Floating Tube Heat Exchangers

Sponsored by: Professor Melinda Keller

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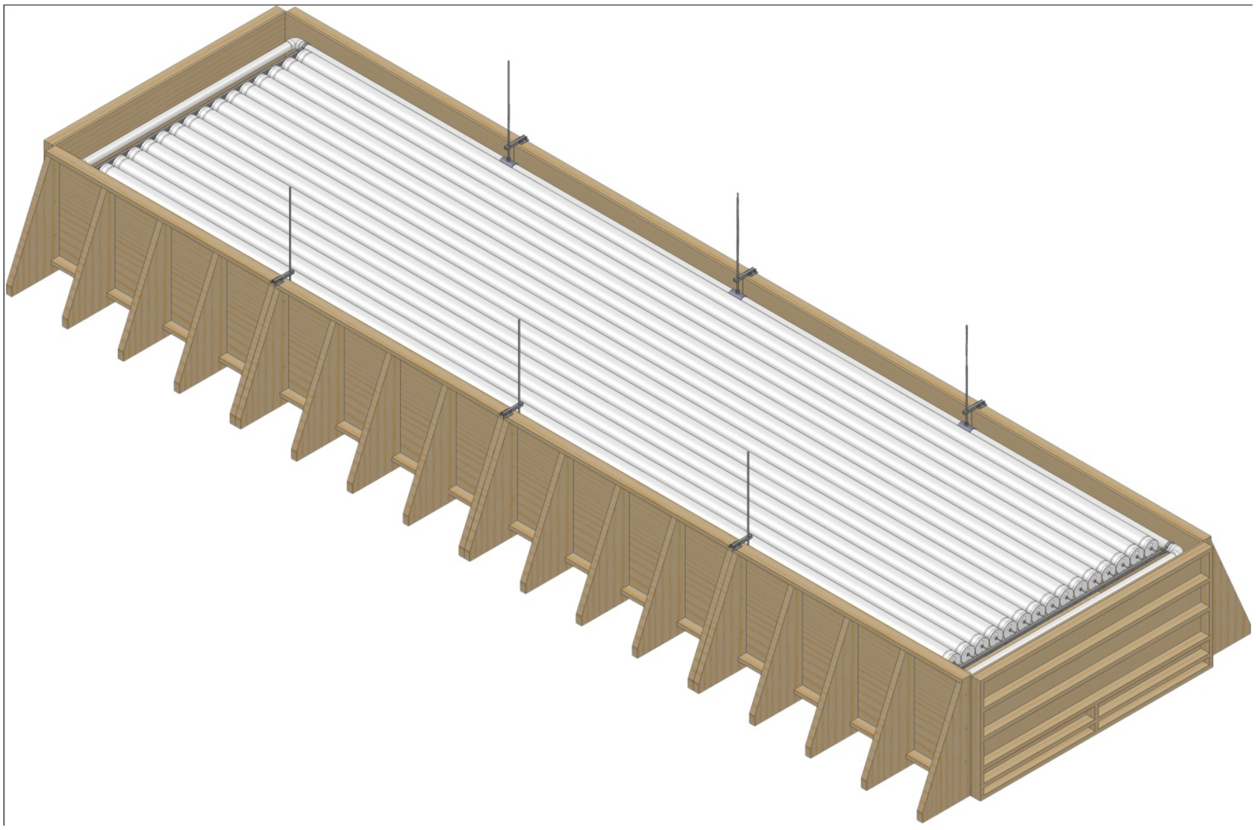

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Abstract

With the slowly diminishing supply of fossil fuels across the world and the heightened risk of carbon dioxide pollution leading to global warming, a shift towards renewable energy is gaining momentum. Recent advances in wind and solar power technology have increased the power density of alternative sources while decreasing the cost per kilowatt-hour, but the technology has not become advanced enough yet for large scale deployment. Combined Power Cooperative has developed a revolutionary design for a concentrated solar power plant that utilizes Fresnel reflectors and a large body of water in which to install them. In addition to being low-cost, the system allows for an integrated large thermal storage tank that can be used as a heat exchanger, using cool ambient air to remove heat from the stagnant water. This senior project will develop a scale model of a commercial-sized deployment and instrument the system to investigate the effectiveness of the cooling. Furthermore, we will examine the viability of using it for a full size heat exchanging system in comparison to a typical heat exchanger. This report will clarify the design of the system and the methods for instrumentation and testing.

I. Introduction

Sponsor Background and Needs

Combined Power Cooperative (CPC) originally set out investigating new methods for cultivating strains of algae for conversion to biofuel while avoiding the typical issues of water depletion and low yield. A new and novel design utilizing plastic tubes in a tank of water was developed and proven to work in a scale model. Over time, the design evolved into a possible use as a solar reflector for a concentrated solar power (CSP) installation. CPC has created a scale model system that utilizes a number of these reflecting tubes in order to focus sunlight on a standard solar collector to produce steam. Using this steam they have been able to power a basic steam engine to produce electricity. A number of different companies and organizations have realized the potential of this system and have invested into bringing the product to fruition. CPC has done a large amount of analysis on the solar reflecting system but has done very little investigation into the feasibility of using the large body of water as a thermal storage system or as a method for removing heat from the hot fluid stream.

Upon completion of the senior project in December 2011 the tank will be used for graduate student analysis of heat transfer and fluid modeling within the tank. Based on this, the tank must be made to withstand several years of possible experimentation, as well as all of the supporting equipment. In addition the system must be relatively mobile for transportation reasons.

Project Definition

Verification of a thermal model for an experimental heat exchanger requires a well constructed and instrumented system for accurate analysis. CPC requires a system that will simulate a commercially deployed tank while allowing for full analysis of many different variables useful for evaluating the overall effectiveness.

Objectives

The goal of this senior project is to provide the backbone for a thorough investigation into the thermal properties of a heated tank of water and its behavior when being cooled with an encapsulated air stream. A scale version of the expected commercial sized tank will be built and instrumented in order to identify thermoclines within the volume of water and a full support system will be designed and built to provide heated water and cooling air to the tank. This senior project focuses on several key decisions required for an accurate analysis applicable to a full size deployment. The first is equipment selection that will be necessary for providing heated water to circulate through the system to simulate a power plant and for blowing air through tubes to remove heat from the system. The second is instrumentation of the entire system in order to verify flow rates, temperatures, and operating conditions for various setups. Third is a comprehensive test selection to ensure that all future tests are accurate and within engineering tolerances as well as building any necessary test equipment.

Need Specifications

The entire project can be broken into a specific set of systems, each of which has their own individual specifications pertaining to expected usage. Each sub-system and their specifications are shown below.

I. Tank

- The overall dimensions of the tank must be approximately 3 meters wide, 10 meters long, and 1 meter tall
- The overall cost of the tank must be below $1200.00
- The tank must be separable into 8 foot transportable sections
- The tank must be modular, allowing for additions in the future
- The tank and all hardware must be weather resistant
- The tank must be primarily derived from the current CPC design
- The tank must be insulated on all sides using an appropriate medium

II. Control Tank

- Overall dimensions of the tank must be 1 meter wide, 1 meter long, and 1 meter tall
- Must be designed identical to full size tank

III. Height Adjustment System

- Must ride on water height with 3 feet of adjustment
- Must be weather resistant and anti-corrosive
- Must allow for attachment to bulkhead device
- Must cost less than $1200.00 including bulkhead device

IV. Water Circulation System

- Fluid pump must be able to sustain 115 gallons per minute (GPM) at 20-30 feet of head
- Fluid pump must be 230-460 volt
- Fluid pump must be self-priming or be able to operate with approximately 3 feet of suction head
- Pipe diameter must be adequately sized for optimum efficiency
- Valves must be used to isolate equipment
- Fluid pump must cost less than $850.00

V. Air Circulation System

- Must be able to evenly distribute air to 15 tubes
- Air blower must be able to provide 2 kg of air a second
- Must utilize quick disconnect fittings for assembly
- Must be able to adjust to height variances of tubes
- Air blower must cost less than $1,785.00

VI. Boiler

- Must be able to provide approximately 850MBtu of heat output
- Must be weather resistant
- Must be able to provide temperatures of 185°F
- Must be able to flow 115 GPM

- Must be liquid propane gas(LPG) capable
- Must cost less than $12,000.00

VII. Instrumentation

- Must consist of at least 150 temperature measurements within the tank
- Must monitor temperatures of the air and water stream before and after all major equipment
- Must monitor water flow rates up to 130 GPM
- Must monitor air flow rates up to 350 cubic feet per minute
- Must monitor ambient temperature and weather conditions
- Must have at least ½ degree Celsius resolution
- Must easily interface with a computer for temperature measurements
- Must cost less than $12,000.00 for all data acquisition components

II. Background

Existing Products and Research

Concentrated Solar Power (CSP) is an existing technology that seeks to harness the power of the sun without requiring the use of photovoltaic (PV) panels. Using sets of mirrors and lenses, the sun can be reflected and focused onto a solar collector to create energy. The technology works through concentrating large amounts of solar radiation onto a small collector area allowing for huge temperature changes depending on different fluid streams. This technology is promising as it does not require costly PV panels and can utilize existing steam turbine facilities or be used to supplement fossil fuel generation techniques. The current downfall of the technology is the relatively high expense of procuring parabolic mirrors or manufacturing tubular reflectors that are necessary for the large concentration ratios.

Figure 1: A concentrated solar power installation using trough style solar reflectors. (Photo courtesy National Renewable Energy Laboratory)

Combined Power Cooperative (CPC) seeks to eliminate cost barriers to deploying CSP by manufacturing a new reflective system that is extremely inexpensive and scales to a very large size, making the solar collector the only major expense in deployment. Utilizing polymer bag structures and a Mylar reflective layer, a fresnel reflector can be created that is lightweight and easily manipulated. The lightweight nature of the tube assembly allows them to float on a body of water reducing the cost of expensive support structures and control motors. Affixing end caps to each end of the tube provides enough rigidity to rotate the tubes to follow the sun's motion, as well as allowing air and water to enter the tubes. The end caps will allow for the tubes to fill halfway with water and maintain neutral buoyancy as well as minimizing any gaps between each tube. By maintaining a cross stream of air across the top of the Mylar strip, the water passing under the tubes can also be cooled, creating a massive heat exchanger.

Figure 2: CPC's CSP installation utilizing floating tube reflectors. (Photo courtesy CPC)

In the final portion of a Rankine steam cycle, water leaves a steam turbine as a high temperature mixed liquid vapor phase and requires cooling to return to a saturated liquid state. In a traditional steam cycle this vapor enters a condenser that uses a working fluid such as water or air to cool the mixture back into its liquid state prior to reentering the boiler. The power cycle's efficiency depends on the difference between its highest and lowest temperatures. In a CSP system utilizing water as a medium, the solar collector acts as the boiler, after which the superheated fluid enters the turbine to produce a work output. The fluid must then be passed through a condenser in order to return the heated vapor into a liquid state. Using CPC's floating tubes allows for a built in heat exchanger, reducing overall cost and simplifying piping schemes. In the new system the mixture is pumped into a large holding tank containing the floating tubes. Ambient temperature air is forced into the tubes from one side, passing over the surface of the Mylar sheet and removing heat from the stagnant water. The heat transfer due to convection between the stagnant water in the tubes and the fluid circulating within the tank will gradually reduce the overall temperature of the tank while the heated air is exhausted to atmosphere.

This senior project focuses on the design of a testing apparatus in order to verify heat transfer models of the tank and tubular system, and not the solar collection system, so existing designs are not specifically applicable. As a heat exchanger, the system is a new approach to cooling water. Typical heat exchangers for liquid cooling consist of one of several different designs. These designs are shown below in Figure 3. In the shell-and-tube heat exchanger, a hot fluid passes through a bundle of small tubes, contained within a larger circular shell. A colder fluid is piped into the shell system, flowing in the opposite direction of the hot fluid. The large surface area possible through using multiple small pipes allows for excellent heat transfer and allows for many different configurations. In a plate heat exchanger multiple thin metal plates are sandwiched within a large frame. The hot and cold fluids enter adjacent plate passages, typically passing through sets of chevrons or other geometry to aid in heat transfer. These systems are especially useful for situations where modularity is an important concern.

In the tube and fin style heat exchanger, a gas medium is used to cool a fluid stream. The hot fluid flows through tubes that have sets of rectangular or circular fins attached to them while the gas is forced through the fins. The low convection coefficients available using forced gases requires the additional surface area in order to reach an acceptable level of heat transfer. These systems are useful where air conditions are favorable for cooling and a lower cost system is required.

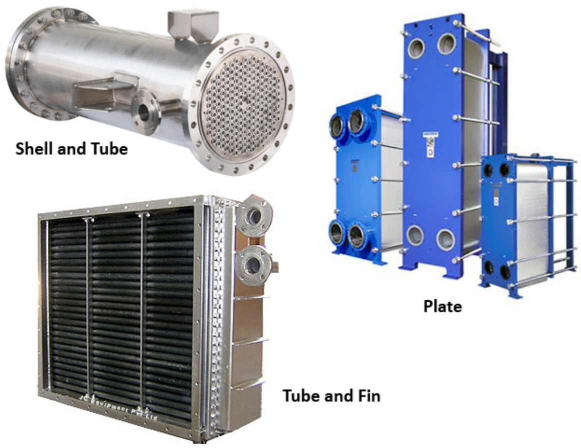

Figure 3: Typical heat exchangers used for cooling liquid substances.

The arrangement used for the new system proposed by CPC is most similar to a simple counter-flow, concentric-tube heat exchanger shown below in Figure 4. In a simple concentric-tube heat exchanger one fluid passes straight through while the other fluid flows through an annular space created by attaching a larger diameter concentric tube. By operating it in a counter-flow arrangement the heat transfer between the two fluids can be maximized and easily analyzed.

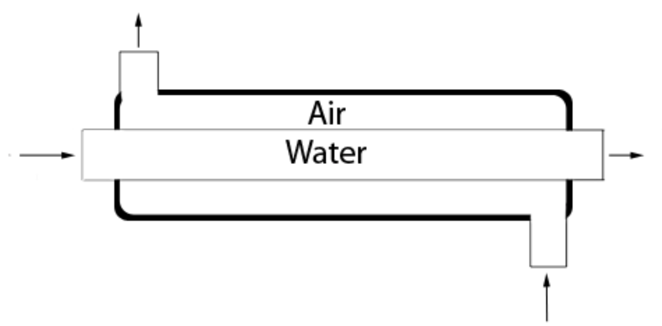

Figure 4: Typical configuration of a counter-flow heat exchanger.

While not identical to the new system, the differences in analyzing it compared to a counter-flow heat exchanger are small. The main negatives in the new system are the relatively small contact surface area and the stagnant fluid in the lower half of the tube.

Specific Data

As indicated earlier, one of the main drawbacks to using the system as a heat exchanger are the low values of heat transfer between the hot water and cold air stream. By modeling the system as a set of parallel rectangular ducts in a counter-flow arrangement, a rough calculation for the heat rate can be determined and compared with typical heat exchanger systems. Otherwise, there are no relevant products with which to compare technical data. Also, for this project, no standards were specifically applicable.

III. Design Development

Preliminary Conceptual Designs

The original scope of the project involved three distinct paths that have since been reduced to one. The first was a model of the system, which mainly consisted of simple models that would grow in complexity; the second was the component selection that would ultimately comprise the testing apparatus; and third, the testing and verification itself. Each path was interlinked in different ways, and would have required a constant shift in focus. Based on realistic expectations of what could be finished during a three quarter senior project as well as delays in funding and design, the project was scaled back to only include designing and building the testing apparatus. In the following section the initial designs for modeling and testing, which have been absorbed elsewhere, as well as the component selection will be explored.

Model

In order to properly begin design of the system, a simple model of the heat transfer was required. Selection of components used later in the testing apparatus are driven by mass flow rates of water and air, which are critical for determining the convection coefficient as well as dimensionless parameters such as the Reynolds and Nusselt numbers. The system was modeled initially as a tube-in-shell heat exchanger, but the geometry and applicable Reynold's and Nusselt number correlations were not accurate. The tube-in-shell design relies on tube diameter, which is a known dimension, but our design has much more complex geometry, shown in Figure 5.

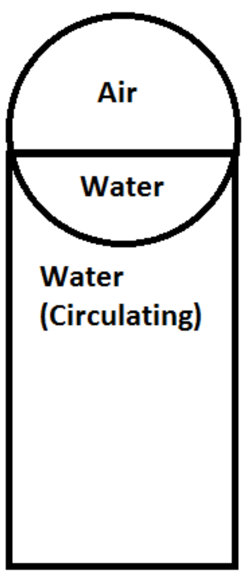

Figure 5: Cross section through one floating tube and tank.

Because of this, and the number of tubes utilized, we found it much more accurate to view the system as a pair of rectangular ducts with width N*D and height D/2 for the air flow, where N is the number of tubes and D is the diameter of the tube. By using an appropriate hydraulic diameter equation, given in Equation 1 we can solve for the Reynolds number of the air and water.

Equation 1: Equation for determining the hydraulic diameter of a non-circular duct. "A" is the cross sectional area and "P" is the wetted perimeter.

$$D_h = \frac{4A}{P}$$

The sectional area of the virtual duct that passes the air is then ${ND^2}/{2}$ and the wetted perimeter is $2ND + D$. In order to calculate the convection coefficient for the air we must also find the Nusselt number using correlations relating it to calculated Reynolds and Prandtl numbers. The intermediate steps are to calculate Reynolds and Prandtl numbers, by using Equation 2 and Equation 3 below.

Equation 2: Equation for determining the Reynolds number in a non-circular duct. "⍰" is the mass flow rate, "P" is the wetted perimeter, and "µ" the viscosity.

$$Re = \frac{4\dot{m}}{P\mu}$$

Equation 3: Equation to determine the Prandtl number. "c_p" is the specific heat at constant pressure, "μ" the viscosity, and "k" the conduction coefficient.

$$Pr = \frac{c_p \mu}{k}$$

With the above values calculated, two correlations for counter-flow in rectangular ducts joined at one wall were chosen (Hewitt) and are provided below in Equation 4 and Equation 5.

Equation 4: Nusselt correlation for forced convection in smooth, straight ducts under turbulent conditions.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right)}\left[1 + \left(\frac{D_h}{L}\right)^{\frac{2}{3}}\right]$$

Where

$$f = (1.82 \log_{10} Re - 1.64)^{-2}$$

Equation 5: Nusselt correlation for forced convection, parallel-plate geometry ducts with uniform wall temperature, constant properties, uniform wall-flux, and laminar conditions.

$$Nu = 1.775\sqrt[3]{RePr\frac{D}{2L}}$$

With a Nusselt number calculated we were able to calculate the overall convection coefficient, which is provided in Equation 6.

Equation 6: Equation for convection coefficient h.

$$h = \frac{Nuk}{D_h}$$

Comparing the generated convection coefficients to expected values allows us to determine if our data is reasonably accurate and if not, the mass flow rates of both air and water can be varied to generate new data. Data for different combinations of mass flow rates are presented in Table 1 and Table 2.

Table 1: Heat transfer values for air blower providing 3450 CFM.

#	Blower (CFM)	Blower (kg/s)				
1	3450	1.93				
#	Centrifugal pumps (GPM)	Centrifugal pumps (kg/s)	T_{air} (K)	Re_{air}	h_{air} (W/m^2*K)	U (kW/m^2*K)
1	108	6.5	317.8	2922	3.17	0.2631
2	110	6.62	318.1	2921	3.17	0.2883
3	115	6.92	319.1	2919	3.17	0.4073

Table 2: Heat transfer values for air blower providing 4000 CFM.

#	Blower (CFM)	Blower (kg/s)				
2	4000	2.24				
#	Centrifugal pumps (gpm)	Centrifugal pumps (kg/s)	T_{air} (K)	Re_{air}	h_{air} (W/m^2*K)	U (kW/m^2*K)
1	108	6.5	315	3396	3.728	0.1893
2	110	6.62	315.4	3396	3.728	0.1982
3	115	6.92	316.1	3394	3.728	0.2238
4	120	7.22	316.9	3392	3.728	0.2563
5	125	7.52	317.7	3391	3.729	0.301
6	130	7.82	318.5	3389	3.729	0.3724
7	135	8.12	319.3	3388	3.729	0.5653

With estimated values for our required flow rates, we were able to move on to component selection. Additional development of the model will be performed by graduate students with advanced knowledge of computerized heat transfer and fluid dynamics.

Component Selection

A full scale deployment of the new CSP system requires approximately 3465 m^2 of area in order to run at full capacity. Our scale system is expected to be about 24 m^2 and will correspondingly require scaling of flow rates as well as expected outlet temperatures. The storage tank, a building block for the project, has been designed by CPC at a scaled size of 15 meters long, 3 meters wide, and 1 meter deep. Our tank has been further scaled to a size of approximately 8 meters long, 3 meters wide, and 1 meter deep – although converted to English units for simplicity of construction – resulting in a tank size of 24 feet long and 8 feet wide. Several different options were considered when planning how to retain the water, most of which were ruled out quickly. One option was a commercially deployed tank in a trench dug in the surrounding environment, utilizing the natural insulation of the earth. For our usage there are no suitable sites with provided utilities, making this decision one of the least attractive. A second design consisted of using plastic road barriers, which when empty are light and easily manipulated. When filled with water or sand they become very heavy, stationary objects, making them ideal for use as supporting walls, as well as being effective insulators. With economics in mind, they were also ruled out due to the prohibitive cost in procuring them. There were also worries about structural integrity due to lack of external bracing. With these two designs ruled out, the third and final design was chosen to be a wooden tank, framed with readily available beams and faced with plywood.

Original concepts for the tank consisted of framed walls built from standard 2”x 4” boards and faced with 3/8” plywood. Each framed wall and the base would be individually constructed, fastened with screws allowing for simplicity in deconstruction and transportation. The individual walls and base would then be bolted together using large hexagonal bolts and nuts to resist shear. An image of the preliminary concept is provided in Figure 6.

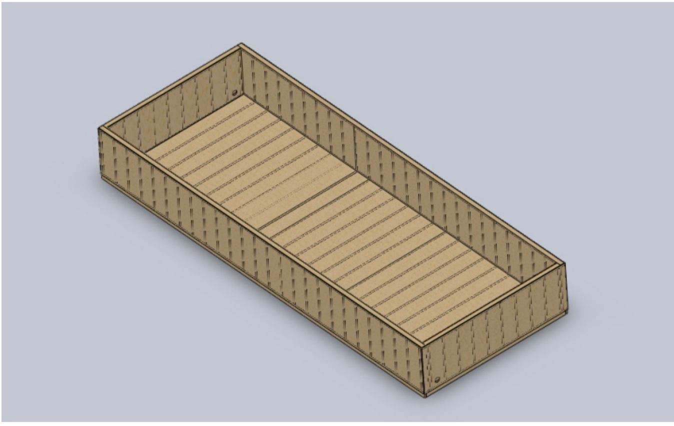

Figure 6: Initial design concept for tank construction. Faint dotted lines indicate 2"x4" supports.

This design was reviewed by both Professor Keller and CPC and was determined to not have adequate bracing to retain the necessary amount of water without bursting.

