (m^3/s)	4.60086E-07		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.177		
Pipe Spacing - Vertical Array (m)	0.102		
Pipe Inner Diameter - Vertical Array (m)	0.008001		
Pipe Outer Diameter - Vertical Array (m)	0.009525		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.0047625		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	333.341125	329.8	5.86851
Absorber Plate Position 2 (K)	330.8854416	328.9	3.42995
Absorber Plate Position 3 (K)	325.6044179	321	8.752911
Absorber Plate Position 4 (K)	320.5062574	321.6	2.302313
Absorber Plate Position 5 (K)	313.188624	318.1	12.22081
Output Water (K)	328.0805343	322.6	9.950038

Test 2: ¼ Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	290.8		
Effective Collector Heat Loss Coefficient (W/m^2*K)	16.80		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	295		
Volumetric Flow Rate - Array Pipe (m^3/s)	4.60086E-07		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.177		

Pipe Spacing - Vertical Array (m)	0.102		
Pipe Inner Diameter - Vertical Array (m)	0.008001		
Pipe Outer Diameter - Vertical Array (m)	0.009525		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.0047625		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	326.7104918	329.8	5.75215
Absorber Plate Position 2 (K)	324.9078446	328.9	7.690852
Absorber Plate Position 3 (K)	320.917765	321	0.171617
Absorber Plate Position 4 (K)	317.0756269	321.6	10.26502
Absorber Plate Position 5 (K)	311.2029174	318.1	18.05381
Output Water (K)	322.6463951	322.6	0.093451

Test 2: ½ Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	292		
Effective Collector Heat Loss Coefficient (W/m^2*K)	12.35		
Incident Insolation (W/m^2)	875		
Temperature - Panel Input (K)	295.2		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.73406E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4351		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.0144526		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	312.3345231	314.3	4.996824
Absorber Plate Position 2 (K)	318.755162	317.8	2.08755
Absorber Plate Position 3 (K)	319.5467568	316.6	6.330746
Absorber Plate Position 4 (K)	320.4418415	321.2	1.59808
Absorber Plate Position 5 (K)	325.2060254	326.8	3.053239
Output Water (K)	311.6093895	317.1	14.22092

Test 2: ½ Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	292		
Effective Collector Heat Loss Coefficient (W/m^2*K)	4.30		
Incident Insolation (W/m^2)	875		
Temperature - Panel Input (K)	295.2		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.73406E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.4351		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.0144526		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	316.200635	314.3	4.399553
Absorber Plate Position 2 (K)	325.7469877	317.8	15.06624
Absorber Plate Position 3 (K)	327.5252873	316.6	20.0371
Absorber Plate Position 4 (K)	329.4577048	321.2	14.62636
Absorber Plate Position 5 (K)	336.6151033	326.8	15.42889
Output Water (K)	317.1020174	317.1	0.004574

Test 2: ¾ Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	292.5		
Effective Collector Heat Loss Coefficient (W/m^2*K)	15.99		
Incident Insolation (W/m^2)	925		
Temperature - Panel Input (K)	295		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.6604E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.22		
Pipe Spacing - Vertical Array (m)	0.15		
Pipe Inner Diameter - Vertical Array (m)	0.0205994		
Pipe Outer Diameter - Vertical Array (m)	0.022225		
Absorber Plate Thickness (m)	0.000635		

Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.00635		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	313.3701186	314	1.560266
Absorber Plate Position 2 (K)	317.5272189	316.2	2.980691
Absorber Plate Position 3 (K)	315.8688747	315.6	0.627203
Absorber Plate Position 4 (K)	N/A	N/A	N/A
Absorber Plate Position 5 (K)	321.6613288	323.2	3.162
Output Water (K)	309.0853931	316.6	20.82451

Test 2: ¾ Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	292.5		
Effective Collector Heat Loss Coefficient (W/m^2*K)	2.90		
Incident Insolation (W/m^2)	925		
Temperature - Panel Input (K)	295		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.6604E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.22		
Pipe Spacing - Vertical Array (m)	0.15		
Pipe Inner Diameter - Vertical Array (m)	0.0205994		
Pipe Outer Diameter - Vertical Array (m)	0.022225		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.00635		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	320.4916566	314	13.66905
Absorber Plate Position 2 (K)	328.3951847	316.2	22.01488
Absorber Plate Position 3 (K)	327.043137	315.6	21.17408
Absorber Plate Position 4 (K)	N/A	N/A	N/A
Absorber Plate Position 5 (K)	337.8662903	323.2	22.61003
Output Water (K)	316.5614433	316.6	0.088511

Test 2: 1 Inch Pipe, Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	294.1		

Effective Collector Heat Loss Coefficient (W/m^2*K)	10.31		
Incident Insolation (W/m^2)	875		
Temperature - Panel Input (K)	295.3		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.45376E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.447		
Pipe Spacing - Vertical Array (m)	0.2025		
Pipe Inner Diameter - Vertical Array (m)	0.026035		
Pipe Outer Diameter - Vertical Array (m)	0.028575		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.012598		
Average Thickness of Solder (m)	0.00127		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	335.2472266	336.1	1.369978
Absorber Plate Position 2 (K)	333.2993151	334.6	2.157048
Absorber Plate Position 3 (K)	326.6444146	324.9	3.25181
Absorber Plate Position 4 (K)	321.1799617	320.2	2.033961
Absorber Plate Position 5 (K)	315.8180365	314.8	2.377588
Output Water (K)	320.1741642	328.5	17.64914

Test 2: 1 Inch Pipe, Matched Output Water

INPUTS			
Ambient Temperature (K)	294.1		
Effective Collector Heat Loss Coefficient (W/m^2*K)	4.10		
Incident Insolation (W/m^2)	875		
Temperature - Panel Input (K)	295.3		
Volumetric Flow Rate - Array Pipe (m^3/s)	1.45376E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.447		
Pipe Spacing - Vertical Array (m)	0.2025		
Pipe Inner Diameter - Vertical Array (m)	0.026035		
Pipe Outer Diameter - Vertical Array (m)	0.028575		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.012598		
Average Thickness of Solder (m)	0.00127		

TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	349.6283467	336.1	17.65449
Absorber Plate Position 2 (K)	346.0288542	334.6	15.64978
Absorber Plate Position 3 (K)	336.1034438	324.9	17.75409
Absorber Plate Position 4 (K)	328.1040294	320.2	14.34383
Absorber Plate Position 5 (K)	320.2614276	314.8	11.55578
Output Water (K)	328.5147495	328.5	0.026569

Photographs of the second test can be seen in Figure 13 of Appendix 2.

The third and final test was also completed in the Spring Semester and was very similar in operation and analysis to the second test. The full-scale collector panel and enclosure, with thermocouples attached at five locations on the surface in the same manner was again placed in the sun at an optimum angle for solar energy. The thermocouples were placed at representative locations across the entire width of the collector so we could evaluate the temperature interactions with multiple pipes in parallel. Each temperature was again measured with a hand-held thermocouple meter periodically over time until steady-state was reached, then the temperatures were recorded at each thermocouple location. The input water temperature, flow rate, ambient temperature, solar insolation, pipe length, pipe spacing, pipe diameters, absorber plate thickness, solder width and thickness, and thermal conductivities were all determined exactly like the second test.

One problem which we found during the second and third tests was the variability of solar insolation due to the sun's movement. The panel and water temperatures were obviously greatly dependent on the amount of solar energy, and throughout the period of a test the solar energy would often change because the sun would move and therefore change the incident angle and sometimes create shade from trees. We found the best way to solve this problem was to wait until the water reached steady state, then record the insolation at this instant as the most accurate value.

The data from the two runs of the third test which we were able to complete was input into the program exactly in the same manner as the second test data. Again, we obtained two solution sets for the assumptions of correct absorber plate and output water temperatures. We made one adjustment to the program during our analysis to more accurately model the flow rate through the parallel pipes. The program originally assumed that the flow coming into the panel is divided evenly through the entire length of each parallel pipe. For example, a panel input flow rate of 4 m^3/s would be divided into four parallel pipes so that the entire length of each pipe (including the horizontal end sections) would be flowing at 1 m^3/s, assuming all of the diameters are equal. This assumption is not exactly correct, because the closest pipe to the input will actually have the entire flow rate (4 m^3/s) through its lower horizontal section, as will the closest pipe to the output through its upper horizontal section. The only horizontal sections which will actually have ¼ of the flow rate are the sections farthest from the input and output. So we adjusted the flow rate value used by the program by creating an effective flow rate value which takes the average flow rate based on the total lengths of pipe at each flow rate. The results of each of the third tests can be seen below.

Test 3.1: Matched Absorber Plate

INPUTS			
Ambient Temperature (K)	294.1		
Effective Collector Heat Loss Coefficient (W/m^2*K)	12.00		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	289.8		
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	1.7453E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.3716		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.013843		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		

Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
Number of Parallel Pipes	4		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	343.2407246	352.6	13.32457
Absorber Plate Position 2 (K)	332.234408	334.5	3.824791
Absorber Plate Position 3 (K)	327.1070429	329.5	4.422635
Absorber Plate Position 4 (K)	309.145342	301.3	21.70499
Absorber Plate Position 5 (K)	338.2493931	344.7	9.88608
Output Water (K)	340.1073631	352.9	19.06294

Test 3.1: Matched Output Water

INPUTS			
Ambient Temperature (K)	294.1		
Effective Collector Heat Loss Coefficient (W/m^2*K)	7.35		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	289.8		
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	1.7453E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.3716		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.013843		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
Number of Parallel Pipes	4		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	356.9364515	352.6	5.166351
Absorber Plate Position 2 (K)	340.9995181	334.5	9.558183
Absorber Plate Position 3 (K)	333.5957338	329.5	6.759112
Absorber Plate Position 4 (K)	311.3152939	301.3	26.13915
Absorber Plate Position 5 (K)	349.4453355	344.7	6.207489
Output Water (K)	352.9413884	352.9	0.051773

Test 3.2: Matched Absorber Plate

INPUTS			

Ambient Temperature (K)	292		
Effective Collector Heat Loss Coefficient (W/m^2*K)	18.00		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	298.1		
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	2.89891E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.3716		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.013843		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		
Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
Number of Parallel Pipes	4		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	327.3775391	333.6	11.44307
Absorber Plate Position 2 (K)	321.3048226	320.8	1.045077
Absorber Plate Position 3 (K)	320.0298592	317.8	4.741369
Absorber Plate Position 4 (K)	309.5953407	304.2	14.74324
Absorber Plate Position 5 (K)	324.7586365	328	6.262459
Output Water (K)	322.1707368	331.1	18.15971

Test 3.2: Matched Output Water

INPUTS			
Ambient Temperature (K)	292		
Effective Collector Heat Loss Coefficient (W/m^2*K)	10.67		
Incident Insolation (W/m^2)	900		
Temperature - Panel Input (K)	298.1		
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	2.89891E-06		
PARAMETERS			
Pipe Length - Vertical Array (m)	1.3716		
Pipe Spacing - Vertical Array (m)	0.1524		
Pipe Inner Diameter - Vertical Array (m)	0.013843		
Pipe Outer Diameter - Vertical Array (m)	0.015875		
Absorber Plate Thickness (m)	0.000635		
Thermal Conductivity - Absorber Plate (W/m*K)	398		
Thermal Conductivity - Array Pipe (W/m*K)	398		
Thermal Conductivity - Solder (W/m*K)	67		

Width of Solder along Abs Plate (m)	0.008509		
Average Thickness of Solder (m)	0.00127		
Number of Parallel Pipes	4		
TEMPERATURE OUTPUTS	Theoretical	Experimental	% Error
Absorber Plate Position 1 (K)	338.7142027	333.6	7.782492
Absorber Plate Position 2 (K)	329.0953535	320.8	14.78795
Absorber Plate Position 3 (K)	326.7073534	317.8	16.58498
Absorber Plate Position 4 (K)	312.245719	304.2	20.50088
Absorber Plate Position 5 (K)	334.3944231	328	10.41532
Output Water (K)	331.1244035	331.1	0.041985

Photographs of the third test can be seen in Figure 14 of Appendix 2.

In order to determine if our theoretical results fell within the range of uncertainty in the measured temperature values, we needed to determine an appropriate level of uncertainty for these temperatures. To accomplish this, we analyzed the uncertainty for two tests: test 2 for the ½ inch pipe and the first run of test 3 because these were the lowest and highest output water temperatures, respectively. To estimate the maximum possible uncertainty in the output water and absorber plate temperatures, each of the input and parameter variables were input at the limits of their individual uncertainties in such a was as to create the hottest and coldest possible combinations. Each combination was solved and the resulting output water and average absorber plate were recorded to be compared to the original values in terms of a nominal value as well as a percent. Finally, an average percent uncertainty between the two tests was calculated and this value is what determined the expected uncertainty which we judged the accuracy of our results by. Therefore, we would like to see the theoretical output water temperatures to be within 13.6% of the experimental values, and the theoretical absorber plate temperatures to be within 10.8% of experimental values. The results of these calculations are shown below.

