Solar Thermal Capstone

Final Report

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DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

The Northern Arizona University Mechanical engineering department's renewable energy course is implementing new labs to inform students about renewable energy sources. These labs are intended to allow for hands-on learning and practical application experiences for students. The department has an evacuated tube solar thermal collector with a manufacturer-reported efficiency curve. It was proposed by clients David Willy and Carson Pete of the NAU Mechanical Engineering that the dollar thermal team utilizes the existing evacuated tube collector to create a test bed. This test bed will measure performance efficiency of the solar collector. Students who that the NAU Renewable Energy course would be expected to compare the measured efficiency coming from the experimental test bed to that of the reported efficiency from the collector's manufacture.

The team met with the clients to understand what was expected of the test bed to be developed. After processing notes, ratings were given to each technical segment to determine its importance in terms of the completion of the project. The categories rated highest will be the ones where attention and preparation are most applied to, these include Safety, Cost, and Data Collection. With further examination of construction standards, a single system design was composed and approved by the project's client and mentor, David Willy and Carson Pete.

The team's first accepted design iteration was an open-to-atmosphere drain-back system. Further details include an adjustable solar declination angle for comprehensive insolation testing and combination tubing of metal and plastic material to decrease cost while simultaneously maintaining integrity. Comparing our selected design to other considered designs, the drain-back system that the team created was most durable in terms of longevity. It should be noted this was one of the principal requirements Dr. Willy asked for the Solar Thermal Project to accomplish. Upon installation of a new functioning system, the efficiency of this system can be compared against the efficiency of SRCC standard full system collectors. It was determined that key measurements include solar radiation, inlet/outlet temperatures, flow rates, and pressure within the system. This information will be used to analyze separate components such as power and the chief calculation as mentioned previously, efficiency.

The team's second proposed design was developed after visiting a professionally designed solar thermal water heating system. The solar thermal capstone team was invited by Brad Kraft and Morgan Stein of Green Earth Energy & Environmental, a local renewable energy engineering firm to visit the site of an active solar thermal system the company has installed. The team observed how the proposed design could be improved upon after visiting the professionally designed system. The second design was a glycol-charged system under elevated pressure to better protect against cold Flagstaff winters.

With the new system in mind, the team designed an experiment that allows students to compare the manufacturer performance efficiency values to experimental performance efficiency. To measure the efficiency experimentally, the team designed a solar thermal system using this collector along with necessary data collection instrumentation. To reiterate, student operation, weather, and safety were considered while designing the testbed and operation procedures. The resulting system is successful in heating a glycol loop that has the option to heat a load of water through a heat exchanger. From this, students can calculate efficiency values of the collector to compare to the reported values, analyze the system's performance in varying conditions, economic impact, and sustainability.

ACKNOWLEDGEMENTS

This capstone project was funded by W.L. Gore and the Northern Arizona University Mechanical Engineering Department. The project was proposed and advised by Professor Carson Pete and Professor David Willy of the NAU Mechanical Engineering department, with professional mentorship from Morgan Stein and Brad Kraft of Green Earth Energy & Environmental.

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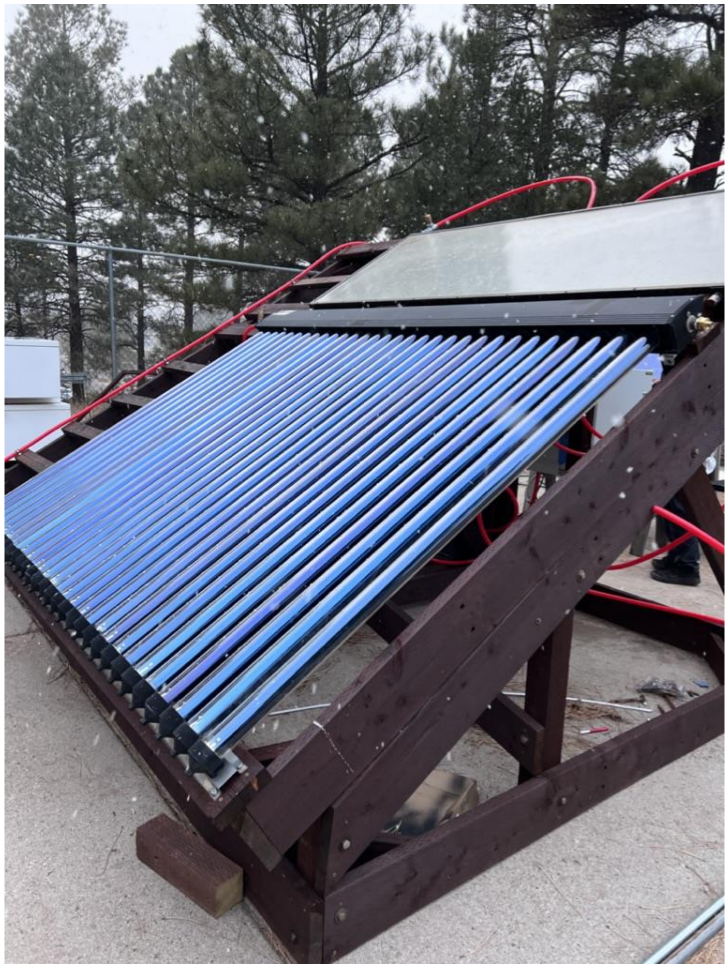


Figure 1. Solar Thermal Testbed

1 BACKGROUND

1.1 Introduction

The clients for this team, David Willy, and Carson Pete. Both clients have a background and interest in renewable energy. They have a significant interest in teaching students about renewable energy. The clients proposed that the team take advantage of an existing solar thermal collector to design an experiment that compares the manufacturer reported efficiency value for the collector with its experimental efficiency. This requires the team to design and assemble a solar thermal system equipped with the proper instrumentation needed to calculate the efficiency of the collector. Using this system, students can calculate efficiency values of the collector to compare to the reported values, analyze the system's performance in varying conditions, economic impact, and sustainability.

1.2 Project Description

Dr. Willy proposed that the team take advantage of an existing solar thermal collector to design an experiment that compares the reported efficiency value for the collector to its actual efficiency. This requires the team to design and assemble a solar thermal system that follows

ICC standards in the renewable energy lab space.

Moving into the second semester our client has changed to Professor Carson Marty Pete as he assumed responsibility for the Renewable Energy lab over the summer. No changes were made for the base expectation of the project, but some additional items were acknowledged that may further enhance the versatility of the project. Professor Pete requested that the test bed have accommodations for 2 other solar thermal systems.

2 REQUIREMENTS

After meeting with the clients, the team compiled given specifications to develop customer requirements. These introduce client-defined qualitative data. The capstone team converted these customer requirements into direct or quantitative, measurable data. These are also known as engineering requirements. Following these definitions, the team presents a House of Quality (HoQ) of Quality Function Deployment (QFD). By using customer needs to apply requirements to this table, the team will gain a better understanding of relationships pertaining to our functions and desired designs.

2.1 Customer Requirements (CRs)

These requirements defined by the client are presented below. These requirements detail what is expected for the system and project completion. It should be noted that these have been iterated since the original proposal of the project. The client requested that the design allows for growth in the scope of the testbed

1. Design and create an experimental test bed housing an evacuated tube solar collector.
    a. Design for system expansion
        i. Additional solar collectors
        ii. Lab variations
2. Write lab procedure for a new ME 451 lab
    a. Applicable to ME & NON-ME majors alike
    b. Procedures revolve around recording data
3. Design an experiment to compare Reported v. Experimental Data from evacuated tube system
    a. Communicate discrepancies among differing efficiencies of solar collector
    b. Follow Previous EGR Lab Methods
        i. Proper engineering experimental procedure
        ii. Cover technical analysis studies of measurements, calculations, and uncertainty
4. Utilizing Existing Evacuated Solar Thermal Collector
    a. Leads to a reduction in cost
    b. Allows for Benchmarking with a physical product
5. Run the system as described in the lab procedure to have master set of data
    a. Report efficiency upon findings

2.2 Engineering Requirements (ERs)

Team Solar Thermal translated customer requirements into bounds with constricted definitions. These definitions are described by the experiment and system functions themselves. With guidance from the ICC standards for a solar thermal system, the team has some “pass of fail” component checklists. Additionally, the team has requirements to complete data collection and budget constrictions. The team decided to reorient some engineering requirements to be less qualitative.

1. System Failure Prevention
    a. Freeze Protection
        i. Intentions to create a system that doesn't falter with drastic weather conditions
        ii. System rated against ASHRAE weather data from last 50 years
    b. Steam Protection
        i. At least 2 ways to handle
        ii. Expansion Tank
        iii. Air Bleed
    c. No system leaks or fluid discharge
2. Cost
    a. Solar Thermal Capstone has limited funds capped at $3200
    b. Potential to receive another $800
3. System Longevity
    a. Contain system in covering, protected against weather and wildlife
    b. Lifespan of 10 years
4. Data Collection
    a. Temp In, Temp Out, Flow Rate, Insolation
5. Simplicity of Operation
    a. Safe, general operation by 1 person.

2.3 Functional Decomposition

Functional decomposition is used to analyze the system by breaking up its functions. This is done using a black box model and a functional decomposition model. An updated process diagram is also discussed which outlines our final design solution for the project. From this the team will have effective visualizations of how the system flows in greater detail.

2.3.1 Black Box Model

The black box model is a system modeling method that visualizes system inputs and outputs. As the name implies, the focus is not what goes on inside of the box, but what is out in and what the system produces. The ins and outs are called flows. The bold arrow indicates material flow, the thin arrow indicates energy flow, and the dashed arrow indicates signal flows. The black box model for the team's proposed system is seen in figure 3. These flows achieve the main goal of heating glycol.

Figure 2. Black Box Model

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The FDM aka. Hierarchical Task Analysis is like looking inside a black box. This model seen in figure [3] focuses on the inputs, outputs, as well as all the steps in between. By using the same arrows to describe the types of flows, this model shows the critical processes in the system. For a system of this nature, the model can be confusing. The summarized process is as follows: the system must have inputs of solar energy, electrical energy, cool glycol, and an on signal. The glycol is pumped through the manifold of the solar collector and then stored in a tank and can cycle through the system again. Between these stages there are sensors for data collection purposes. This model allows the team to focus on the processes that must happen in the system. From there, subsystems can be identified.

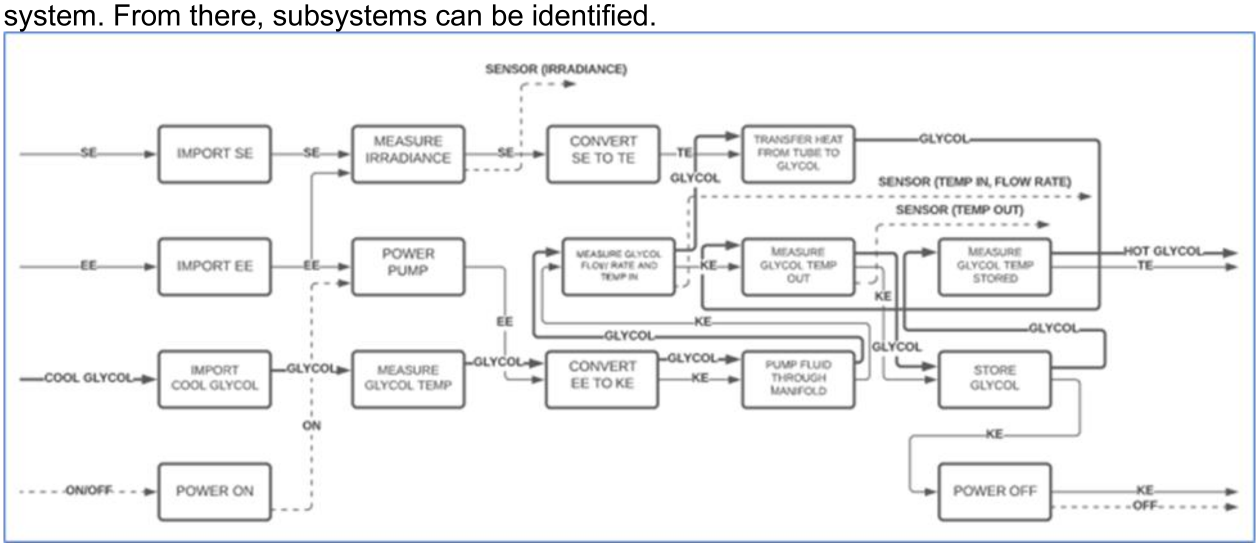


Figure 3. Functional Decomposition Model.