CPC has fully designed a tank which has been engineered by an outside consultant with a PE license. Due to the project not focusing on the civil engineering aspect of the tank design, we have opted to simply modify their design to suit our needs. CPC's design relies on triangular buttresses spaced along the length of the tank that are fastened to cross beams running under the base of the tank. On the short sides, a simple frame consisting of horizontal beams is joined to vertical beams using joist hangers. CPC's design was originally made for use with thick acrylic sheets that were then sealed with a waterproof bonding agent such as silicone to negate any requirements for an internal waterproof barrier. Our design has been modified to use plywood sheets rather than acrylic, for ease of construction, and a thick plastic pond liner will be used to effectively create a waterproof barrier. The design has also been optimized to be built in sections, allowing the 24 foot long tank to be separated into six 4-foot sections that can be moved and transported as necessary. Fasteners will consist of #6 x 2" screws, horizontal beams will be fixed with Simpson Strong-Tie A34 braces, and the corners braced using Simpson Strong-Tie A35Z braces. The final tank design is shown in Figure 7.

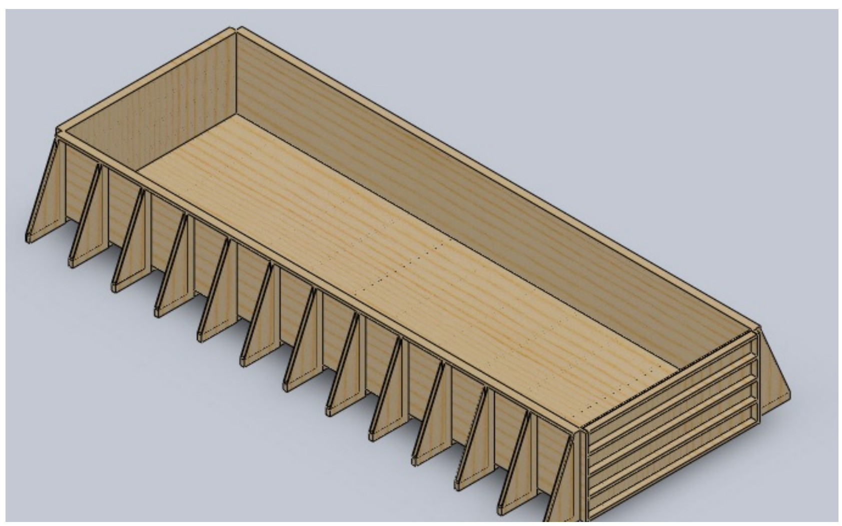

Figure 7: Final design for tank construction.

With the tank design finished, we were able to move on to constructing a piping scheme for the system. With 15 cm diameter tubes provided by CPC, up to 15 tubes may be installed, allowing for room on the edges to install a floating frame. Requirements for the plumbing are shown below.

- Must not pierce pond liner
- Provide intake airflow to 15 tubes
- Exhaust air to ambient for 15 tubes
- Allow for easy disassembly
- Adjustable length for varying water heights
- Minimum bends and tube length to reduce losses
- Equal mass flow rate in each tube entry region

The integrity of the pond liner is very important in maintaining a waterproof tank, and therefore the first requirement was to ensure that no plumbing would affect the liner. All designs spawned from this, effectively requiring plumbing to go up and over the sides of the tank. In order to provide air to all fifteen tubes, several different options are being considered. The first is to design and build a tubular style manifold that sits very close to the tube ends, which is supplied by a large diameter pipe from the air blower. The benefits of this design are the short runs of pipe from the manifold to the tubes, allowing for less tubing, simplified construction, easy disassembly by disconnecting the manifold, and a single pipe from the blower to the manifold. The drawbacks are the complexity in maintaining an equal flow in each tube out of the manifold, the difficulty in designing a proper manifold, and the additional size and weight added to the end of the tubes.

The second design consists of individual pipes running to each tube. The benefits are the simple nature of the system, the ability to individually run each pipe, and the flexibility in routing the pipes. The drawbacks are the additional length of pipe, the difficulty in merging the 15 tubes together at the blower, and the different lengths of pipe. Currently the decision is to move ahead with multiple pipes with flexible lengths, in order to adjust to water height, merging together at the blower outlet. The pipes will have no full 90° bends due to using flexible hoses, and possibly elevating the blower. The pipe lengths will also be minimized by placing the blower at the intake end of the tank. Pipes will be fit with quick disconnect fittings, most likely cam-and-groove couplings, and the diameter of each pipe is recommended by CPC to be two inches. A manifold plate will be fabricated for the blower outlet that will split the air flow into 15 separate pipes. Valves may be installed on each pipe in order to regulate flow to ensure it is equal in each tube. A preliminary assembly drawing is shown below in Figure 8.

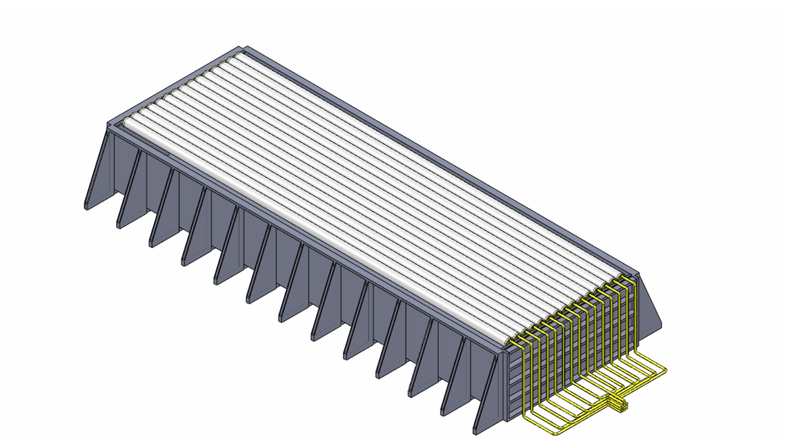
Figure 8: Tank assembly showing poly tubes and basic piping layout for delivering air.

Commercially deployed systems intended for power generation have the benefit of being attached to a steam turbine, producing a nearly constant stream of heated water. For analysis we intend to model the same temperatures that we expect to see exiting a turbine, approximately 82°C, and cool to approximately 45°C. At a projected water flow rate of 7.25 kg/s, the required input to heat the water from 45°C to 82°C in a single pass would be approximately 1.37 Megawatts (MW), a value that is nearly impossible to reach with commercially available boilers, and when available, are astronomical in cost. Using a more conventionally available boiler, such as a gas-fired tankless water heater, provides an output of approximately 54kW but is only rated for .6 kg/s, requiring two passes to reach 82°C and taking over 11 hours to complete each pass provided there are no external heat losses and efficiency is 100%. This boiler poses the largest problem in our design and no solution seemed readily apparent. One possible solution is to use a readily available boiler located on the roof of the Bonderson Engineering Center even though water at the specific flow rates and temperature we require is not guaranteed and parts and labor costs for utilizing the boiler are high. In addition to these issues, the liquid is not pure water and is a chemical solution, complicating our heat transfer model as well as evaporation and other effects.

One component in our system that remains unchanged, in all but scale, is the pump. It will be placed in series with the other system components after the outlet of the condenser and will be the key cause of the system's pressure gradient responsible for cycling the water. Commercially deployed systems will require large pumps with high flow rates in order to cycle the large volume of water. High flow rates are ideal because the closer to scale our system is, the more accurate it will be. The ideal pump flow rate is one maximizing the rate of heat transfer, but this is not reasonable within our budget, as in the case with the water heater. Primary decisions have been to focus on centrifugal water pumps with flow rates between 100 and 200 gallons per minute, resulting in mass flow rates of 7 to 10 kg/s. An important note to make is that since the system is scaled, the water heater, pump, etc. do not need to be ideal to minimize, or even maintain, the water outlet temperature. This is the case because the system may still be modeled with the help of a proper Data Acquisition System (DAQ).

Analogous to the pump for its water circulation system is the blower for the air circulation system. This system component will be the same as the field blower except in two regards. The orientation of the pipe distributing system to each tube will likely be different and, like the pump, the blower will be scaled. The great distinction between the blower and pump is that air has a much lower density. This means that the distribution of air between the blower and the floating tubes will be significantly different where the length and major losses due to friction in our scaled system contribute possibly orders of magnitude more loss compared to the field air circulation system. This calls for the slim design shown by the yellow pipes in Figure 8. An alternative design was considered where the blower would be attached to a manifold that is perpendicular to the floating tubes with smaller diameter pipes distributing the flow from the manifold into individual tubes. In this design there is great reduction in major and minor losses (due to geometric flow changes) while the distribution of air is more even because it is first pumped into the manifold, creating a pressure gradient that is more evenly distributed over the interfaces of the lead-in pipes. Similar to the water circulation system, the air system will require scaling when configured to a field model due to the longer tube lengths and additional tubes. This means that the scaled-power of our blower can be proportionately less than the scaled-power of the water pump.

Essential to the analysis of our system is the data acquisition that we are capable of maintaining during our test runs. The initial estimate of the amount of thermocouples needed was 160 in order to provide temperature measurements throughout the volume of the condenser system, ambient control system, and around the remaining components of our system. With this many thermocouples, specific temperature gradients can be accurately observed along the length of multiple floating tubes, between floating tubes, along the x-, y-, and z- axial directions within the pool, and many other examples. Another key data sensor would be the flow meters for the water and air circulation systems. These should be placed on the outlets and inlets of these systems and perhaps be used with pitot-static tubes. Connecting and relaying these sensors will be the actual DAQ that will either save the data in local memory or send it to a nearby computer via cable or wirelessly. Based on the number of thermocouples, as well other instrumentation required, we found that a DAQ system with at least 128 channels and the ability to be expanded in the future is the best system available. Contact with multiple companies provided vital information about possible systems. According to price quotes from handful of sources, this DAQ unit has turned out to be an expensive component. Data acquisition is one of the most critical steps for verifying our thermal model, and sacrificing features for cost is not ideal. If cost becomes a significant issue the DAQ system can also be scaled down to record only the measurements that are most critical for model verification – namely the inlet and outlet water temperatures, the inlet and outlet air temperatures, and the flow rates throughout the system.

The weather system in this project has had the least attention particularly because it is simpler and does not require scalability. On the positive side, this means that our weather monitoring system may mimic the field system. The five key parameters that should be measured are: temperature, humidity, wind speed, rainfall, and irradiance (including surface temperatures). These can all be measured with standard equipment that can be procured on campus or nearby hardware stores.

Test

In order to verify the heat transfer model we must gather data about the behavior of the tank during its cooling cycle. A test plan has been formulated that focuses on analyzing the pond at three separate water depths as well monitoring evaporation of the pond. The test plan is outlined below.

<u>Control Pond:</u>

Used to track the evaporation differences between our test pond and a control environment.

- Area of base: 1 m^2
- Record volume of water required to fill control pond and test pond to initial depth

<u>Test Pond:</u>

Initial Data Run

- Verify flow rates with calibrated Venturi flow nozzle or other flow bench device borrowed from Aero Department
- Check thermocouples vs. thermometers
- Check weather station vs. local weather
- Gather data for 48 hours from nominal depth of .25m. Check order of magnitude.

Test 1

- Gather data with variable boiler settings at depth of .25 meters
- At each boiler setting, vary:
- Air flow rate
- Water flow rate
- Perform this test 3 or more times over a period of two weeks

Test 2

- Gather data with variable boiler settings at depth of .50 meters
- At each boiler setting, vary:
- Air flow rate
- Water flow rate
- Perform this test 3 or more times over a period of two weeks

Test 3

- Gather data with variable boiler settings at depth of 1.0 meters
- At each boiler setting, vary:
- Air flow rate
- Water flow rate
- Verify thermoclines, entrance region, and thermal model

Concept Selection

With the elimination of the modeling and testing portions of the project, focus could be dedicated on the component selection and the construction of the testing apparatus as a whole. Key design decisions were made prior to moving to the final design, which is detailed in Chapter 4. The tank design engineered by CPC was chosen to serve as the base for our design, and we chose to use wood as the construction material. To insulate the tank several different options were considered but hay was

selected due to its relatively low cost and good heat transfer properties. To provide weather resistance to the tank it was coated with several layers of oil or latex based primer and several layers of latex paint. Corrosion resistant screws and fasteners were used for all construction. For the water system a centrifugal pump was chosen to be the best design, with piping being constructed from PVC for low cost.

To heat the water it was originally decided to utilize the boiler provided by Bonderson while using a commercially available heat exchanger to transfer the heat from the closed loop to our loop, but the high cost of construction to hook up to this system has prevented it. Rather than utilizing an existing boiler the project will purchase a commercially available gas-fired hot water boiler and install it in line with the water system. This design change and the corresponding calculations are detailed in Chapter 5. The air system was chosen to consist of a single large blower unit entering a stagnation manifold and then being piped to each individual pipe. Valves on each air inlet are used to control and regulate the flow through each tube. The data acquisition system is no longer a commercially off the shelf system and has instead been purpose built by a local company. A mesh of digital temperature sensors will be used to determine temperature distribution within the tank as well as temperatures of fluids within piping systems. Pitot-static tubes will be used to monitor air and water flow for the system. To monitor weather data an off-the-shelf weather system will be used.

Preliminary Analysis

The design of each sub-system requires basic calculations in order to generate data required for component selection. The general layout of calculations for each sub-system is provided below, with results of the analyses provided in Chapter 4.

For the water circulation system an adequate pump must be selected, as well as a piping diameter in order to maximize efficiency while minimizing costs. Calculations to determine the necessary pump head are given by Bernoulli's equation, shown below in Equation 7.

Equation 7: Bernoulli's equation with pump head and head losses.

$$\frac{\boldsymbol{p_{in}}}{\boldsymbol{\gamma}}+\frac{\boldsymbol{V_{in}^2}}{\boldsymbol{2g}}+\boldsymbol{h_{in}}+\boldsymbol{h_{pump}}=\frac{\boldsymbol{p_{out}}}{\boldsymbol{\gamma}}+\frac{\boldsymbol{V_{out}^2}}{\boldsymbol{2g}}+\boldsymbol{h_{out}}+\boldsymbol{h_{loss}}$$

With conditions expected in the system, all of the terms of the above equation are eliminated, leaving the relation shown below in Equation 8.

Equation 8: Relation between pump head increase and system head losses.

$$\boldsymbol{h_{pump}}=\boldsymbol{h_{loss}}$$

To determine the head loss in the system, the major and minor losses are added together to generate the relationship shown below in Equation 9.

Equation 9: Head loss in piping system consisting of major and minor losses.

$$h_{loss}=f\left(\frac{L}{D}\right)\frac{V^2}{2g}+K\frac{V^2}{2g}$$

In the above equation, several terms are known; while others will need to be solved in an iterative process. The velocity of the fluid in the system is given by the fixed mass flow rate and the geometry of the piping system and can be represented by Equation 10.

Equation 10: Relationship between fluid velocity and mass flow rate.

$$V = \frac{4\dot{m}}{\rho \pi D^2}$$

In the above equation the only variable is the diameter of the pipe, D, and the equation can be solved for different diameters of pipe to determine the change in velocity and the corresponding change in head loss. The friction factor, *f* in Equation 9 is a function of the Reynolds number, Re, and the relative roughness of the piping, ε/D, each of which are functions of pipe diameter and can be solved for a variety of diameters. The loss coefficient K for a variety of different restrictions is provided in "Fundamentals of Fluid Mechanics." (Munson, Young and Okiishi)

In addition to head losses and the corresponding required head from the pump, the net positive suction head (NPSH) that is available to the pump must be calculated. The calculation to determine the $NPSH_a$ is provided below in Equation 11.

Equation 11: Equation to determine available NPSH with a tank exposed to atmosphere and a positive elevation change.

$$NPSH_a = \frac{p_0 - p_v}{\rho g} + \Delta z - h_L$$

In the equation above, p_0 represents the pressure acting on the water surface in the tank, p_v is the vapor pressure of the fluid, *z* is the elevation change, measured from the center of the pump impeller to the fluid level, and h_L is head loss in the piping prior to the pump.

For the air circulation system the calculations are much the same as the water system. To determine the required head for the blower, Equation 8 is used in the same way with the required mass flow rates determined from heat transfer models. For the air system there is no $NPSH_a$.

To determine an appropriate heat exchanger to use for transferring heat from the Bonderson boiler to the condenser loop, a simple heat transfer analysis is required. The equation provided below in Equation 12 is used to find the maximum possible heat transfer in a standard heat exchanger.

Equation 12: Maximum possible heat transfer in a heat exchanger.

$$q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

In the equation above, C_{min} is the minimum heat capacity rate, which is found by comparing the heat capacity rates for the hot and cold fluid and using the lesser value. The definition of the heat capacity rate C is provided in Equation 13

Equation 13: Definition of the heat capacity rate, C

$$C \stackrel{\text{def}}{=} \dot{m} c_p$$

The heat capacity, c_p is evaluated at each fluid's mean temperature, and the mass flow rate and inlet temperatures are known based on standard operating conditions and system expectations.

IV. Final Design

Overall Description

With various decisions already made in the concept selection, the overall system design came together on its own. The tank is designed in a modular fashion, taking advantage of commercially available timber, and able to be added to in the future. The size of the tank was expanded to 32 feet long by 8 feet wide, allowing for additional heat transfer through the length of the tubes. A height adjustment system was designed to brace the poly tubes and ride on the height of the water and consists of aluminum supports and a PVC frame. The water circulation system uses a Gould centrifugal pump with a three inch diameter suction pipe and two and a half inch downstream pipe. Piping for the water system is formed from Schedule 40 PVC with a check valve and ball valve on the suction side and five ball valves on the downstream side, two located before and after the pump, two located before and after the heat exchanger, and one used to bypass the heat exchanger when necessary. Digital temperature sensors are inserted into the PVC tubes at the entrance and exit of the tank as well as before and after the heat exchanger. To monitor the flow rate of the water a standard rotameter is mounted vertically. The heat exchanger is a shell and tube exchanger capable of 1.6 million Btu/hr, designed from stainless steel and able to handle design flow rates. A bypass loop allows the water flow to pass around the heat exchanger through the fifth ball valve. The air system consists of a blower delivering 150 CFM to a stagnation chamber that splits the air flow to fifteen poly tubes. Valves are included on each inlet hose in order to control the flow and computer fans at the ends of the poly tubes are used to measure the air flow rate. The system used to measure thermoclines in the tank consists of 180 digital thermometers outputting to controller boards connected to a PC. Nine layers of 20 thermometers can adjust to provide a dense mesh based on distribution of temperature.

Detailed Design

Tank

Very few changes were made from the initial design to the final design, with only minor structural additions and a different method to assemble the entire tank. One concern about deflection in the plywood along the span between cross sections prompted the installation of a 2” x 4” beam to distribute the load. This modification in the design was made after construction of the cross sections had begun, requiring time-consuming adjustments. The initial design intended to build the walls in four foot sections, with each section assembled on a shared cross beam. This design was found to be difficult to disassemble if necessary, and was changed. The new design is shown below in Figure 9. In the new design, five cross beams spaced approximately 24 inches apart are attached via 2”x4” beams at the tops and bottoms, with ¾” plywood to form the walls and floor. The triangular buttresses consist of 3/8” plywood triangles attached to upright

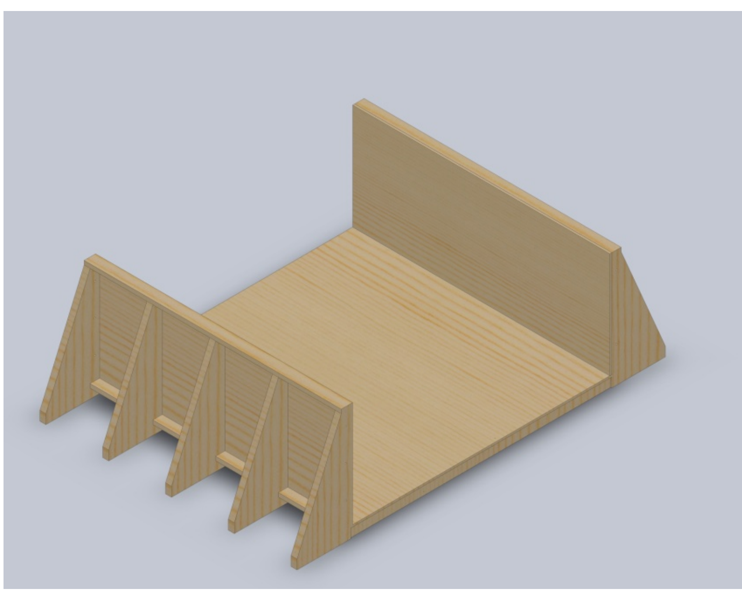

Figure 9: Eight foot tank section with final design revisions.

2”x4” beams, angled 2”x4” beams, and the long 2”x4” beams that form the cross beams. The total section has an internal dimension of exactly eight feet wide by eight feet long with a one meter height. The cross beam at either end of the eight foot section has three holes drilled in each triangular buttress, spaced at even intervals along the height of the buttress. Each hole is drilled to accept a ½” hexagonal bolt for joining full sections together. A side view of a single cross beam with triangular buttresses and holes drilled is shown below in Figure 10.

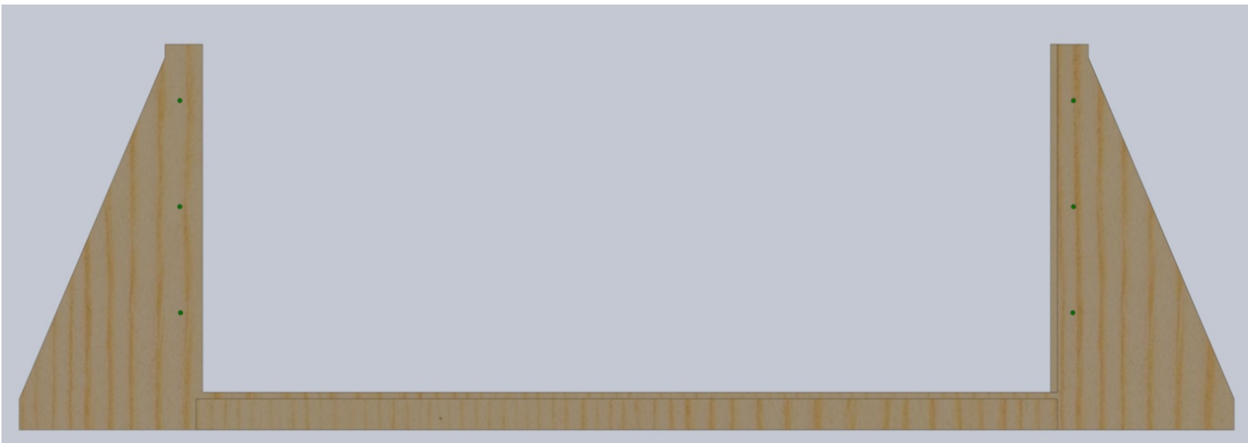

Figure 10: Side view of the last cross beam in a tank section. Holes are highlighted in green.

The design of the end walls changed very little from the initial design, but during the construction slight modifications were required for fitment reasons, which affected the structural strength negatively. In order to mitigate this issue extra 2”x4” beams were used to add bracing. The drawings were changed to reflect this difference and the new design is shown below in Figure 11.

Figure 11: View of the end walls with 2"x4" beams highlighted in black.