Error Analysis-Test 2: 1/2 Inch				
Parameter	**Original Value**	**Uncertainty**	**Hottest Variation**	**Coldest Variation**
Ambient Temperature (K)	292	2	294	290

Effective Collector Heat Loss Coefficient (W/m^2*K)	12.35	2.00	10.35	14.35
Incident Insolation (W/m^2)	875	10	885	865
Temperature - Panel Input (K)	295.2	2	297.2	293.2
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	1.73E-06	7.57E-08	1.66E-06	1.81E-06
Pipe Length - Vertical Array (m)	1.4351	0.01	1.4451	1.4251
Pipe Spacing - Vertical Array (m)	0.1524	0.01	0.1624	0.1424
Pipe Inner Diameter - Vertical Array (m)	0.0144526	0.0001	0.0145526	0.0143526
Pipe Outer Diameter - Vertical Array (m)	0.015875	0.0001	0.015775	0.015975
Absorber Plate Thickness (m)	0.000635	0.0001	0.000735	0.000535
Thermal Conductivity - Absorber Plate (W/m*K)	398	10	408	388
Thermal Conductivity - Array Pipe (W/m*K)	398	10	408	388
Thermal Conductivity - Solder (W/m*K)	67	20	87	47
Width of Solder along Abs Plate (m)	0.008509	0.005	0.013509	0.003509
Average Thickness of Solder (m)	0.00127	0.001	0.00027	0.00227
Temperature - Panel Output (K)	*311.61*	*4.87*	*316.63*	*306.89*
	Percent Uncertainty=	***12.61***		
Average Absorber Plate Temperature (K)	*318.25*	*4.30*	*323.01*	*314.42*
	Percent Uncertainty=	***9.49***		
Error Analysis-Test 3.1				
Parameter	**Original Value**	**Uncertainty**	**Hottest Variation**	**Coldest Variation**
Ambient Temperature (K)	294.1	2	296.1	292.1
Effective Collector Heat Loss Coefficient (W/m^2*K)	12	2	10	14
Incident Insolation (W/m^2)	900	10	910	890
Temperature - Panel Input (K)	289.8	2	291.8	287.8
Inlet/Outlet Volumetric Flow Rate - Array Pipe (m^3/s)	1.75E-06	3.84E-08	1.71E-06	1.78E-06
Pipe Length - Vertical Array (m)	1.3716	0.01	1.3816	1.3616
Pipe Spacing - Vertical Array (m)	0.1524	0.01	0.1624	0.1424
Pipe Inner Diameter - Vertical Array (m)	0.013843	0.0001	0.013943	0.013743
Pipe Outer Diameter - Vertical Array (m)	0.015875	0.0001	0.015775	0.015975
Absorber Plate Thickness (m)	0.000635	0.0001	0.000735	0.000535
Thermal Conductivity - Absorber Plate (W/m*K)	398	10	408	388
Thermal Conductivity - Array Pipe (W/m*K)	398	10	408	388
Thermal Conductivity - Solder (W/m*K)	67	20	87	47
Width of Solder along Abs Plate (m)	0.008509	0.005	0.013509	0.003509
Average Thickness of Solder (m)	0.00127	0.001	0.00027	0.00227
Temperature - Panel Output (K)	*340.11*	*9.84*	*350.60*	*330.92*
	Percent Uncertainty=	***14.66***		
Average Absorber Plate Temperature (K)	*331.70*	*7.10*	*339.49*	*325.29*
	Percent Uncertainty=	***12.09***		

Average Output Water Percent Uncertainty	**13.6**			
Average Absorber Plate Percent Uncertainty	**10.8**			

A summary of our results for all of the tests can be seen below.

All Tests: Matched Absorber Plate

Test 1 Results							
	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
1/2 Inch Pipe	5.18	43.26	45.33	4.77	19.16	21.22	10.77
3/4 Inch Pipe	9.22	52.87	54.30	2.71	33.09	34.52	4.33
1 Inch Pipe	8.79	43.17	42.75	0.97	18.16	17.74	2.30
Test 2 Results							
	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
1/4 Inch Pipe	6.47	55.03	49.60	9.87	33.03	27.60	16.45
1/2 Inch Pipe	3.61	38.61	44.10	14.22	16.41	21.90	33.46
3/4 Inch Pipe	2.08	36.09	43.60	20.82	14.09	21.60	53.35
1 Inch Pipe	2.24	47.17	55.50	17.65	24.87	33.20	33.47
Test 3 Results							
	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
First Run	10.63	67.11	79.90	19.06	50.31	63.10	25.43
Second Run	7.65	49.17	58.10	18.16	24.07	33.00	37.10

All Tests: Matched Output Water

Test 1 Results								
	Average Absorber Plate Temperature Difference (°C)	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
1/2 Inch Pipe	-3.51	7.50	45.29	45.33	0.08	21.19	21.22	0.16
3/4 Inch Pipe	-2.76	8.97	54.31	54.30	0.01	34.53	34.52	0.02
1 Inch Pipe	4.43	9.96	42.75	42.75	0.01	17.74	17.74	0.02
Test 2 Results								
	Average Absorber Plate Temperature Difference (°C)	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
1/4 Inch Pipe	3.72	8.39	49.65	49.60	0.09	27.65	27.60	0.17
1/2 Inch Pipe	-7.77	13.91	44.10	44.10	0.00	21.90	21.90	0.01
3/4 Inch Pipe	-11.20	19.87	43.56	43.60	0.09	21.56	21.60	0.18
1 Inch Pipe	-9.91	15.39	55.51	55.50	0.03	33.21	33.20	0.04
Test 3 Results								
	Average Absorber Plate Temperature Difference (°C)	Average Absorber Plate Temperature Error (%)	Theoretical Output Water Temperature (°C)	Actual Output Water Temperature (°C)	Output Temperature Error (%)	Theoretical Temperature Increase (°C)	Actual Temperature Increase (°C)	Temperature Increase Error (%)
First Run	-5.94	10.77	79.94	79.90	0.05	63.14	63.10	0.07
Second Run	-7.35	14.01	58.12	58.10	0.04	33.02	33.00	0.07

Our first objective was to get the model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a single pipe and controlled temperature boundary condition. This objective corresponded to test 1. The results of test 1 show that this objective was accomplished because all of the average absorber plate temperatures were within the 10.8% expected uncertainty and all of the output water temperatures were within the 13.6% expected uncertainty. Even though we met this objective, we believe the results of the first test should be taken with a grain of salt. The method we used to analyze the model by estimating the hot point temperatures until the theoretical temperatures matched is questionable, and is not how the program was intended to operate. However, these results do show that even when we solved the program to match the absorber plate temperatures, the water temperatures were still within our expected range of uncertainty. This suggests that the program accurately models the heat transfer from the plate into the water.

Our second objective was to get the model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a single pipe and known insolation. This objective corresponded to test 2. The results for the ¼ inch and ¾ inch pipes of test 2 are highlighted in red because they should not be used to verify the accuracy of the program due to the error in the flow rate measurement for these tests. So for the two remaining pipes, this objective was not met. For the solution set which matched the absorber plate temperatures, the output water temperature errors and the change in water temperature errors were all outside of the 13.6% expected uncertainty. For both cases, the theoretical output water temperature was lower than the experimental water temperature, causing the error. This could mean one of two things. First, the model could be incorrectly modeling the heat transfer from the plate into the water. We don't want to jump to this conclusion too quickly though, since the model did so well at this for the first test. Secondly, the experimental absorber plate temperatures themselves could be too low, which would mean that the temperatures we are matching to them are low which would therefore make the theoretical water temperature colder. To help determine the likelihood of this second possibility, we can look to the second solution set which assumed the output water temperature to be correct. For this solution, the average absorber plate error was outside of the 10.8% expected uncertainty, so this could lead us to the conclusion that the error is not in the experimental absorber plate temperature values. Based on a rough calculation using the thermal conductivity of the heat sink compound, an estimated thickness of 1 mm, and a heat flux equal to the solar insolation, the difference in temperature between the absorber plate and the thermocouple should only be about one degree. The uncertainty inherent in the thermocouples themselves is also about one degree, so the maximum error we could expect in the absorber plate temperature measurement is only about two degrees; not enough to account for the error. Another potential factor could be that the area of the plate which is covered by the tape and heat sink compound that hold the thermocouple in place is cooler because it is blocked from the sun's energy, but again this would probably be insignificant because conduction through the copper is so great that the surrounding areas would easily conduct heat into this shielded area. The best way to evaluate the effect of attaching thermocouples this way would be to compare experimental temperatures of thermocouples attached this way with those being soldered directly to the plate. Whether the error is resulting from incorrect modeling of the heat transfer into the water or incorrect absorber plate temperature readings will have to be determined in the future.

Our third objective was to get the model absorber plate and water temperatures within the expected range of uncertainty of experimental temperature results for a pipe array and known insolation. This objective corresponded to test 3, and again was not met by our tests and analysis for the same reasons as the second objective. Again, for the solution which matched the absorber plate temperatures, the theoretical output water temperature was consistently colder than the experimental values. We believe this problem will be solved for the third test when it is solved for the second test. Even though we did not meet our third objective, the third test was still partly a success. The main purpose of constructing a full collector panel was to test the assumptions made in the modeling of multiple pipes in parallel. The main assumption here was that the temperatures at the same locations in each of the parallel pipes is the same for all of the pipes. From our results, this assumption seems to be completely valid, because our measured temperature values throughout the absorber plate (between different sets of pipes) were consistent.

Our fourth objective was to identify any limits to system parameters that cause model temperatures to fall outside the expected range of uncertainty of experimental temperature results. While our model temperatures for the second and third tests did fall outside of the expected ranges of uncertainty, we do not believe this was a result of limits to the program being able to accurately model our selected system parameters. As discussed previously, the errors are consistent across all of the tests, so the problem seems to be in the modeling of the heat transfer into the water itself or simply incorrect temperature measurements. Therefore, we could not identify any limits to the parameters of pipe diameter, pipe spacing, or pipe length in the ranges of variation in our tests.

Our fifth objective was to identify manufacturing lessons learned during the construction of our test prototype collectors. This objective was completed, and the manufacturing technique we developed was discussed in Section 3.1.

Our final objective was to identify a set of available materials and costs for U.S. manufacturing of parallel pipe flat collectors. This objective was accomplished for the materials we used to construct our collector panels and their enclosures. The breakdown of our expenses is given in Section 5. As an estimate for construction of a full collector panel and enclosure, the raw materials we purchased just for the construction of our test 3 prototype and enclosure was approximately $260. Obviously this does not include the cost of the equipment used for soldering the pipes or cutting the boards for the box. These costs would need to be taken into account for full-scale production of solar collectors, and the high capital cost involved in such equipment could only be economically justified by the production of a large number of collectors.

In addition to the objectives of our tests, we also hoped to meet our specifications for the model and tests. Since the model is still in the process of being turned into a useable program by other members of the Thermosyphon group, we were unable to evaluate the ability of the model to take minimal explanation and be easy to use. While the model does not simulate the experimental temperatures as accurately as we would like it to, it does comprehensively manage all of the possible input variables as it is specified to. All of our test prototypes and test runs were within the required specifications for flow rate, input water temperature, pipe material, absorber plate material, pipe diameter, pipe spacing, pipe length, glass thickness, applied plate boundary temperature, incident insolation and insulating R-value. The remaining specifications were directly tied to a specific objective which was already discussed.

4 Schedule

For our project, we created a Gantt chart, which provides a quick and easy way to see where and how our project is doing (see Appendix 1). By viewing our Gantt chart, it is easy to see which milestones are crucial to the success of our project. A large part of our project was the three tests that we have planned, constructed, run, and analyzed. We scheduled 3 weeks for general planning and then 2 weeks to construct, 2 weeks to run, and 3 more weeks to analyze the results for each test. Another important aspect of our project was meeting with Brendon Earl every other Monday. This was crucial because it allowed us to ask questions with a previous member of the '04-'05 thermosyphon senior project group who designed the model we are working with.

Our original Gantt chart was a very rough estimate of scheduling that was made before our project was entirely defined. Since then we have modified it to include the three tests we ran as well as all of the necessary meetings and paperwork and presentation deadlines. We completed the construction of test 1 and test 2 about 2 weeks behind schedule. We began running our first test on December 7, and completed it before we left for the fall semester. The results of the first test were analyzed over Christmas break in order to catch up with our schedule for the spring. We ran test 2 about a month behind schedule but complete the construction for test 3 and ran test 3 right on schedule. The analysis for tests 2 and 3 was completed about 2 weeks behind schedule.

5 Budget

The following is a breakdown of our budget for the project ($ Allotted/$ Spent).