2.3.3 Process Diagram

After reassessing the design, the team created a process diagram that describes the system. The closed loop, indirect system is pumped through the collector to a heat exchanger and back to the start of the loop. The cold side of the heat exchanger has been designed to be connected to a load for system cool down and lab expansion. By using the required instrumentation for calculating efficiency.

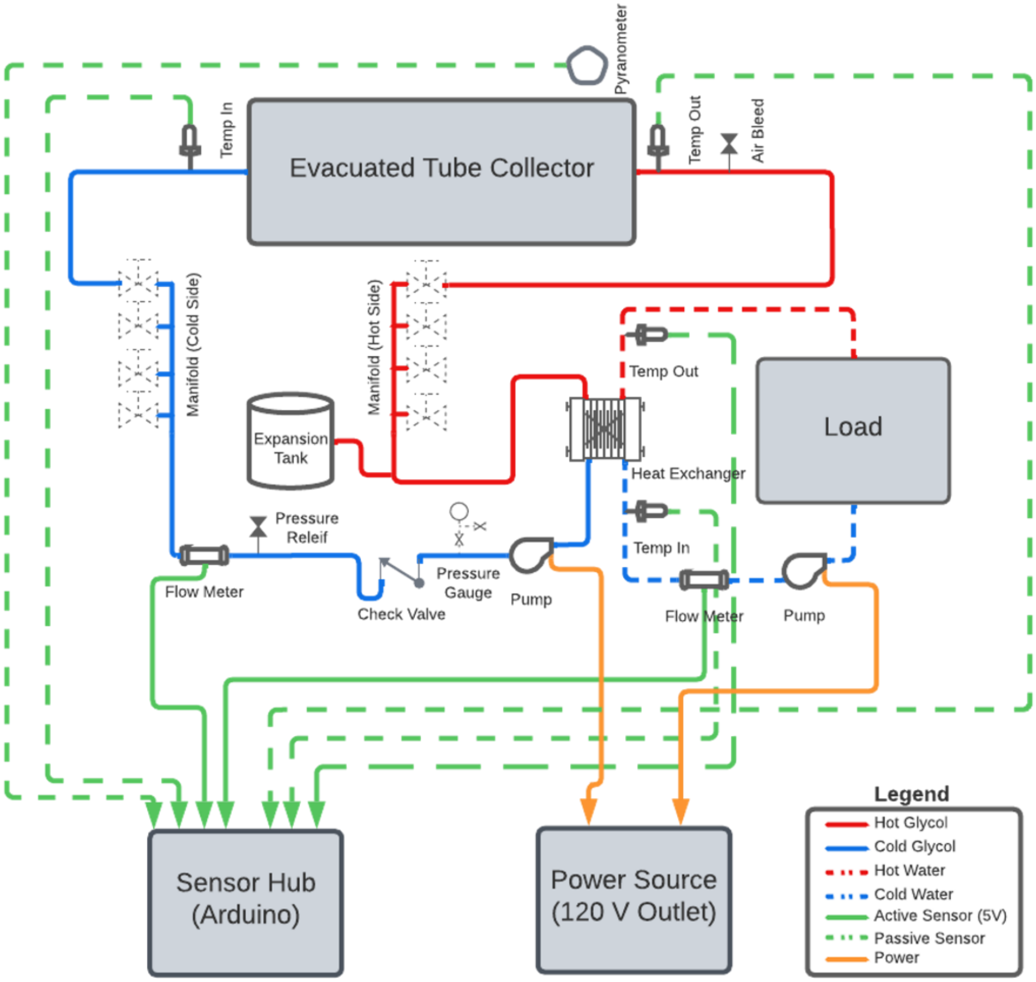


Figure 4. Process Diagram for Semester 2 Design

2.4 House of Quality (HoQ)

Within the project design process, the House of Quality compares the customer requirements directly to the engineering requirements (also known as technical requirements) in efforts to find an absolute and relative technical importance. Customer requirements were numbered 1-5 ranging in relativity to the lab. Each of these are associated with a significance tied to each technical requirement. This number across the figure represents Relative Technical Importance, for example Data Collection and Cost received high ranking for this criterion. The team applied weights to the technical requirements relative to our definition of importance in the “Absolute Technical Importance” section. ICC Standards and Safety are awarded with the highest ranking here. Total Relative Technical Importance was found by summing the customer requirement weights associated with the engineering requirements. Even though the team self-applied weightings to the engineering requirements, the Relative Importance totals assisted in presenting a different scale of importance. The House of Quality evaluation concluded that our methods for acquiring data and our cost analysis will come into great play as Team Solar

Thermal continues with this project. This figure can be found in Appendix A.

2.5 Standards, Codes, and Regulations

The standards below are the global standards for how a solar thermal collector and system must be constructed. The team used these standards to design our solution and satisfies them appropriately for the current setup. Some revision may be necessary if the design solution is used in another way in the future. The last standard in the table is the standard dictating how drawings must be annotated and reported.

Table 1: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ICC 901/SRCC 100-2020	Solar Thermal Collector Standard	Describes the way in which Collector are constructed and with which aspects they are designed in mind with
ICC 900/SRCC 300-2020	Solar Thermal System Standard	Describes the way in which a System must be assembled to ensure safe and reliable operation
ATSM Y14.5	Dimensioning and Tolerancing Standard	Outlines the way in which drawings are labeled and units are displayed.

3 DESIGN SPACE RESEARCH

No member of the team came into the project with knowledge of solar thermal systems, there were many references used to inform the team. This section describes the most significant reference used by the solar thermal team.

3.1 Literature Review

The following section is a literature review of reverences used by the team. These sources are relevant to the technical position of each student.

Standard 100:
The ICC 901/SRCC 100 Solar Thermal Collector Standard [2] is a series of codes that a solar collector must abide by to be deemed certified by the ICC and SRCC. It is important to define some of the acronyms found within the title of this source. ICC stands for the International Code Council; this is an association that works towards developing codes and standards. These standards are for buildings, structures, systems, devices, and many other products of engineering that require a certified level of safety, sustainability, or efficiency. The solar collector to be used for this project is one of these items. The SRCC is the Solar Rating & Certification Corporation. This corporation evaluates the codes that will be in the standard. Within this standard are all the specifications for a certified solar collector. It is important that the solar collector is certified by these parameters to ensure safety, especially in an environment where people will be close to this collector. This is relevant to the project in the way of being familiar with what kind of qualities a solar collector should have. Although the team is not designing the collector, knowing this information is useful in recognizing possible issues with the collector.

Standard 300:
The ICC 901/SRCC 100 Solar Thermal System Standard [3] similarly to the ICC 901/SRCC 100

Solar Thermal Collector Standard, is a series of codes a solar thermal system must abide by to be deemed certified by the ICC and SRCC. This standard is even more relevant to this project as this standard must be followed to build a system. The team's client, Prof. Willy, requests that the final system follows all the codes of this standard. The team used this standard to shape engineering requirements. These standards heavily influenced the concept selection concept. For example, the standard requires that every system have 2 anti-freezing failure precautions. This was implemented in all the concept variants. These standards will continue to be used by the team to abide by the client's wishes.

Prof. Willy's Presentation:
The team's client David Willy provided the team with a presentation, "Flat Plate Solar Thermal" [4]. These slides highlight solar thermal systems. These slides comprise a presentation that Prof. Willy prepared for the previously offered renewable energy course. This presentation explains the types of solar thermal collectors which are flat plate and concentrator. The team will be working with the latter. The presentation highlights the effectiveness and application. Performance ratings, and the equations used to calculate them are included. This presentation provides a lot of relevant information for the project. Not only was this informative for the team, but it showed what kind of information the students in this course will be given before working with the actual system

Infrared imaging method for flyby assessment of solar thermal panel operation in field settings:

The paper, "Infrared imaging method for flyby assessment of solar thermal panel operation in field settings" [5] investigates the ability to decide if a solar thermal system is functioning using infrared sensors on flyover dorms. Although the research for the paper is not relevant to this project, the test bed used in the experiment has similar traits to the team's desired testbed. Additionally, part of this work was done by David Menicucci and he is referenced by Prof. Willy. The test bed in this article simulates a residential load but has many sensors for data acquisition. This is relevant to the project because creating a test bed like this is the team's goal and it serves as a reference.

SunMaxx Product Data Sheet:
The SunMaxx Solar VHP30 Product Data Sheet provides information about the solar collector the team is using for this project [6]. SunMaxx is a company that sells a variety of solar voltaic and solar thermal systems. This document contains technical specifications about the collector. Some of this information includes dimensions, fittings, maximum pressures, and much more. Most importantly the document has performance rates. This information is critical in analyzing the system. Knowing the system's performance is part of the client's proposed learning outcomes from the completed lab. Additionally, these specifications give insight to what conditions the collector is expected to operate under.

Principals of Solar Engineering [7]:
This is a textbook that was used for the ME451 Renewable Energy course in the past. On Dr. Willy's recommendation we were advised to obtain this text to gain an understanding of how solar thermal process work and how the principals learned in other course apply to the analysis of solar thermal systems. The key governing equations that we will use for our experiment and that will be introduced to students are obtained from chapters 4-5 on solar thermal applications.

Solar Engineering of Thermal Processes, photovoltaic and wind [8]:
Similarly, this text was recommended by Dr. Willy as an alternative to Principals of Solar

Engineering. Michael is using this as an alternative way to interpret and supply equations as we finalize our testing procedures. The alternative presentation of solar thermal processes helps further his understanding of solar thermal systems.

Udemy Hackster Arduino Introduction Course [9]:
As the test engineer Michael is anticipating a more hands-on approach to how we will conduct our experiment. To facilitate this, he is refreshing some knowledge of the Arduino system. The sensors available and the ease of interface with Microsoft Excel allows him to quickly prototype and test data collection. The general knowledge supplied by this course allows him to grasp some of the more niche applications of Arduino quicker.

Paul McWhorter YouTube Channel [10]:
Paul McWhorter runs a YouTube channel focused on Arduino and its surrounding tools. He has content from introductory topics to niche topics on how the microcontroller functions on an electrical basis. Michael will be using some of his more specific videos on implementing sensors to verify that our system is working as expected before potentially purchasing an easier interface with the experiment to help students learn.

Theory and Design of Mechanical Measurements [11]:
This textbook is the same as the one currently being used for the ME495 Experimental Methods of Thermal Sciences. The book covers a range of topics including sensor types, and error analysis. These topics are the most important when developing our test bed as any unforeseen errors in our data collection may confuse students and decrease their understanding of the topic of solar thermal systems.

SolidWorks Tutorial: Basic Techniques - Design Tables [12]:
This tutorial teaches you to modify component dimensions through a design table. Within one file, you can create the same part with a multitude of variations. This feature allows us to quickly alter configurations in SolidWorks. With additional features such as suppressing design aspects, editing part files comes with ease. This Tutorial is applicable to this project for these reasons.

SolidWorks Tutorial: Advanced Techniques – Equations [13]:
It is useful to understand that SolidWorks has an imbedded calculator. This can be used for defining dimensions of a length and extrusions of a body. Furthermore, equations can be applied to extrusions, fillets, and linear patterns. Initially, global variables must be defined, these are the ‘given’ values. Sequentially, one can create equations for other dimensions within the part file using global variables integrated within said equation.

SolidWorks Tutorial: Advanced Techniques – Advanced Drawings [14]:
Upon completing the drawing tutorial, basic use of the sheet functions such as displaying different views with dimensions were acquired. As Andrés completed the advanced portion, it was realized the depth of potential with portraying parts and assemblies with drawing sheets. Instead of using dimensions, a datum can be utilized to show distances from a central axis. He learned distinctions among the section cuts used to show the interior of front, side, and top views for 3D models. Additionally, how to insert a Bill of Materials alongside balloons tagged to each component within the drawing. This knowledge will aid the team in the demonstration of our digital prototype in the conclusion of the Spring 2022 Semester.

SunMaxx Shop Parts Catalog [15]:
SunMaxx Solar is a company working directly with production of solar thermal systems. In the

development of Team 3's outsourced solar system, this catalog presents a multitude of parts for evacuated tube collectors, water storage tanks, and hot water accessories. All components are accompanied by dimensions and materials used for installation and replacement. In development of our computer aided design, Andrés will use these defined standards to evolve our experiment more accurately.