The original design length was constrained by the available space in the Bonderson project yard to a maximum of 24 feet, but due to other projects being removed, the length was able to be extended to 32 feet. With the final design being highly modular, it is a trivial task to add a fourth eight foot section to the three already in place and bolt them together. Each eight foot section is bolted together at

adjoining cross beams using six ½" x 6" hexagonal bolts, six hex nuts, and 12 washers, all made of zinc for corrosion resistance. Internal to the tank, galvanized steel plates are used to tie the cross beams together along the bottom and sides for additional strength. The cross sections at each end have the walls attached using ten Simpson Strong-Tie A23 galvanized angles, five in each corner. The fully assembled tank (without hardware) is shown below in Figure 12.

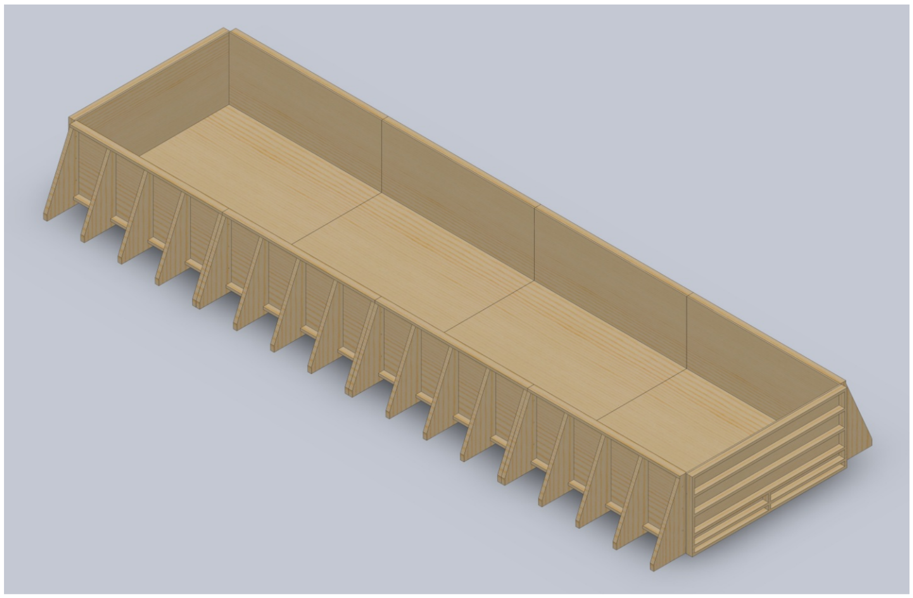

Figure 12: Fully assembled tank with four cross sections totaling 32 feet long.

The entire tank is coated with oil or latex based primer on all exposed surfaces and then coated with a latex based final coat. Paint is applied thick enough to prevent moisture from seeping into cracks and openings that would cause rot. Hay bales are used to insulate the long walls of the tank while fiberglass batting with an R-13 value is used to insulate the short ends. A cohesive pond liner is used to provide a waterproof barrier to contain the water and is wrapped around the hay bales to provide protection and support.

The control pond used to serve as a test for evaporation is constructed in the same way, utilizing the same style of cross beam and end wall. The scaled size has internal dimensions of a one meter cube to make measurement of evaporation simple with a ruler or flow totalizer. Hay bales are again used to insulate two sides of the tank while fiberglass batting is used on the two other sides. The control pond is shown below in Figure 13.

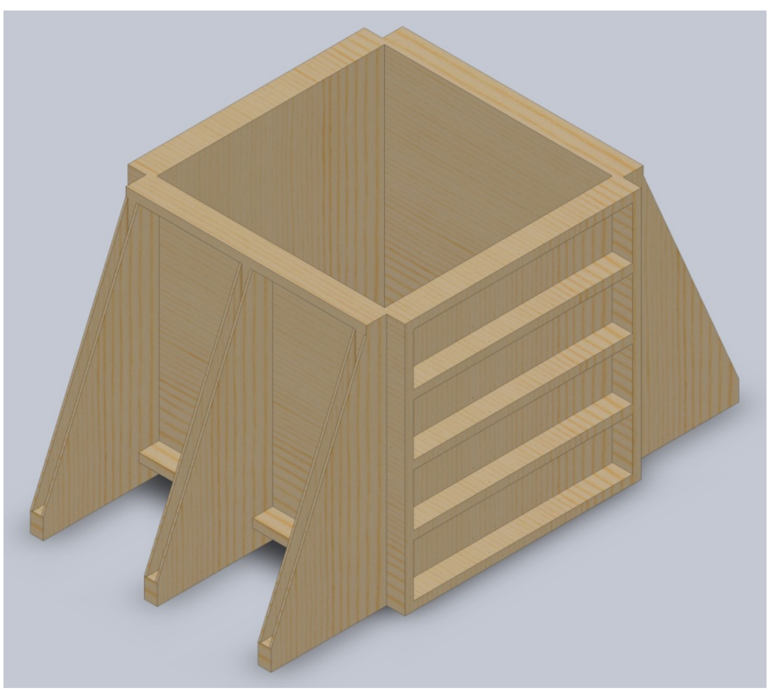

Figure 13: Control pond without hardware.

Height Adjustment System

The space between the tubes and the tank walls requires a buffer in order to ensure that the tubes cannot be damaged as well as evaporation being minimized. CPC's prototype design used a PVC frame with adjustment in all three directions with PVC fittings, but was unwieldy, was not watertight, and suffered from becoming waterlogged. With the issues using PVC fittings for movement, they were eliminated all together in our design. Our design uses 2-1/2" nominal diameter PVC pipe to create a rectangular frame joined in the corners with 90° elbows and coupled every eight feet along the long sides of the tank. To couple the pipes on the long sides a reducing tee is used, providing a 2-1/2" pass through and a vertical ½" opening on the top. An example of the tee is shown in Figure 14. All PVC pipes and fittings are joined together using PVC cement to create a chemical bond that is watertight, preventing the system from sinking and using the natural buoyancy of the water to float at the level of the water.

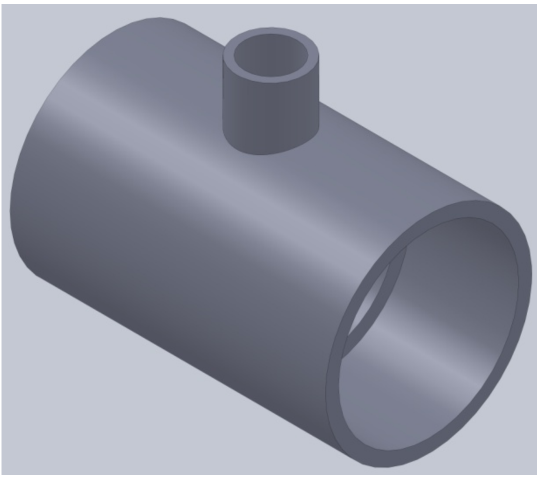

Figure 14: Height adjustment tee with 2-1/2" pass through and 1/2" top opening.

To anchor the PVC frame to the wooden tank an aluminum arm has been designed to replace the PVC system that CPC uses. Original designs for the aluminum arm consisted of simple flat bar stock bolted together, but rigidity was determined to be an issue with flat bars. To replace the bars, one inch square extruded tube was substituted. The extruded tubes are cut to a length of eight inches and slotted at one end with four slots slightly over .25" in height and .75" long. These slots allow for movement in one horizontal direction when fixed with .25" diameter screws. On the tank side of the arm a round hole is drilled through the top and bottom sides with an upper diameter of .75" and a lower diameter of .625". This hole is designed to accept a .625" nylon bushing with a .75" lip sourced from McMaster-Carr. The wall thickness of .0625" for the aluminum tube is adequate for good rigidity while reducing cost and weight. The completed design for the arm is shown in Figure 15.

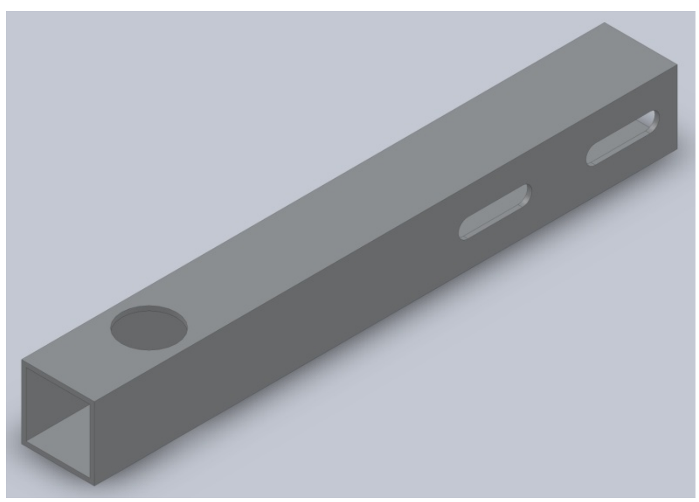

Figure 15: Completed design for height adjustment arm.

To anchor the arm to the tank frame, a pair of one inch aluminum angle pieces is bolted through the slots using .25" aluminum machine screws and nuts. The angle pieces are then screwed into the wood frame using aluminum coarse thread screws. A 36" aluminum round rod is used to provide attachment from the PVC frame to the height adjustment arm, passing through the nylon bushing to create a low friction state. The nylon bushing allows for a slight clearance to ensure that there is no binding but prohibits movement in any direction. The aluminum rod is joined to the PVC tee at the base using epoxy to join all the parts together. An assembly mockup of the height adjustment system is shown below in Figure 16.

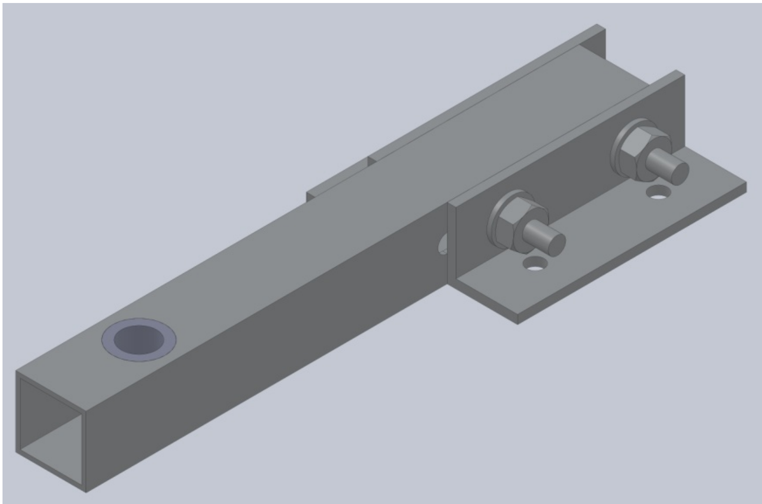

Figure 16: Height adjustment assembly with all hardware included.

Six height adjustment assemblies are spaced at eight feet intervals along either side of the tank, providing an appropriate amount of resistance against movement in any direction. The slots in the square tube allow for micro-adjustment during construction to ensure proper alignment, and tightening the screws ensures that it locks in place when necessary.

The poly tubes that float on the surface of the water must be fixed to a specific object in order to ensure alignment with the water and air systems, but cannot be fixed to the tank due to the varying height. In a commercial deployment, the tubes must also be allowed to rotate in order to track the sunlight as it moves across the sky, but our testing does not require that level of sophistication. In our design we use an approximately eight foot long one inch square aluminum tube with a .05" wall thickness with holes drilled to accept the tube axle. Fifteen holes are spaced 15 cm apart, drilled slightly over .3125", the diameter of the tube axles. At either end of the box tube a clamp is fabricated from aluminum sheet, designed to encircle the PVC pipe and attach to the box tube using a .25" aluminum machine screw. Two of these bulkheads are used, one at each end of the poly tubes.

The entire system is designed to be lightweight and easy to manipulate. With the PVC tubes remaining airtight, there should be no issues with water leakage and sinking, avoiding the problems that CPC has encountered. The nylon bushings and good alignment of the system should prevent any loading on the height adjustment arms, removing the need for expensive high strength materials. The use of aluminum for all components reduces chances of corrosion, while retaining strength. The entire system is shown below in Figure 17.

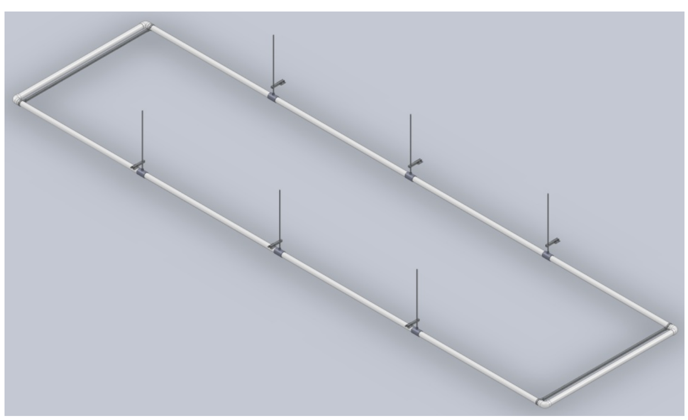

Figure 17: Full height adjustment system with bulkheads and height adjustment assemblies in place.

Water System

In order to cycle water through the system a water distribution system must be designed, involving any necessary piping and fluid pumps. The design flow rate of the system, determined from the initial heat transfer calculations, indicated a necessary mass flow rate of 7.25 kg/s. This high flow rate set initial constraints for the velocity of the fluid in the piping, based on diameter, and helped build a model to determine the total head loss in the system. Necessary pipe lengths were determined using the solid model of the accepted tank, as well as fittings necessary for routing. A total of approximately 10 90° elbows were determined to be necessary, with four ball valves to isolate the pump and heat exchanger. Losses in the heat exchanger were determined to be negligible. Several calculations were performed, shown in the following Analysis Results section, to determine a total head loss in the system. The total head loss and desired flow rate were then used to select an appropriate centrifugal pump. Consultation with several pump manufacturers determined that the Gould 4BF2G5G0 would be an adequate pump, operating at 1725 RPM and reaching a desirable efficiency at our desired system operation. Dimensions of the pump inlet and outlet fittings are 3” and 2.5”, respectively, which drove the final diameter of the piping system. Calculations for head loss with 3” and 2.5” piping were recalculated to ensure that the pump would be adequate.

One of the largest issues with pumping water, especially when near its boiling temperature, is cavitation at the pump inlet. To ensure that cavitation does not occur, pumps are rated with a Net Positive Suction Head Required ($NPSH_R$). At desired operation, the Gould pump has a required NPSH of approximately 3.5 feet. In most standard pumping facilities, the reservoir is located at an elevation above the pump to ensure an adequate available NPSH, or the system is designed to ensure few losses in the suction system. In our system the $NPSH_A$ is slightly different, based on pipe routing as shown in Figure 18, which simulates the head at the same level of the tank. Based on calculations shown in the Analysis Results section, the $NPSH_A$ is shown to exceed the $NPSH_R$, requiring no additional work to prevent cavitation. A second issue with pumping is priming the pump. For systems where the fluid reservoir is above the pump, no priming is necessary as the pump stays flooded at all times. In our system the pump is lower than the tank fluid level when full, but fluid in pipes above the tank can drain back into the tank, resulting in air pockets in the system. By using a check valve on the suction inlet the fluid can be prevented from escaping, leaving the pump flooded at all times.

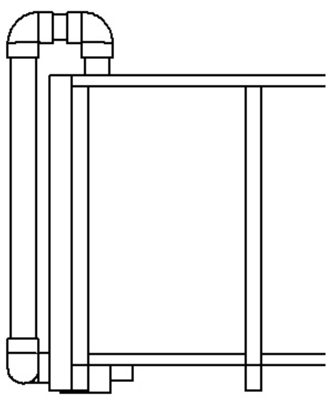

Figure 18: Water pipe routing over tank walls.

One additional design consideration was a method of bypassing the heat exchanger when the tank has reached operating temperature, while maintaining a constant fluid flow through the tank. A bypass loop was designed using a separate ball valve to navigate around the heat exchanger when necessary. To prevent flow from passing through the heat exchanger the isolation valves around the exchanger are closed while the bypass valve is opened.

Pipes are all constructed of PVC, using socket weld joints at all fittings and PVC cement to join them together. Flanges may be used at the pump and heat exchanger to aid in removal if necessary. To insulate the pipes to prevent heat losses, closed cell foam is used and painted with vinyl paint for outdoor usage. To monitor the flow through the system a rotameter style flow meter is used, capable of measuring up to 200 GPM and requiring very little to install.

Air System

The air system consists of a single fan supplying air to 15 different floating tubes. A Plenum chamber will be use to evenly distribute the airflow in all 15 tubes. The hot air at the end of the tubes will be exhausted to ambient conditions. See Figure 23 for a complete project schematic of the layout of all the parts.

A 150 CFM and 46" static pressure centrifugal fan will be connected to a plenum chamber. The plenum chamber will stabilize pressure for a more even distribution of air into 15 different pipes. See Appendix Section A for detailed plenum chamber drawings.

Figure 19: Plenum chamber obtained from Aerospace department.

The pipes will be connected to the chamber using barbed fittings. These pipes have a 1-1/4'' inner diameter. Each pipe will have a ball valve to control the flow of air into each floating tube and the flow will be adjusted as needed to have similar flows in all tubes. Even though ball valves are not specially designed for flow control, they are good enough for the level of accuracy required in the airflow system. The pipes will be connected to the specially designed floating tube end cap shown in Figure 20. The end caps have two ¾" barbed fittings and a 1-1/4" barbed fitting. The air flow system pipes will be connected to the 1-1/4" barbed fitting. Tube inlet 1 will be used to interconnect all the floating tubes together so that they can be pressurized. Tube inlet 2 is used to fill the floating tubes with a control volume of water. The pipe is secured to the barbed fittings, barbed tees, and barbed elbows using hose clamps.

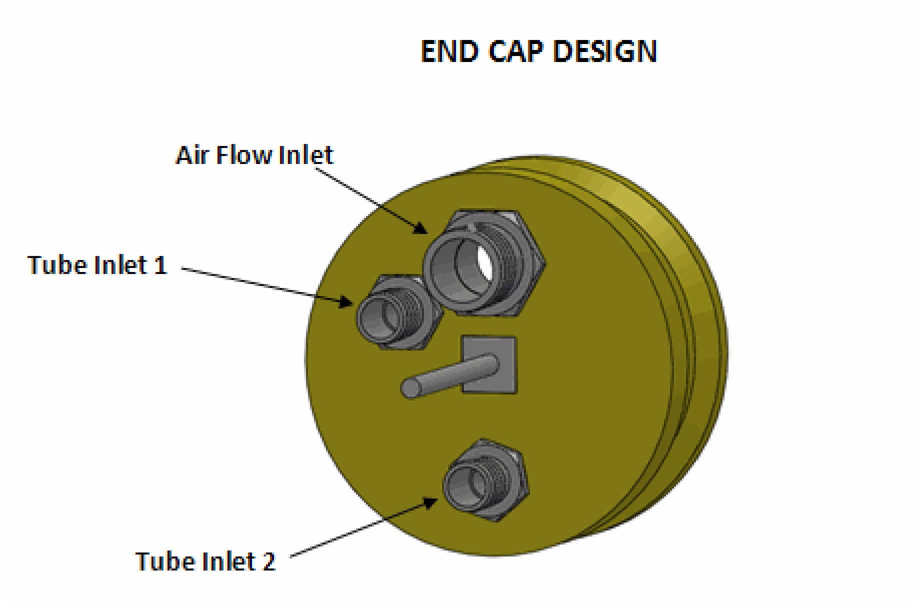

Figure 20: End cap with barbed fittings.

The air flow rate in the floating tubes will be measured using computer-cooling fans, which will be connected in the floating tube exits.

Heat Exchanger

When used in industrial applications, the tank will be continuously supplied with hot water from a power plant. In order to accurately simulate a real-world scenario, the tank should be supplied with water at 180°F. The first option considered was purchasing a boiler and installing it on location behind Bonderson. Considering the massive amount of hot water necessary for this project, industrial-sized boilers seemed to be the only option. However, installing and operating such a boiler would be beyond the capabilities of this project due to cost, paperwork, location and several other constraints. Further contemplation revealed another, more realizable option: using the boiler already installed on top of Bonderson.

Since the boiler uses a water-glycol mixture, it cannot be used directly with the tank. Therefore, the current plan is to heat the tank water by running it through a heat exchanger with the hot water from the boiler. The cold side of the heat exchanger will be the tank water.

Temperature System

To determine the temperature distribution within the tank a dense mesh of thermometers must be used. Initial designs attempted to use thermocouples with an off the shelf datalogging system, but the cost was prohibitive for large scale usage. The datalogging system alone would have cost upwards of $6000, outside our budgetary constraints. Contact with a local instrumentation company provided an alternative to using costly thermocouples by using digital temperature sensors that plug into a one-wire bus. Any number of these sensors can be plugged into a single wire which communicates with a simple controller board and interfaces to a computer using a USB interface. Each sensor has a hard coded unique identifier, allowing them to be identified easily and effectively. The accuracy of the sensors is .5° C, which is slightly less than desirable, but well within limits for measuring a gradual temperature gradient. To water proof these sensors they are dipped in a plastic rubberized coating. A total of 180

sensors will be used to create a mesh of the tank, nine layers of 20, oriented with five sensors on the long side and four on the short side.

To determine temperatures elsewhere in the system, such as at the piping inlet and outlet, the same sensors will be used in order to minimize reading differences. For sensors located in PVC tubing, a PVC coupler will be used that has been drilled to accept a sensor that will insert into the fluid stream. The holes will be thoroughly sealed to prevent any fluid leakage but will retain the ability to be removed if necessary.

Analysis Results

Tank

The tank had no necessary analysis, as a detailed engineering study on the tank design was performed by a licensed civil engineer for CPC.

Height Adjustment System

There should be no significant loading on the system and all fasteners used should be under little or no shear. The bushing clearance sizing is based on a loose sliding fit and does not require significant strength or slipperiness as there is no rotational speed.

Water System

Based on certain constraints for the piping system, such as the overall length of pipe, the necessary fittings, valves, and characteristic properties of new pipe, the calculations for head losses at different pipe diameters were performed using Engineering Equation Solver (EES). The calculations for the major, minor, and total head losses are shown below in **Error! Not a valid bookmark self-reference.**Table 3.

Table 3: Head losses in the water piping system.

Pipe Diameter (in)	Major Head Loss (ft)	Minor Head Loss (ft)	Total Head Loss (ft)
1	1001	109.7	1114
1.5	115.6	21.66	140.6
2	25.23	6.854	35.36
2.5	7.788	2.807	13.88
3	2.994	1.354	7.629
3.5	1.339	0.7307	5.351
4	0.6691	0.4283	4.378
4.5	0.3638	0.2674	3.912
5	0.2114	0.1755	3.668
5.5	0.1296	0.1198	3.53

To calculate the $NPSH_A$, Equation 11 was used with a pipe diameter of 3” including applicable fitting and valve losses, resulting in a value of approximately 20.2 feet which is well above necessary design parameters.

Air System

The chamber analysis was performed using hand calculations and the SolidWorks FlowSimulation . In the calculations, steady, inviscid, and incompressible flow was assumed in order to apply Bernoulli’s

equation, shown in Equation 14. Equation 15 was also used to find the flow rate going into each individual 1-1/4"tube.

Equation 14: Simplified Bernoulli's equation.

$$p_1 + \frac{1}{2}\rho {V_1}^2 + \gamma z_1 = p_2 + \frac{1}{2}\rho {V_2}^2 + \gamma z_2$$

Equation 15: Continuity equation.

$$A_1 V_1 = A_2 V_2$$

The analysis shows that the fan and the chamber will be able to provide a flow rate of 6.63 CFM to each pipe. The flow rate is significantly lower than required in the specifications. See Section D in the Appendix for detailed airflow calculations in EES.