Raw Materials:

Pipe and Fittings - $200.00/$149.43

Sheet Metal - $250.00/$149.46

Solder and Flux - $15.00/$0.00

Insulation - $15.00/$10.26

Glass-$0.00/$79.50

Other Construction Materials - $20.00/$28.08

Tooling - $0.00/$0.00

Phone Usage - $0.00/$0.00

Research Costs - $0.00/$0.00

Travel Costs - $0.00/$0.00

Total Budget: $500.00/$416.73 (includes tax)

The following is a breakdown of the amount we have spent on each item to-date.

Part Used	Place of Acquisition	Unit Cost	Units Purchased	Total Cost
1″x5′ Type L Copper Pipe	Lowe's	$26.73	1	$26.73
¾″x5′ Type M Copper Pipe	Lowe's	$13.23	1	$13.23
½″x5′ Type M Copper Pipe	Lowe's	$8.17	1	$8.17
¼″x2′ Copper Pipe	Lowe's	$5.43	2	$10.86
1″x ¾″ Threaded Copper Fitting	Lowe's	$9.23	4	$36.92
1″x ¾″ Copper Adapter	Lowe's	$2.97	1	$2.97
1″x ½″ Copper Adapter	Lowe's	$2.93	2	$5.86
½″x ¼″ Copper Adapter	Lowe's	$0.97	1	$0.97
¼″ Copper Coupling	Lowe's	$0.43	1	$0.43
¾″ Copper Hose Adapter	Messiah Engineering Shop	$0.00	1	$0.00
24″ Copper Flashing	R.F. Fager Company	$7.05	10	$70.50
Solder	Dickinson College Maintenance	$0.00	1	$0.00
Flux	Dickinson College Maintenance	$0.00	1	$0.00
R13 Faced 3 ½″ Insulation	Lowe's	$9.68	1	$9.68
Wood Stands	Messiah Engineering Shop	$0.00	2	$0.00
¼″, ½″, ¾″, 1″ Hoses and Hose Clamps	Messiah Engineering Shop	$0.00	1	$0.00
5/8″ x 12″ x 6′ Particle Board Sheet	Lowe's	$5.38	4	$21.52
½" x 5′ Type L Copper Pipe	Lowe's	$11.17	5	$55.85
½″ 90° Copper Bend	Lowe's	$0.45	2	$0.90
½" Copper T	Lowe's	$.073	6	$4.38
½″ x ¾" Copper Adapter	Lowe's	$3.93	1	$3.93
24″ Copper Flashing	R.F. Fager Company	$7.05	10	$70.50

15 oz. Flat Black Paint	Lowe's	$4.97	1	$4.97
24" x 60" x ¼" Glass	Carlisle Glass Service	N/A	N/A	$75.00
Glass	Carlisle Glass Service	N/A	N/A	$24.20
		Subtotal		***$447.57***
		Tax		***$26.85***
		Total		***$474.43***

Our main source of funding for this project has been the Messiah College Engineering Department. The department allots $500.00 from the college to be used for our project, and we managed to stay under that amount for all of our construction. Our funding does not include any form of gifts-in-kind.

6 Conclusions

Overall, our project can be deemed a success. While certain percent errors are outside the intended results, there were many positives that can be taken from this project. First, we designed and manufactured 4 different straight-pipe prototypes and one full-size collector panel. These prototypes and panel were valuable for our own testing, but will also be valuable for future testing. Another important aspect of this manufacturing is that we were able to learn many different lessons about the manufacturing of collector panels. For instance, we learned the important of clamping down the pipe array onto the collector plate before soldering the two together. This is very important because it maintains a good connection between the two pieces at all times. Another important manufacturing lesson that we learned was the importance of each surface being cleaned before soldering. This is also extremely important because the quality and strength of the solder rises drastically if the proper cleaning procedure is used.

Another success of our project was the mastering of different instrumentation. Throughout our project, our group used many different types of measuring instruments. We became very familiar with thermocouples and the different ways to read their outputs. Mainly for our project, we used the handheld thermocouple readers and the multiple channel data acquisition box which graphed the data in LoggerPro.

As far as our specific objectives, we did not meet all of them. As first three objectives, which were to have the temperature errors within the expected error (13%), we reached this objective only for test 1. Both test 2 and test 3 were outside this expected error, but the results were still helpful. The results for both of the latter tests were consistent with each other. In fact, on all three tests, the program's theoretical output temperature of the water was less than the experimental temperature measured. As discussed earlier, this could be a result of the program incorrectly modeling the heat transfer into the water or incorrect absorber plate temperature measurements. For the fourth objective, which was to identify any limits to system parameters that cause a greater difference between model and experimental results than our expected uncertainty, we did not meet. Instead of looking for these specific limits, we focused more on the accuracy of the program first. We felt that it was more important to work on the program's accuracy before trying to find the limits of the program. Our fifth and sixth objectives were to create a manufacturing lessons list and a materials list. While both of these lists are short at the moment, we succeeded in completing these objectives. As mentioned earlier, we learned many different lessons while manufacturing the collector panel. As far the materials list for production in the United States, we were able to include the specific costs of materials for our prototypes as well as a total cost for the production of a full collector panel.

As stated earlier, we learned many different manufacturing lessons. However, there many other lessons that we learned. First, we learned the importance of time management skills. It was extremely important for our group to start manufacturing and testing as early as possible. This was very important for test 3 because we needed ample time for testing due to the weather (we needed sunny, warm days). A lesson that goes right along with time management skills is the idea of splitting work. By splitting up different aspects, we were able to accomplish much more in the same amount of time. Overall, we learned many different lessons about working in a group and manufacturing of collector panels. Our senior project was a success due to these lessons learned, the different test prototypes manufactured, and the furtherance of the Thermosyphon Design Project.

7 Recommendations for Future Work

With the assumption that in future years this project will be continued and improved upon we would now like to discuss some areas in which we believe there needs to be more work done.

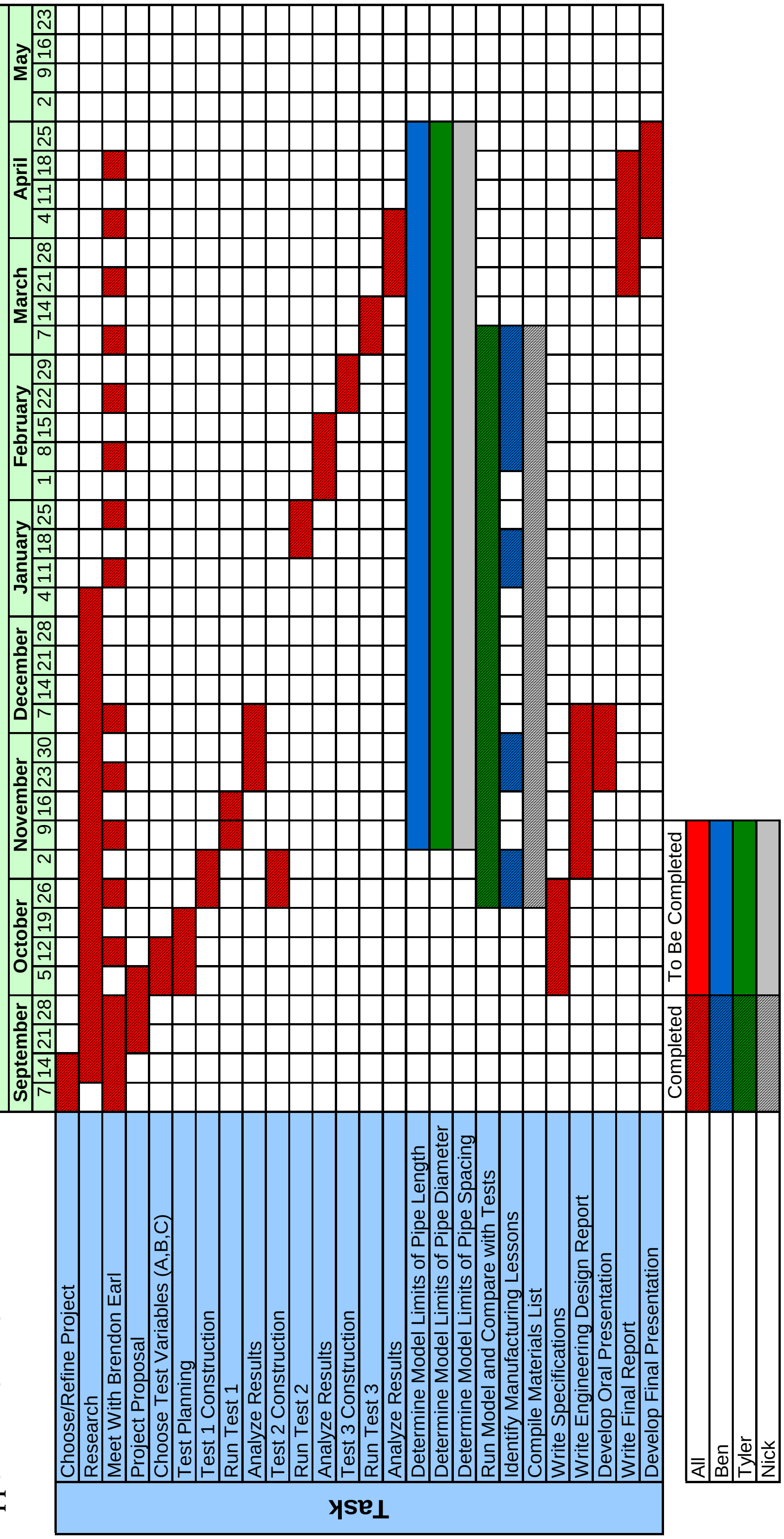
One area that needs to receive more concentration in our project is the testing. As we all know the more testing that can be completed the more confident one can be in the results achieved. Not only can there be more testing done with the current prototypes but more different prototypes can be built and tested as well. This more complete testing will accomplish a number of things. First, as we stated before, more complete and accurate results can be achieved. Another thing that can be examined through more testing is the effect of using solder to attach the thermocouples to the collector panel versus our method of using high temperature tape and thermal conductivity paste in order to see if there is significant error in our temperature readings. One of our objectives was to create a materials list for the manufacturing of these solar water heaters. As more testing is completed this list could also be expanded and used to test the effectiveness of different materials. Another one of our objectives was to create a manufacturing lessons learned list. As with the material list, as more prototypes are built for testing this list can be added too. One final thing that more testing could achieve deals with the program. As we discussed, there are possible limits that the program might have. With more complete testing we would better be able to find out what these limits are and where exactly they lie.

Another area that has great potential for future work is the rest of the thermosyphon system. As we discussed previously, our group decided to concentrate on only the collector panel for various reasons. There are, however, multiple other sections of the entire system that need to be tested and verified if this program is going to be the best it can be. There is a lot of potential for future work and other senior projects in the area.

Appendices

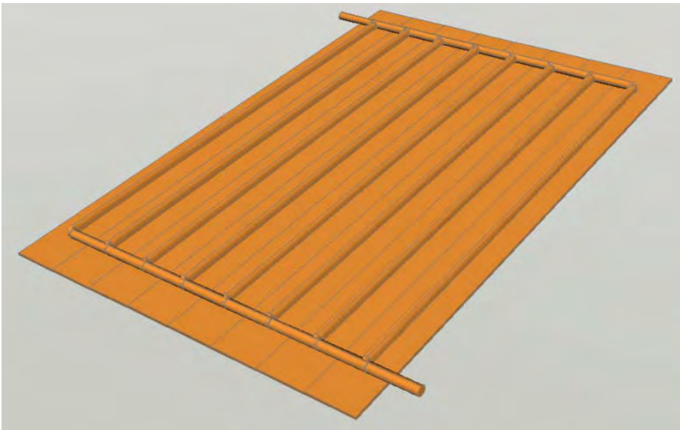
Appendix 1: Gantt Chart

Appendix 1: Gantt Chart

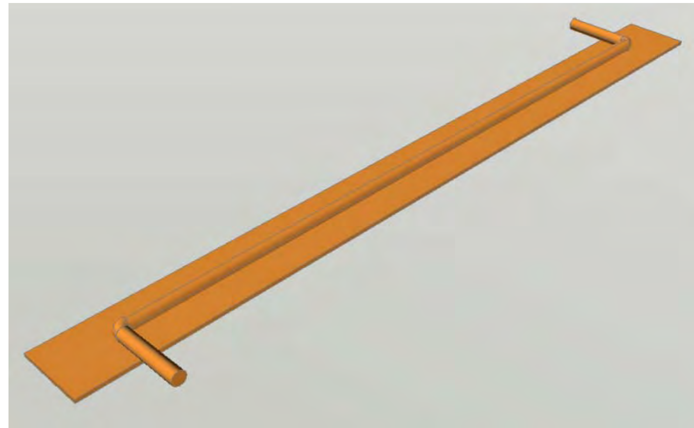


Appendix 2: Drawings, Schematics, Analyses

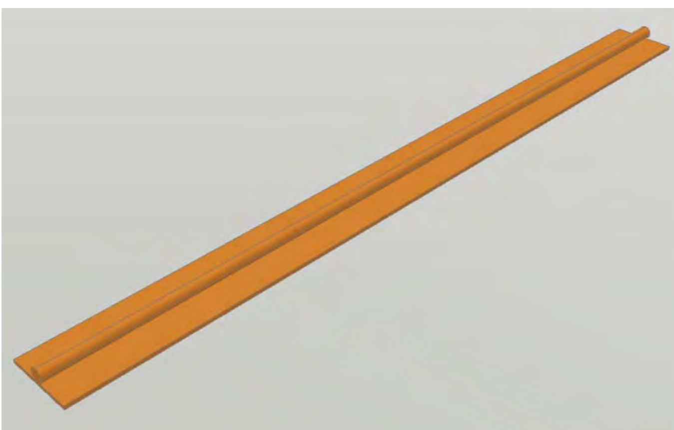
Figure 1: Pipe Modeling



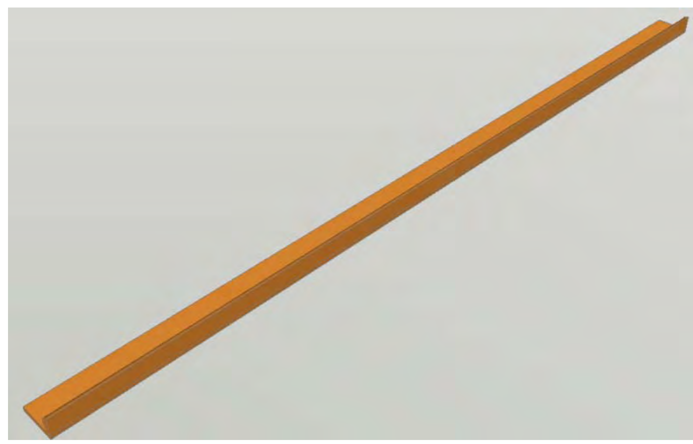
a. parallel pipe array (bottom view)
with bends