Fundamentals of Solar Photovoltaic Systems [16]:
Within the context of Solar Systems, it is vital to understand that these devices are electrically powered, even if the photovoltaic process relates to converting solar light into energy. The solar capacity of the system is initially determined by the current, voltage, and resistance existing within this functioning model. Power is examined and graphed to compare which of these properties are most influential. To ensure safety for this electrical system, building standards require wire protection such as wire coverings and grounding to prevent electrical hazards. For more understanding, solar systems are generally designed to operate close to the short circuit current so protective implications must be considered. Therefore, this resource can be recovered and acknowledged upon the physical assembly of our lab experiment. TPC Training provides insight into the electrical construction and importance of safety for solar thermal collector devices.

3.2 Benchmarking

Some similar projects have been conducted but the relationship to ours is tenuous. The most prominent example of this is the way in which the ICC and SRCC conduct their tests to meet the certification requirements of a solar thermal system. Every solar thermal collector that is targeted at consumers must meet these certifications to be considered "up to code". While we are still in the initial stages of developing our data collection methods we will focus on the components of solar thermal systems and how we may best implement them on the test bed.

3.2.1 System Level Benchmarking

Many designs are not directly applicable to the project as we are more focused on the experimental procedure and resulting implications. Here we will discuss some similar systems in relation to the solar thermal collection process i.e., evacuated tubes, flat plate, and concentrating collectors. All these systems follow the general layout below. We will discuss each of these systems using this template

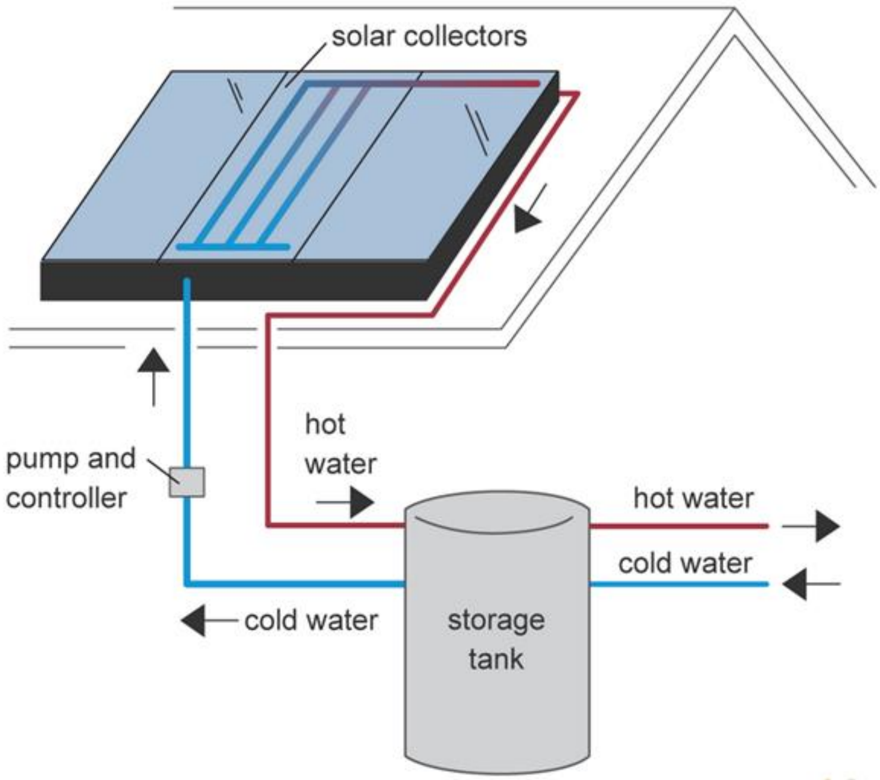


Figure 5. General layout of a Residential Solar Thermal Collector.

3.2.1.1 Existing Design #1: Evacuated Tubes

The primary function of each type of solar collector remains the same but the way solar energy is harvested changes based on the configuration of the solar thermal collectors. We are most interested in the evacuated tube style as it is the style that we are required to repurpose for this project.

Evacuated tubes benefit from the vacuum that is created between the outer layer, typically glass, and the inner conductive element. The vacuum allows losses due to convection to be minimal, allowing maximum operation in non-peak hours based on location. The internal element may contain a working fluid with a high convective coefficient to facilitate a useful amount of heat transfer. The central element may also be made of a solid rod of a material with high conduction. Concentrated heat from each tube is then transferred to a manifold containing a working fluid that is then used in whichever application is most useful for the consumer, typically for hot water.

3.2.1.2 Existing Design #2: Flat Plate

Flat plate solar thermal collectors are used in the same fashion as the evacuated tubes; however, the flat plate has the benefit of significantly reduced cost across all levels of manufacturing and installation. Flat plates with this cost benefit typically have smaller useful operation hours compared to other configurations. This comes from the fixed angle that the plate is mounted at where the evacuated tubes or concentrating collectors do not have this drawback but suffer from increased costs. We cannot utilize this system but the comparison of efficiency between systems may be an interesting question for a post lab analysis.

3.2.1.3 Existing Design #3: Concentrating Collectors

A concentrating solar collector produces the same result as other thermal collectors but is the most expensive in comparison and is typically only implemented in larger industrial settings. Concentrating collectors use actuated reflective surfaces, sometimes other solar panels to focus the sun's radiation onto a fixed element. The actuation is used to capture the maximum amount of the sun's radiation at any time of day. This is where the largest cost comes into the equation the set up related to tracking the sun and the size in which these collectors are typically configured in does not allow most consumers to even consider this an option when considering a solar thermal system. These collectors are typically only used for large scale production.

3.2.2 Subsystem Level Benchmarking

Here we will examine the three subsystems that we anticipate the most trouble implementing namely, data collection, fluid pumps, and safety devices. You can see where data collection and fluid transport systems are represented significantly in our functional decomposition model. Data collection occurs at multiple points of the system and is the final integration to allow a student to process data. Fluid transport is how all energy is transferred throughout the system and is therefore a major consideration. Safety is one of our requirements that we have weighted the heaviest for our design criteria and as students will be interacting with the test bed, we want to ensure that the system can be operated safely and will have the ability to be used for years to come.

3.2.2.1 Subsystem #1: Data Collection

[Describe this subsystem from your functional decomposition. Discuss why this subsystem is important to your overall project.]
Our first subsystem to consider is how we are going to be collecting data. There are many tools that have been introduced to us as students. Here we will look at some of the ways in which data can be measured and processed. The main considerations at this time will be data collection in, Arduino, LabView, SunMaxx system controller.

3.2.2.1.1 Existing Design #1: Arduino

Arduino is a useful DIY tool for small projects and prototyping. We expect to utilize the Arduino suite of tools to test our experiments initially to validate that our system works and that the correct analysis can be performed to find the efficiency of the system. The Arduino unit is fully capable of importing measurements into some of our more useful analysis software. As this experiment is designed for students, we will typically be looking at how to interface with Microsoft Excel.

3.2.2.1.2 Existing Design #2: LabView

LabView is a professional tool for data collection and measurements. The LabView software is already implemented into the ME 451 class and would be a convenient way to interact with our experiment for the students as they will already be exposed to the software for their other labs. The main drawback of implementing LabView into our experiment will be the logistics of where our test bed finally ends up. As we expect that it will likely be outside, we will need a way to get a computer for the experiment to utilize LabView. This introduces an unnecessary cost as a new license for LabView is on the order of a few thousand dollars.

3.2.2.1.3 Existing Design #3: SunMaxx System Controller

SunMaxx is the company that originally manufactured the solar collectors that we are using, and they have a system controller that monitors all the variable that we are interested in. Within the timeframe of this preliminary report, we were unable to verify exactly how one might extricate those measurements and allow a student to analyze the data. It is likely that this is focused more for a technician to troubleshoot a system rather than to facilitate an analysis of the performance of the system in the same way that we are interested in. We have plans to pursue this avenue moving forward once we finalize our testbed layout.

3.2.2.2 Subsystem #2: Pumps and Fluid motion

Fluid transfer is the main consideration for how much useful energy can be harnessed from the sun. Here we discuss some alternatives to how we will flow fluid through the system. The main designs we are interested in are the pump station produced by SunMaxx, a general inline pump, similarly a submersible pump. These are some of the most feasible options for us to implement.

3.2.2.2.1 Existing Design #1: SunMaxx Pump station

SunMaxx manufactures many parts that would be useful for the construction of our experiment. One that we are most interested in is the pump station that would typically be installed alongside the collectors for a residential application. The overall convenience of using this pump would allow for easier installation and service in the future. The main concern about using this pump is first the cost associated with it as some other options that we will discuss are less than $100 where this one is $300. Typically, this pump station is used in a residential application and may be overbuilt for our application of testing efficiency.

3.2.2.2.2 Existing Design #2: Inline pump

The cost associated with an inline pump is low in comparison and would allow us more flexibility in configuring the plumbing of our system. An inline pump is easily replaceable as well considering maintenance and troubleshooting. The main drawback of this is that the pump depending on our working fluid may need to be replaced more frequently due to corrosion or mineral deposits.

3.2.2.2.3 Existing Design #3: Submersible Pump

A submersible pump is the cheapest alternative compared to the other options. We would likely not use this pump for more than validating the function of our overall system. This style of pump is typically used in storage containers that are open to the atmosphere. As our system is not confirmed to be inside or outside an open storage container, there are further considerations in both instances.

3.2.2.3 Subsystem #3: Safety Systems

Safety is one of our main requirements both for the operation of the system as well as the ability of a student to interact with it safely. Some safety requirements are laid out by the ICC/SRCC standards against freezing, pressure, and overheating. We will discuss all of these in some capacity here and how they relate to our requirements.

3.2.2.3.1 Existing Design #1: Freeze Protection

As we are in Flagstaff, we are required to implement a minimum of two protections against freezing. In all configurations and designs we will implement a manual intervention as one protection. The way that we would like to control the freezing potential is by utilizing a drain back system where all the fluid in the system is removed to an integral storage container. This will allow us to protect the system in the winter months and more freezing protections may be implemented based on time and requirements.

3.2.2.3.2 Existing Design #2: Pressure Controls

The accumulation of pressure is of some concern as the production of steam in the plumbing of the system was observed by the previous capstone that was utilizing the equipment. If this pressure accumulation becomes too large for our system to contain a catastrophic failure could occur resulting in injury and system destruction with no potential to recover. At minimum the system must be able to contain 100psi, but the implementation of a safety valve or emergency release is something that we are considering.

3.2.2.3.3 Existing Design #3: Overheat Conditions

As we have not finalized our working fluid or plumbing materials, we need to consider the maximum operating temperature of the system. If this temperature exceeds the boiling point of our working fluid, we may need to implement a way to control the total thermal capacitance of the system. If the temperature is higher than some of the cheaper plumbing options, namely PVC or PEX we may need to spend more on plumbing on the hot side of the system

4 CONCEPT GENERATION

The Solar Thermal Team presents concept variants applying acquired information from benchmarking. Within this section whole systems are brainstormed by connecting different components from subfunctions. Following, descriptions of subfunctions are given with alternative variations. This section provides insight into the physical continuation of this experiment configuration.

4.1 Full System Concepts

Below are three fully designed systems the team compiled using separate subfunctions. Their differences from other systems are listed as pros and cons.

Full System Design #1: Manually Operated Protective System

Pros:

- Drain-back system allows for freeze protection
- Water increases simplicity of system
- Stored inside to protect against natural destruction

Cons:

- Metal components increase cost
- Manual intervention protection
- Adjustable angle increases complexity

4.1.1 Full System Design #2: Automatic Glycol System

Pros:

- Non-Integrated Supply creates freeze protection
- Auto Temperature Senser automatically detects excessive heat
- Back-Up Pump used to ensure system running with consistency

Cons:

- Metal increases expenditure
- Digital data acquisition
- System must be transported outside for each day of testing

4.1.2 Full System Design #3: Indirect Shaded Glycol System

Pros:

- Using glycol eliminates heat transfer complexity
- Analog data collection
- Horizontal Orientation creates easier assembly of components

Cons:

- Manual intervention protection
- Adjustable angle adds to system complexity
- System exposed to weather and wildlife

4.2 Subsystem Concepts

Within this section, subfunctions for the Solar Thermal Collector are presented with definitions and differentiations from other subfunctions.