The SolidWorks Flow Simulator results shown in **Error! Reference source not found.**Figure 21 confirms that the pressure is evenly distributed throughout the plenum chamber.
Figure 22 shows that the velocity in the chamber is zero. The total pressure of 5.2 lb_f/in^2 delivered by the centrifugal fan was used as the input boundary condition. The simulation results agree with the hand calculations.

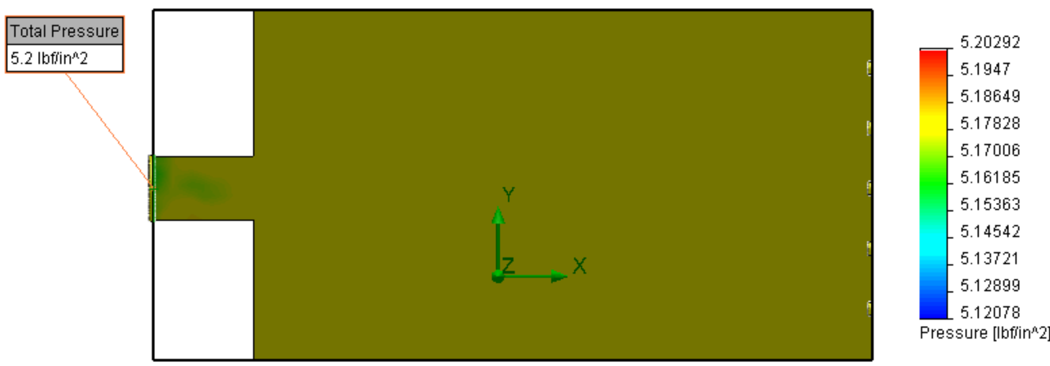

Figure 21: Plenum chamber pressure analysis.

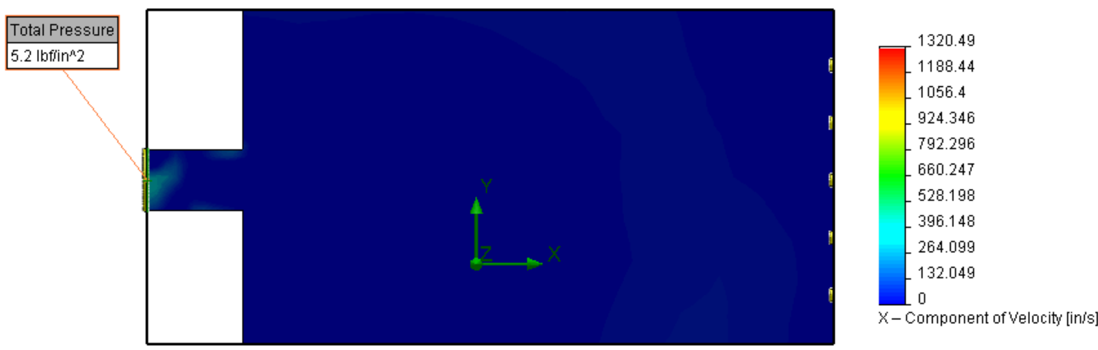

Figure 22: Plenum chamber's velocity Analysis.

There are two different methods to measure the airflow rate. The first method consists of using the fan's tachometer pin that outputs a signal. The tachometer signal is a square waveform output signal that can be used to measure the rotation speed of the fan. The square signal will be displayed in a digital oscilloscope. From the oscilloscope, the period will be obtained, which will be used to calculate the frequency using Equation 16. Using Equation 17 and Equation 18 the fan blade velocity can then be calculated.

Equation 16: frequency (f), and period (P)

$$f = 1/P$$

Equation 17: Angular velocity (ω) in rad/sec

$$\omega = 2\pi f$$

Equation 18: Blade Speed

$$U = r\,\omega$$

The actual fluid velocity is calculated using the vector sum of the relative velocity and the blade velocity. The blade angle will be a key value to perform this calculation. After the velocity is found, the flow rate can be calculated using Equation 20. A spreadsheet applying all these equation will be provided to ease the measuring process.

Equation 19: Fluid Velocity

$$V = W + U$$

Equation 20: Flow rate equation

$$Q = A\,V$$

The second method consists of using a non-contact laser tachometer. A piece of reflective tape is put on the fan blade and the revolutions per meter can be digitally displayed. After this the process to find the flow rate is basically the same as described for method one.

Heat Exchanger

The tank water will enter the heat exchanger at approximately 70° F and should leave the heat exchanger as close to 180°F as possible with a flow rate of 115 GPM. The hot side will consist of the boiler's water-glycol mixture entering at 185°F with a flow rate of 10 GPM. Following basic heat transfer calculations (see Equations 12 & 13) the load was determined to be at least 500 MBtu.

Cost Analysis

Tank

The costs of the tank and control pond are fixed amounts, with no way to reduce costs other than using a different vendor. Hardware selection could have been slightly varied to reduce cost, such as using nails rather than screws and reducing the number of reinforcing brackets, but it would risk undermining the structural integrity or increasing the difficulty in disassembly. The full cost breakdown is shown in the Appendix E.

Height Adjustment System

There were multiple ways to design the height adjustment system, some of which may have been cheaper. To design a system identical to CPC's would have cost approximately $21.53 per bracket based on prices from McMaster-Carr, in comparison to the $25.43 that the aluminum system cost. The cost difference is not significant enough to warrant using an inferior design. A full cost breakdown for the height adjustment system is shown in Appendix E.

Water System

Costs of the water system are highly variable depending on the size of the pipe used and the material. The ideal pipe diameter for the system is between 2 and 3 inches, with the cost of materials increasing with the change in size. While costs could have been minimized by using a pipe diameter of 2 inches, it was considered counterproductive to use a pipe diameter that would require adaptation to fit the pump. The initial cost of the pump is significant, but can be offset based on the reduction in power usage. While PVC is not the ideal material for a long term installation that pumps hot water, it was selected based on cost analysis. Ideally bronze, iron, or another metal would have been a better choice for use in the water piping system, but the costs were too high for the short time span the project expects. To control the water flow in the system, PVC ball valves are used due to their low cost and easy manipulation. Brass valves would have been ideal but are more than three times the cost of a similar PVC valve.

Insulation for the piping system is also a highly variable cost. For indoor usage most closed cell foams are adequate and require no shielding against the elements, but for outdoor usage some foam requires either PVC jackets or vinyl painting. An analysis of several different foam materials indicated that using foam that allows painting is more cost effective than using foam that requires a jacket. To monitor the flow rate of the water in the piping system, several different methods were entertained, but the majority of flow meters are very expensive. A system that requires only a 5/8" hole to be drilled into any pipe and is then strapped to the pipe was found to be the least expensive while maintaining a desirable accuracy and flow capacity.

Air System

Two different methods to supply air to the floating tubes were considered. The second option was selected because it is within our budget. The total price for the second option is one third of the total price of the first option as shown in Table 4. Cost was the main driver for choosing the method to deliver air into the floating tubes.

Table 4: Cost breakdown for the air system instrumentation.

Air System Instrumentation				
Option 1				
Part	**Quantity**	**Units**	**Price**	**Total**
FanTech Fans	15	each	$135.20	$2,028.00
Speed Controller	15	each	$ 18.50	$ 277.50
1-1/4" Tubing (50 ft long)	4	each	$ 99.00	$ 396.00
3/4" Barbed Tees	3	pack of 10	$ 10.62	$ 31.86
1-1/4" Barbed Tees	6	pack of 5	$ 8.69	$ 52.14
3/4" Barbed Elbow	4	pack of 10	$ 7.75	$ 31.00
1-1/4" Barbed Elbow	1	pack of 5	$ 12.39	$ 12.39
Hose clamps	15	per pack of 10	$ 13.30	$ 199.50
			Total	$3,028.39
Option 2				
Part	**Quantity**	**Units**	**Price**	**Total**
Centrifugal Blower	1	each	Free	Free
Computer cooling Fans	15	each	$ 4.99	$ 74.85
1-1/4" Ball Valves (Threaded)	15	each	$ 6.70	$ 100.50
/4" Clear PVC Tubing (10 ft long	2	each	$ 18.82	$ 37.64
1/4" Clear PVC Tubing (50 ft lon	4	each	$ 99.00	$ 396.00
1-1/4" Insert Male Adapter	45	each	$ 1.54	$ 69.30
3/4" Barbed Tees	3	pack of 10	$ 10.62	$ 31.86
1-1/4" Barbed Tees	6	pack of 5	$ 8.69	$ 52.14
3/4" Barbed Elbow	4	pack of 10	$ 7.75	$ 31.00
1-1/4" Barbed Elbow	1	pack of 5	$ 12.39	$ 12.39
Hose clamps	15	per pack of 10	$ 13.30	$ 199.50
Plenum Chamber	1	each	Free	free
			Total	$1,005.18

Heat Exchanger

The heat exchanger must be within budget and cost less than $3000. From McMaster-Carr, the 35185K58 stainless steel heat exchanger for $2436.75 was selected.

Temperature System

The driving selection criterion for the temperature system was the overall cost. Standard data logging systems capable of reading 150 to 200 channels cost upwards of $6000, while single thermocouple probes cost nearly $10 each, approaching a total system cost of nearly $7500 for only the tank mesh, without accounting for thermocouple wire and data logging software. The new system designed by Argent Systems is extremely cost effective, costing $6 per sensor and only $.25 per foot of cable. Each cable is terminated with a single controller board which costs $55. This results in a total cost for the tank mesh of approximately $1,863 based on using nine controller boards.

Material, Geometry, and Component Selection

Tank

The designs for the tank and control pond require standard sized wood beams and panels to construct, without requiring a particular type of wood. Easily available Douglas fir was used due to the low cost and ease of use. Pressure treated lumber has better weather resistant properties, but with proper coating there should be no difference in longevity. The geometry of the tank is driven by the commercial application with a substantial scaling factor. Hay bales were used as an insulation material due to the low cost per unit surface area when compared with commercial batting, as well as the relative ease to deploy it. Fiberglass batting was used on the end walls due to the spacing being ideal for

commercially available insulation and to save space. To measure the required amount of water to refill the main tank and the control pond a flow totalizer is used. The selection of an adequate totalizer was based on the units of measurement preferred (liters), and the ease to attach it to a standard garden hose. Additionally, the ability to reset the total flow was required.

Height Adjustment System

The driving factor behind the material choice for the height adjustment system is corrosion resistance. Some parts will be in contact with water at all times or exposed to the elements. Steel would have been an excellent material for use in the height adjustment system, but would have required possible costly coatings and constant attention to ensure corrosion was kept under control. Using plastic would have avoided any chance of rusting, but would sacrifice strength and workability. Aluminum has excellent corrosion resistance without any sort of coating as long as it is not in contact with any other metals. For that reason all components used in the height adjustment system are made from aluminum, including the nuts, bolts, and washers.

Water System

As described above, ideally the material used for the piping system would have been metal, but the extravagant cost for using large diameter metal piping prevented its usage. Most forms of PVC have a recommended operating temperature of approximately 140° F, while a similar product, CPVC has an operating temperature of approximately 200°F. The general difficulty in procuring CPVC (Chlorinated PVC) led to the use of normal PVC for the piping system, but several tests were run with PVC in boiling temperature water at pressure to ensure that it would withstand the operating conditions we expect to see. Most other components used in the water system were chosen based on cost to keep initial costs at a minimum.

Air System

The PVC pipe was chosen because the rated pressure is suitable for our required maximum pressure and the operating temperature is between 33 and 175 degrees Fahrenheit, which is within our temperature constrains. The material will also withstand exposure to the elements. The ball valves were selected because of the inexpensive price relative to the price of other valves such as needle valves. Also the accuracy and precision of the flow control is relatively low for our application so PVC ball valves will fulfill the air flow control requirement.

Due to the budget constraints, the plenum chamber and the centrifugal fan selected are being used because they were available from the aerospace department at no cost. Both components will be tested and if they do not satisfy the project requirements, both will be replaced.

Heat Exchanger

Once the load was determined, the next step was choosing a type of heat exchanger. Due to limited space behind Bonderson, it is important that the heat exchanger not be extremely large. Also, the heat exchanger will be kept outdoors for a couple years so it must be able to withstand abuse from harsh weather and other outdoor hazards. Most importantly though, the heat exchanger must be within budget and cost less than $3000. McMaster-Carr provides reasonably priced shell-and-tube heat exchangers with baffled tubes that make four passes in three different options of materials: steel, brass, and stainless steel. Since no highly corrosive liquids will be used in this application, a steel heat exchanger seemed adequate.
The critical determining factor in selecting which heat exchanger to use was our cold side flow rate. Although a smaller heat exchanger could achieve the desired cooling capacity, it would not be capable of accommodating the design flow rates. Because of this, a larger heat exchanger was chosen. From

McMaster-Carr, the 35185K58 stainless steel heat exchanger for $2436.75 was selected. It has a surface area of 34.0 square feet and a cooling capacity of 1.6MBtu/hr. Most importantly it has a flow capacity of 126 GPM with a shell pipe diameter of 2 inches and a tube pipe diameter of 1½ inches. The shell-and-tube heat exchanger has a head diameter of 7¾ inches and an overall length of 41-1/8 inches. The overall length of the chosen shell-and-tube heat exchanger is just less than 3½ feet making it easily able to fit with the rest of the project equipment behind Bonderson. Even though stainless steel is not necessary for corrosion prevention purposes, it was chosen because it can handle the more extreme working conditions of this project.

Temperature System

The geometry of the temperature mesh simply follows the shape of the tank. A more dense mesh would have been preferable for creating a detailed temperature gradient, but the more sensors the higher the cost. The most effective mesh was determined to be layers of 20 sensors, five sensors spaced 240 cm apart on the long side, and four sensors spaced between 60 and 80 cm apart on the short sides. Nine sets of these layers are used to generate a full tank mesh of 180 sensors.

Diagrams

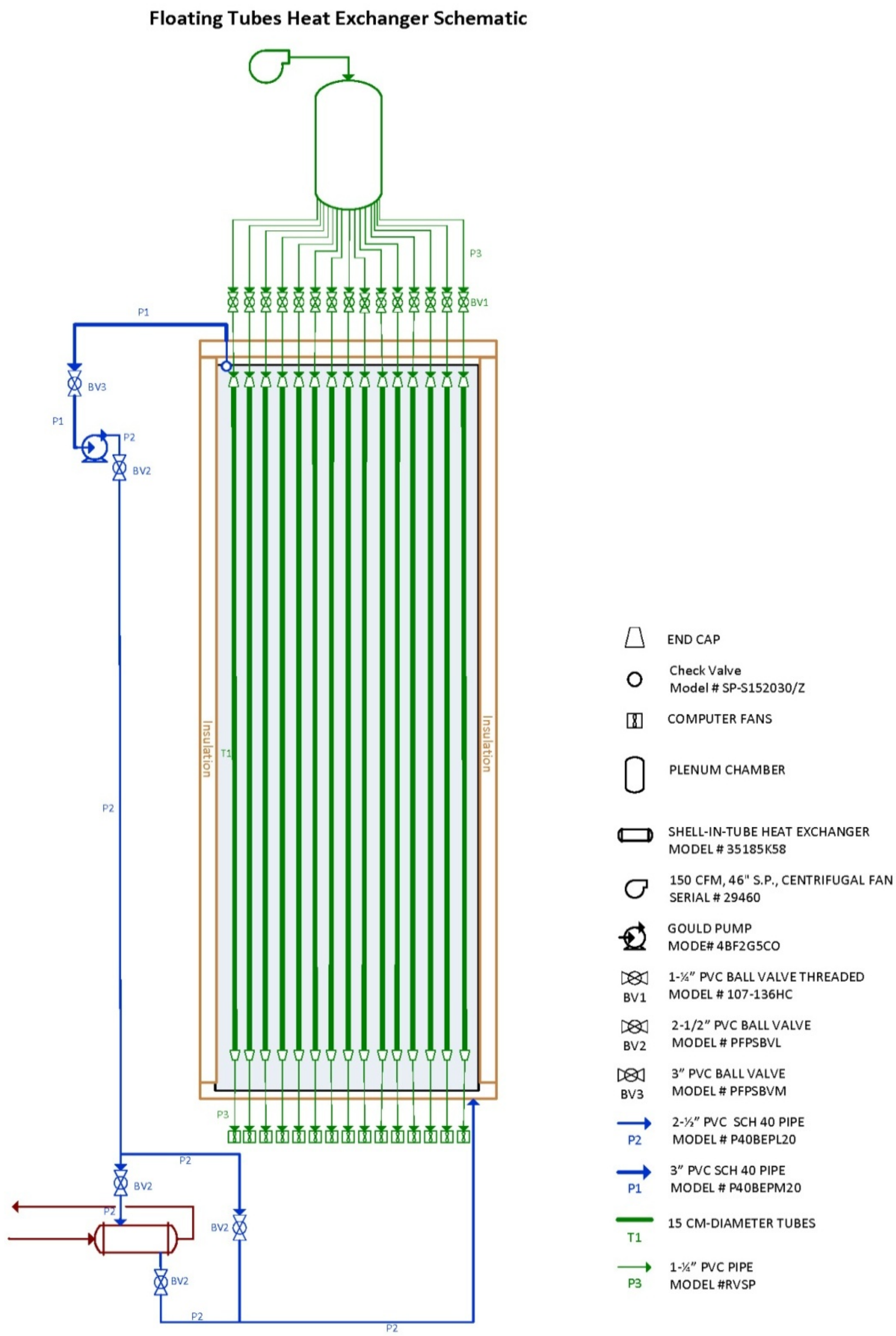

Figure 23: Schematic for the air and water systems.

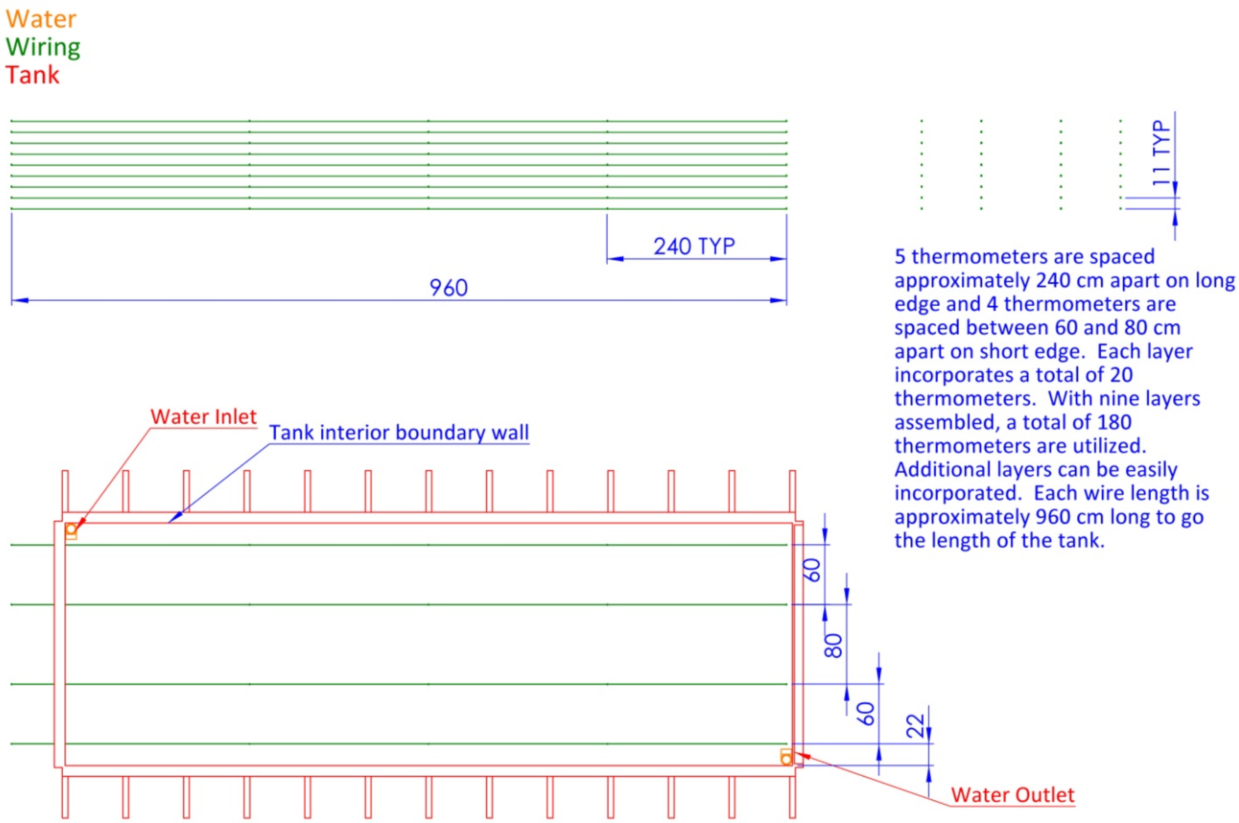

Figure 24: Thermometer mesh for inside the tank.

Safety Considerations

Tank

The biggest concern with the tank is the overall structural integrity. If the tank suffers a catastrophic failure, thousands of gallons of water will be released, potentially destroying hundreds of thousands of dollars worth of mechanical equipment inside the Mustang '60 Machine Shop. The tank was overdesigned heavily by CPC in order to prevent a failure of that magnitude, and will be monitored closely in order to identify possible failure points as the load increases.

Height Adjustment System

There are no safety considerations in the height adjustment system as it is not a load bearing component and is under no stress.

Water System

The most significant safety consideration is the fact that the PVC is outside its standard operating range and must be inspected regularly to ensure no breakdown of the material or leakage. If a pipe bursts or becomes damaged it can be dangerous to those in the immediate vicinity as well as potentially releasing large amounts of water before it can be shut off. The pump itself is not very dangerous as it is close coupled and no moving parts are exposed.

Air System

The air in the exit of the tubes will be hot so safety measures will be taken to prevent any person from getting hurt. The space at the exit of the floating tubes will be blocked, which will prevent people from getting burned. Also warning signs will be put in place to warn people of possible burns.

The centrifugal fan inlet has to be secure to prevent debris from getting into the fan blades.

Heat Exchanger

Other factors taken into consideration were working temperatures, safety, maintenance and repair. The selected stainless steel heat exchanger has a rated working temperature of 450° F which is 150° F greater than that of the steel and brass heat exchangers. In this application, the maximum operating temperature will be 185° F and therefore significantly below the rated working temperature. The main safety precaution with the heat exchanger was to choose a model that could handle high flow rates without bursting. For this reason, a stainless steel heat exchanger with capabilities beyond our design requirements was chosen.

Maintenance and Repair Considerations

Tank

The tank was designed for easy movement and maintenance. All parts are off the shelf and easily available if replacement is necessary. Future additions can be made easily through removal of six bolts and several screws. Cleaning the tank can be performed easily due to the vinyl paint and can be done using a pressure washer or other similar method. Wood replacement due to rot should be unnecessary over the lifetime of the project.

Height Adjustment System

The components of the height adjustment system are easily manufactured and replaced if necessary in the future, but should require no maintenance or repair. Disassembly of the assembly is simple and straightforward and can be completed rapidly if necessary.