b. single symmetric parallel pipe



c. single straight pipe
symmetry



d. half of pipe and plate by

Figure 2: Heat Transfer and Resistance Diagrams

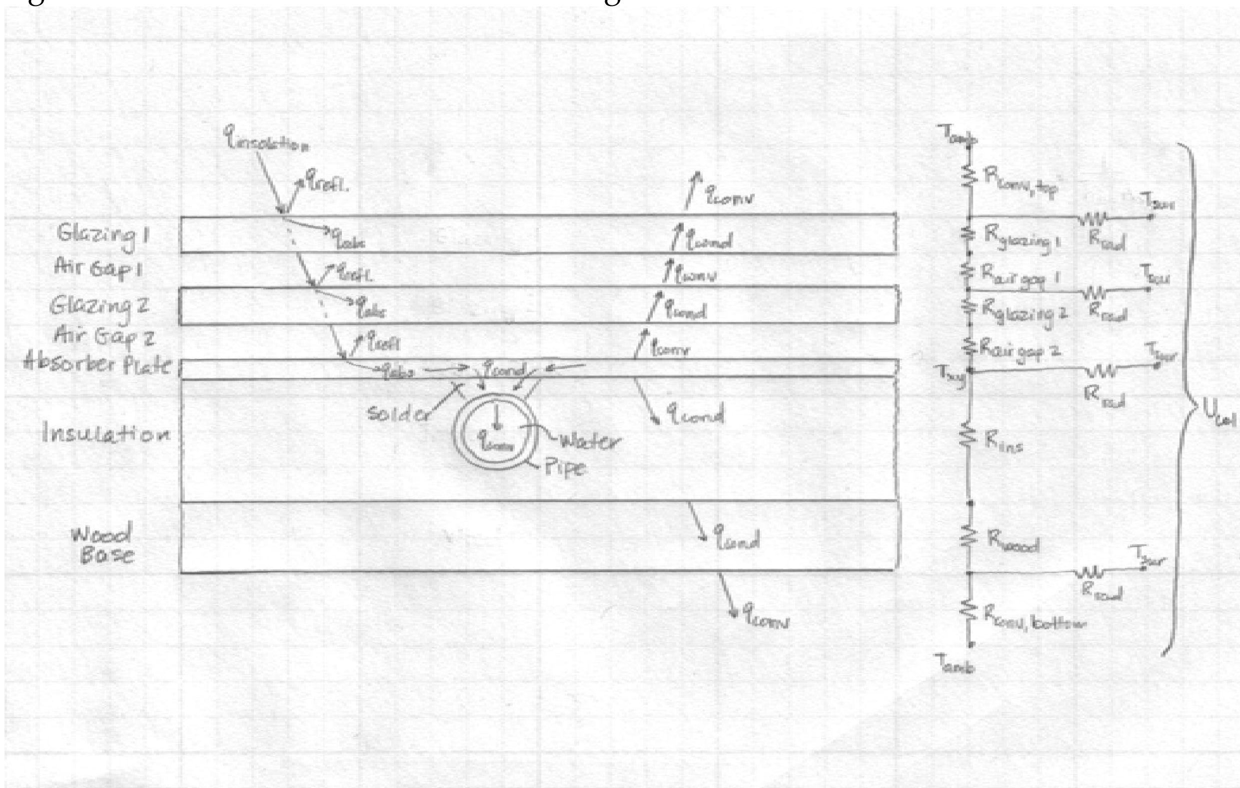
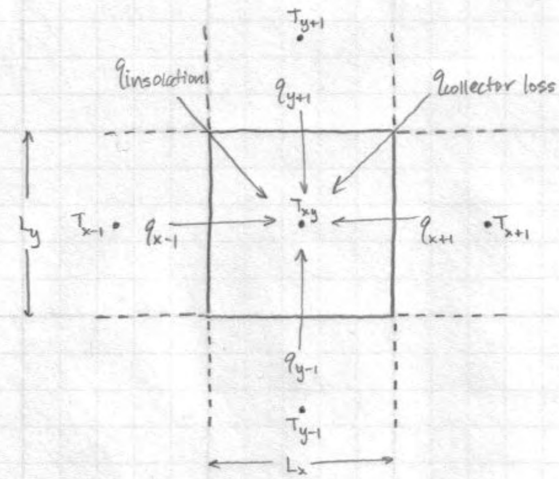


Figure 3: Finite Element Temperature Equation Derivation



$$q_{x-1} = \frac{K_{abs}A_{\perp x}}{L_x}(T_{x-1}-T_{xy})$$

$$q_{x+1} = \frac{K_{abs}A_{\perp x}}{L_x}(T_{x+1}-T_{xy})$$

$$q_{y-1} = \frac{K_{abs}A_{\perp y}}{L_y}(T_{y-1}-T_{xy})$$

$$q_{y+1} = \frac{K_{abs}A_{\perp y}}{L_y}(T_{y+1}-T_{xy})$$

$$q_{col} = U_{col}A_{xy}(T_{amb}-T_{xy})$$

$$q_{ins} = I \cdot A_{xy}$$

$$\dot{E}_{in} - \cancel{\dot{E}_{out}} + \cancel{\dot{E}_{gen}} = \cancel{\dot{E}_{st}}$$

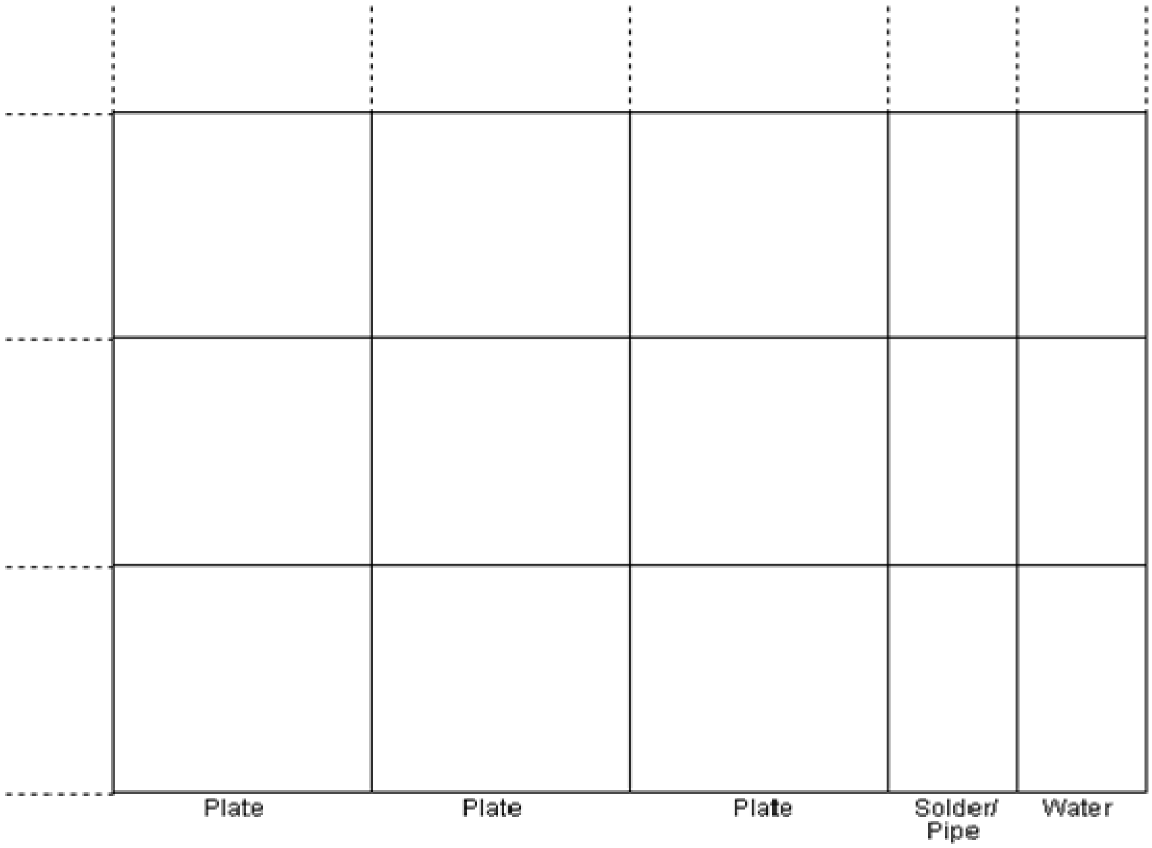
$$q_{x-1} + q_{x+1} + q_{y-1} + q_{y+1} + q_{col} + q_{ins} = 0$$

$$\frac{K_{abs}A_{\perp x}}{L_x}(T_{x-1}-T_{xy}) + \frac{K_{abs}A_{\perp x}}{L_x}(T_{x+1}-T_{xy}) + \frac{K_{abs}A_{\perp y}}{L_y}(T_{y-1}-T_{xy}) + \frac{K_{abs}A_{\perp y}}{L_y}(T_{y+1}-T_{xy}) + U_{col}A_{xy}(T_{amb}-T_{xy}) + I \cdot A_{xy} = 0$$

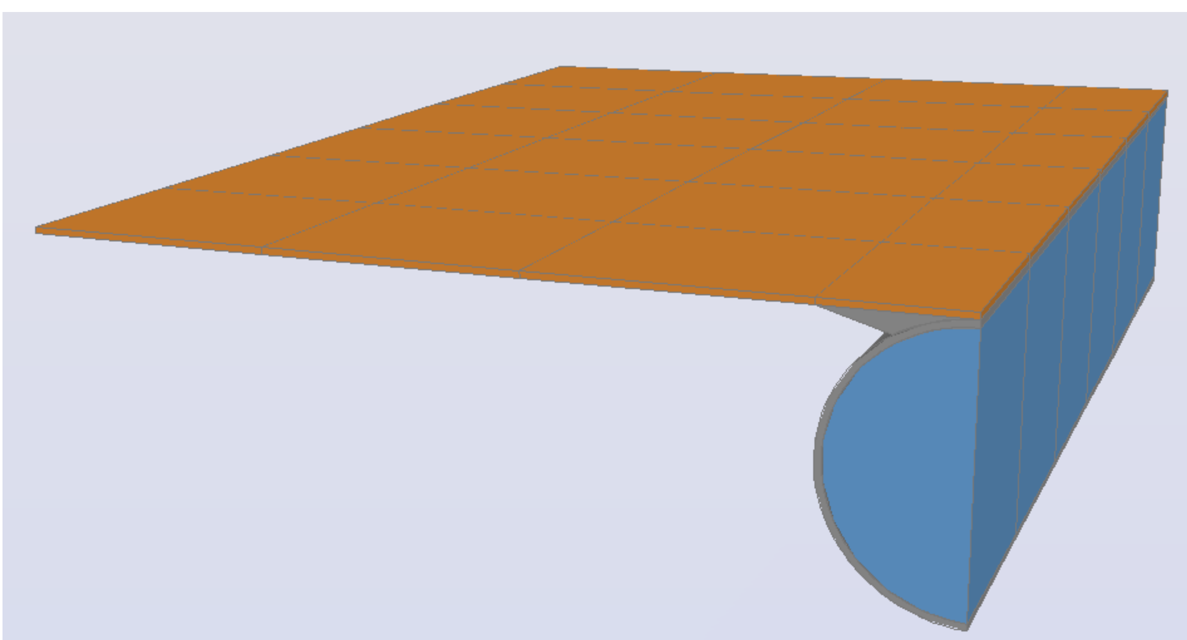
$$\frac{K_{abs}A_{\perp x}}{L_x}(T_{x-1}+T_{x+1}) + \frac{K_{abs}A_{\perp y}}{L_y}(T_{y-1}+T_{y+1}) + U_{col}A_{xy}T_{amb} + IA_{xy} = \left(\frac{2K_{abs}A_{\perp x}}{L_x} + \frac{2K_{abs}A_{\perp y}}{L_y} + U_{col}A_{xy}\right)T_{xy}$$

$$T_{xy} = \frac{\left[IA_{xy} + \frac{K_{abs}A_{\perp x}}{L_x}(T_{x-1}+T_{x+1}) + \frac{K_{abs}A_{\perp y}}{L_y}(T_{y-1}+T_{y+1}) + U_{col}A_{xy}T_{amb}\right]}{\frac{2K_{abs}A_{\perp x}}{L_x} + \frac{2K_{abs}A_{\perp y}}{L_y} + U_{col}A_{xy}}$$