Subsystem #1: System Type

Design #1: Direct System

Pros:

- Skips the heat transfer aspect from one fluid to the next

Cons:

- Potential excessive heat exposure

1.1.1.1 Design #2: Drain-Back System

Pros:

- Retracts fluid into separate tank from functioning system

Cons:

- Must reapply fluid back into system for experimentation

1.1.1.2 Design #3: Integral Storage

Pros:

- Simple system startup

Cons:

- Potential for fluid to freeze within system

1.1.2 Subsystem #2: Freeze Protection

1.1.2.1 Design #1: Freeze Plug

Pros:

- Naturally expels from system when fluids expand inside

Cons:

- Can fail from improper coolant
- Can fail from lack of temperature control

1.1.2.2 Design #2: Manual Intervention

Pros:

- Can manually control inputs such as flow rate
- Can manually control overall system temperature

Cons:

- Must be actively monitoring solar collector system

1.1.2.3 Design #3: Auto Temperature Sensor (Thermocouple)

Pros:

- Low resistance from lead wire
- Fast time response for data recording

Cons:

- Power supply necessary

1.1.3 Subsystem #3: Steam Protection

1.1.1.1 Design #1: Release Valve

Pros:

- Relieves pressure from the system that builds from heat accumulation
- Returns to closed position after acceptable pressure is reached

Cons:

- Prone to leakage when system operated at high temperatures

1.1.1.2 Design #2: Water Powered Back-Up Pump

Pros:

- Water-powered back up pump has theoretically infinite run time
- Long lifespan without having to change parts regularly

Cons:

- Must test regularly for functionality

1.1.1.3 Design #3: Shade/Cover

Pros:

- Removable attachment

Cons:

- Manual application

5 DESIGN SELECTED – First Semester

The following section outlines the selected design at the end of the first term of the capstone project. The design has remained largely the same as was initially proposed in the preliminary report. Any changes moving forward will be due to refining of the design in the prototype loop or based on the availability of materials. Each team member's technical analysis topics are presented but they are not yet due. The current CAD package and low fidelity prototypes are presented as they relate to the current design. The current design will see minor changes pending logistical requirements and design changes, although these are up to date.

1. Design Description

The design decided on is a system that utilizes the main features of a drain back system, a working fluid of glycol, freeze protection in the form of freeze plugs, plumbing with a combination of plastic and metal, overheat protection with a shade cover and release valves, data collection with both analog and digital measurements.

At minimum the team must meet the ICC/SRCC standards 100 and 300 for solar thermal systems any design that does not satisfy them was not considered for selection. The key sub functions that are related to our requirements are system type, working fluid, plumbing, freeze protection, steam protection, data collection, storage, configuration.

As stated above all designs must satisfy the ICC/SRCC standards. This is primarily related to construction and system minimums. Some key features of this are a minimum of two methods of protection against freezing temperatures, minimum pressure tolerance of 100 psi. Other standards of construction apply but do not affect this stage of our design process but may need consideration after implementing and modifying our design.

Safety is one of our highest concerns as many students may use our system if successfully implemented. Steam and pressure protections are most closely related to the safety of personnel, whereas freeze protection is most closely tied to the safety of the system from a catastrophic event. If the system injured any personnel, the project would be terminated, and a redesign would be necessary. If a freezing event occurred before any preventative measures could be taken the system would likely need numerous repairs. .

The general layout of the design will follow the fluid where fluid is stored in a reservoir, pumped to the collector where Temperature and volumetric flow rate will be measured. Flowing through the collector heat will be transferred to the glycol and the solar irradiance will be measured. Leaving the collector temperature will be then measured again and the fluid will be returned to a reservoir. This loop is the minimum requirement to measure the efficiency of the collector. The chart below outlines this process.

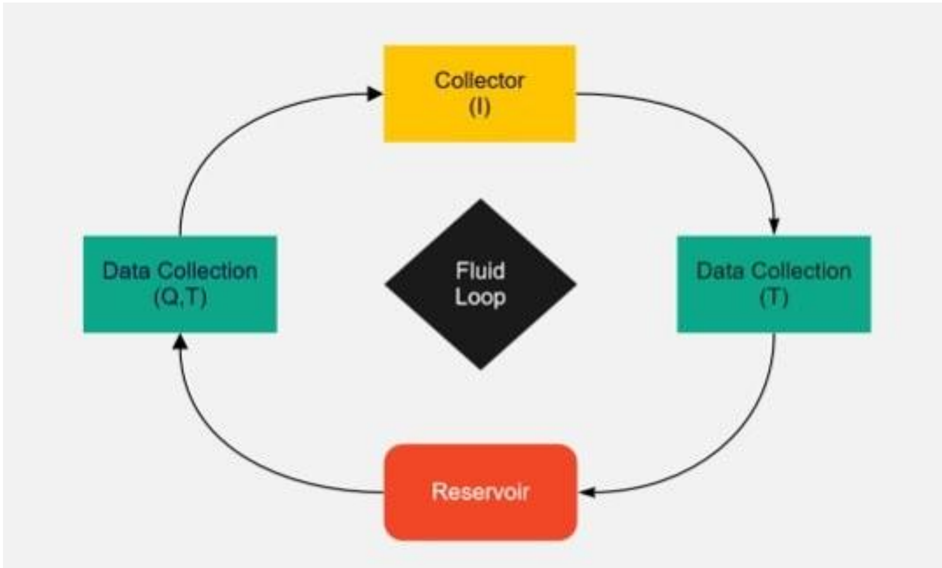


Figure 6. General System Layout

Based on material availability plumbing will be galvanized steel wherever possible. The usage of polymer-based plumbing will be restricted to areas that will be protected from UV radiation. Plumbing will relay glycol to and from the collector from a reservoir that will be stored in a detached shed. The shed allows sensitive or expensive equipment to be stored in a covered location that is securable. All sensors are being verified for data collection during the prototype phase where Arduino based DAQ will be used. Once this has been finalized the team will transition data collection to a LabView VI. The final prototype for the first term was incomplete at the stage of writing this report and a low fidelity was completed before the deadline of this project and is presented below. The current CAD models are provided in the Appendix, but revisions are anticipated.

The low fidelity prototype was related to the data collection needed for the efficiency analysis. The usage of k-type thermocouple and hall effect flow sensor was verified with some general measurements. Both parameters were successfully collected, and further prototyping will be completed in conjunction with a ME 495 design project. This design project will be a preliminary run on the analysis that will be conducted in the new lab testing space. This prototype will consist of a small loop of water through the collector where temperature in and out will be measured along with the volumetric flow rate and insolation. A presentation of this will occur before the end of the semester.

Each of the three team members is tackling a specific engineering problem in relation to the design. DaJae will be examining system losses, Andres will be analyzing the convective flow within the system, and Michael will analyze the total absorbed solar irradiance. These analyses have not been completed at this stage but will be completed before the end of the semester.

2. Implementation Plan

A compact prototype will be completed in conjunction with an ME 495 design project where all necessary parameters will be measured, and the efficiency analysis will be completed. Upon verifying that the necessary data and analysis can be completed the team will use the results of their individual analysis to address any remaining concerns. This primarily related to a thermal runaway condition and flow rate requirements. Completing this phase before the end of the semester will allow the team to order any materials over the summer where in the next term the test bed will be constructed.

Finalizing a build plan over the break and completing construction in the first 2-3 weeks of the next term adhering to the ICC/SRCC standards testing and analysis will occur. The system will be run to collect the necessary data to perform the efficiency analysis. After this is validated, the system will be stress tested and run for an entire day until a problem arises. One expected fault will be an under or oversized fluid reservoir. This will require a change in how heat is discharged from the system. A CAD drawing of the proposed layout is presented in the appendix.

The first 2-3 weeks of the next term will consist of building the test bed. Weeks 4-5 will be data collection and analysis. Weeks 6-8 stress testing and potential faults will be addressed as well as transitioning to a LabView VI for data collection. Assuming no major issues, the remainder of the semester will be devoted to finalizing any remaining details associated with the lab handout and instruction.

The necessary resources to complete this plan will be the required materials from the bill of materials in the appendix, LabView, an additional 40sqft of the Renewable energy area. No other specialized resources are needed. Usage of general hand tools available through one of the team is anticipated. Approximately 85% of the budget will be spent on required materials, The remaining 15% will be reserved for improvements in data collection or addressing any unforeseen circumstances.

3. Prototype

The prototype that was constructed in semester one tested our ability to collect data and perform the overarching analysis of the project. An image of the prototype is below. Data collection was handled via Arduino and processed in Excel. The prototype validated our expectation that the collector was still functional and that our analysis fell in line with what we expected given the manufacturers specification.

Figure 7. Prototype of System

From this prototype it was observed that hot water production in a small volume was greater than expected where the liquid was heated to 70℃. This raised some concerns about how the system would behave in the long term assuming that there was no requirement for utilizing the heated fluid. At this point the semester was ending and our design changed minimally from an open loop to a closed loop system that would be able to handle the seasonal shifts of Flagstaff.

6 Project Management – Second Semester

6.1 Gantt Chart

Actual Gantt chart for the second semester. Describe everything and then reflect on how your actual is different from the original one that you created at the beginning of the semester. What could you have done better?

Table __ is the team's final Gantt chart. The chart is broken done by types of assignments. These tasks then have their start and end dates reported beside them. Project milestones were tasks associated with the hardware of the system. In class deliverables were tasks that were presentations to the rest of the class. Team assignments were online submissions that were to be completed by the entire team. Individual assignments were completed by each team member. Finally, the Engineering fest items were all the items required in preparation for the engineering fest. The team broke down tasks significantly more than they were in the original Gantt chart. The team made sure to stagger the timeframe of certain tasks. The Gantt chart did not have this timeframe breakdown at the beginning semester. This is because the team did not have a firm grasp of how long the various tasks would take. When there were unexpected setbacks, the team had to push back plans and reorganize the schedule. If the team were to do this project again, more time for everything would have been useful.

Table 2: Final Gantt Chart

Tasks	Start	End
Project Milestones		
Hardware Status Update 33%	9/6/22	9/26/22
Final Schematic of Rack	9/6/22	9/23/22
Source Rack Breakdown	9/23/22	9/23/22
67% PO	9/6/22	9/23/22
New Rack Construction	9/24/22	9/24/22
Final BOM of Rack	9/25/22	9/25/22
Hardware Status Update 67%	9/26/22	10/17/22
Design Rack Lifting System	9/26/22	9/26/22
Enclosure mounting	10/11/22	10/11/22
Collector Mounting	10/13/22	10/13/22
Primary Component Mounting	10/13/22	10/13/22
100% build PO	9/6/22	10/16/22
Hardware Status Update 100%	11/7/22	11/7/22
Rack Staining	10/21/22	10/21/22
Rack Lifting System Manufacturing	11/24/22	11/28/22
Plumbing Installation	11/11/22	11/13/22
Initial Testing Results	11/21/22	11/21/22
Flow Meter Calibration	11/1/22	11/16/22
Thermocouple Calibration	11/14/22	11/15/22
Leak Down	11/14/22	11/20/22
Budget Check	11/15/22	11/17/22

Primary Component Protection Check	11/1/22	11/3/22
Lab Run	11/20/22	11/21/22
Final Testing Results	11/21/22	11/30/22
Rack Lifting System Manufacturing	11/24/22	11/28/22
Product Demo	11/28/22	11/30/22
Rack Lifting System Installation	12/12/22	12/12/22
Team Assignments		
Project Management	9/2/22	9/2/22
Website Check 1	10/14/22	10/14/22
Headshots	9/28/22	9/28/22
Upload Materials	10/13/22	10/13/22
Testing Plan	11/4/22	11/4/22
Final CAD Package	11/14/22	11/23/22
Final Report	11/28/22	12/5/22
Final Website Check	11/28/22	12/7/22
Lab & Operation Manual Hand-Off	11/28/22	12/14/22
Outline Lab Manual	10/19/22	10/19/22
Individual Assignments		
Self-Learning or Individual Analysis	9/6/22	9/16/22
Topic Selection	9/6/22	9/6/22
Write Up	9/6/22	9/16/22
Engineering Fest		
Abstract	10/17/22	10/24/22
Draft of Poster	10/24/22	10/31/22
Final Poster and PowerPoint	11/14/22	11/25/22

6.2 Purchasing Plan

The purchasing plan is in our bill of materials which for this project is provided in the appendix. The total cost of the project was $3109.92 after taxes and shipping. Items were organized into five categories. Data, Electrical, Fluid, Rack, Supplies. Where data encompasses sensors, wiring and other data collection items. Electrical are the items to handle electrical routing and protection. Similarly, Fluid are the components to secure and route the closed loop of the system and ensure proper operation of the collector. Rack is labeled as components related to the construction and reinforcement of the structure which the collector is mounted. Supplies are assorted tools and consumables necessary.