Water System

All components used in the water system are easily sourced from local vendors, negating any possible downtime if replacement is required. PVC breaks down easily when exposed to ultra violet light, but with insulation covering all visible surfaces there should be no material breakdown. The pump should not be used frequently enough to warrant replacement of any wear items, but if necessary repair or replacement can be provided by the pump manufacturer. Valving has been built into the system so as to facilitate removal of any major components, requiring little work for any maintenance.

Air System

If any of the air flow system components are damaged, they can be easily replaced. These components are available in local stores such as Home Depot or Farm Supply Company.

Heat Exchanger

Another benefit of this heat exchanger is that the ends can be taken off to allow for cleaning of the tubes. This is important because fouling of the tubes can dramatically decrease the efficiency of the heat exchanger.

Temperature System

The system relies heavily on communication with the sensors, and a breakage in any wire would significantly affect the system. By using a wire bus with several wires, a second wire can be used as a failsafe in case of damage to the primary wire. If any sensors fail, it proves to be very easy to replace the individual sensor with a new one. Moisture control is important to prevent any short-circuiting of the system as well. Each sensor is dipped in a rubberized coating to prevent moisture from penetrating, and the USB controllers will be sealed in a plastic container to prevent any moisture from reaching the circuit board. All parts are off the shelf and easily purchased in case replacement is necessary.

V. Product Realization

Construction

An accelerated time schedule for starting the project resulted in construction beginning in the second quarter with expectations of finishing the underlying tank structure and being prepared to begin constructing the water, air, and temperature systems during the summer break. The entire tank was finished during the last week of May 2011 and was moved and prepared for installation of the insulation and liner during the first week of June 2011. The control pond was finished mid-May 2011 and was prepared for insulation and installation of the liner in early June 2011. The liner and insulation for both the main tank and the control pond were installed at the beginning of June. Assembly of the height adjustment mechanism was completed by the first week of July in preparation for installing the tube system. The tube assembly was assembled and put into place by the second week of July with the corresponding air system assembled and complete by the first week of August. From August through the first week of September the assembly of the water distribution system took place, but was not completed. The tank went through preliminary leak testing and tube commissioning during the second week of August. The system is approximately 80% finished and has been handed off to another project team for completion.

Tank

Construction of the tank began with cutting of the plywood triangles that form the buttresses for the cross sections. Eight triangles can be made from a 4'x8' plywood sheet and were cut using a circular saw and straight edge. The long beams that make up the base of the tank were cut from 12 foot 2"x4" beams using a miter saw and a tape measure accurate to 1/16". Upright beams for the cross sections were cut from 8 foot 2"x4" beams using a miter saw. Beams and triangles were then joined using 1-1/4" screws at the appropriate spacing to prevent splitting. A 1.5"x4" cut was then made in the triangle support structure to allow for the horizontal 2"x4" bracing beam. Five cross sections are required for each eight foot section piece and were completed and painted prior to assembly of the eight foot section. All exposed surfaces were painted using oil or latex based primer in two or more coats and then painted with several coats of a latex based exterior paint. Five cross sections were oriented and spaced approximately 24" apart and the horizontal beams attached to fix them in place. Prior to attaching upper horizontal beams the surface was cut flush using a jigsaw. Plywood was attached to the completed section walls to retain the shape. Each section was completed but left un-floored until all sections were completed and fit. Once all sections were completed and fitted together, floor panels were trimmed and installed to fit. End walls were built separately and attached after all sections were joined together.

Hay bales were used to insulate the entire exterior of the tank after being cut using an electric chain saw. The bales were left slightly oversized to allow for a tight fit between each triangular cross section. To reduce convection between the concrete slab and the bottom of the tank, loose straw was also packed underneath the tank. The straw should prevent the movement of air, reducing convection due to air buoyancy. Hay was also used on the ends of the tank rather than fiberglass batting as originally intended. Following the installation of the hay, the pond liner was installed as a single piece. The liner was formed to the tank and bunched in the corners to try to ensure proper installation. After installation was complete, a specialized glue gun was used to seal any visible punctures in the liner and the edges of the liner were stapled to the outside of the tank.

The control pond was assembled in the same fashion, building the cross sections separately and then joining them together using horizontal beams. The walls and the floor were installed prior to the end walls being affixed. The entire assembly was painted together. Insulation was done in the same fashion as the main tank and the liner was installed in the same way.

Figure 25: Preparing to paint the end walls.

Figure 26: Preparing to paint the end walls.

Figure 27: Preparing to paint the end walls

Figure 28: George painting the cross sections.

Figure 29: Christina painting a cross section.

Figure 30: Leonel painting a cross section.


Figure 31: Painting cross sections.


Figure 32: Painting cross sections.


Figure 33: Painting cross sections.


Figure 34: Cross sections arranged for painting.


Figure 35: Adding cross sections.


Figure 36: Lining up eight foot sections.

Figure 37: Attaching new cross sections.

Figure 38: Preparing to join eight foot sections together.

Figure 39: Gap between sections prior to bolting.

Figure 40: Sections bolted together

Figure 41: Detail view of bolt.

Figure 42: Aligning floor panels.

Figure 43: Modifications to end walls.

Figure 44: Detail view of end wall modifications.

Figure 45: Completed and unpainted control pond.

Figure 46: Detail of control pond end wall bracing.

Figure 47: Gap left for fitment.

Figure 48: Corresponding edge for fitment.

Figure 49: End wall fit with cross section.

Figure 50: View of end wall fitment with cross section.

Figure 51: Fitment of end wall at base.

Figure 52: Dry fit attachment of end wall to cross section.

Figure 53: Cross section for control pond.

Figure 54: Interior of control pond.

Height Adjustment Assembly

In order to help anchor the tube system in place and ensure correct placement within the overall tank, a floating system is utilized. In order to construct the system it was manufactured as two separate components. The first component is the rectangular PVC frame that resides within the tank inner perimeter. The PVC lengths were cut using a miter saw for accurate vertical cuts and then assembled with the reducing tees using PVC cement within the tank. Final measurements were taken prior to cutting the PVC in order to modify overall dimensions based on the site. The reducing tees were aligned to 90 degrees by placing a three foot length of ½” PVC into the reduced socket and aligning it using a

level. The end lengths were cemented last in order to ensure the entire system was on the horizontal plane.

The second component consists of the aluminum brackets which were fabricated from 1"x1/16" aluminum box tube, 1"x1"x1/8" aluminum angle, and ¼" aluminum machine screws and nuts. The box tube was cut to length using a metal band saw and then drilled to accept the nylon bushings. Slots in the box tube were milled using a CNC end mill and a ¼" bit. All edges had burrs removed using a metal file and the counter bored holes were filed for tight fitment with the bushings. The angle aluminum was drilled using a drill press and had burrs removed using a sharp edged tool. The nylon bushings were pressed into the aluminum by hand and then lightly filed in order to adjust fitment with the aluminum rods. The aluminum rods were cut into 36" lengths using a band saw and then adhered to the PVC caps using JB-Weld epoxy. The entire system was assembled using aluminum machine screws.

Figure 55: PVC frame being assembled.

Figure 56: PVC frame laid out in tank.

Figure 57: Box tube drilled and counter bored.

Figure 58: Nylon bushings in the process of being installed.

Figure 59: Slots cut and cleaned in box tube.

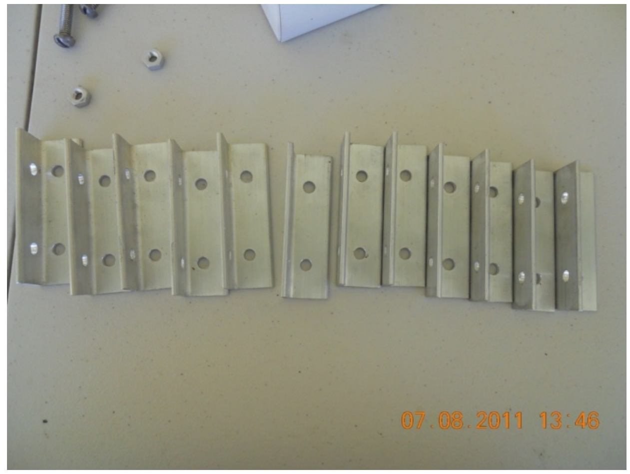

Figure 60: Angle brackets cut to length and drilled.

Figure 61: Angled brackets attached to arm.

Figure 62: PVC caps epoxied to end of aluminum rods.

Figure 63: Bulkheads drilled and ready for installation.

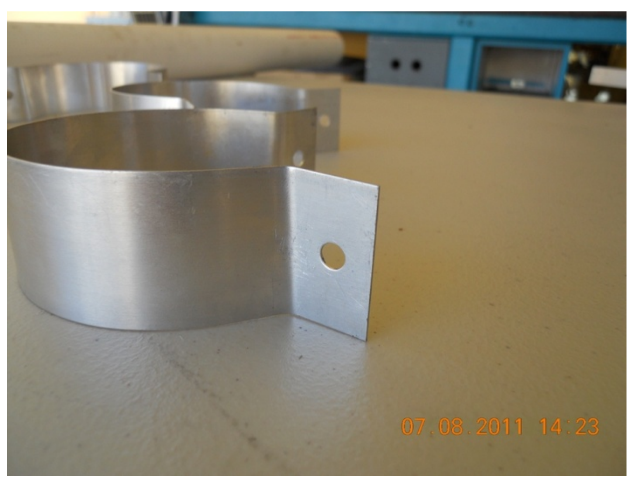

Figure 64: Bulkhead brackets bent and drilled for installation.

Water System

Construction of the water system began in parallel with the height adjustment system but was stalled due to not having possession of the pump and heating system. The PVC pipes were cut using a compound miter saw and joined together using PVC primer and cement after removing burrs with a file. The system was started at the inlet and outlet with elbows being aligned using a flat surface and an engineering square to ensure perpendicular surfaces. Assembly of the system progressed in order of components. Reducing tees were used in order to provide access for temperature and flow monitoring as well as to prime the system. Valves will be installed to isolate the pump and heating system but will not be assembled until the major equipment is acquired.

Figure 65: Check valve installed on the inlet water pipe.

Air System

Construction of the air system was performed after completion of the height adjustment system and preliminary placement of the end caps. Holes were bored through the top of the air plenum chamber lid using an electric drill and cleaned using a wood file. Male hose barb adaptors were installed onto the air plenum chamber using rubber washers and plastic pipe nuts on the underside of the chamber lid while silicon was used to seal the top mating surface to ensure an airtight connection. The edge of the plenum chamber where the lid interfaces with the chamber was resealed using 5/8" foam weather stripping and new clasps were installed to lock the lid to the chamber.

Figure 66: Installing rubber washers onto air plenum chamber.

Figure 67: Installing hose barb adaptors into air plenum chamber.

1-1/4" ID clear vinyl tubing is used to distribute the air to the end caps from the plenum chamber with cam-lock quick disconnect fittings in the center for ease of assembly. PVC ball valves are installed immediately after the quick disconnect fittings, allowing for flow control prior to the final tube runs. Tubing was routed to try to ensure nearly equal length runs to each end cap while allowing for flexibility with the water height within the tank. All hoses were clamped using stainless steel worm drive hose clamps. Hoses are routed through a wooden bulkhead to help strengthen and organize the hose paths.

Figure 68: 1.25" Ball valve with hose adaptors installed

Figure 69: Initial hose runs from plenum chamber to quick disconnects.

Figure 70: Female cam-lock couplings installed on plenum hoses.

Figure 71: Valves and cam-locks installed in bulkhead

Figure 72: All 15 distribution hoses installed in plenum chamber.

Figure 73: All hose runs completed and ready to be attached.

On the exit side of the system the hose barbs have been capped off to prevent water from entering the inner tubes and will eventually be piped into an exhaust box to allow the air to escape to atmosphere.

To provide air and water to inflate and ballast the tubes to operating conditions, distribution systems were designed and installed. To provide air to the outer tubes a distribution system was built consisting of PVC fittings and 3/4” vinyl hose. Attachment to shop available pressurized air was facilitated using a brass quick disconnect air fitting that also seals against backflow. Brass thread adaptors and a hose barb adaptor were used to attach it to the distribution system. All tubes are simultaneously pressurized using an adapted air gun until reaching the desired internal pressure. Due to the nature of air the tubes will self regulate in order to equalize the pressure in each tube.

Figure 74: Connector to adapt to common air fitting.

Figure 75: Air distribution system partially assembled.

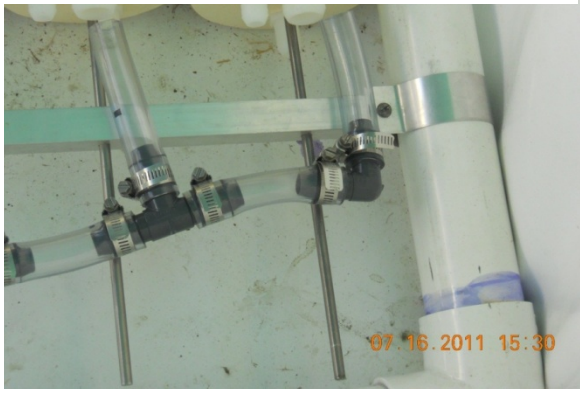

Figure 76: Air distribution system partially assembled showing end point.

Figure 77: Completed and attached air distribution system.

To provide water to the tubes, individual fill lines were built from 3/4” vinyl hose, a 3/4” PVC ball valve, and a quick disconnect adaptor to easily fill using a standard garden hose. Tubes are filled by attaching a garden hose to an individual line, opening the corresponding valve, and allowing water to fill until the tube is adequately ballasted. At that point the valve is closed and the garden hose disconnected. Each tube is individually filled, but water is allowed to travel between tubes through the air distribution system if a particular tube is overfilled or over pressurized.

Figure 78: 3/4" ball valves with hose barbs installed.

Figure 79: 3/4" water fill ball valve with brass garden hose adaptor installed.

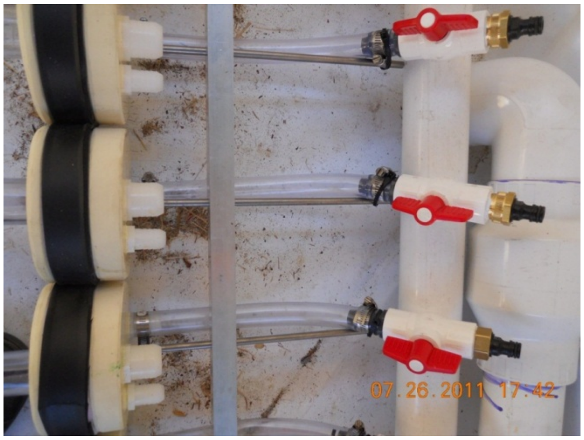

Figure 80: Completed fill lines.

Figure 81: Detail of fill lines, quick disconnect adaptor

Design Changes

During the construction of the project many changes were made based on availability of materials, design modifications, and issues that arose during the building process. In addition to specific design changes, the scope of the project was also modified due to financial and time constraints. Minor modifications were made to the tank and water system while major changes were made to the air system and heating apparatus. No instrumentation of the tank was performed and the components selected for instrumentation have also been changed. Test verification on the majority of the systems involved was not possible, but protocol for testing is still the same. Detailed information on design changes are provided below.

Tank

The overall design of the tank was not changed during construction, but several modifications were required to correct errors made during the process. Two of the cross sections were cut in the center and extended by approximately an inch to two inches in order to make the lengths equal to other cross sections. This was performed by attaching two additional 2”x4” beams and sandwiching the original 2”x4” between them. Twelve screws were used to attach each additional beam to the center beam. Figure 82 shows the extent of the required repair.

Figure 82: Detail of repaired cross sections.

In addition to the repair, it was also decided that using strictly hay bales, rather than a combination of hay bales and fiberglass batting, would be more uniform and therefore easier for eventual modeling.

Water System

The water system has had a variety of different design changes, varying from minor piping changes to a completely different pump. The overall piping schematic has not changed, but the heat exchanger has been replaced by a gas fired hot water boiler. The existing bypass loop will still be used as designed. Additions to the piping not reflected in the schematic are as follows:

1. Addition of a fill port on the suction pipe at the highest point. Fill port is assembled from a 3/4" reducing tee, 3/4" threaded nipple, 3/4" ball valve, and a garden hose adaptor and quick disconnect. This assembly allows for fast priming of the water system prior to startup.
2. Addition of 1/2" reducing tees in four locations in order to allow for temperature measurement:
    a. Suction entrance
    b. Discharge exit
    c. Boiler entrance
    d. Boiler exit
3. The system was not drilled for installation of an analog rotameter. It was decided during construction that a digital flowmeter that would easily interface with a computer was required for the extensive data collection expected during the experiment. Different choices for a flowmeter will be explored and chosen by the following project group.
4. Installation of a pressure release valve after the pump discharge to prevent pipe burst is recommended but has not been installed or purchased.
5. A pressure gauge has been prepared for installation after the pump discharge in order to monitor the pressure during operation to ensure that pipe burst does not occur.

In addition to changes in the piping system, the pump has also gone through several possible design changes. Funding concerns as well as the potential availability of several viable centrifugal pumps from the University of California at Santa Barbara (UCSB) stalled the purchasing of the specified Gould pump. Several possible pumps were explored at UCSB but approval to borrow those pumps including required insurance and other issues have prevented their acquisition. The project intends to return to the Gould pump originally specified and it will be installed by the following senior project team.

Air System

Several changes were made to the air system during construction. In the originally planned design, the air taps for the plenum chamber were set to be at the far end, spaced evenly apart. Due to the location of the plenum chamber and to minimize the length of hose runs, the taps were instead installed on the top of the chamber. Relocating the taps to this location allows for the ability to run even lengths of hose to each end cap and reduces the possibility of hose kinking. Figure 83 shows the location of the hose taps with half of them installed.

Figure 83: Half of the plenum chamber taps installed in the top of the chamber.

It was also decided that for ease of transportation and maintenance that quick disconnect couplings were required on the air inlet hoses. Nylon cam-lock connectors with stainless steel latches were decided to be used for this, as they have high durability and are relatively inexpensive while retaining a good seal. Other changes in the air system design were the additions of quick disconnect garden hose adaptors on the stagnant water fill lines, the addition of a quick disconnect compressed air coupler for pressurizing the tubes, and the eventual installation of an exhaust box to direct the exhausted hot air upwards and away from the surrounding area. Design of the exhaust box will be completed by the following project team.

For instrumentation and measuring of air flow through the system it was found that computer fans would not be adequate. Additional ideas were generated and the option found to be the most feasible and inexpensive is measuring the air flow through a single tube using a pitot-static tube and a pressure transducer to produce a digital signal capable of capture. Each individual tube will be tested prior to experimentation to equalize the flow rates through the system and then experimental measurements will be taken on only a single representative tube. Additionally, temperatures will be measured at the entrances and exits of the tubes to help verify the thermal model.

Heating System

The original design for the heating system called for utilizing the Bonderson boiler in a closed heating loop with a heat exchanger, requiring approval from Campus Facilities as well as forcing the construction to go through campus union workers. Original proposals were submitted in early June, but multiple design changes and a long length of time for approval delayed a final estimate until late October. We estimated between $6,000 and $12,000 for the required parts and labor to plumb the system, but the final estimate was $46,000, well outside our budget for heating the tank. Based on this setback it was decided to go back to the original option of using a gas fired boiler and a locally sourced propane tank. Using project purchased equipment and by utilizing the assistance of campus shop volunteers we can expedite the work and avoid campus utilities.

Design considerations for sizing a boiler to heat the tank are shown below:

1. Ability to heat the entirety of the tank in 8 hours
2. Ability to heat the tank to 180°F
3. Dual fuel or propane fired
4. Between $8,000-$12,000 in cost for boiler and accessories

Based on these expectations for a boiler, we were able to perform calculations to generate an estimation for required heat output. Using a simple First Law analysis shown in Equation 21 and the generalized assumption that the temperature will change an equal amount each cycle of water, as well as there being no losses in the tank, we can find a heat input value.

Equation 21: First law analysis to calculate the required heat input to raise the water temperature.

$$q = \dot{m}c_p\left(T_f - T_i\right)$$

Using design values of 115gpm and a total temperature change of 116°F (60°F heated to 176°F) over eight hours, the temperature change in each pass is approximately 14.5°F. Calculating a required heat input to achieve that change in temperature results in a value of 836MBtu. As mentioned above, this required value is only an estimate, as the tank will have possibly significant losses and boiler efficiency and input ratings are significantly affected based on the inlet water temperature. For sizing and quote purposes this value is appropriate.

In order to supply fuel to the boiler a large liquid propane tank is required. Based on 80% heating efficiency in the boiler, there is a required heat input of approximately 1,000MBtu. Over an eight hour heating cycle 8,000,000 Btu will be consumed. A gallon of propane provides approximately 91,600 Btu, therefore requiring approximately 87 gallons of propane for a single cycle. Ideally the tank will have the capacity to run at least two cycles with extra capacity as needed. Based on this information it was decided that a 250 gallon tank would be the ideal size, allowing for flexibility in running the experiment.

Procurement of the boiler and propane tank, as well as the hookup of the systems will be performed by the following project team. Price quotes have been requested for boiler systems and propane tank rentals and estimates appear to be around $11,000 for a boiler system and $80-$100 for tank rental and $2.20-3.20 per gallon of LPG.

Instrumentation

Instrumentation for the system consists of the temperature sensors throughout the tank and piping system, as well as flow measurement for the water and air. Purchase and installation of sensors and measuring devices has not occurred due to more investigation into alternative systems. Design for the temperature mesh within the tank has changed slightly but retains the original 180 sensors. There are now 5 layers of sensors, each layer containing 36 sensors in a 9x4 array arranged length by width, respectively. Four temperature sensors are utilized within the water delivery system, and temperature sensors will also be included at air inlet and exit as well as ambient air. Flow measurement for the water system has shifted from an analog rotameter to a digital paddle wheel based flow meter that outputs a digital signal that will be interpreted by an off-the-shelf data logger. Air flow measurement will utilize a pressure measuring device, such as a Pitot - static tube or orifice plate, and a transducer to produce a voltage from the pressure difference. Selection of these components and eventual installation will be completed by the following project group.

Future Recommendations

There are many things we have learned through the duration of this project, and many places that would benefit from future iterations. In addition to items that can use refinement, there are also many improvements that can be made to advance the research using the tank. Current plans for the project include adding the ability to cultivate algae, installing a filtration system in line with the water system, designing and building a cover for the tank and control pond, and completing a full CFD/CHT simulation to model the fluid flow and heat transfer throughout the system. Changes that would benefit the current iteration of the tank are listed below:

1. More research into corrosion resistant metal materials and the interaction between metals. The implemented design for all submerged metal components required aluminum, as it has good anti-corrosion properties when not in contact with dissimilar metals. Unfortunately the axles on the CPC provided end caps are a stainless steel and caused a galvanic reaction with the aluminum bulkhead including the aluminum fasteners and brackets. This reaction has caused a buildup of material on the bulkhead that is slowly eating away the metal and has also seized the bolts used on the brackets. All of these components will now need replacement or repair to prolong their life. This could have been avoided by investigating the materials that CPC uses for construction and working around them, or coating all submerged metals with a durable finish.
2. A better timeline for project critical milestones. There were a number of critical steps in the project that were not well scheduled and would have benefited from early attention. The biggest roadblock to the project was the lack of approval on acquiring major equipment and in

achieving an estimate from facilities. These two specific tasks set us back several months, stalling any additional work from being completed in fall quarter. These issues could have been easily avoided by specifying equipment early and providing detailed quotes and a clear reasoning behind the choices. Conversations could have been started with facilities prior to the project to determine the feasibility of using campus utilities, rather than spending months waiting for an estimate.