Figure 4: Finite Element Diagrams



a. 2D finite element model



b. 3D finite element model

Figure 5: Test 1 Setup Diagram

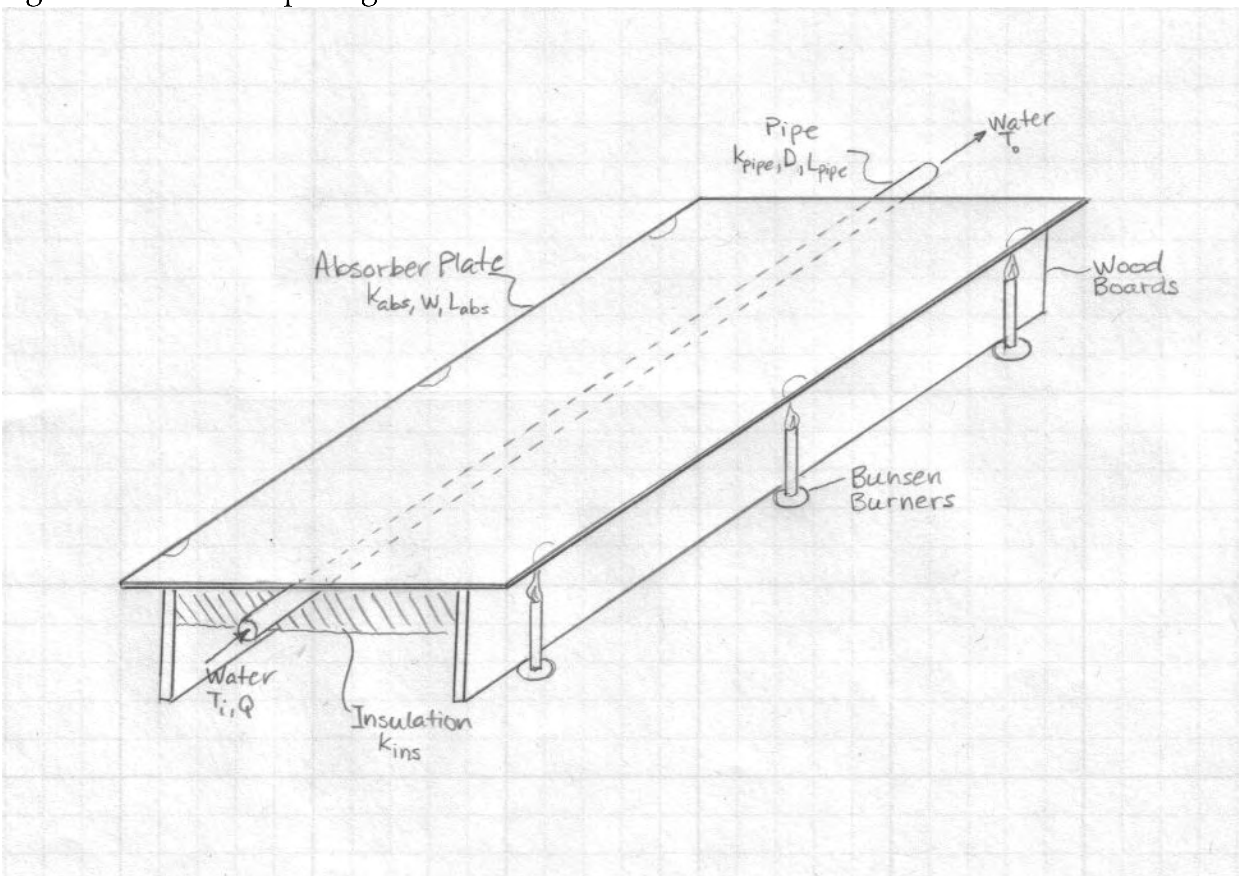


Figure 6: Test 1 Prototype Designs

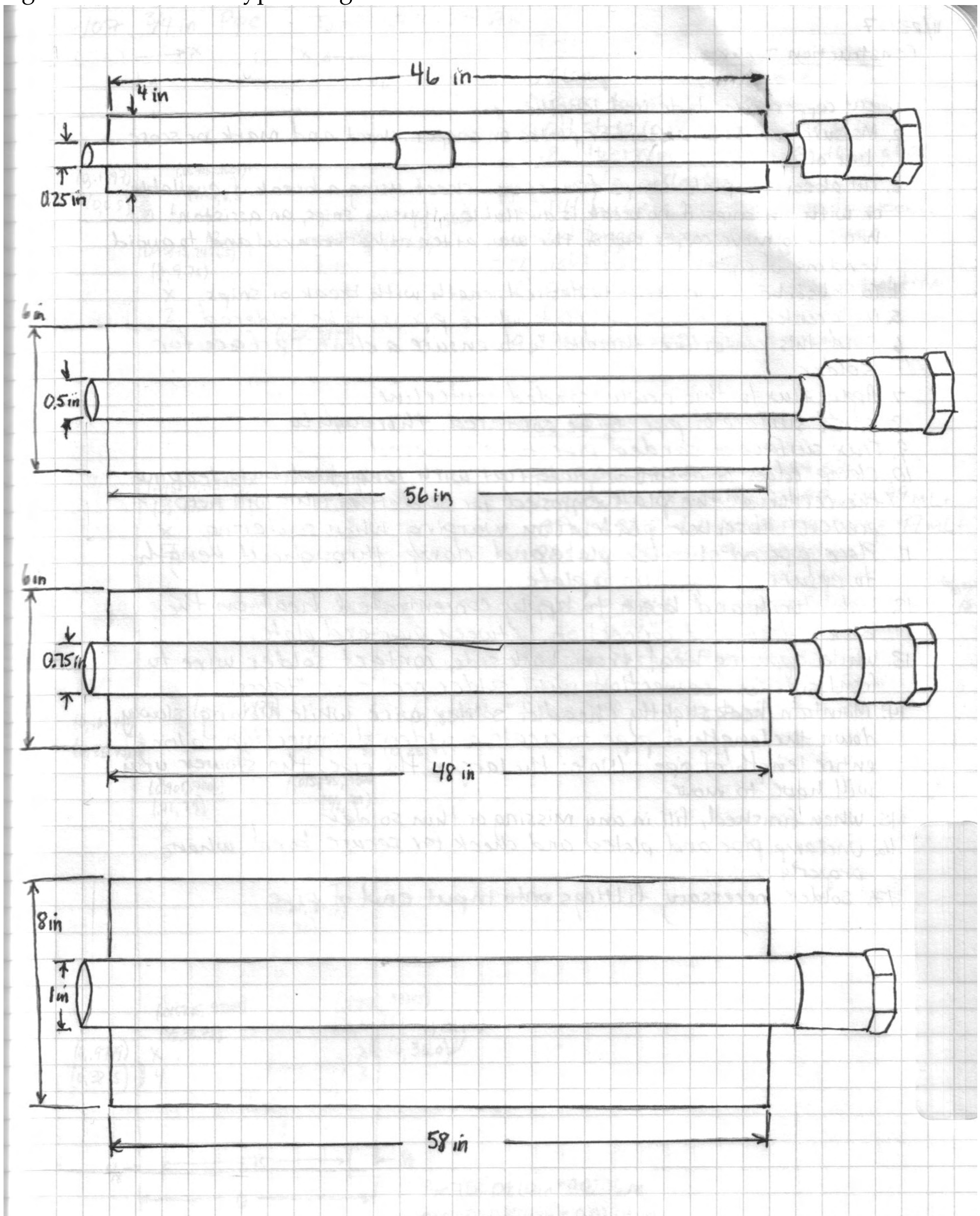