Purchasing was broken into three stages that coincided with the 33%,66% and 100% build updates. The first third was to get everything to construct the rack. The second third was installing all the primary components necessary for the system to operate. The last was to use all the Fluid and Electrical components to tie everything together.

Generally everything was accounted for in our initial bill of materials. The only issues we experienced were with longer lead times than what were forecasted by the purveyors and processing on the University side. Due to these delays some tasks had to be moved further down the schedule. To quell these issues ordering things sooner would have been wiser on our end as no edits were required during our build phase.

6.3 Manufacturing Plan

As above the manufacturing plan is tied to the bill of materials in the appendix. The largest manufacturing task that we had was for the adjustable locking system that allowed the collector pitch to be changed from its resting angle to a max angle of 15 degrees. Other manufacturing tasks were more in line with cutting timber, hose, and drilling holes. These are not specifically noted as they were insignificant decisions made during the assembly of the system,

To construct the pin system, we planned to use a series of plates, square tube, and clevis pins to lock the collectors at various angles decreasing from latitude. A minimum number of 8 5"x5" plates needed to be drilled at all four corners with 4 of them with an additional hole of 1" in the center that allowed a clevis pin to be welded to the plates. These series of plates could then be mounted to the rack. The square tube needed to be drilled with holes to match the clevis pins and additionally along the length to allow for locking. The square tube could then be put in place to allow for the collector to be supported at each length.

The only changes we had from the beginning of the semester to the end were in the construction of the pin system for adjustment as this was the item with the greatest lead times. This caused this sub-system to be delayed significantly but as it was not required by the client it was acceptable. Some issues were also from shipping delays and issues which were addressed appropriately and did not affect the overall timeline of the project.

7 Final Hardware

7.1 Final Hardware Images and Descriptions

Below is a front view of the fully constructed test bed. The evacuated tubes are in the bottom right, a flat plate collector is mounted above that, and along the left side is a PEX coil low tech collector. These three levels of solar thermal technology are typical for what might be seen on the residential or small commercial scale. The collectors are mounted on a portion of the rack which can be raised to a minimum tilt of 15 degrees. The inlets of the collectors are configured to be on the right and the outlets on the left.

Figure 8. Front view of solar thermal testbed.

They are routed to a manifold which is tied to the pumping station mounted in the light gray box pictured below. The manifold allows the flow to be restricted to each one of the collectors independently. Next to the pumping station is a heat exchanger which allows a point in which one could connect a load to use the collected thermal energy.

Figure 9. Pumpstation, manifold, and heat exchanger

Here fluid is pumped to each of the collectors based on which valves are open. In its storage state all the valves are open allowing for even distribution of fluid to all of the collectors where it functions as a large solar collector made of collectors connected in parallel. Pictured below is a dark gray storage box where the expansion tank is mounted, and space has been left for storage of other extra components.

Figure 10. Expansion tank and general storage.

7.2 Design Changes in Second Semester

The design from semester one to semester two saw some minor adjustments based on a site visit we took near the end of the first semester. GREE is a company based in Sedona that works in the solar renewable field. They allowed us to observe a system that they had previously installed at Indian Gardens in the Village of Oak Creek. From this visit we made the change to a closed loop system that would handle the daily pressure differential of heated and cooling, as well as the incorporation of a heat exchanger. Other design changes were the result of our change in client where some aspects were excessive.

7.2.1 Design Iteration 1: Change in Closed Loop discussion

At first, we had decided to have a system that vented to atmosphere to avoid the case of pressure build up. Upon further revision the usage of an expansion tank allows us to seal the system while maintaining an appropriate level of safety. This change also has cascading effects on overall system layout and the previous requirement of a drain back tank. The picture below is provided for clarity consult the process diagram in the appendix for changes.

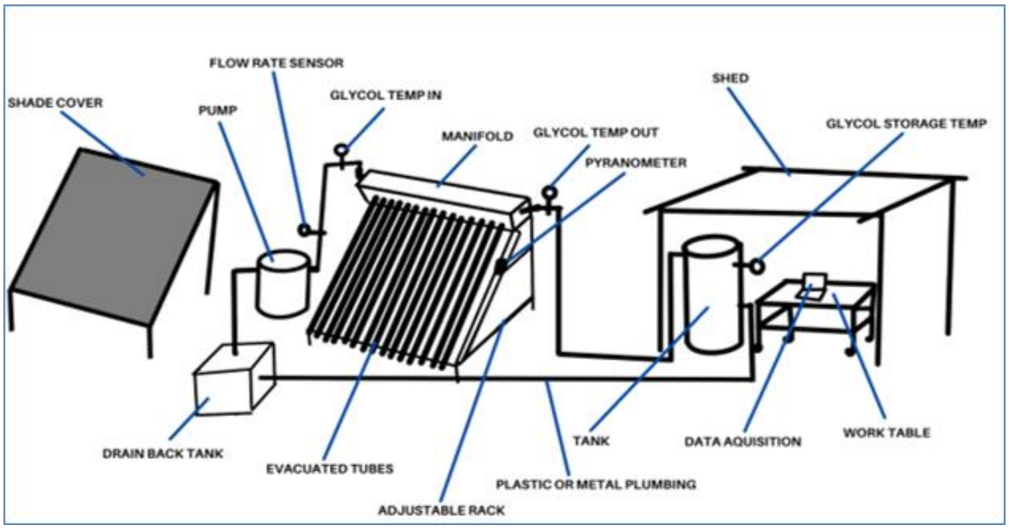


Figure 11. Drain back Semester One Design

Design Iteration 2: Addition of Heat Exchanger discussion

With the change discussed above the system is now sealed which means to use the energy a way to have heat transfer with another fluid loop is necessary. The renewable energy lab does not have any running water or a need for heated fluid currently so the decision to use a heat exchanger to allow for future usage of the collected energy becomes an easier task than reworking a system without one,

7.3 Challenges Bested

As we moved into the winter months, longer days outside spent doing assembly became a challenge. On more than one occasion we had to call it on account of the weather. A few days after all of our materials arrived, we were able to finish our 100% build. To reach the first and second milestones an average of 20-man hours was necessary. For the final milestone more was required. For the 100% build we experienced a delay in shipping and processing of our orders due to unknown circumstances. In the first week of our 100% build we were at a standstill without anything to work on, so we moved ahead with some of our later deliverables until parts arrived. When parts did arrive, we were squarely in the winter season with light snow and rain. More than one of the team got sick during this time. A few days bundled up on the weekend and the system was finished.

8 Testing

8.1 Testing Plan

The team must verify that the proposed system meets all the engineering requirements. Most importantly, that the design abides by the ICC/SRCC standards that ensure system longevity and safety. To accomplish this the team. The testing procedure has been developed by the team as well as using ICC/SRCC standards.
The below testing summary shows what tests were developed to verifying if all of the customer and engineering requirements were met or not.

Testing Summary

The following table outlines the tests the team will conduct and the design requirements a given test covers.

Table 3. Testing Plan

Test Number	Test Name	Relevant DR
T1	Flow Meter Calibration	CR3 ER4
T2	Thermocouple Calibration	CR3 ER4
T3	Leak Test	ER1
T4	Lab Run	CR1 CR2 CR5 ER4
T5	Verify Budget Constraints	CR4 ER2
T6	Confirm Primary Component Protection	ER3

8.1.1 *T1: Flow Meter Calibration*

Summary:

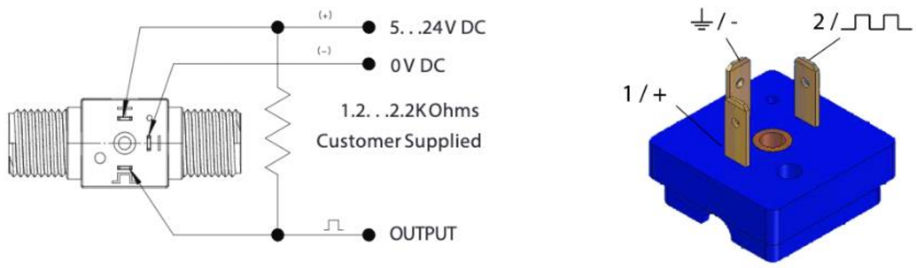
The purpose of this test is to calibrate the flow meters that will be used for the data collection. With this test, the team hopes to create a calibration curve for the flow meters being used in the system. The design requirements fulfilled by this test are detailed in Table 3.

DR	Description	Reason
CR3	Design an experiment to compare Reported v. Experimental Data from evacuated tube system	Flow rate is required for efficiency measurement
ER4	Data Collection	*Q, flow rate*

The flow meter of focus is an Omega 3/8” Turbine Flow Meter and an Adafruit ½" Turbine Flow Meter. To perform this test, the team needs the flow meters, appropriate connectors and hose, a pump, a graduated cylinder, proper wires, resistors, Arduino, Protoboard, and a computer to stream data from the Arduino. The team will have all these materials in possession by the time of testing. The variables isolated will be fluid temperature, and flow rate provided by the pump. The measured variable will be the flow rate recorded by the flow meter.

Procedure:

To test the flow meters the team must first ensure the flow meter is wired correctly to interface with Arduino. The Adafruit flow meter has simple wiring with no resistors needed. The Omega flow meter comes with circuit diagrams that should be followed for proper measurement and to avoid damage to the sensor and Arduino as seen in Figure 12.



With DIN Connector	
Function	**DIN Termination**
V+	1
–	⏚
Output	2

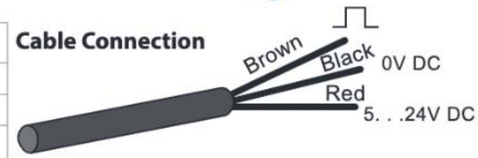


Figure 12. Omega Flow Meter Wiring Diagram

Knowing the voltage draw and considering the source of 5V the team will connect each flow meter with a voltage divider with an appropriately sized resistor. The sensor will be interfaced with Arduino using previously sourced code.

The team will then connect the meter to the pump. Once the meter is in line and able to stream data, calibration measurements will commence. This will be accomplished by streaming the flow meter data while recording a series of bucket timer tests. An average of 3 bucket timer tests while recording data from the meter will be used to create a calibration curve.

Results:

The expected result is that the team will use the frequency output received from the flow meters and the flow rate from the bucket timer test to adjust Arduino code to stream flow rate values. The result of this test will be comparable to a calibration curve similarly found in Figure 13 [1].

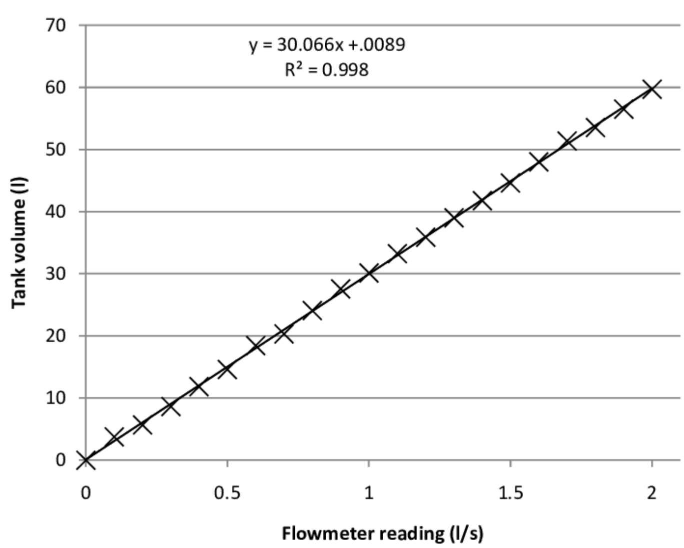


Figure 13. Flow Meter Calibration Curve

8.1.2 *T2: Thermocouple Calibration*

Summary:

Related to the flow rate calibration; T1, the purpose of this test is to calibrate the thermocouples that will be used for the data collection. With this test, the team hopes to create a calibration curve for the thermocouples being used in the system. The design requirements fulfilled by this test are detailed in Table 3.

DR	Description	Reason
CR3	Design an experiment to compare Reported v. Experimental Data from evacuated tube system	Delta T is required for efficiency calculation
ER4	Data Collection	*Tin and Tout for both the collector and load*

The thermocouples purchased by the team play an integral part in the overall goal of being able to calculate the efficiency of the solar collector.

Procedure:

To calibrate the thermocouples, the team will use room temperature, ice, and boiling water. Using distilled water, Ice water should be around 0 degrees Celsius, room temperature around 20 degrees Celsius, and boiling water around 93 degrees Celsius here in Flagstaff. First, the team will connect the thermocouples to Arduino using the pinout in Figure 14.