3. Replacing the PVC pipe with a stronger and more durable material, such as cast iron or steel that is rated at higher temperatures and pressures and therefore incorporate a higher safety factor. Initial costs for piping the system using metal piping rather than PVC would have increased the cost to at least five times the amount spent on PVC piping, fittings, and valves. Replacing the pipe with aluminum or stainless steel for longevity would cost upwards of 10 times more than currently spent.
4. Better communication between all parties involved in the project. There are four separate groups involved in the project, including the senior project instructor, and communication between all parties is extremely critical to ensure project deadlines are met and that the design and construction are appropriate and complete. Communication breakdowns between different groups caused the project to stall at certain critical points, preventing additional progress from being completed. This could have been easily solved by facilitating additional communication between groups, rather than through intermediaries.
5. Material ordered in advance of construction. Many materials were purchased locally, but in many cases the inventory of these suppliers was not adequate for our needs, setting back construction progress a manner of days or weeks in some cases. Many of these materials could have been ordered from alternative suppliers for a relatively small cost difference and would have been on site immediately.

There are many additional details that would benefit from an additional iteration, but the scope of the project did not allow for a large amount of reworking. The information gained through building this tank was valuable as it is, and will serve as a learning tool for any following projects and for CPC.

VI. Design Verification Plan

This senior project initially intended to complete full instrumentation of the system as well as all testing to ensure reputable measurement during any experimentation. Due to unforeseen delays in procuring instrumentation this was not possible, and a following project team will be responsible for installing sensors in the tank and verifying the results. Below is the verification plan to test all instrumentation used in the system. Instrumentation methods not typically used require specific calibration that must be performed in a laboratory setting under specific conditions to ensure correct readings. The tests for all sensors used to instrument the system are detailed in the following section.

Temperature Sensors

Temperature sensors come pre-calibrated from the factory but must provide reasonable data in accordance with other, calibrated sensors.

- Cool a flask of water to 0°C using an ice bath.
- Insert calibrated thermometer or thermocouple
- Insert digital temperature sensor (with rubberized coating)
- Ensure no sensors are touching the bottom or side of the container
- Apply heat using an electric burner on low
- Monitor and record the temperature every 30 seconds as the water heats up.
- Repeat test three times
- Curve fit data from both sensors and identify reading differences
- Repeat test using a digital sensor on a long length wire to investigate effect of wire resistance

Pressure Measurement

To measure the airflow within the tubes a pressure differential will be measured using a Pitot-static tube or similar device. Prior to measuring the airflow, the Pitot-static tube, pressure transducer, and data logger must be tested to verify accuracy. The transducer and data logger will be verified against a calibrated, handheld, digital pressure readout.

- Record local temperature and pressure
- Position Pitot-static tube within a constant, developed airstream provided by a flow bench or wind tunnel
- Attach Pitot-static tube to both the pressure transducer and handheld readout using a tee or similar connection
- Note any deviation from zero with no airflow on both devices
- Provide varying air speeds/flow rates using the testing apparatus and record all pressure differentials for both instruments
- Repeat test three times at 5 different air speeds
- Plot data from calibrated readout and transducer and note any differences in readings

Water System Flow Meter

The water flow meter comes pre-calibrated from the factory but should be verified against a more accurate flow meter. To calibrate the sensor the following steps are used.

- Record local temperature and pressure
- Attach flow meter to a system capable of varying flow rates in the proper orientation.
- Set the system to provide a specific flow rate, allow it to stabilize for five minutes, ensure no variation in flow rate.

- Record the flow rate using a calibrated flow meter or by timing the filling of a bucket and measuring the mass of the bucket and fluid.
- Record the flow rate using the water system flow meter
- Vary the flow rate five times, recording the values each time.
- Repeat test three times.
- Curve fit data from both sensors and identify reading differences.

VII. Project Management plan

The three main steps in the project were design, build, and test. Goals for the project were to finish each of these tasks in a single quarter – ten weeks, with the summer session and final quarter being allowed for additional building and testing. The majority of the project was completed on schedule, with all construction being completed by the end of the summer break. As noted above, the scope of the project was changed and will not allow for verification testing until the system is complete. The final approved timeline is provided in the Appendix.

VIII. Conclusions and Recommendations

Any senior project is a huge undertaking, requiring significant resources and extraordinary devotion. We found that our particular project was massive, touching all aspects of the mechanical engineering field. The amount we have learned in a project of this scope exemplifies the very reason why Cal Poly exists. We have discovered firsthand the difficulty in working with a diverse team with multiple managers, and have learned how to use that diversity to positively affect the outcome of the project. We have explored our own strengths as team members, while also embracing our weaknesses and working towards bettering ourselves professionally. We have found that sacrifices and compromises are required in any project in order to reach completion, and they must be weighed carefully to determine their criticality.

From the original project we have reduced our scope to strictly focusing on the design of the system and the corresponding selection of equipment. We originally intended to fully complete the construction of the testing apparatus, including all the instrumentation, but we found that delays in design and procurement prevented this from happening. The design of the system has been fully completed and several different options have been provided for the final implementation, while the construction is approximately 90% completed, with only the major equipment and final piping runs requiring installation. A detailed design for installing instrumentation has been completed, and several different options have been investigated for datalogging the system, allowing for a well informed decision by the subsequent project team. Overall the project is at an appropriate level of completion and is prepared for final implementation by the following project team.

Recommendations we make for the succeeding project team and future project teams:

- Maintain open communication between the group members and advisor, it is critical to the success of the project.
- Create a detailed schedule early in the project and adhere to it, ensuring you track delays and work towards resolving them.
- Compartmentalize the project, allowing each group member to become an expert on their specific portion, but make sure that members share their information with the entire team via weekly meetings.
- Buy parts far in advance of needing them on site, delays are inevitable and even slight delays can stop forward momentum.
- Justify all design decisions with detailed and objective analysis as your sponsor can at any time ask why a specific choice was made.

IX. References

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Martinez-Solano, F Javier, et al. "Modeling Flow and Concentration Field in Rectangular Water Tanks." International Environmental Modeling and Software Society (2010): 1-10.

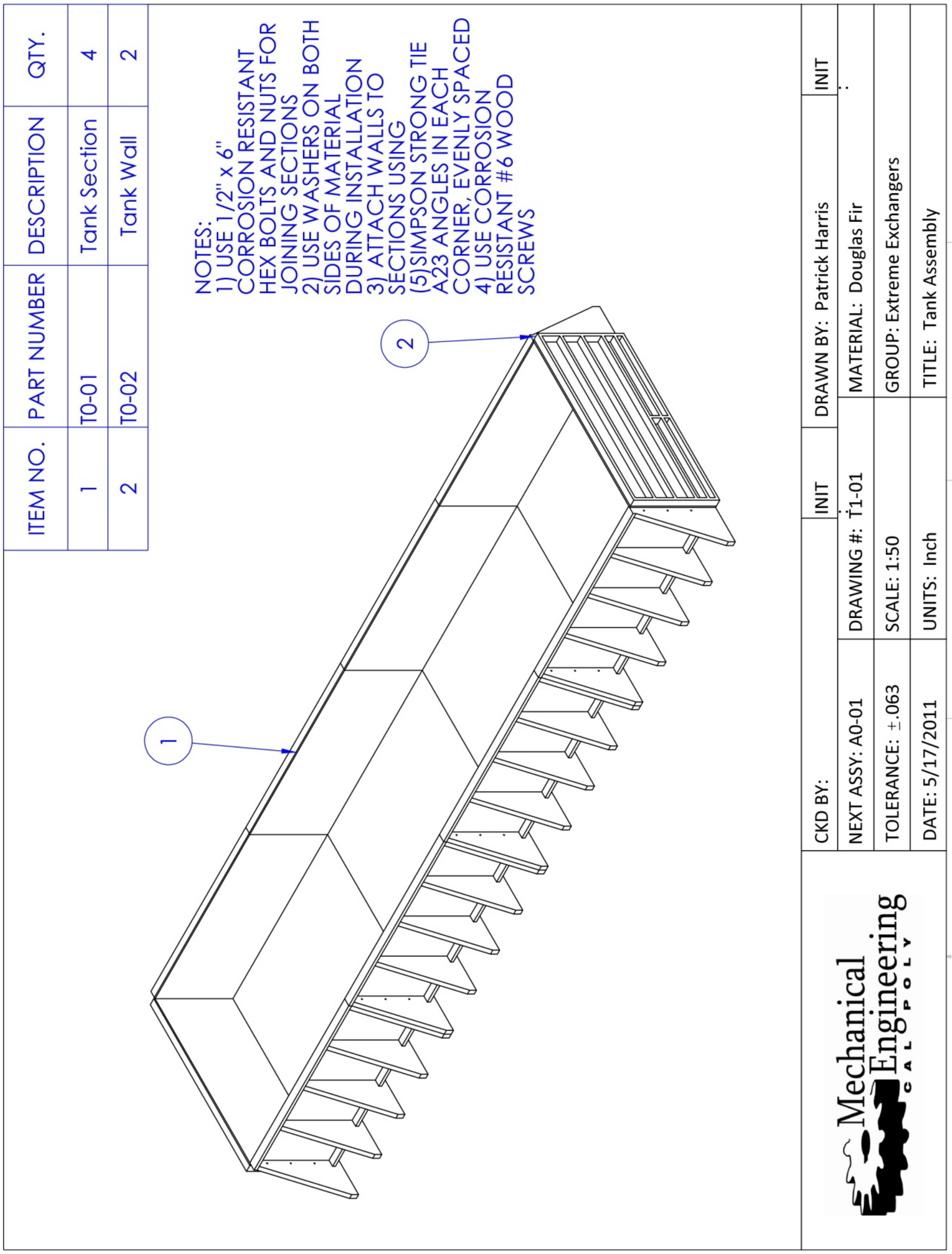
Munson, Bruce R, et al. Fundamentals of Fluid Mechanics. 6th. John Wiley & Sons, 2009.

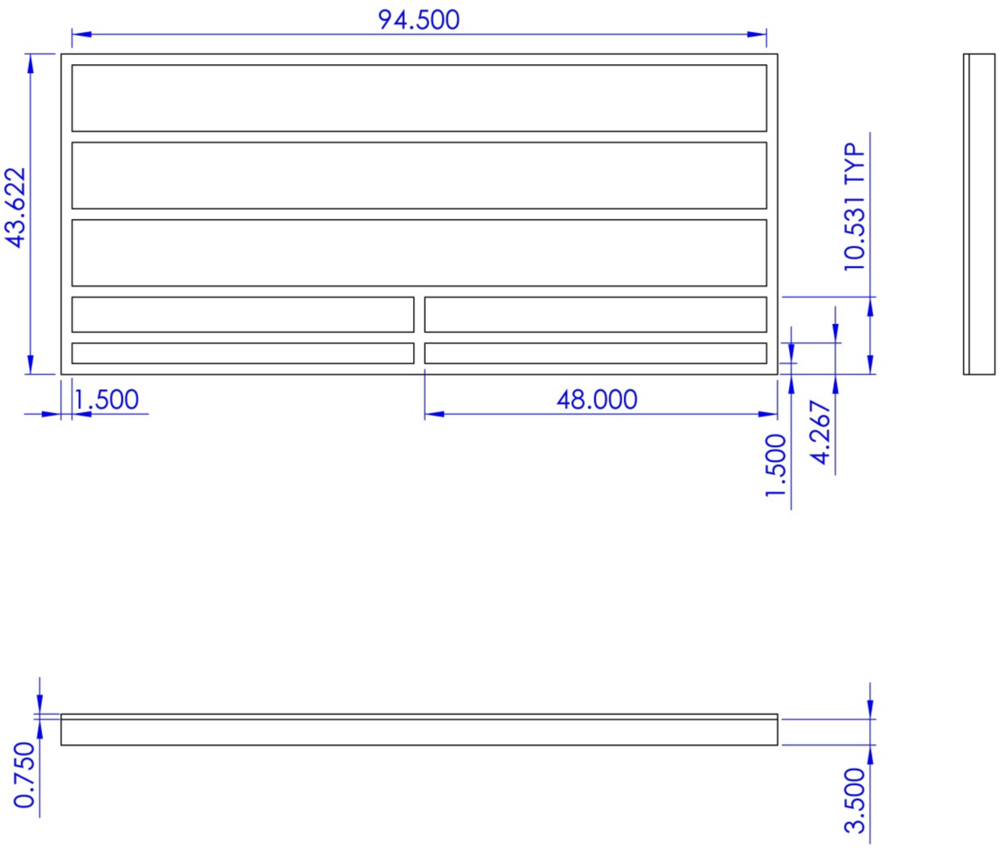
National Renewable Energy Laboratory. January 2011 <http://www.nrel.gov>.

Ward Tank and Heat Exchangers. <http://www.wardtank.com>.

X. Appendix

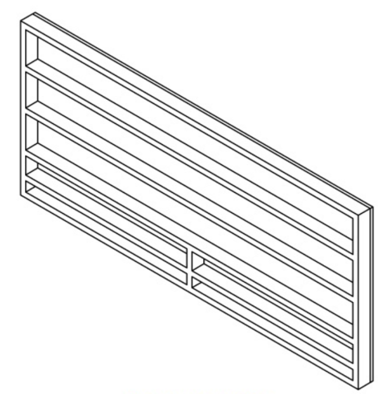
a. Drawings





COMPONENT	COST	QTY.
2" x 4" x 8'	$2.55	8
4' x 8' x 25/32"	$17.93	1
STRONG-TIE A34	$0.43	28

NOTES:
1) USE CORROSION RESISTANT #6 WOOD SCREWS
2) USE SIMPSON STRONG-TIE A34 ANGLES ON ALL PERPENDICULAR JOINTS



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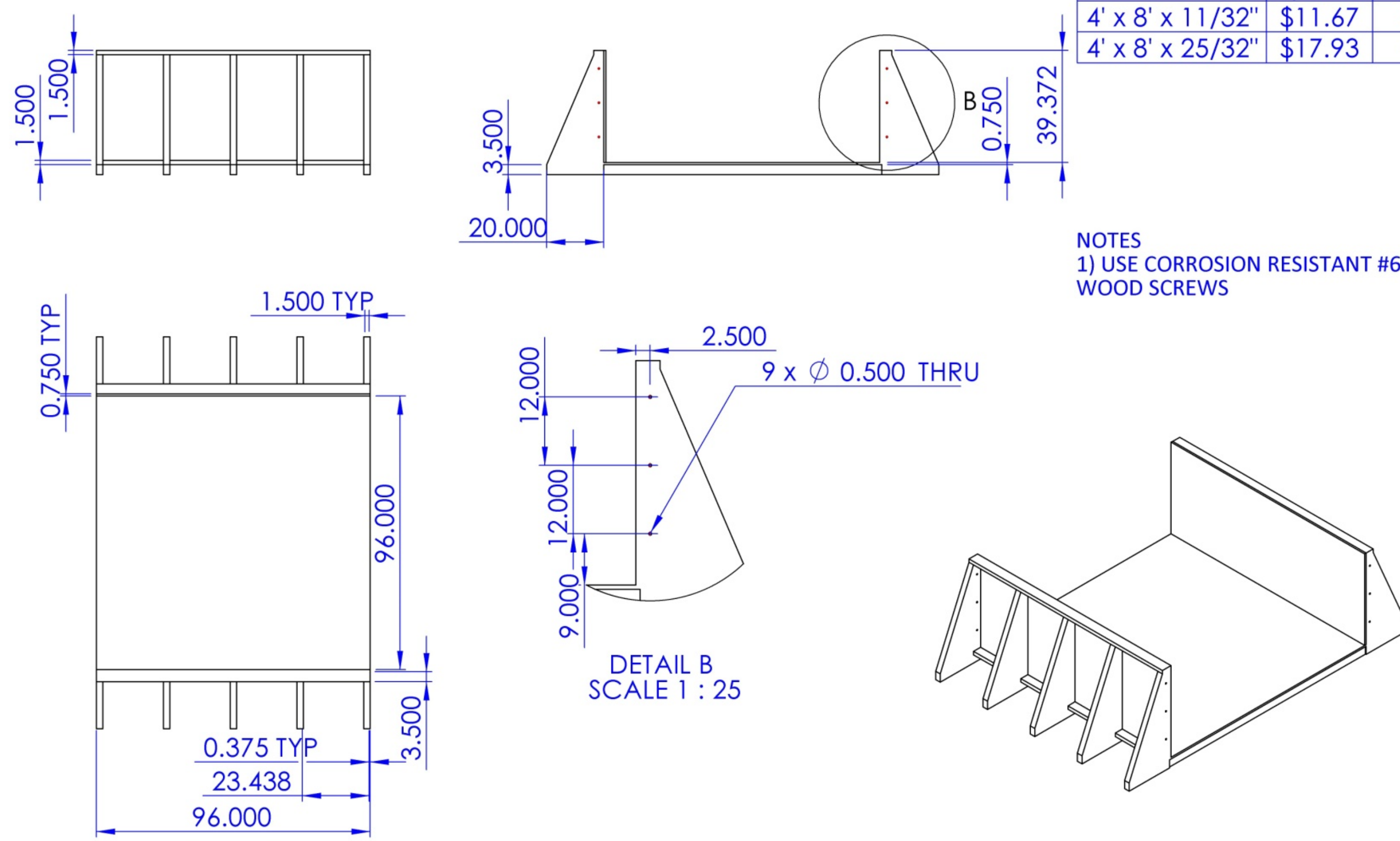
DATE: 5/17/2011	UNITS: Inch	TITLE: Tank End Wall	

5 4 3 2 1

COMPONENT	COST	QTY.
2" x 4" x 8'	$2.55	14
2" x 4"x 12'	$3.67	5
4' x 8' x 11/32"	$11.67	3
4' x 8' x 25/32"	$17.93	4



NOTES
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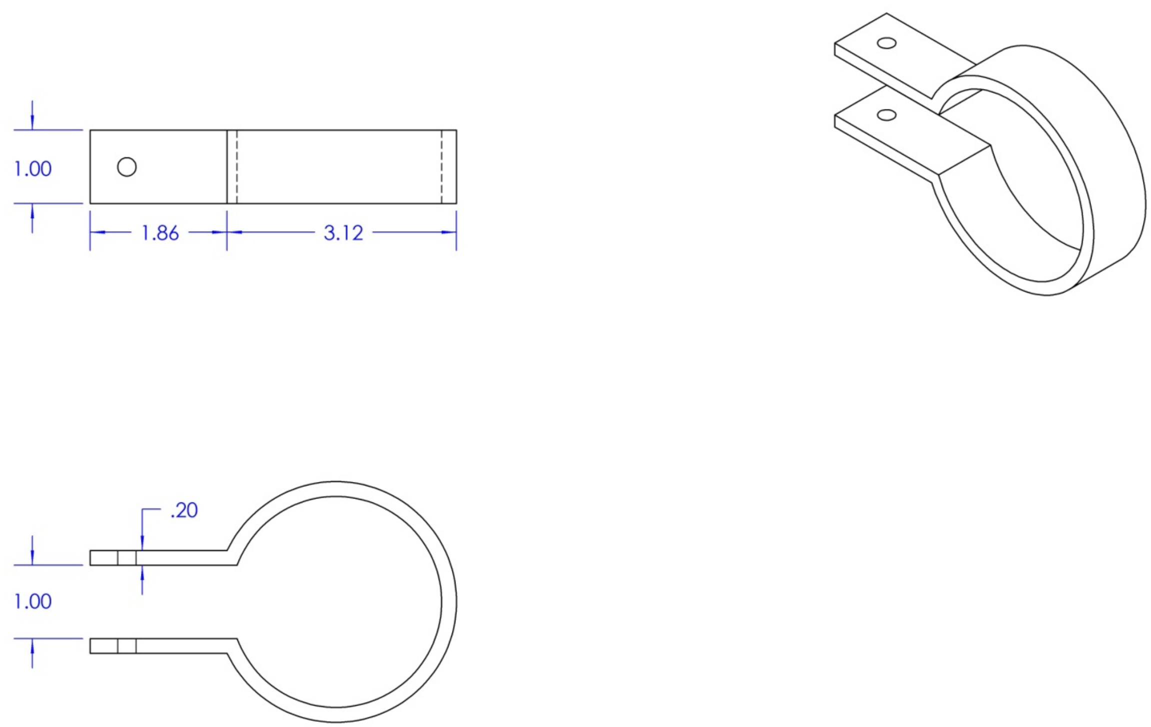

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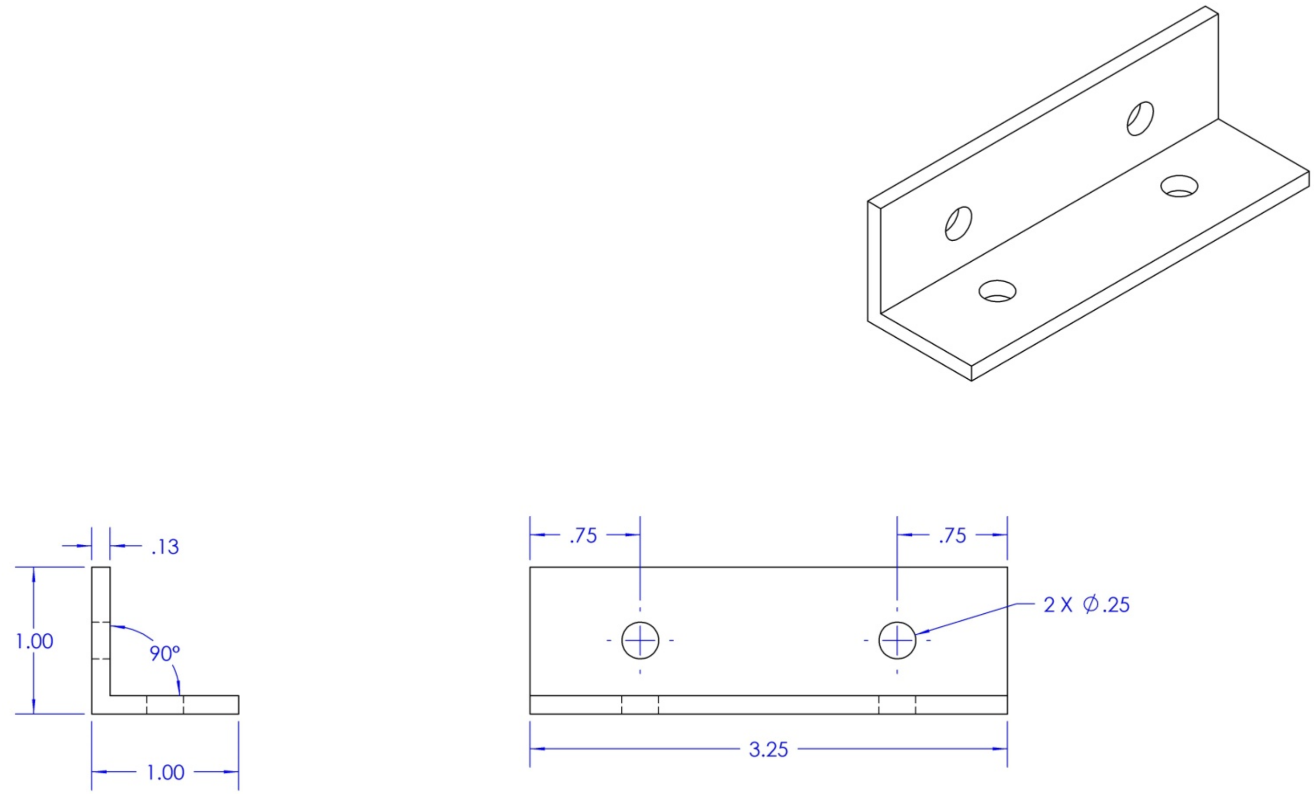