Figure 7: Test 2 Setup Diagram

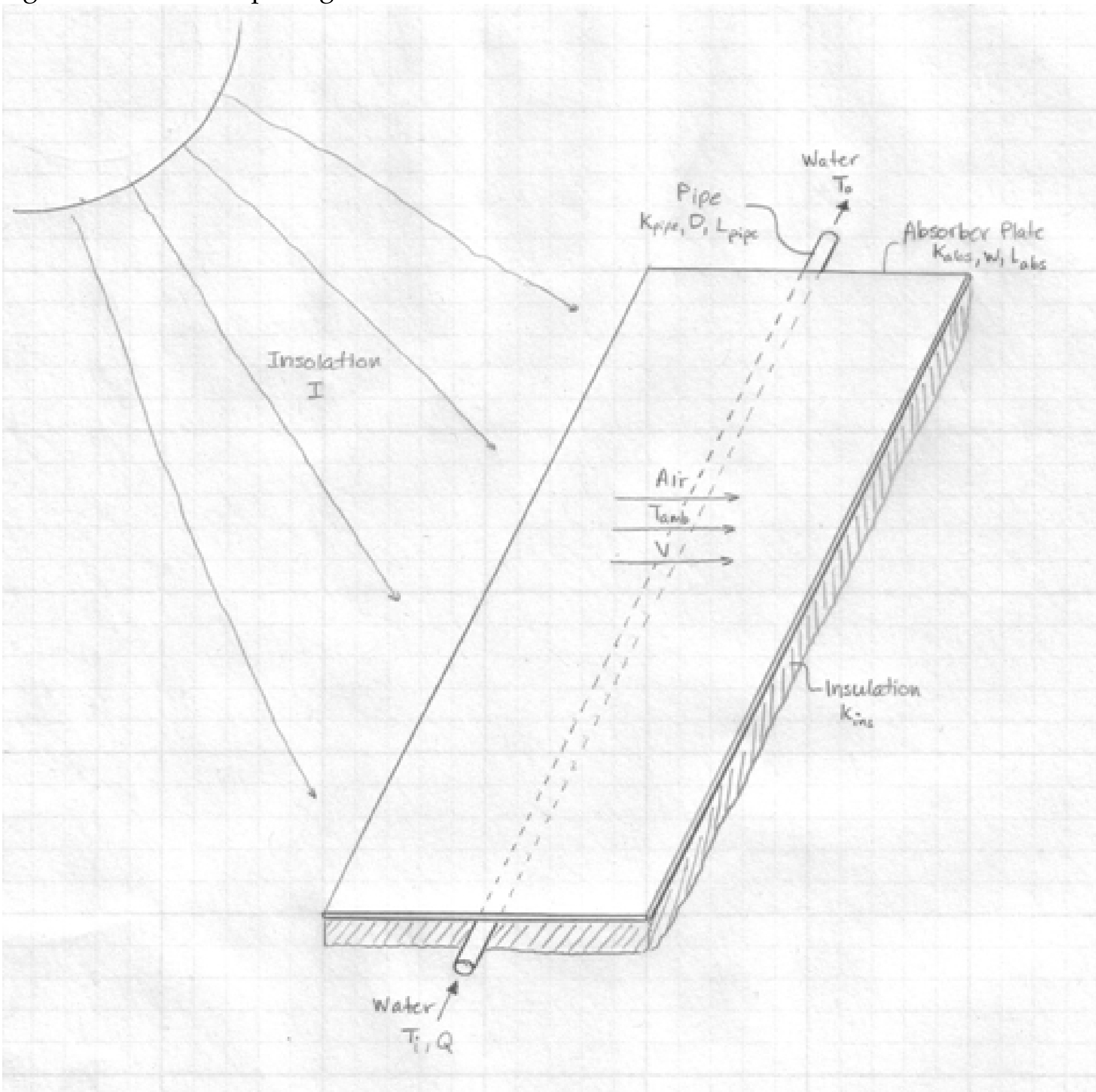


Figure 8: Test 2 Enclosure Design

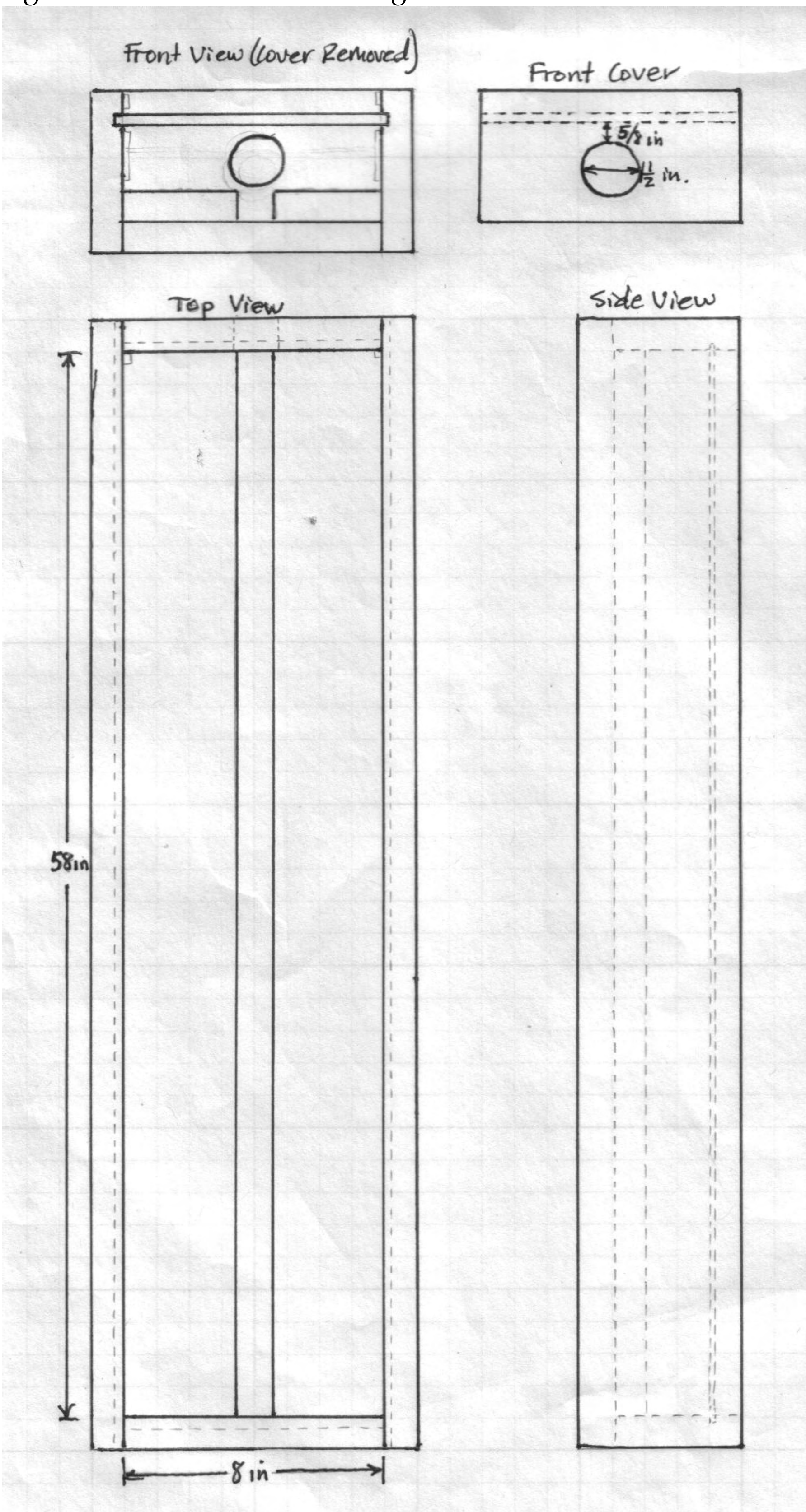


Figure 9: Test 3 Setup Diagram

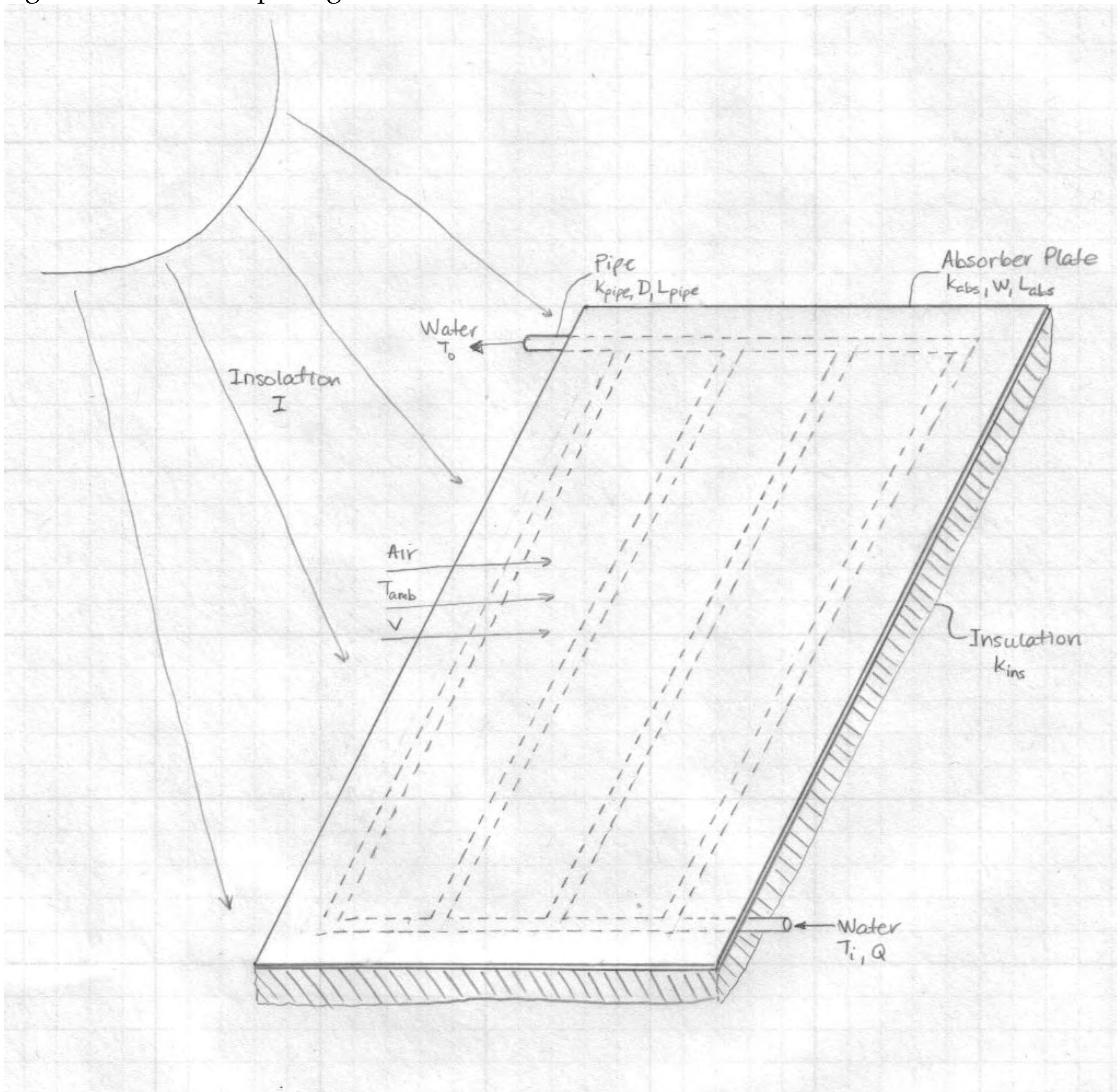
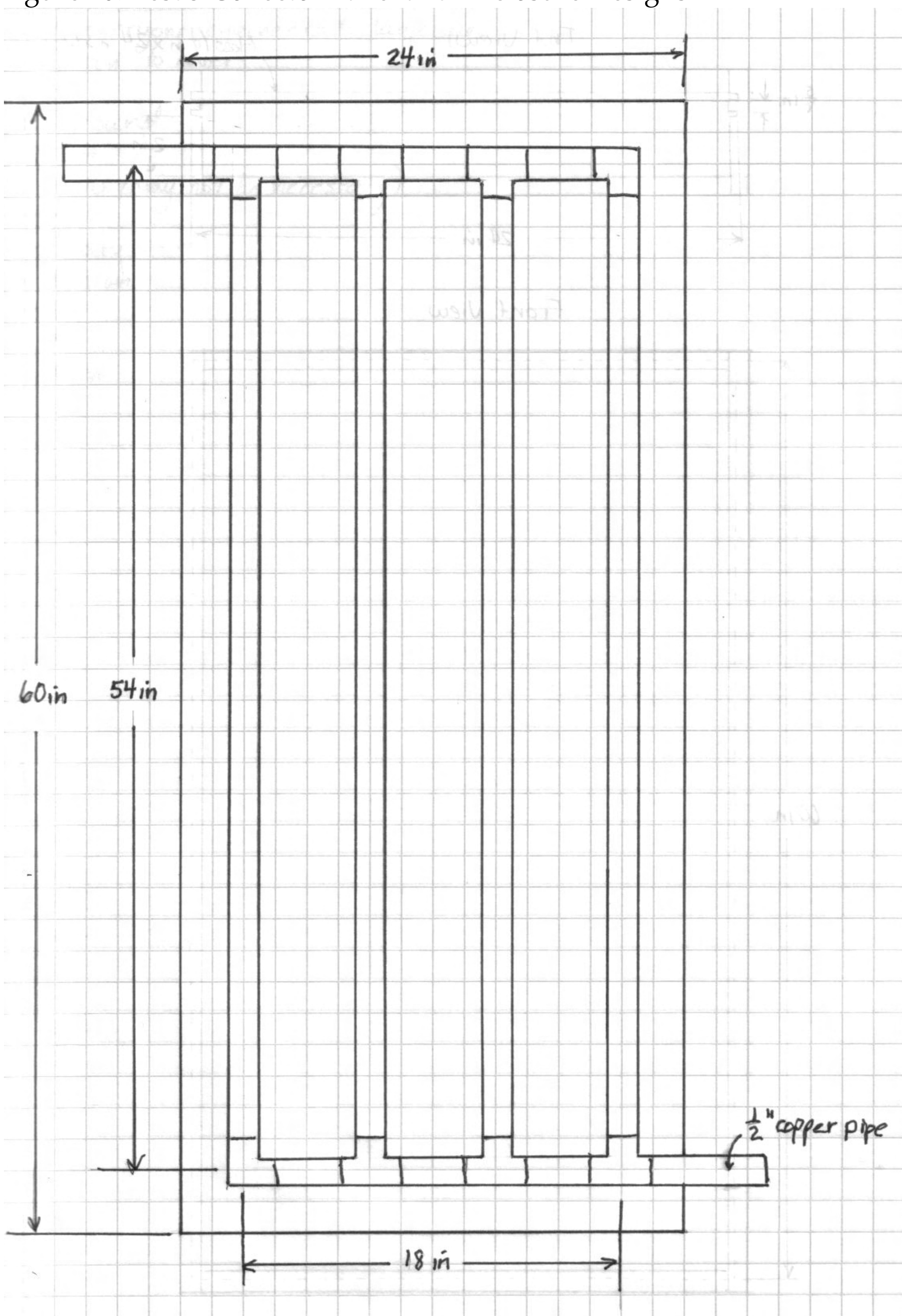