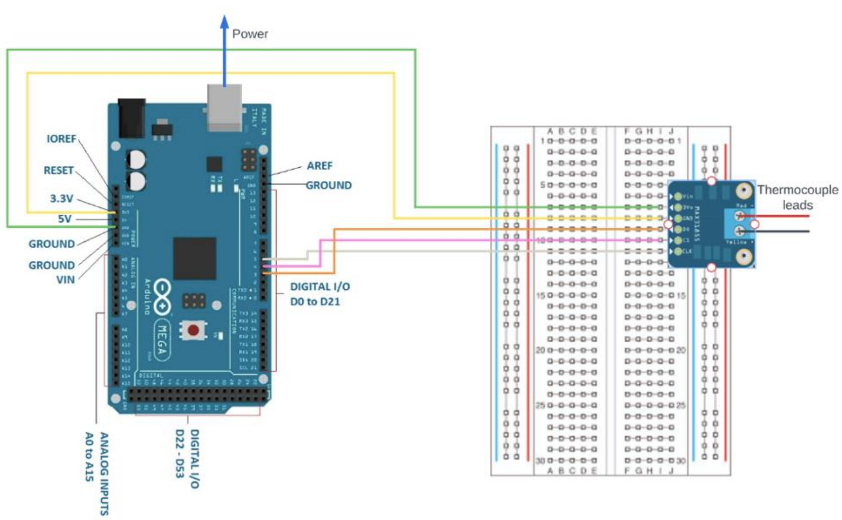


Figure 14: Pin out for Thermocouple Calibration

Second, the team will measure freezing water by creating an ice water bath with distilled water.

The team will take readings until the temperature stabilizes. Third, the process will be repeated with room temperature water. Finally, the process will be repeated with boiling water.

The team will generate a calibration curve using the thermocouple reading to those from a digital thermometer as well as known values. This entire process will be repeated for all four thermocouples that will be used in the system.

Results:

The expected result is that the team will use the voltage output received from the thermocouples and the known temperature of each testing condition to adjust Arduino code to stream temperature values. The result of this test will be a calibration curve analogous to this thermocouple calibration curve calculated in ME495.

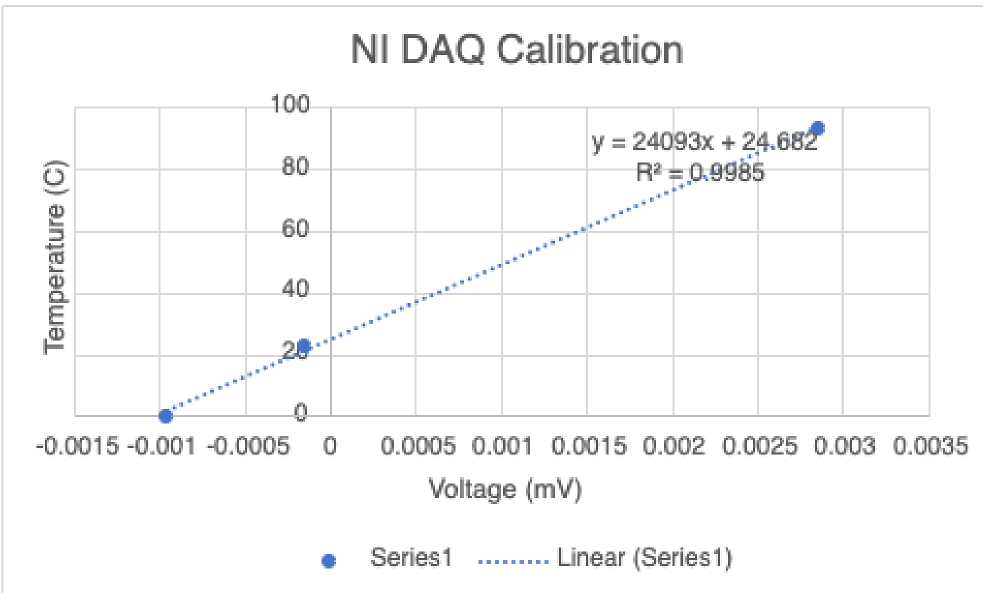


Figure 15: Thermocouple Calibration Curve

The expectation is that a linear profile such as this one will be created for each one of the thermocouples. From here, adjustments to each thermocouple can be made to ensure the reading is in alignment with what was measured.

8.1.3 *T3: Leak Test*

Summary:
The question we are aiming to answer is if the tubed system has been properly sealed or not. Testing for this section cannot be performed until the entirety of the system has been filled, closed, and charged. This requirement has been met contingent upon fittings and tubing to be firmly attached to each other, without any fluid escaping the collector's loop.

DR	Description	Reason

ER1	No system leaks or fluid discharge	Pressurized system must be fully encapsulated

Procedure:
To test this sector, the system first needs to be charged with glycol. After the loop is closed and secured, the pump will be turned on to run fluid through the pipes. Subsequently, visual, audial, and physical examinations will be done by the team with focus on the working loop. Signs such as dripping, hissing, escaping pressure, or wet spots will indicate that the working fluid is leaving the closed system.

Results:
The team hopes that with proper installation the system will have no leaks. In the case of leakage, the team has prepared to examine where to perform adjustments of tubing and fittings.

8.1.4 *T4: Lab Run*

Summary:
The objective of this test is to verify that the overall objective of this project has been met, namely the performance analysis of the evacuated tube solar collector. The design requirements for this test are customer requirements 1,2 and 5 as well as engineering requirement 4.

DR	Description	Reason
CR1	Design and create an experimental test bed housing the evacuated tube solar collector.	Progressing ME 451 Labs
CR2	Write lab procedure for a new ME 451 lab	Overall lab operation
CR5	Complete the lab to have master set of data	One baseline set of data
ER4	Data Collection	T_{in}, T_{out},$\dot{m}$, $\boldsymbol{I}$
ER5	Safe, general operation by one person	Going through all the lab procedures without safety issues.

The necessary equipment for this test is the four sensors required to measure the necessary data for our efficiency analysis, computer and data collection Arduino, and the solar test bed. Since the main objective of this test is to verify that we can collect data and execute the appropriate analysis related to the project prompt. The system will be analyzed at its resting position solar panel angle [Equation], with a constant flow rate of 0.25 L/min for at minimum one 15-minute interval from a “cold” state. This test should take place during any daylight hour where the sun is unobstructed by shading. Note that in the Fall between 1:00pm-2:00pm the collector is partially shaded. This test will be initially conducted with water as the working fluid to verify system measurements before charging the system with our glycol solution. From our measurements we can calculate the energy carried away by the system using [Equation]. Comparing this with a measured irradiance, I that is incident with the surface area of the collector [Equation] will give us our efficiency [Equation]. From our calculated [Equation], we can compare to the reported value of [Equation] for the collector as well as other forms of solar thermal technology.

Procedure:

To begin the test all connections should be rechecked, and the resting temperature of the collector should be noted. Open the manifold in the loop in which you are interested in measuring, for our scope this is the evacuated tube system but the process that follows will be the same for the rest of the solar thermal collectors. Ensure that all data collection devices are working properly, and that data is being recorded in some fashion for our purposes we will be using an Arduino data steamer excel plugin. Make note of any shading on the collector, and weather for the day. Measure the Irradiance normal to the collector or corrected for time of day, year and latitude. If the system is being started from a dry position allow the pump to cycle for 1 minute to purge air from the system. Skip this step if the system has been fully constructed and the closed loop of the working fluid is finalized. Begin collecting data for the convective energy transfer. Check that the data is accurate and seems reasonable i.e.. Nan data indicates a sensor error, and values below freezing and above boiling should be omitted and noted for analysis. If this discrepancy persists note, why in and ways to address as part of the lab. Collect data for 15 minutes. If there is an issue with this time interval due to unforeseen reasons collect data for at minimum 5 minutes, pause data collection and restart in 5 minutes and record for another 5 minutes. This will allow a long enough time interval to measure the general performance of the system. Process the data and note percent error from reported efficiency and theoretical performance given STC. Repeat data collection for as many iterations as possible or necessary to trouble shoot any issues. If you come back on a different day, repeat the procedure from the beginning.

Results:

For this test we expect that our total [Equation] should not exceed 20[Equation] and that our flow rate is directly related to this which we can control up to our max of 2gpm. Irradiance for this time of year given solar noon is approximately [Equation] values larger than this should be noted, and external factors should be noted. Using the efficiency equation [Equation], we expect values no higher than 45% and values no lower than 25% any higher or lower indicates an error in data collection or calculation and should be addressed. Upon successful completion of this test at least one set of data will be collected and analyzed and reported in the appropriate ways in which we are interested in our lab.

8.1.5 *T5: Verify Budget Constraints*

Summary:

This test is to verify that we have not exceeded any amount of our budget for this project. It is a simple check that verifies the below design requirements.

DR	Description	Reason
CR4	Utilizing Existing Evacuated Solar Thermal Collector	Items owned by the department not in use to enhance the learning of students
ER2	Cost	Min/Max the overall quality of our project

The necessary documents for this test are the total purchases submitted for the project and associated cost as well as our update bill materials. The only variability in our cost comes from unaccounted shipping, taxes and market changes for construction material. A simple summation of our expenditure should be less than our total budget.

Procedure:

Collect all purchase orders or invoices and sum the totals. Compare this to our total budget. Report discrepancies and budget usage. For any mischarged items address at the soonest possible time.

Results:

Based on our purchase history we should be maximizing our total budget with a 10% overhead for unforeseen situations.

8.1.6 *T6: Primary System Protection*

Summary:

This is a generic check to ensure that all storage containers are sealed appropriately to protect all our expensive and primary components. While most of our components will handle outside conditions the extra protection will help with the longevity and general organization of the system layout. The DR correlated with this test are shown in the table below

DR	Description	Reason
ER3	System Longevity	Overall system protection of primary parts

For this test we will use our water tank that is at the lab and a sump pump. All connections will be left in their stored state and container doors will be closed. No calculations are done in this test, it is a qualitative test based on observation.

Procedure:

To do this test if there has not been any recent precipitation the water tank and pump will be set up near the storage containers. A simulated rainfall of mild to severe intensity will be done for 5-10 minutes over both storage containers. Allowing 1 minute of dripping time for collected water to run off the containers will then be opened, and the interior inspected for moisture. If there is moisture present note what is happening to it. If standing water is observed and does not appear to go anywhere after 10 minutes address drainage and sealing on the storage container.

Results:

One of our containers is IP66 or NEMA4 and the other is in line with the ratings of NEMA3. We expect that the former will see no liquid penetration and will be negligibly affected by weather conditions. The latter some water may enter it and some form of drainage may need to be addressed but the overall effects of this penetration would be negligible.

8.2 Testing Results

Below are the tables that compile our customer and engineering requirements respectively. Through our testing we have concluded that the design solution satisfies all but our requirement for the efficiency comparison. An alternative comparison that satisfies our client was used.

Table 4: Customer Requirements Met

Customer Requirement	CR met?	Client Acceptable
CR1 – Test Bed	✓	✓
CR2 – New Lab	✓	✓
CR3 – Efficiency Comparison	x	✓
CR4 – Utilize Pre-owned Solar Thermal Collectors	✓	✓
CR5 – Base Data set	✓	✓

Table 5: Engineering Requirements Met

Engineering Requirement	Target	Tolerance	Measured/ Calculated/ Observed	Met	Customer Acceptable

ER1 - System Failure Prevention	2 Freeze, and Pressure protection methods	-26.1℉ (50yr low) 40psi+/- 10psi (half of maximum expected pressure)	-30 ℉ 25psi	✓	✓
ER2 - Cost	$3083	+800*	$3109	✓	✓
ER3 - Lifespan	10years	+/-2years	25	✓	✓
ER4 - Data Collection	Uncertainty <10%	+/-5%	12%	✓	✓
ER5- Simplicity of Operation	1 Person Operable	+3 people	1	✓	✓

9 RISK ANALYSIS AND MITIGATION

Within the following section, the team provides areas demanding attention to their improvement. These areas highlight failure prevention and their effects, supplying descriptions which should be considered as action is taken in the advancement of the project.