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Mechanical Engineering
CAL POLY

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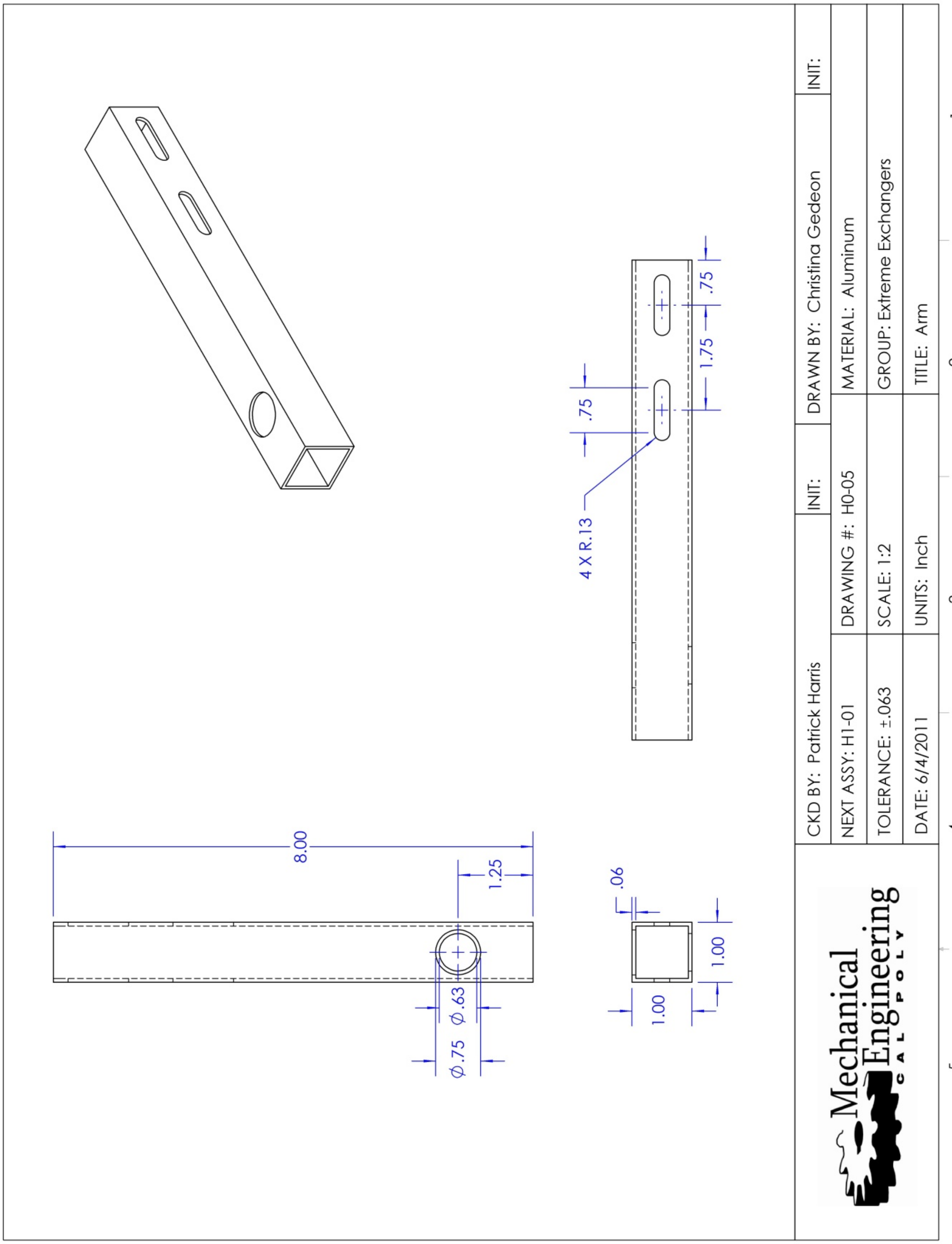

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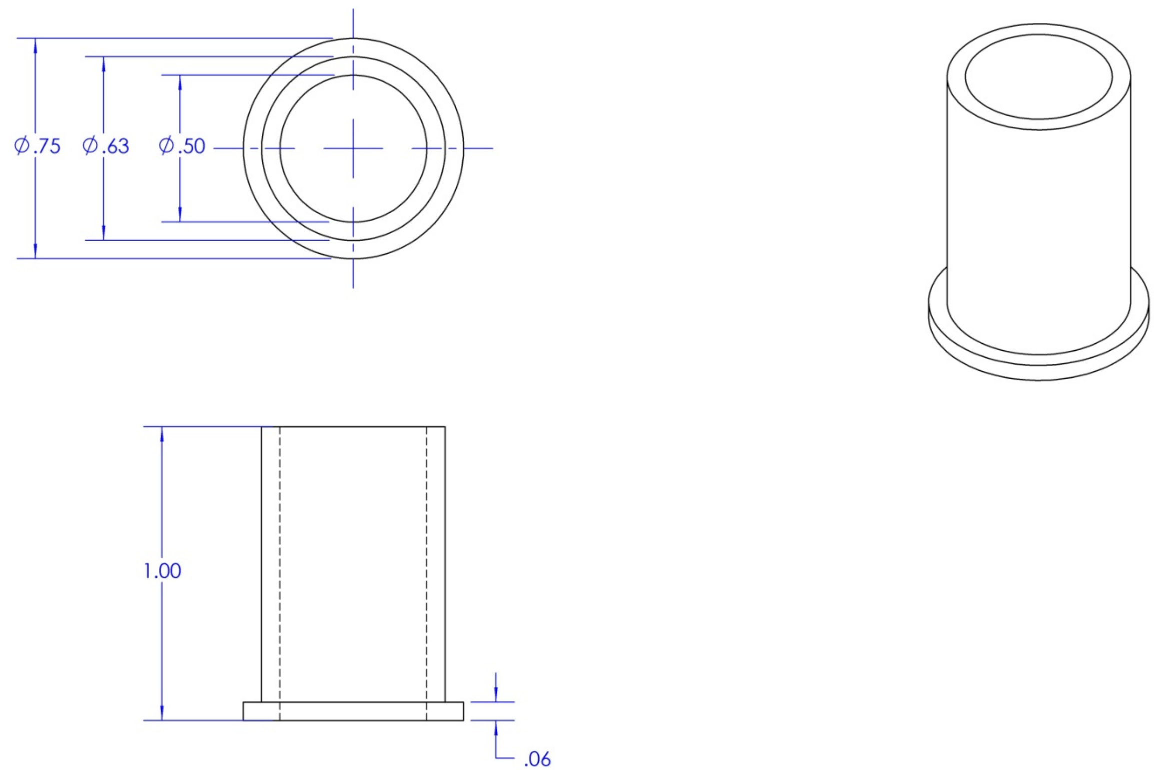

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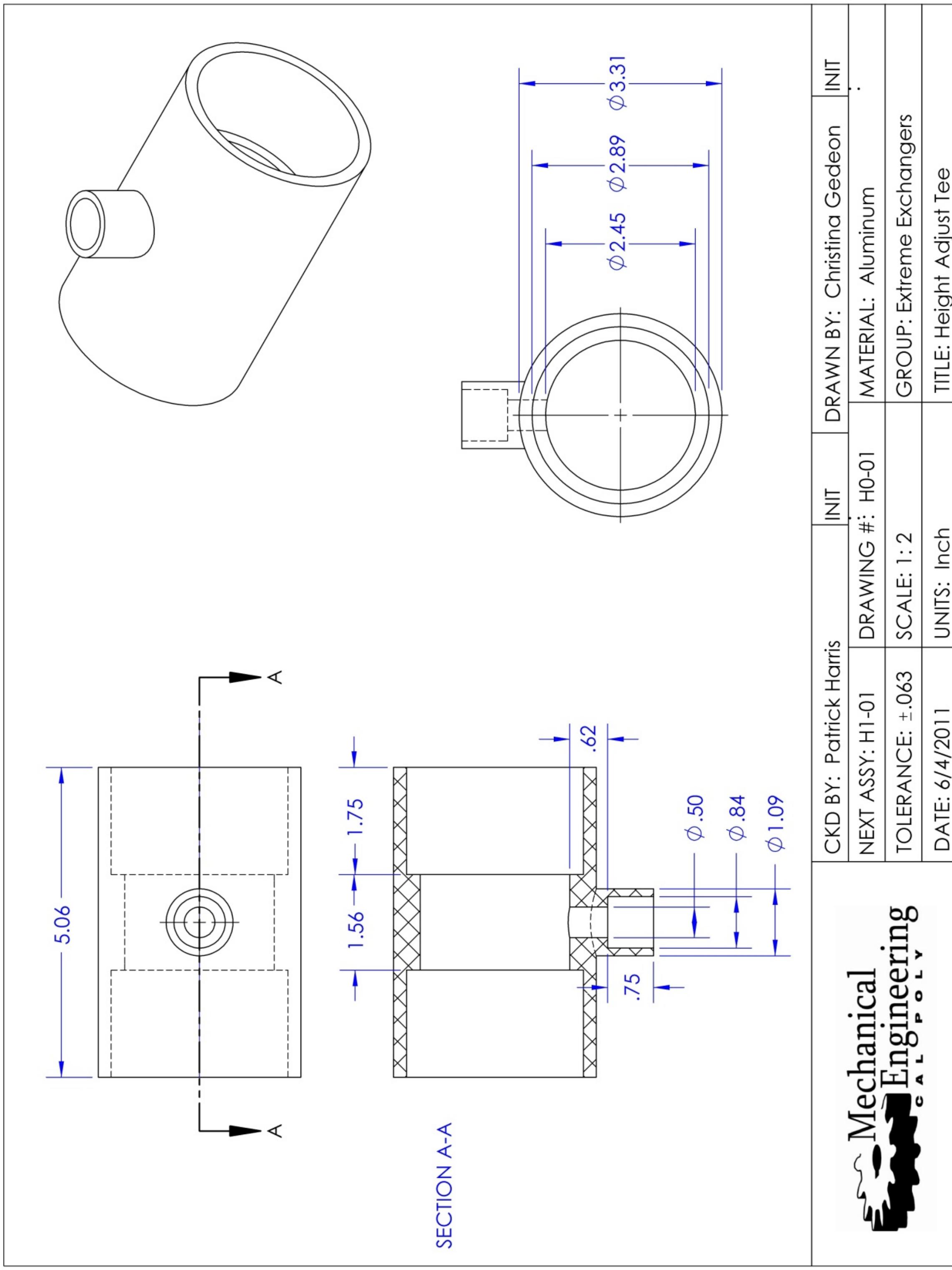

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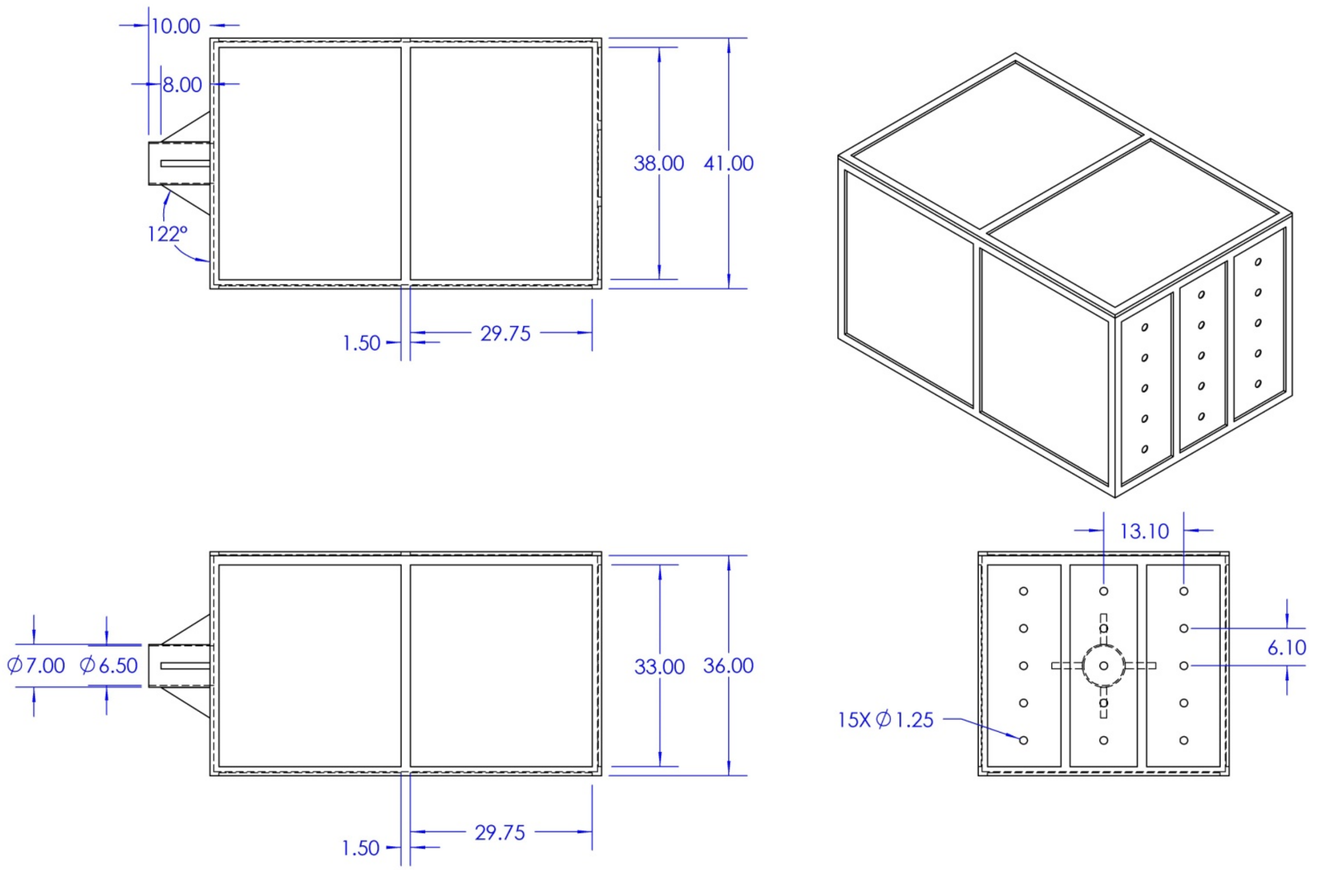

Mechanical Engineering CAL POLY

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5 4 3 2 1

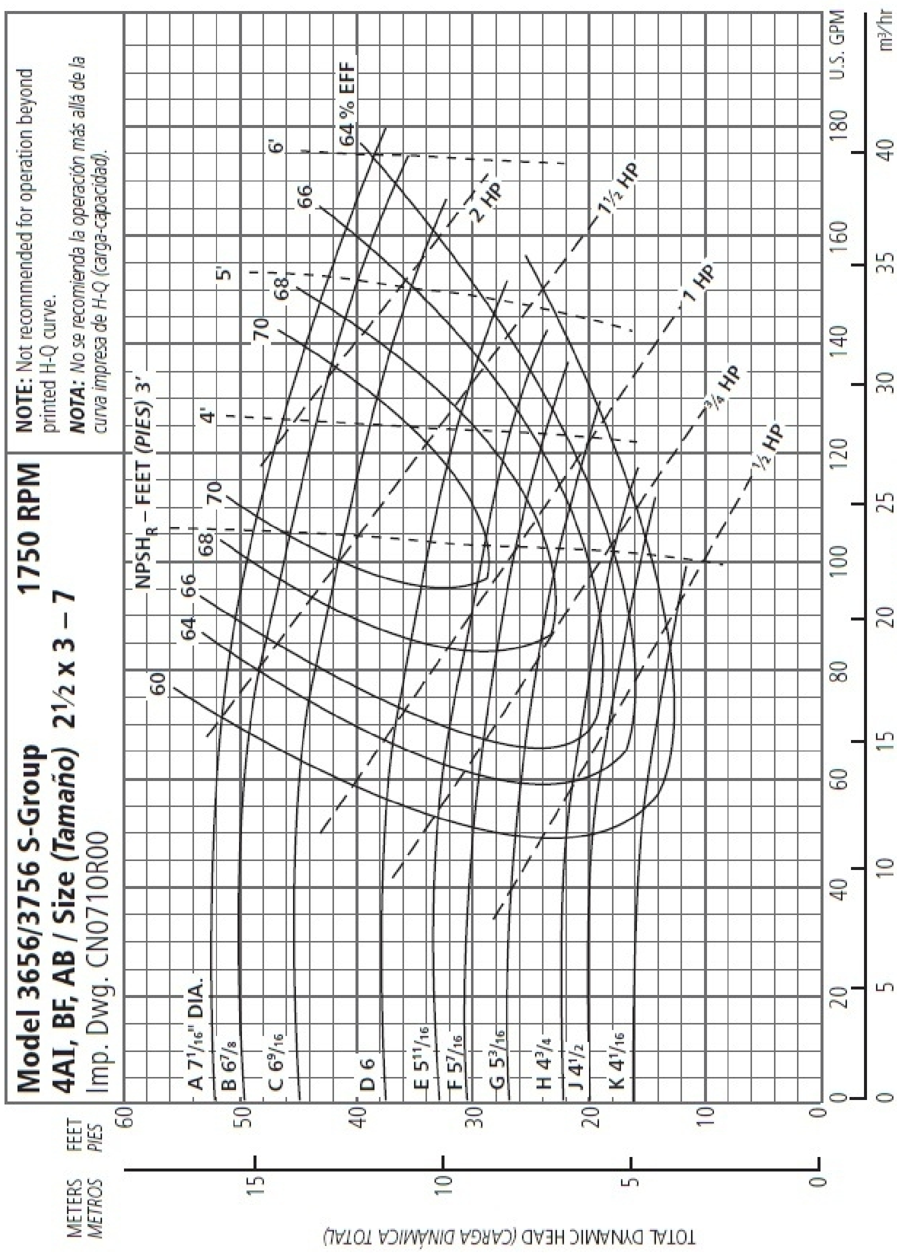
b. Vendors

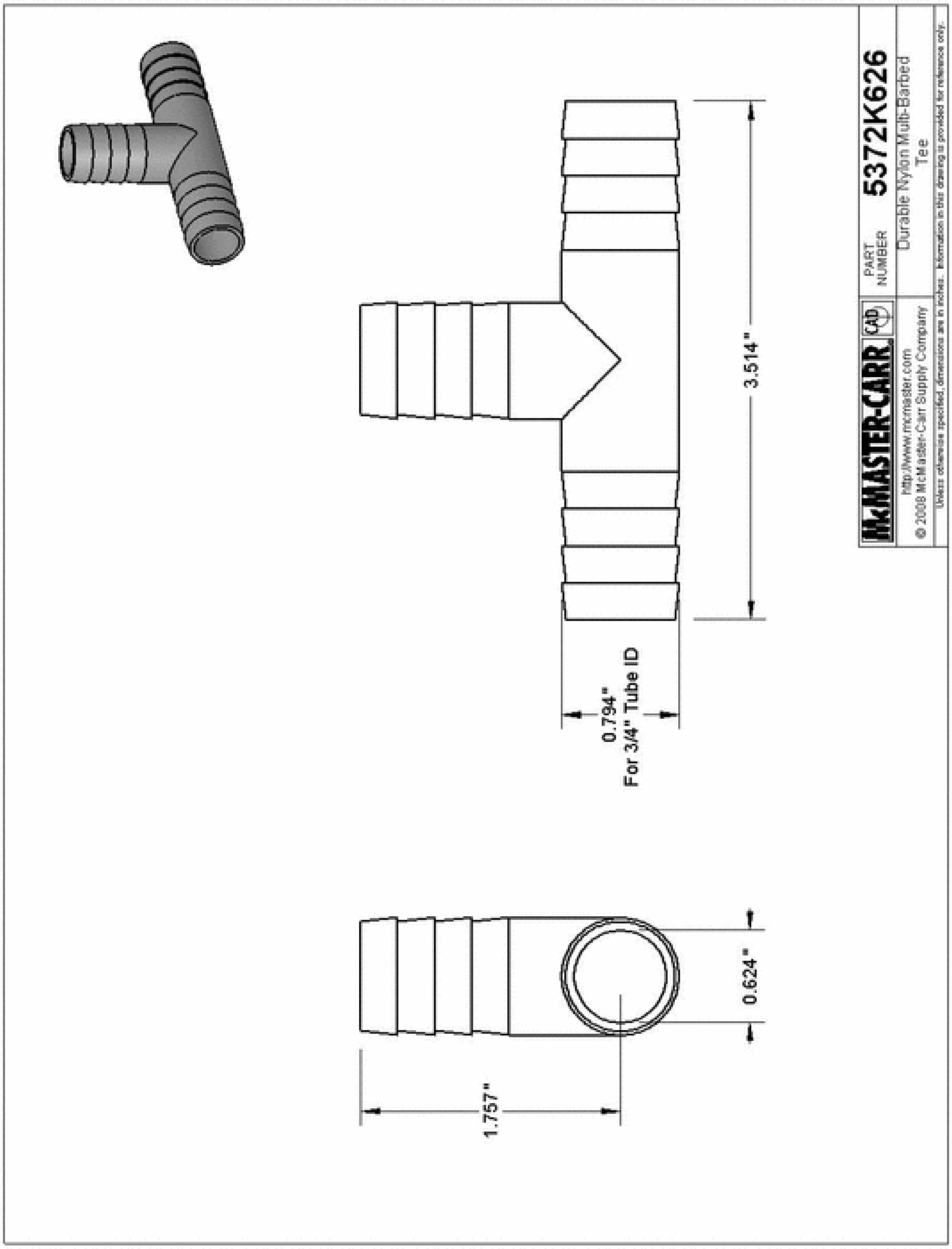
Vendor	Phone Number	Website
McMaster-Carr	562-463-4277	http://www.mcmaster-carr.com
Home Depot	805-596-0857	http://www.homedepot.com
Ferguson Plumbing	805-594-5380	http://www.ferguson.com
Newegg	1-800-390-1119	http://www.newegg.com
Enco	1-800-USE-ENCO	http://www.use-enco.com
Argent Systems	1-800-274-4076	http://www.argentdata.com

c. Vendor Specifications

Optional Impeller *Impulsor optativo*	
Ordering Code *Código de pedido*	**Dia.** *Diá.*
A	7 1/16"
B	6 7/8
C	6 9/16
D	6
E	5 11/16
F	5 7/16
G	5 3/16
H	4 3/4
J	4 1/2
K	4 1/16

NOTE: Pump will pass a sphere to 7/16" diameter.
NOTA: *La bomba dejará pasar una esfera de hasta 7/16 de pulgada de diámetro.*