Figure 10: Test 3 Collector Panel and Enclosure Designs



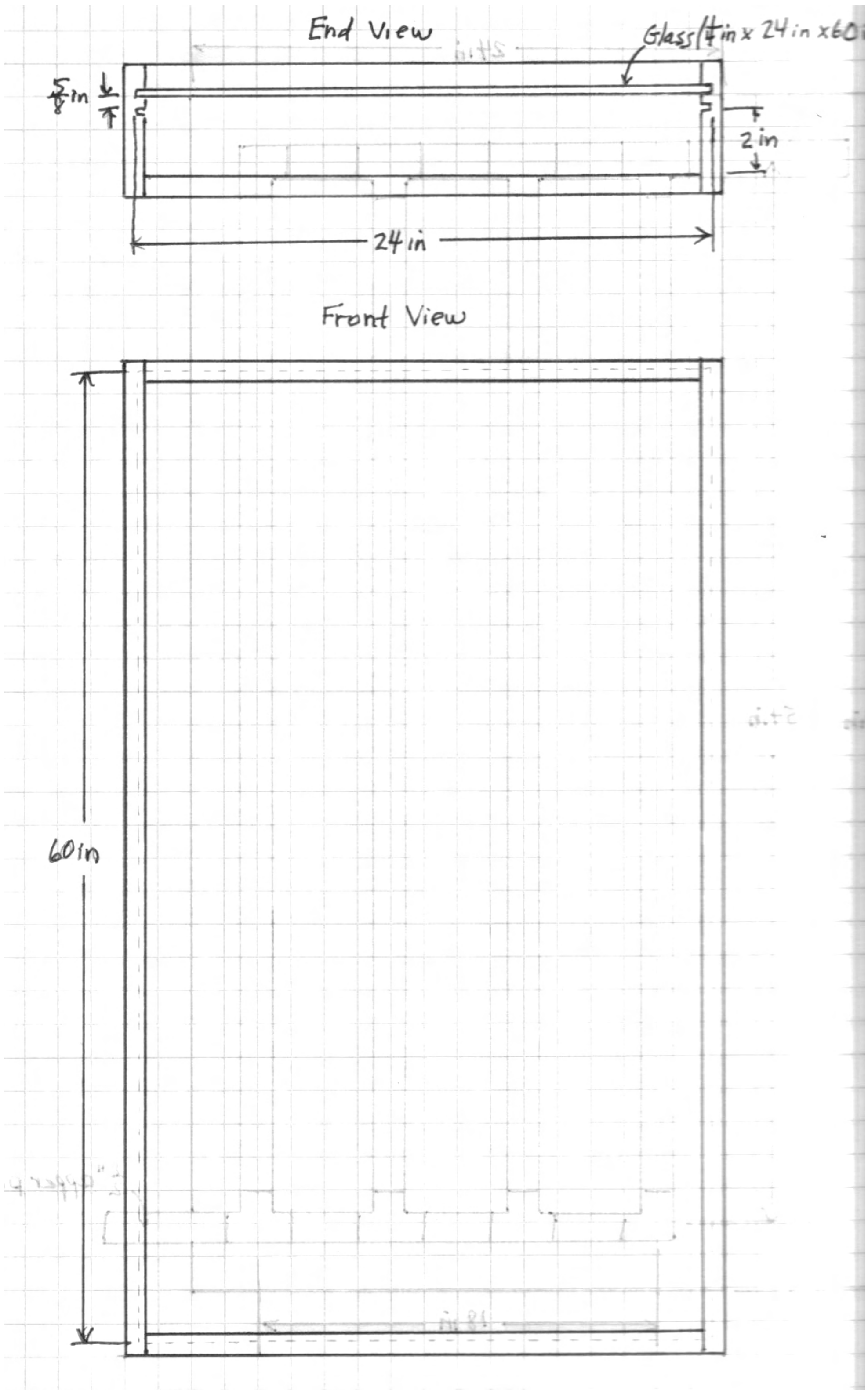
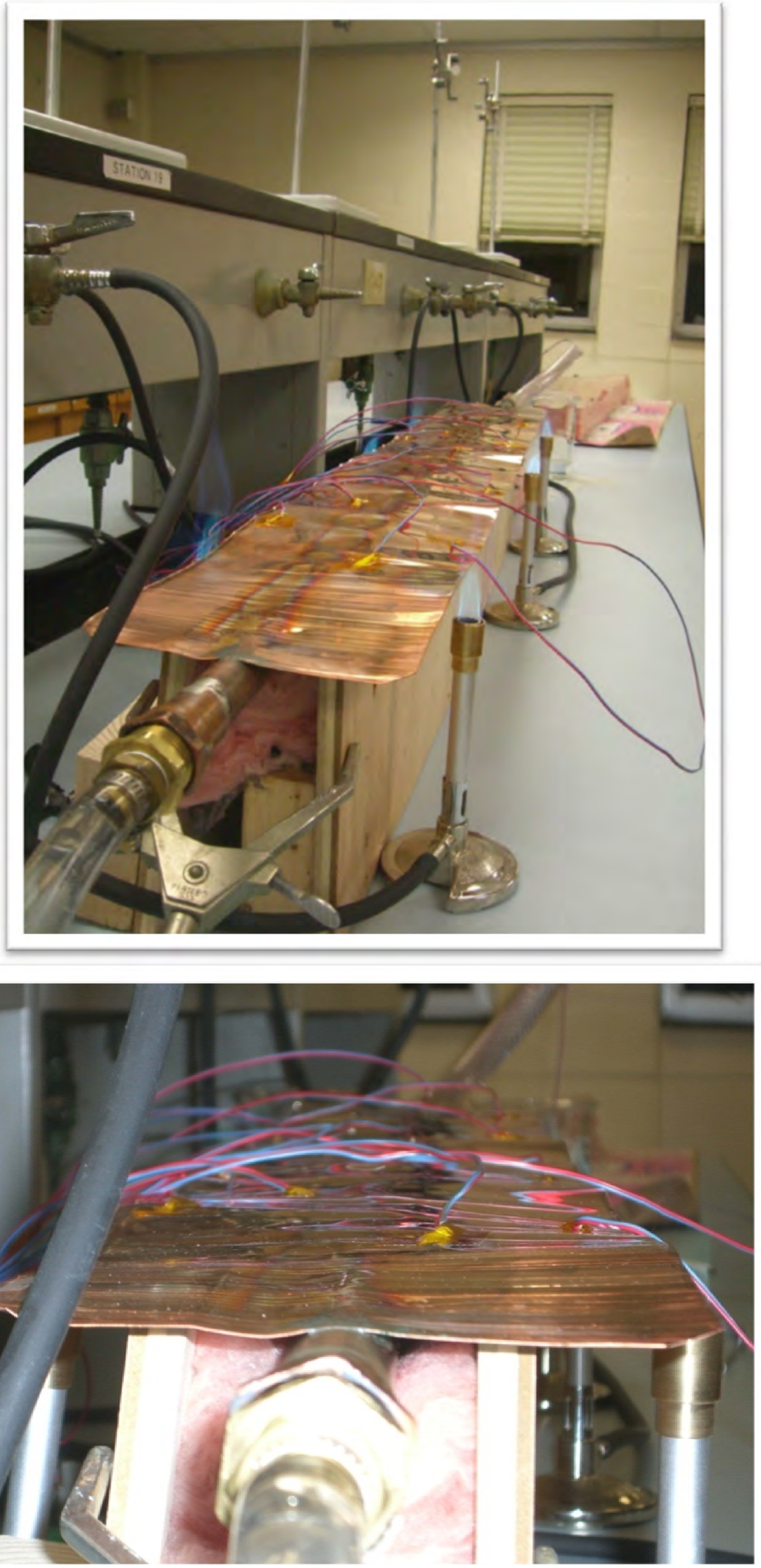

End View
Glass 1/4 in x 24 in x 60 in
5/8 in
2 in
24 in
Front View
60 in

Figure 11: Test 1 Photographs



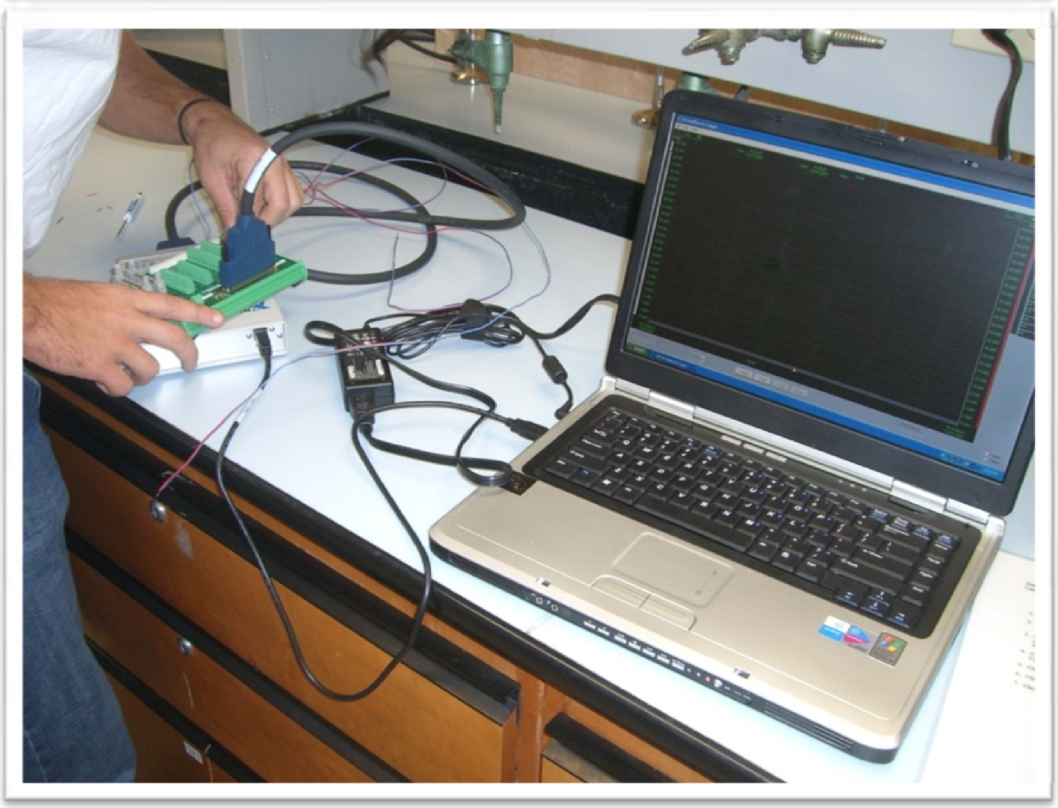
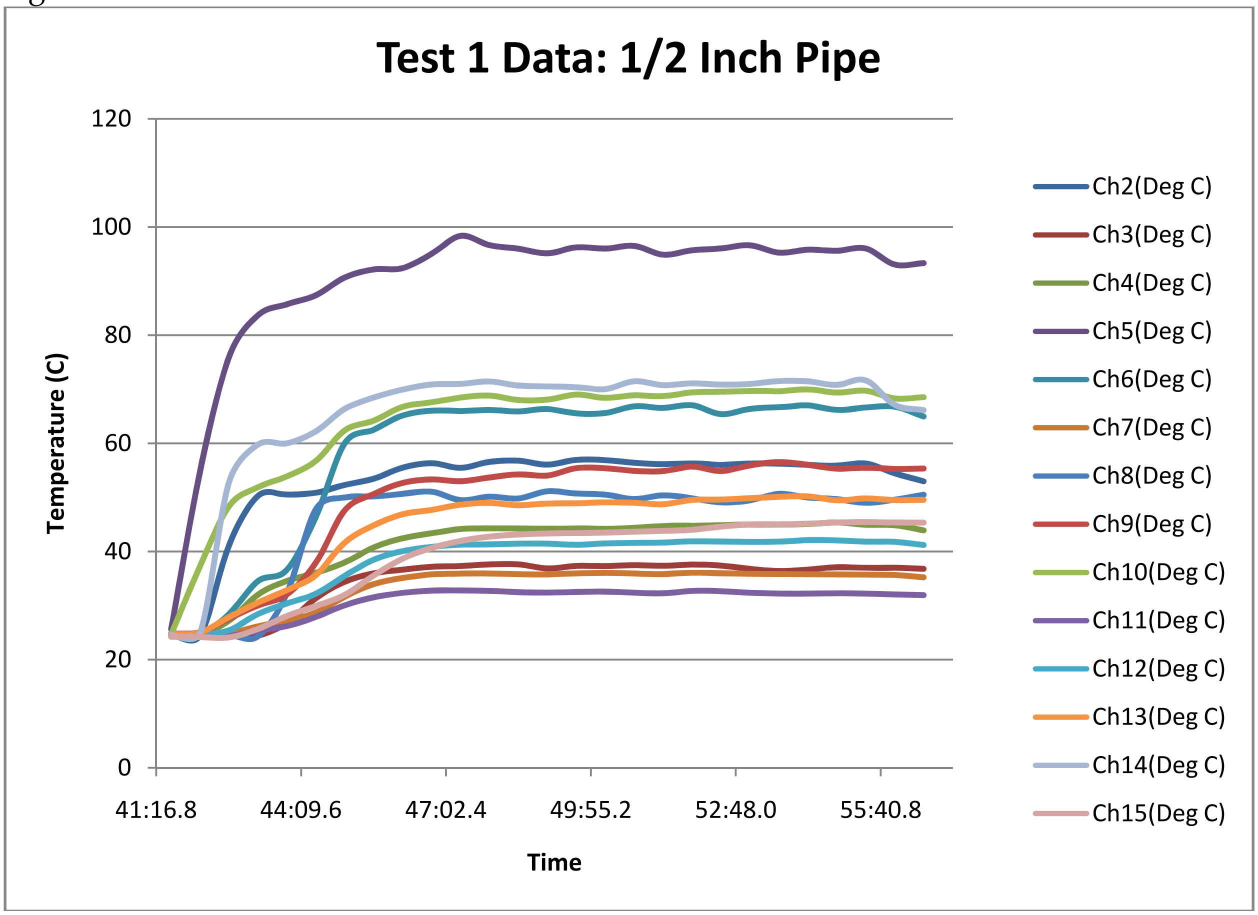
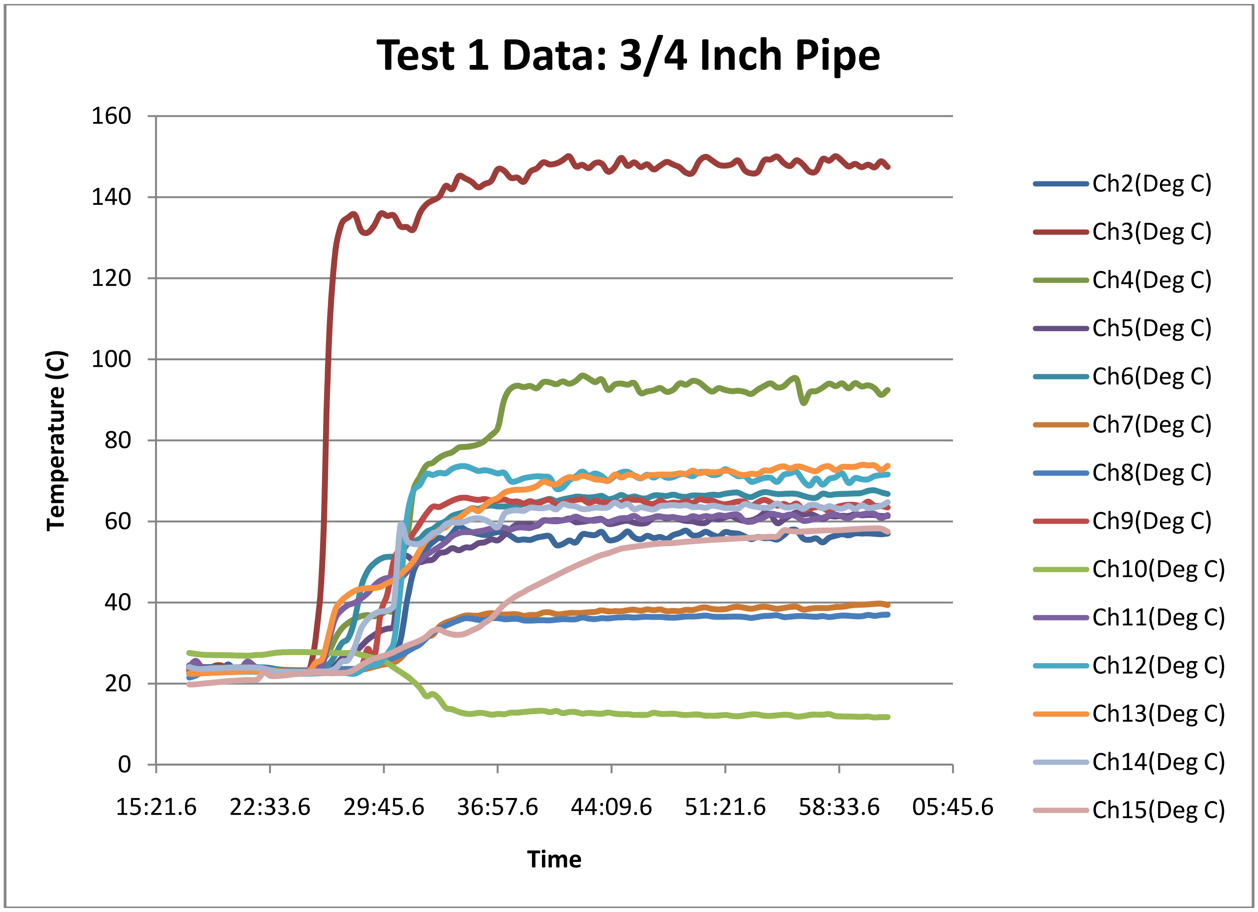