9.1 Potential Failures Identified First Semester

The following critical failures were encapsulated from the original testing of the system. The team thought through many possible ways a system such as this could fail,

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure
Hot Water Tank	Chemical Corrosion, Rupture, Thermal Fatigue	Leaks, Damage to floors inside
Thermocouples	Corrosion, Electrical Failure	No Data Collected
Flow Rate Sensor	Electrical Failure, High-cycle fatigue	No Data Collected
Pressure Gauge	Corrosion, Fatigue	No Data Collected
Pump	High-cycle Fatigue, Electrical Overload, Thermal Fatigue	Static Water in System, No Data Collected
Storage Shed/Cabinet	Impact, Wear Corrosion	System Integrity Compromised
Working Fluids	Freezing, Vaporization	Damaged Equipment, Refill Manifold
Piping Plastic	Thermal Fatigue, Wear, Abrasion	Leaks
Piping Steel	Corrosion, Cracking	Leaks
Valves	Low-cycle fatigue, Wear friction	Leaks
Fittings	Thermal Fatigue, Wear, Abrasion, Corrosion, Cracking	Leaks
Lumber/plank	Wear	Collector Instability
Rack	Abrasion, Force/Temp induced, Deformation	Collector Instability, Rack Collapse
Pyranometer	Impact, Electrical Failure	No Data Collected
Collector	Impact Fracture, Lost Vacuum	No heat collected, Broken Glass

9.2 Potential Failures Identified This Semester

The team's first FMEA was fully encompassing of all the failures except for improper pipe fitting sealing. This was a significant problem the team faced. This failure manifested in PEX crimps as well as the threaded fittings. This issue was added to the FMEA.

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure
Hot Water Tank	Chemical Corrosion, Rupture, Thermal Fatigue	Leaks, Damage to floors inside
Thermocouples	Corrosion, Electrical Failure	No Data Collected
Flow Rate Sensor	Electrical Failure, High-cycle fatigue	No Data Collected
Pressure Gauge	Corrosion, Fatigue	No Data Collected
Pump	High-cycle Fatigue, Electrical Overload, Thermal Fatigue	Static Water in System, No Data Collected
Storage Shed/Cabinet	Impact, Wear Corrosion	System Integrity Compromised
Working Fluids	Freezing, Vaporization	Damaged Equipment, Refill Manifold
Piping Plastic	Thermal Fatigue, Wear, Abrasion	Leaks
Piping Steel	Corrosion, Cracking	Leaks
Valves	Low-cycle fatigue, Wear friction	Leaks
Fittings	Thermal Fatigue, Wear, Abrasion, Corrosion, Cracking, Improper Seal	Leaks
Lumber/plank	Wear	Collector Instability
Rack	Abrasion, Force/Temp induced, Deformation	Collector Instability, Rack Collapse
Pyranometer	Impact, Electrical Failure	No Data Collected
Collector	Impact Fracture, Lost Vacuum	No heat collected, Broken Glass

9.3 Risk Mitigation

Mitigation is essential in preventing critical failures of the system. Prevention primary comes in the form of inspecting the lab space and equipment. This lab space is outside and is subject to many more hazards due to this condition. If the team can inspect every component carefully and operate the system by the standard requirements, most critical failures can be avoided. If the components are chosen carefully to meet the needs of the system, there will be significantly less issues within the system.

Corrosion due to the working fluid is negligible as a 50% glycol and distilled water mixture was chosen to reduce corrosion and mineral build up in the system. Thermal fatigue for the materials chosen are expected to withstand 25 years of use. Impact events may be inevitable, but the storage solutions chosen are able to withstand a reasonable load. An unreasonable load would be intentional mishandling of the system. The same applies to the evacuated tubes and other attached collectors. The lumber used for the rack structure is pressure treated wood that has been freshly sealed with an oil-based stain. This should allow the stability of the structure to exceed the usage of the system. Electrical failure was mitigated by using the proper fittings and rain tight connections while routing power and signals to and from sensors and pumps. From this we can determine that the hardest failure to address was the leaking of improperly installed fittings which took the greatest amount of effort to address.

10 LOOKING FORWARD

Despite the efforts from the solar thermal capstone team, there is always room for improvement of the project. Time and budget limitations will always limit a project. If given more resources towards the project, the team has some ideas for improvements.

10.1 Future Testing Procedures

The team collected data at a suboptimal time of the year. Because of the shading the collector experiences in the wintertime, the data collected by the team was in the morning or late afternoon, both times of decreased solar irradiance. If the team would like to properly compare the measured efficiency to the manufacturer provided efficiency, the test should take place while there are higher amounts of irradiance.

10.2 Future Iterations

The designed testbed can be expanded upon to have a variety of solar concepts tested and used in educating students. Options include but are not limited to; comparing the performance factors of different types of solar thermal technology, analyzing the performance of collectors at various angles of tilt, and analyzing the system's performance given an applied thermal load.

11 CONCLUSIONS

The purpose of this project is to create a solar thermal system worthy of being implemented into the learning environment of Renewable Energy at NAU. Utilizing existing equipment, the Solar Thermal Lab Team has put forth efforts reconstructing a fully functioning solar radiance collector. Alongside satisfying all client specifications, the system additionally fulfilled requirements set by the ICC & SRCC for safety and longevity applications. By following these standards, we ensure that measures are taken to include components that encourage the highest quality of fluid flow within the system using resources given to fund the project. Furthermore, the team underwent critical processes to choose the most viable design for the system. Preliminary calculations were done to ensure the process of lab analysis. Simultaneously, the prototype built at the time was used to collect data usable in finding solar collector efficiency. The up-to-date build has been finalized and will be applied to the Renewable Energy Laboratory. CAD diagrams have been revitalized as well as the BOM; both represent detailed designs with visual and written extensive descriptions. Conclusively, the team will deliver lab manual in conjunction with a solar system.

11.1 Reflection

Factors most important to the project included safety, lab design, and data collection. Collectively these topics were supported throughout analysis of the physical build, efficiency, and sensor calibrations. The solar thermal system lab can be operated by a singular person, supporting user safety. Requirements from the International Code Council and Solar Rating Certification Corporation are integrated into the design of this experiential test bed. This includes two features of steam and freeze prevention, not limited to air relief, pressure relief, and glycol existing as the working fluid. This project was an opportunity for the team to understand an assembly of principles including engineering phenomena, significance of design iterations, and the problem-solving procedure. Overall, the effect implicated from this project is aimed to inform students about renewable energy. There was no previously running solar thermal system within the NAU renewable energy lab space. With the new testbed, students will be allowed to have hands-on experience with a solar collector such as this one. This will increase workforce development in renewable energy as well as diversify the experiences of students graduating from NAU.

11.2 Resource Wishlist

Two things would be requested upon the continuation of this project. Specialized equipment would bring a splendid improvement to the grand scheme of the project. This can include more expensive equipment, as well as a development to the overall design. Secondarily, the positioning of the current state of the art solar thermal test bed is not ideal. It would be of interest to the Renewable Energy Lab course to allow the system to exist in the sun's direct rays year-round. This can be accomplished by moving the rack or trimming the trees south/southeast of the Renewable Energy Lab space.

11.3 Project Applicability

In terms of real-world implications, the Solar Thermal Capstone has taught the team to focus on creating and adapting to a problem-solving process. Many skills including coding, brazing, constructing, organizing, and formatting were learned or further developed. Moreover, an abundance of growth cast over the team as we all progressed with the mindset of expecting the best whilst preparing for the worst.

12 REFERENCES

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13 APPENDICES

13.1 Appendix A: House of Quality

Table A1. Semester 2 House of Quality

System QFD

Project: **Solar Thermal**
Date: 11/30/22

#		1	2	3	4	5
1	Failure Prevention					
2	Cost	9				
3	System Longevity	9	6			
4	Data Collection					
5	Operation Simplicity		3	3	9	

#	Customer Requirements	Customer Weights	Failure Prevention	Cost	System Longevity	Data Collection	Operation Simplicity
			Engineering Requirements				
1	Design and Create Test Bed Housing Solar Systems	4	9	9	9	3	9
2	Write a Lab Procedure for a new ME 451 Lab	3				9	9
3	Design an Experiment for comparing Efficiency Data	4	9			9	9
4	Utilize Existing Evacuated Tube Solar System	2	6	3	9		3
5	Run system to Acquire Master Data Set	2				9	
	Technical Requirement Units		Methods	$	Years	Sensors	Persons
	Technical Requirement Targets		4	3109	10	4	1
	Absolute Technical Importance		84	42	54	93	105
	Relative Technical Importance		5	1	4	2	3

13.2 Appendix B: Failure and Risk Assessment

Table B1. Semester 1 Full Risk Assessment

Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Hot Water Tank	Chemical Corrosion, Rupture, Thermal Fatigue	Leaks, Damage to floors inside	9	Exposure to Elements, Overheating, Impact	2	Fill tank check for leaks	1	18	Source newer Tank
Thermocouples	Corrosion, Electrical Failure	No Data Collected	6	Exposure to Elements, Electrical Overloading	4	Inspection Corossion, Calibration	1	24	Spare thermocouples available
Flow Rate Sensor	Electrical Failure, High-cycle fatigue	No Data Collected	7	Electrical Overloading, Cycles Exceed Failure Number	6	Inspection, Calibration	2	84	Use Ultrasonic Sensor
Pressure Gauge	Corrosion, Fatigue	No Data Collected	7	Over-pressurization	2	Inspection	2	28	Non-essential to function of system have spares
Pump	High-cycle Fatigue, Electrical Overload, Thermal Fatigue	Static Water in System, No Data Collected	8	Use beyond life span of part	3	Inspection, Use	1	24	Andrés purchases new
Storage Shed/Cabinet	Impact, Wear Corrosion	System Integrity Compromised	4	Falling objects, Weather	1	Inspection, Stand inside and check for light coming through unexpected areas	2	8	Andrés purchases new
Working Fluids	Freezing, Vaporization	Damaged Equipment, Refill Manifold	7	Weather, Excess heat generation	3	Inspection, Low temperatures	3	63	Freeze Protection, Manual Intervention
Piping Plastic	Thermal Fatigue, Wear, Abrasion	Leaks	5	Overheating, Impacts, Physical Contact	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Piping Steel	Corrosion, Cracking	Leaks	5	Freezing, Chemical Reaction	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Valves	Low-cycle fatigue, Wear friction	Leaks	5	Use beyond life span of part	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Fittings	Thermal Fatigue, Wear, Abrasion, Corrosion, Cracking	Leaks	5	Freezing, Chemical Reaction, Thermal Overload	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Lumber/plank	Wear	Collector Instability	2	Exposure to elements	5	Inspection, Check for unexpected tilt	1	10	Weather-Proof Repellent
Rack	Abrasion, Force/Temp induced, Deformation	Collector Instability, Rack Collapse	8	Impact, Physical Contact, Exposure to Elements	3	Inspection, Check for unexpected tilt	1	24	Warranty, Reinforce Physicality
Pyranometer	Impact, Electrical Failure	No Data Collected	7	Impact, Electrical Overloading	2	Inspection, Calibration	2	28	Andrés purchases new, Find alternative
Collector	Impact Fracture, Lost Vacuum	No heat collected, Broken Glass	10	Impact	3	Inspection, Check for broken glass and tubes	1	30	Replace Damaged Tube

Table B2. Semester 1 Full Risk Assessment

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Hot Water Tank	Chemical Corrosion, Rupture, Thermal Fatigue	Leaks, Damage to floors inside	9	Exposure to Elements, Overheating, Impact	2	Fill tank check for leaks	1	18	Source newer Tank
Thermocouples	Corrosion, Electrical Failure	No Data Collected	6	Exposure to Elements, Electrical Overloading	4	Inspection Corossion, Calibration	1	24	Spare thermocouples available
Flow Rate Sensor	Electrical Failure, High-cycle fatigue	No Data Collected	7	Electrical Overloading, Cycles Exceed Failure Number	6	Inspection, Calibration	2	84	Use Ultrasonic Sensor
Pressure Gauge	Corrosion, Fatigue	No Data Collected	7	Over-pressurization	2	Inspection	2	28	Non-essential to function of system have spares
Pump	High-cycle Fatigue, Electrical Overload, Thermal Fatigue	Static Water in System, No Data Collected	8	Use beyond life span of part	3	Inspection, Use	1	24	Andrés purchases new
Storage Shed/Cabinet	Impact, Wear Corrosion	System Integrity Compromised	4	Falling objects, Weather	1	Inspection, Stand inside and check for light coming through unexpected areas	2	8	Andrés purchases new
Working Fluids	Freezing, Vaporization	Damaged Equipment, Refill Manifold	7	Weather, Excess heat generation	3	Inspection, Low temperatures	3	63	Freeze Protection, Manual Intervention
Piping Plastic	Thermal Fatigue, Wear, Abrasion	Leaks	5	Overheating, Impacts, Physical Contact	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Piping Steel	Corrosion, Cracking	Leaks	5	Freezing, Chemical Reaction	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Valves	Low-cycle fatigue, Wear friction	Leaks	5	Use beyond life span of part	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Fittings	Thermal Fatigue, Wear, Abrasion, Corrosion, Cracking, Improper Seal	Leaks	5	Freezing, Chemical Reaction, Thermal Overload	3	Inspection, Check for liquid on ground	1	15	Apply Sealent, Available Replacements
Lumber/plank	Wear	Collector Instability	2	Exposure to elements	5	Inspection, Check for unexpected tilt	1	10	Weather-Proof Repellent
Rack	Abrasion, Force/Temp induced, Deformation	Collector Instability, Rack Collapse	8	Impact, Physical Contact, Exposure to Elements	3	Inspection, Check for unexpected tilt	1	24	Warranty, Reinforce Physicality
Pyranometer	Impact, Electrical Failure	No Data Collected	7	Impact, Electrical Overloading	2	Inspection, Calibration	2	28	Andrés purchases new, Find alternative
Collector	Impact Fracture, Lost Vacuum	No heat collected, Broken Glass	10	Impact	3	Inspection, Check for broken glass and tubes	1	30	Replace Damaged Tube