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© 2008 McMaster-Carr Supply Company
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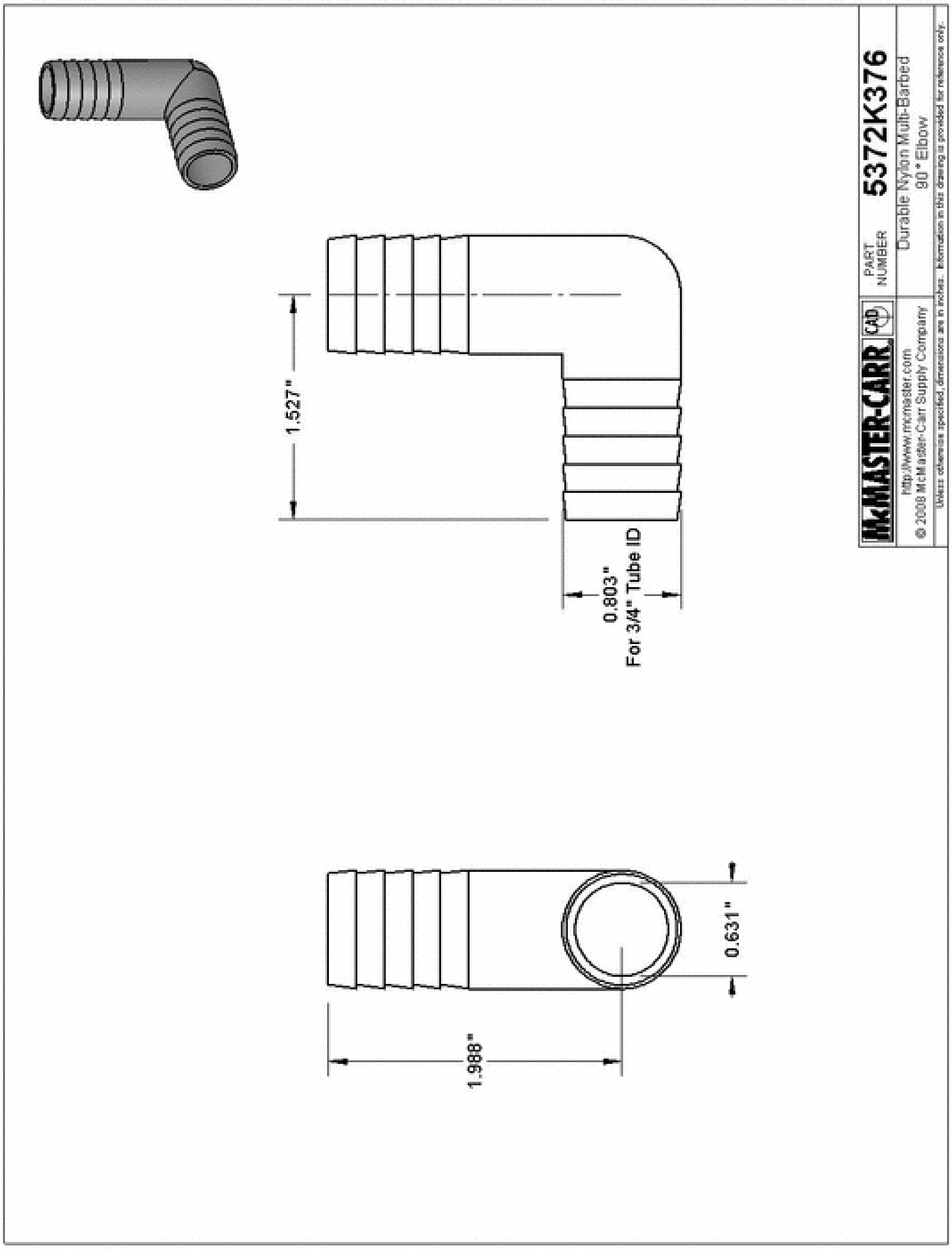
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http://www.mcmaster.com
© 2008 McMaster-Carr Supply Company
Unless otherwise specified, dimensions are in inches. Information in this drawing is provided for reference only.

d. Supporting Analysis

Plenum Chamber Analysis

Constants

$\rho_{water} = 1.94$ [slugs/ft³]

$\rho_{air} = 0.00238$ [slugs/ft³]

$g = 32.2$ [ft/s²] *Gravity Constant*

Centrifugal Fan Exit

$D_{1,in} = 6.5$ [in] *Blower exit Diameter in Inches*

$D_{1,ft} = \frac{D_{1,in}}{12}$ *Blower exit Diameter in Feet*

$h_{st} = 46$ [in] *Head Supplied by Fan*

$Q_1 = 150$ [ft³/min] *Volume flow Rate Supplied by Fan*

Plenum Chamber

$L_{in} = 61$ [in] *Chamber Length in Inches*

$H_{in} = 36$ [in] *Chamber Height in Inches*

$W_{in} = 41$ [in] *Chamber width in Inches*

$L_{ft} = \frac{L_{in}}{12}$ *Chamber Length in Feet*

$H_{ft} = \frac{H_{in}}{12}$ *Chamber Height in Feet*

$W_{ft} = \frac{W_{in}}{12}$ *Chamber width in Feet*

$V_2 = 0$ [ft/s]

State 1

$A_1 = \pi \cdot \frac{D_{1,ft}^2}{4}$ *Chamber Inlet Area*

$V_1 = \frac{Q_1}{A_1}$

$P_{static} = \rho_{water} \cdot g \cdot h_{st} \cdot \left[\frac{1}{12}\right]^3$ *Static Pressure*

$P_{dynamic} = 1 / 2 \cdot \rho_{air} \cdot \frac{V_1^2}{144}$ *Dynamic Pressure*

$P_{1,total} = P_{static} + P_{dynamic}$ *Total Pressure*

State 2

$A_2 = H_{ft} \cdot W_{ft}$

$Q_2 = V_2 \cdot A_2$

$P_{2,total} = P_{1,total}$ *Using Bernoullis equation and assuming dynamic pressure at state 2 is 0 and ignoring loses*

SOLUTION

Unit Settings: Eng F psia mass deg

$A_1 = 0.2304$ [ft^2]

$D_{1,ft} = 0.5417$ [ft]

$g = 32.2$ [ft/s^2]

$H_{in} = 36$ [in]

$L_{ft} = 5.083$ [ft]

$P_{1,total} = 5.164$ [psi]

$P_{dynamic} = 3.502$ [psi]

$Q_1 = 150$ [ft^3/min]

$\rho_{air} = 0.00238$ [slugs/ft^3]

$V_1 = 650.9$ [ft/s]

$W_{ft} = 3.417$ [ft]

$A_2 = 10.25$ [ft^2]

$D_{1,in} = 6.5$ [in]

$H_{ft} = 3$ [ft]

$h_{st} = 46$ [in]

$L_{in} = 61$ [in]

$P_{2,total} = 5.164$ [psi]

$P_{static} = 1.663$ [psi]

$Q_2 = 0$ [ft^3/min]

$\rho_{water} = 1.94$ [slugs/ft^3]

$V_2 = 0$ [ft/s]

$W_{in} = 41$ [in]

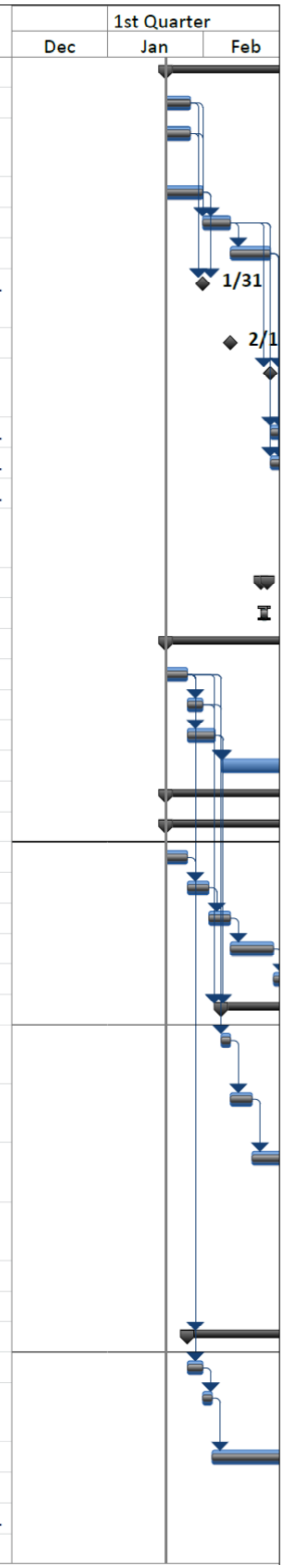
e. Bill of Materials

Indented Bill of Material (BOM)												
Floating Tube Heat Exchanger												
Assembly Level	**Part Number**	**Description**						**Model**	**Vendor**	**Qty**	**Cost**	**Ttl Cost**
		Lvl0	Lvl1	Lvl2	Lvl3	Lvl4	LvL5					
0	A1-01	Final Assy										
1	T1-01		Tank									
2	T0-01			Section						4		
3					2"x4"x8'			441317	Home Depot	14	2.55	35.7
3					2"x4"x12'			603597	Home Depot	5	3.67	18.35
3					4'x8'x11/32"			166065	Home Depot	3	11.67	35.01
3					4'x8'x25/32"				Home Depot	4	17.93	71.72
3					#6x2" Gold Screws 5lb			832608	Home Depot	1	21.97	21.97
2	T0-02			End Wall						2		
3					2"x4"x8'			441317	Home Depot	8	2.55	20.4
3					4'x8'x25/32"				Home Depot	1	17.93	17.93
3					Strong-Tie A34			461466	Home Depot	28	0.43	12.04
3					#6x1-5/8 Gold Screws 1lb			832189	Home Depot	1	6.47	6.47
2				1/2"x6" Hex Bolt					Home Depot	18		0
2				1/2" Hex Nut					Home Depot	18	0.025	0.45
2				1/2" Washer (Bag of 25)				328243	Home Depot	2	4.5	9
2				Strong-Tie A23				251408	Home Depot	20	0.88	17.6
2				#8x3" Gold Screws 1lb				832916	Home Depot	1	6.47	6.47
2				Hay Bales						32	4	128
2				3-1/4"x15"x32' Insulation				559352	Home Depot	2	9.4	18.8
2				Pond liner					ALG	64	4	256
1			Height Adjust							1		
2				1"x1/16"x48" Box Al				469599	Home Depot	1	19.54	19.54
2				1/2"x72" Rod Al				505-3647	Enco	3	13.74	41.22
2				1"x1/8"x48" Angle Al				325-4343	Enco	1	11.45	11.45
2				1/4"-20 x2" Al screws (Bag of 25)				93143A550	McMaster-Carr	1	9.18	9.18
2				1/4"-20 Al nuts (Bag of 100)				90670A029	McMaster-Carr	1	4.9	4.9
2				1/4" Al washer (Bag of 100)				93286A029	McMaster-Carr	1	6.8	6.8
2				#8x1-1/2" Al Screw (Bag of 2)				760381	Home Depot	12	0.63	7.56
2				2-1/2" PVC Elbow				P4089L	Ferguson	4	5.76	23.04
2				2-1/2"x1/2" PVC Tee				P40STLLD	Ferguson	6	6.697	40.182
2				2-1/2"x1' PVC Pipe				P40BEPL20	Ferguson	80	1.454	116.32
2				1"x1/20"x96" Box Al				797005	Home Depot	2	16.27	32.54
2				Nylon Bearing (Bag of 5)				6389K447	McMaster-Carr	2	5.87	11.74
2				32oz ABS Cement				361317	Home Depot	1	11.39	11.39
1			Water System									
2				Pump				Gould 4BF2G5G0	PumpBox	1	1406	1406
2				3"x1' PVC Pipe				P40BEPM20	Ferguson	20	1.902	38.04
2				2-1/2"x1' PVC Pipe				P40BEPL20	Ferguson	60	1.454	87.24
2				3" Check Valve				SP-S152030/Z	Ferguson	1	47.23	47.23
2				3" Ball Valve				PFPSBVM	Ferguson	1	58.14	58.14
2				2-1/2" Ball Valve				PFPSBVL	Ferguson	4	46.35	185.4
2				3" PVC Elbow				P40S9M	Ferguson	5	6.598	32.99
2				2-1/2" PVC Elbow				P40S9L	Ferguson	7	5.76	40.32
2				2-1/2" PVC Tee					Ferguson	2		0
2				2-1/2" x 2" Reducer						2		0
2				3" Flowmeter				4349K6	McMaster-Carr	1	110.66	110.66
2				2-7/8"x3/4"x6' Pipe Insulation				4734K164	McMaster-Carr	10	21.77	217.7
2				3-5/8"x3/4"x6' Pipe Insulation				4734K166	McMaster-Carr	20	27.86	557.2
1			Heat Exchanger					35185K57	McMaster-Carr	1	2,266.78	2266.78

1	Air System					
2	Blower		Cal-Poly	1	0	0
2	3/4" PVC Tubing (10')		Home Depot	2	18.82	37.64
2	1-1/4" PVC Tubing (50')		Home Depot	4	99	396
2	1-1/4" Ball Valve		Home Depot	15	6.7	100.5
2	1-1/4" Male Adaptor		Farm Supply	45	1.54	69.3
2	3/4" Barbed Tees (Bag of 10)		McMaster-Carr	5	10.62	53.1
2	3/4" Barbed Elbows (Bag of 10)		McMaster-Carr	4	7.75	31
2	Hose Clamp (Bag of 10)		Home Depot	30	13.3	399
2	Plenum Chamber		Cal-Poly	1	0	0
2	40mm Computer Fans	N82E16835104004	Newegg.com	15	1.99	29.85
1	Temperature System					
2	Temperature Sensor	DS18S20	Argent Systems	220	3	660
2	Socket		Argent Systems	220	0.4	88
2	Cable (300 ft)		Argent Systems	1	49	49
2	Controller Board		Argent Systems			0
2	Twine	726001	Home Depot	1	33.37	33.37
1	Tube System					
2	Outer Tube		ALG	15		
2	Inner Tube		ALG	15		
2	Outer Endcap		ALG	30		
2	Inner Endcap		ALG	30		
2	1-1/4" Barb Fitting		ALG	30		
2	3/4" Barb Fitting		ALG	60		
2	Outer Gasket		ALG	30		
2	Inner Gasket		ALG	30		
1	Control Pond					
2	2"x4"x8'	441317	Home Depot	15	2.55	38.25
2	4'x8'x11/32"	166065	Home Depot	2	11.67	23.34
2	4'x8'x25/32"		Home Depot	3	17.93	53.79
2	Strong-Tie A34	461466	Home Depot	32	0.43	13.76
2	#6x2" Gold Screws 5lb	832608	Home Depot	1	21.97	21.97
2	Flow Totalizer	9978K76	McMaster-Carr	1	166.88	166.88
2	Hay Bales			4	4	16
2	3-1/4"x15"x32' Insulation	559352	Home Depot	1	9.4	9.4
1	Weather Station		Cal-Poly	1	0	0
1	10'x10' Shade Awnings	6-22710	Sears	4	79.99	319.96

f. Project Timeline

ID	ℹ	Task Mode	Task Name	Duration	Predecessors	Start
1	✓		**Class Deliverables**	**100 days**		**Thu 1/20/11**
2	✓		Problem Definition	6 days		Thu 1/20/11
3	✓		Research of Prior Work	6 days		Thu 1/20/11
4	✓		Project Requirements	8 days		Thu 1/20/11
5	✓		Concept Design	7 days	4,2,3	Tue 2/1/11
6	✓		Concept Model	9 days	5	Thu 2/10/11
7	✓		Project Requirements Document Due	0 days	2,3,4	Mon 1/31/11
8	✓		Design Review	0 days		Thu 2/10/11
9	✓		Conceptual Model Due	0 days	6,5	Tue 2/22/11
10	✓		Bill of Materials	4 days	5,6	Wed 2/23/11
11	✓		Concept Report	4 days	5,6	Wed 2/23/11
12	✓		Concept Report Due	0 days	11	Mon 2/28/11
13	✓		Final Design Report Due	0 days		Thu 6/9/11
14	✓		**Field Trips**	**1 day**		**Sun 2/20/11**
15	✓		Trip to San Diego	2 days		Sun 2/20/11
16			**System Modeling**	**244 days**		**Thu 1/20/11**
17	✓		Simple Model	5 days		Thu 1/20/11
18	✓		Nusselt Correlation	3 days	17	Thu 1/27/11
19	✓		Resistance Analogy	7 days	17	Thu 1/27/11
20			Complex Model	232 days	19,17,18	Mon 2/7/11
21			**Design**	**85 days**		**Thu 1/20/11**
22	✓		**Holding Tank**	**28 days**		**Thu 1/20/11**
23	✓		Research Design	5 days		Thu 1/20/11
24	✓		Engineer Design	5 days	23	Thu 1/27/11
25	✓		Model the Design	5 days	24	Thu 2/3/11
26	✓		Bill of Materials	10 days	25	Thu 2/10/11
27	✓		Purchase Materials	3 days	26	Thu 2/24/11
28			**Pump Selection**	**44 days**	**17,18,19**	**Mon 2/7/11**
29	✓		Research Available Pumps	3 days	17	Mon 2/7/11
30	✓		Generate Heat Transfer Tables	5 days	29	Thu 2/10/11
31	✓		Select Adequate Pump	30 days	30	Thu 2/17/11
32	✓		Correlate with Piping	3 days	31	Thu 3/31/11
33	✓		Bill of Materials	3 days	32	Tue 4/5/11
34			Order Pump	0 days	33	Thu 4/7/11
35			**Fan Selection**	**42 days**	**17**	**Thu 1/27/11**
36	✓		Research Available	3 days	17	Thu 1/27/11
37	✓		Generate Heat Transfer Tables	3 days	36	Tue 2/1/11
38	✓		Select Adequate Fan	30 days	37	Fri 2/4/11
39	✓		Correlate with Piping	3 days	38	Fri 3/18/11
40	✓		Bill of Materials	3 days	39	Wed 3/23/11
41			Order Pump	0 days	40	Thu 3/24/11



ID	Indicators	Task Mode	Task Name	Duration	Predecessors	Start
42			**Weather System Selection**	**15 days**		**Mon 2/28/11**
43	✓		Develop Requirements	3 days		Mon 2/28/11
44	✓		Research Available	7 days	43	Thu 3/3/11
45	✓		Bill of Materials	4 days	44	Mon 3/14/11
46			Order	1 day	45	Fri 3/18/11
47			**DAQ Selection**	**25 days**		**Mon 2/21/11**
48	✓		Develop Requiremen	3 days		Mon 2/21/11
49	✓		Research Available	14 days	48	Thu 2/24/11
50	✓		Bill of Materials	7 days	49	Wed 3/16/11
51			Order	1 day	50	Fri 3/25/11
52			**Boiler Selection**	**23 days**		**Mon 2/28/11**
53	✓		Develop Requirements	5 days		Mon 2/28/11
54	✓		Research Available	14 days	53	Mon 3/7/11
55	✓		Bill of Materials	3 days	54	Fri 3/25/11
56			Order	1 day	55	Wed 3/30/11
57	✓		**Plumbing**	**42 days**		**Mon 2/21/11**
58	✓		Develop Requirements	5 days		Mon 2/21/11
59	✓		Research	5 days	58	Mon 2/28/11
60	✓		Model	14 days	59	Mon 3/7/11
61	✓		Analyze	5 days	60	Fri 3/25/11
62	✓		Iterate	10 days	61	Fri 4/1/11
63	✓		Bill of Materials	2 days	62	Fri 4/15/11
64	✓		Order	1 day	63	Tue 4/19/11
65			**Instrumentation**	**58 days**		**Mon 2/28/11**
66			**Thermocouples**	**17 days**		**Mon 2/28/11**
67	✓		Design	14 days		Mon 2/28/11
68	✓		Bill of Materials	2 days	67	Fri 3/18/11
69			Order	1 day	68	Tue 3/22/11
70			**Flowmeters**	**17 days**		**Fri 3/18/11**
71	✓		Design	14 days		Fri 3/18/11
72	✓		Bill of Materials	2 days	71	Thu 4/7/11
73			Order	1 day	72	Mon 4/11/11
74			**Totalizers**	**17 days**		**Fri 3/18/11**
75	✓		Design	14 days		Fri 3/18/11
76	✓		Bill of Materials	2 days	75	Thu 4/7/11
77			Order	1 day	76	Mon 4/11/11
78			**Construction**	**96 days**		**Tue 3/1/11**
79			**Tank**	**41 days**	**22**	**Tue 3/1/11**
80	✓		Cut Buttresses	14 days		Tue 3/1/11
81	✓		Cut 2x4	14 days		Tue 3/1/11
82	✓		Fasten	14 days	81,80	Mon 3/21/11
83			Install Liner	4 days	82	Fri 4/8/11
84			Leak Test	3 days	83	Thu 4/14/11
85			Install Height Control	3 days	84	Tue 4/19/11
86			Install Bulkhead	3 days	85	Fri 4/22/11

1st Quarter: Dec, Jan, Feb

ID	Indicators	Task Mode	Task Name	Duration	Predecessors	Start	Dec	1st Quarter Jan	1st Quarter Feb
87			Install Tubes	1 day	84	Tue 4/19/11			
88			**Air System**	**23 days**	**35,57,65,22**	**Thu 5/19/11**			
89	✓		Modify Endcaps	7 days		Thu 5/19/11			
90			Create Manifold	7 days		Thu 5/19/11			
91			Cut Piping	3 days		Thu 5/19/11			
92			Install Piping	14 days	90,91,89	Mon 5/30/11			
93			Install Instrumentation	4 days	90,91,89	Mon 5/30/11			
94			Install Fan	1 day	93,92	Fri 6/17/11			
95			Leak test	1 day	92,93,94	Mon 6/20/11			
96			**Water System**	**25 days**	**28,57,65,52,2**	**Wed 5/18/11**			
97			Cut Piping	14 days		Wed 5/18/11			
98			Install Piping	7 days	97	Wed 6/8/11			
99			Install Instrumentation	7 days	97	Wed 6/8/11			
100			Install Boiler	2 days	98,99	Fri 6/17/11			
101			Install Pump	2 days	98,99	Fri 6/17/11			
102			Leak test	2 days	101,100	Tue 6/21/11			
103			**DAQ System**	**39 days**	**22,47,57,65**	**Thu 5/19/11**			
104			Calibrate Sensors	7 days		Thu 5/19/11			
105			Install Probes	14 days	104	Mon 5/30/11			
106			Wire Probes	14 days	105	Fri 6/17/11			
107			Install Weather	2 days		Thu 5/19/11			
108			Configure DAQ	3 days	106	Thu 7/7/11			
109			Test	1 day	108	Tue 7/12/11			
110	✓		Control Pond	3 days	79	Wed 4/27/11			
111			**Testing**	**116 days**	**78**	**Wed 7/13/11**			
112			**Run Control Test**	**30 days**		**Wed 7/13/11**			
113			Daily Volume Measurements	30 days		Wed 7/13/11			
114			**Run system**	**42 days**		**Wed 7/13/11**			
115			.25 Meter Depth	14 days		Wed 7/13/11			
116			.5 Meter Depth	14 days	115	Tue 8/2/11			
117			1 Meter Depth	14 days	116	Mon 8/22/11			
118			Correlate Data	14 days	115,116,117	Fri 9/9/11			
119			**Prove Model**	**74 days**	**114**	**Fri 9/9/11**			
120			Verify thermoclines	30 days		Fri 9/9/11			
121			Verify Entrance Region	45 days		Fri 9/9/11			
122			Verify thermal model	60 days		Fri 9/9/11			
123			Iterate	14 days	120,121,122	Fri 12/2/11			