Figure 12: Test 1 Data





Test 1 Data: 3/4 Inch Pipe
Temperature (C)
160
140
120
100
80
60
40
20
0
15:21.6
22:33.6
29:45.6
36:57.6
44:09.6
51:21.6
58:33.6
05:45.6
Time
Ch2(Deg C)
Ch3(Deg C)
Ch4(Deg C)
Ch5(Deg C)
Ch6(Deg C)
Ch7(Deg C)
Ch8(Deg C)
Ch9(Deg C)
Ch10(Deg C)
Ch11(Deg C)
Ch12(Deg C)
Ch13(Deg C)
Ch14(Deg C)
Ch15(Deg C)

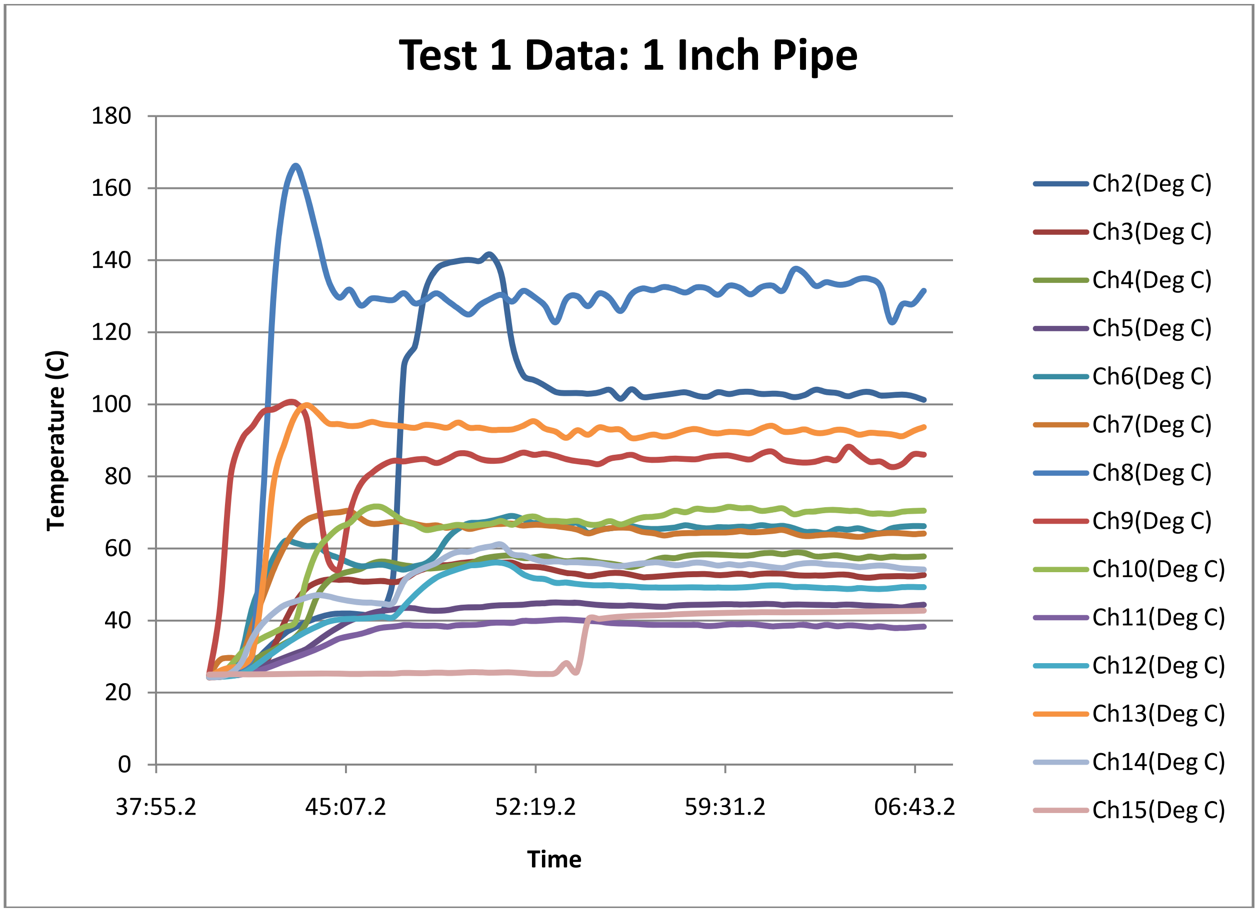

Test 1 Data: 1 Inch Pipe
180
160
140
120
100
80
60
40
20
0
Temperature (C)
37:55.2
45:07.2
52:19.2
59:31.2
06:43.2
Time
Ch2(Deg C)
Ch3(Deg C)
Ch4(Deg C)
Ch5(Deg C)
Ch6(Deg C)
Ch7(Deg C)
Ch8(Deg C)
Ch9(Deg C)
Ch10(Deg C)
Ch11(Deg C)
Ch12(Deg C)
Ch13(Deg C)
Ch14(Deg C)
Ch15(Deg C)

Figure 13: Test 2 Photographs

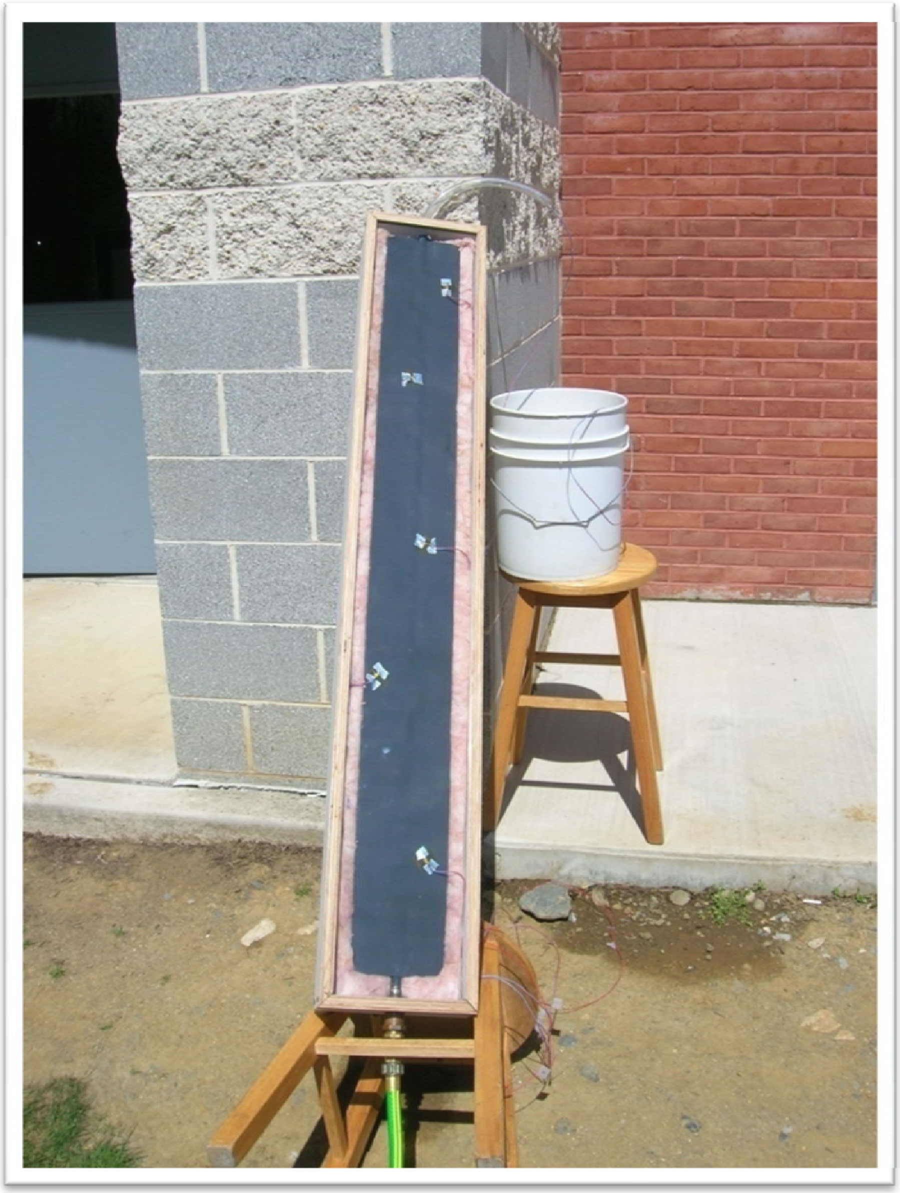


Figure 14: Test 3 Photographs

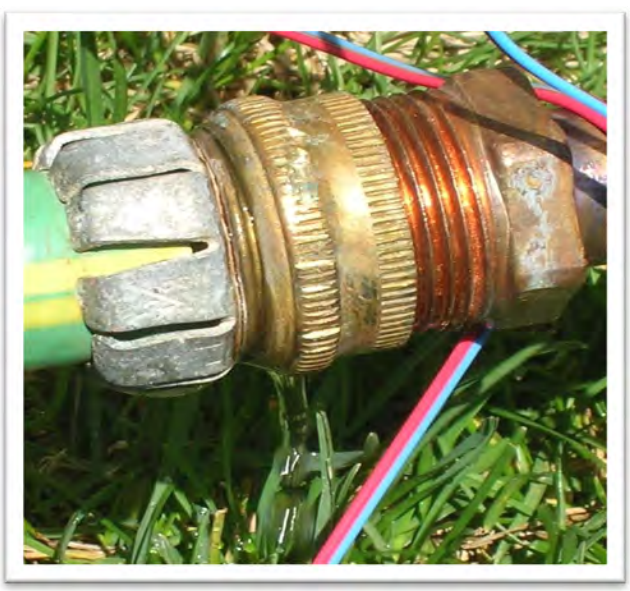


Figure 15: Collector Panel Construction