13.3 Appendix C: Bill of Materials

Table C1. Final Bill of Materials

Solar Thermal Capstone

Invoice For: Total System

Item #	Description	Manufacturer/Brand	Qty	Unit Price	Category	Hyperli	Image	Purchased	Manufacturing	Notes	Status	Price
7	Brass 3 wire Flow meter	Omega	1	$ 124.80	Data	https://w ww.omeg		Received	al install pending calibrat	$15 Ship	Calibration	$ 124.80
11	Themocouples K-type	twidec	2	$ 11.99	Data	########		Received	al install pending calibrat	*	Calibration	$ 23.98
1	Electrical Component Storage	Vervor	1	$ 134.99	Electrical	https://w ww.amaz		Received	Mounting Completed	$0 Ship	Completed	$ 134.99
2	Expansion Tank Outdoor Storage	Seville Classics	1	$ 129.99	Electrical	########		Received	Mounting Completed	$0 Ship	Completed	$ 129.99
1	Sheilded 3 Wire Signal	southwire 500'	1	$ 109.99	Electrical	https://w ww.home		Received	install	General Sensor wire	Completed	$ 109.99
2	Conduit 3/4	EMT	10	$ 11.19	Electrical	https://w ww.home		Received	install	Total electical run	Completed	$ 111.90
3	3/4" EMT T-Fitting	Halex	1	$ 11.83	Electrical	#######		Returned	Alternative used	T for power and building		$ 11.83
4	3/4" EMT Rain Tight Fitting	Halex	1	$ 6.82	Electrical	.00567593		Cancelled	Alternative used	Water tight connection from box to main elec run		$ 6.82
5	Electrical Grommet (Multipack)	ispinner	1	$ 10.99	Electrical	#######		Received	Install/Modify	Grommets for elec and plumbing	Completed	$ 10.99
10	EMT Joiners	Halex	1	$ 22.63	Electrical	https://w ww.home		Cancelled	Alternative Used	connectors for electrical system		$ 22.63
12	Power Supply Cord for Pump	CCCEI	1	$ 12.99	Electrical	########		Received	Install	Appropriate may need modification	Completed	$ 12.99
3	10 Plate Heat Exhanchanger	Toolots	1	$ 89.99	Fluid	########		Received	Mounting Completed	$11 Ship	Completed	$ 89.99
4	4 Loop Manifold	AB/WiseWater	1	$ 142.99	Fluid	https://w ww.amaz		Received	Mounting Completed	$0 Ship	Completed	$ 142.99
5	Solar Pumping Station	SunMaxx	1	$ 475.14	Fluid	https://w ww.sunma		Received	Mounting Completed	$30 Ship	Completed	$ 475.14
6	Expansion Tank	Varem	1	$ 110.15	Fluid	https://w ww.pump		Received	Mounting Completed	$0 Ship	Completed	$ 110.15
6	3/4 t fitting galvanized	southland	2	$ 4.96	Fluid	https://w ww.home		Received	Install	t fitting for thermocouples in heat exchanger	Completed	$ 9.92
7	3/4x3/8 reducer Galvanixed	stz	2	$ 4.21	Fluid	########		Received	Install	Coupler for flow meter to general loop	Completed	$ 8.42
8	3/4 Copper Sweat Plug (5 pack)	The Plumbers Choice	1	$ 9.99	Fluid	########		Returned	Aternative	plugs for flat plate solar collector		$ 9.99
9	3/4 Threaded Plug Glavanized	stz	2	$ 1.81	Fluid	########		Received	Installed/Thermocouple ports tapped	threaded plugs for flat plate solar collector	Completed	$ 3.62
17	PEX Oxygen Barrier 300'	Everhot	1	$ 150.95	Fluid	https://w ww.pexuni		Received	Cut to appropriate length	General Fluid flow. Free Shipping Ordered w/insulation	Completed	$ 150.95
18	Automatic Air Vent	Watts	3	$ 25.30	Fluid	########		Received	Install	air vent needed at 3 locations	Completed	$ 75.90
19	3/4 pex to 1"Female	Apollo	3	$ 5.77	Fluid	https://w ww.home		Received	intall	evac tube mani to pex	Completed	$ 17.31
20	90 deg barbs PEX (25)	Apollo	1	$ 46.73	Fluid	https://w ww.home		Received	install	genral plumbing 90 deg	Completed	$ 46.73
21	90deg sweat connector	Apollo	2	$ 5.47	Fluid	https://w ww.home		Retuned		90 deg sweat for flat plate top		$ 10.94
22	3/4 female adapter (10)	efield	1	$ 30.99	Fluid	https://w ww.amaz		Received	install	Pump station an manifold connections	Completed	$ 30.99
23	3/4 male adapter (10)	efield	1	$ 29.98	Fluid	########		Received	install	threaded portion of flat plate and air vent	Completed	$ 29.98
24	3/4 PEX crimp rings (50)	ispinner	1	$ 13.59	Fluid	########		Received	install		Completed	$ 13.59
25	PEX Clamps (20)	lokman	1	$ 14.99	Fluid	########		Received	install		Completed	$ 14.99
28	Glycol (gal)	Prestone	6	$ 12.97	Fluid	https://w ww.home		Received	Charge system	working fluid	Completed	$ 77.82
29	1/2 Male NPT-3/4 Male NPT (2)	Amazon	1	$ 8.99	Fluid	########		Received	install		Completed	$ 8.99
30	1/2 Male NPT-3/4 Female NPT (1)	Amazon	4	$ 8.13	Fluid	https://w ww.amaz on.com/A		Received	install	hot side (HE)	Completed	$ 32.52
31	3/4 Male GHT-3/4 Female NPT (2)	Amazon	1	$ 8.99	Fluid	https://w ww.amaz on.com/A		Received	install		Completed	$ 8.99
32	1" Male NPT-3/4 PEX (1)	Home Depot (Apollo)	1	$ 5.83	Fluid	https://w ww.home depot.co		Received	install	can be picked up	Completed	$ 5.83
33	Hot Water Supply Line 60"	Everbilt	1	$ 13.99	Fluid	https://w ww.amaz		Received	install	Exp Tank	Completed	$ 13.99
34	Hot Water Supply Line 12"	Everbilt	1	$ 7.05	Fluid	https://w ww.amaz on.com/E		Received	install	Hot water line	Completed	$ 7.05
35	Hot Water Supply Line 20"	Everbilt	1	$10.17	Fluid	https://w ww.amaz on.com/E		Received	install	Cold water line	Completed	$ 10.17
44	Plumbing Insulation	Pex Universe	10	$3.85	Fluid	https://w ww.pexuni		Received	install	Free Shipping Ordered w/PEX	Completed	$ 38.50
45	Distilled Water	Walmart	8	$1.16	Fluid	https:// www.wa lmart.co		Received	charge system	For Scientific Purposes	Completed	$ 9.28
1	Pressure Treated Lumber 4x4x8		12	$ -	Rack			Received	Completed 9/24	Raw Materials Available	Completed	$ -
2	Pressure Treated Lumber 2x8x12		16	$ -	Rack			Received	Completed 9/24	Carpentry Assistance by Prof. Pete	Completed	$ -
3	Pressure Treated Lumber 2x6x8		16	$ -	Rack			Received	Completed 9/24	Completed Construction 9/24/22	Completed	$ -
8	Hinges HD	Spring Creek	2	$ 34.27	Rack	https://w ww.spring		Returned	na	$15 Ship	Error in Shipping	$ 68.54
13	Wood Sealant	Ready Seal	1	$ 146.54	Rack	https://w ww.amaz		Received	Paint	*	Completed	$ 146.54
14	End Cap for Tubes	SunMaxx	1	$ 35.94	Rack	https://w ww.sunma		Received	install		Completed	$ 35.94
15	Z-channel for plate support	Figure 8	3	$ 21.75	Rack	https://w ww.crane-		Cancelled		For RE expansion		$ 65.25
37	2x2x3'Steel Square Tube 11ga	MetalDepot	2	$49.02	Rack	https://w ww.metal		Received	Cut to 3 1/2' and drill holes at ends and midpint adjustment	T12211, do a custom length of 3'...Order all metaldepot items	n client approval	$ 98.04
38	2-1/2x2-1/2x2' Steel Square Tube 11ga	MetalDepot	1	$24.88	Rack	https://w ww.metal		Received	Cut to 4" lenth and drilled through with 1" hole	T121211	n client approval	$ 24.88
39	1/4" Steel Plate 1'x4'	MetalDepot	1	$71.36	Rack	https:// www.me talsdepo		Received	5 holes to be drilled 1" in center 1/2" in corners	P114, do a custom length of 1'x4'	n client approval	$ 71.36
40	1" Diam 4.5" Long Clevis Pin	McMaster	4	$9.71	Rack	https:// www.mc master.c		Received	CAD and welding planned to be sent to machine shop	98306A675	n client approval	$ 38.84
16	Solder	Bernzomatic	1	$ 6.98	Tools	https://w ww.home		Received		For flat plate repair and sweat connection		$ 6.98
26	PEX Crimper	JWGJW	1	$ 18.50	Tools	########		Received		May be availble through aquaintance		$ 18.50
27	PEX Cutter	IWISS	1	$ 7.85	Tools	########		Lost		May be availble through aquaintance	Replaved	$ 7.85
36	Conduit bender	NSI	1	$20.83	Tools	#######		Received		May be availble through aquaintance		$ 20.83
41	4 in chip brushes 12pk	HarborFreight	1	$15.99	Tools	https://w ww.harbo		Received		Staining		$ 15.99
42	7ml Nitrile Gloves	HarborFreight	1	$7.99	Tools	https://w ww.harbo		Received		Staining		$ 7.99
43	5'6"x7'6" Tarp Blue	HarborFreight	1	$2.99	Tools	https://w ww.harbo		Received		Staining		$ 2.99
	33% Build											
	66% Build											$ 38.50
	100% Build	********************										
					Invoice Subtotal					$ 2,824.67		
					Tax Rate							
					Sales Tax					$ -		
					Other					$ 116.45		
					Deposit Received							
					TOTAL					$ 2,941.12		

13.4 *Appendix D: Specification Sheet*

Table D1. Customer Requirements Specification Sheet

Customer Requirement	CR met?	Client Acceptable
CR1 – Test Bed	✓	✓
CR2 – New Lab	✓	✓
CR3 – Efficiency Comparison	X	✓
CR4 – Utilize Pre-owned Solar Thermal Collectors	✓	✓
CR5 – Base Data set	✓	✓

Table D2. Engineering Requirements Specification Sheet

Engineering Requirement	Target	Tolerance	Measured/Calculated/Observed	Met	Customer Acceptable
ER1 - System Failure Prevention	2 Freeze, and Pressure protection methods	-26.1℉ (50yr low) 40psi+/-10psi (half of maximum expected pressure	-30 ℉ 25psi	✓	✓
ER2 - Cost	$3083	+800*	$3109	✓	✓
ER3 - Lifespan	10years	+/-2years	25	✓	✓
ER4 - Data Collection	Uncertainty <10%	+/-5%	12%	✓	✓
ER5- Simplicity of Operation	1 Person Operable	+3 people	1	✓	✓