CALIFORNIA POLYTECHNIC STATE UNIVERSITY

PG&E Flow Loop Simulator

Senior Project

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1.0 Executive Summary

PG&E's Diablo Canyon Power Plant requested a full-sized Flow Loop Simulator to train technicians by giving them hands-on experience. The basic design requirements were established to determine the scope of the project and develop the specific characteristics of the system. The detailed system design is composed of a piping schematic, a three-dimensional layout of the system components and piping, and a skid structure for the support and transportation of the system. Heat transfer and fluid mechanics were used to analyze the system to size components. A cost analysis spreadsheet was made to select components.

Note that this report is for the system team and does not communicate any of the design associated with the controls for the system.

2.0 Introduction

The technicians at PG&E's Diablo Canyon Power Plant are required by law to go through a complete training process before they are cleared to work inside the actual power plant. The technicians go through many hours of training to learn the maintenance procedures that they will use in the plant. Technicians are also given as much hands on experience with the tools and components they will see in the plant as possible. However, technicians have no working system with full-sized components to train on before entering the power plant.

3.0 Background

The Diablo Canyon Nuclear Power Plant Learning Center currently has an inoperable, full-scale simulation system comprised of numerous pumps, multiple feed water tanks, a heat exchanger, a lube oil system, a chemical injection system, and many valves and controllers of various types. The 16 ft long by 8 ft wide unit is inoperable due to oversized pumps coupled with incorrect piping sizes.

In addition to the full-scale simulation system, the Diablo Canyon Power Plant's Instrumentation and Controls department currently uses a similar, scaled down flow loop system with good success. However, due to its scaled down size, the system does not accurately represent the true components in the plant. For example, clear, rubber tubing is used instead of 4 in. stainless steel pipe to transport the working fluid.

PG&E has offered components straight from their warehouse that keeps stock of many of the components found in the power plant. This will allow the simulator to use components that technicians will see in the power plant. A database of available materials and components in the plants large warehouse has been offered, but cannot be accessed outside the local plant computer system. It was recommended to use the parts list from the current, inoperable system as a starting point, before seeking information about other available components. The new system components will not be strictly limited to in-stock items, allowing the possibility of ordering large materials and components to be considered based on item importance and cost.

Lastly, numerous codes and standards will apply in both the design and construction phases due to the systems proposed usage in a nuclear power plant setting. Due to federal regulations, power plants have strict regulations on the standards required in construction. Because of the wide range and large volume

of strict guidelines, the plant suggested waiting until the design stage is well underway before determining which codes and standards will apply.

3.1 Objectives

The objective of this report is to communicate the final system design plans for the Flow Loop Simulator and make recommendations for the components to be purchased so that the construction process can begin.

The objective of the project is to design and build a full-sized, functional Flow Loop Simulator to train workers at the Diablo Canyon Power Plant in the fundamentals of thermal systems and system operations. The new Flow Loop Simulator will contain components technicians will commonly see in the power plant, but provide the technicians the opportunity to gain experience with these components under operating conditions before stepping inside the power plant. The primary goal of this project is to provide a safe way for trainees to learn how to control a system, deal with potential problems as they arise, and perform general maintenance on various system components in an environment that is safer and less critical than within the plant.

3.2 Engineering Specifications

PG&E developed a set of engineering specifications to drive the design of the Flow Loop Simulator. The requirements are as follows:

1) System must be built on a structure(s) capable of being transported without the need for special permits pertaining to weight, length, height or width.
2) System must have a hot loop and a cold loop
3) System must replicate the plant environment by:
    a. Using as many possible components and subsystems commonly found in the plant environment:
        i. Valves (flow control, check, isolation)
        ii. Controls (temperature, flow, pressure, tank level)
        iii. Instrumentation (temperature, flow, pressure, level)’
        iv. Heat exchanger
        v. Pumps
        vi. Tanks
        vii. Piping (4”-6”)
        viii. Snubbers
        ix. Chemical addition tank
        x. Metering pump
    b. Replicating common procedures performed in plant maintenance and operation
    c. Possibly replicating common scenarios for technicians and operators such as:
        i. Vortexing
        ii. Voiding
    d. Using components that have a similar scale as those commonly found in the plant.
    e. Adhere to standards and regulations commonly used by the plant as dictated by the Piping Specifications handbook
4) System must operate on available utilities
    a. Compressed air (110psi)
    b. Electricity (480 VAC)
    c. Potable Water
5) Primarily use components commonly stocked by the plant
6) System must be safe to operate

4.0 Project Management

Considering the scope of this project, the design team is divided into two sub-teams, a systems team and a controls team. The systems team is responsible for the design and construction of the main system and the selection of all pumps, heat exchanger, tanks, and other components. The controls team is responsible for the selection and implementation of all gauges, valves, control valves, and controllers, as well as setting up a controls interface and operation procedures. The two sub-teams are working together to ensure the system and controls fit together and work properly. This report describes only the design and construction plans of the system of the Flow Loop Simulator. Any controls related material is not included.

4.1 System Team Management Plan

The system team, composed of Seth Berger, Cole Brooks, and Ben Thacker, is responsible for the design and construction of the Flow Loop Simulator. Seth, the team lead, conducted the analysis and design of the water heater and cooling component. Cole was responsible for the implementation of the system's pumps and the analysis and design of the skid. Ben was in charge of the system's heat exchanger as well as the injection of chemicals into the system. Although each member of the team was assigned specific tasks, each member conferred their design with the rest of the team.

The team gathered and documented all pertinent information and project progress using Google Groups, allowing instant access to the latest updates. The final system assembly will be completed by May 10, 2010. A more detailed system team project schedule with a list of tasks, and the time designated for each task, can be found in Appendix B.

5.0 System Design Considerations

5.1 Method of Approach

In the process of designing the flow loop simulator, the typical design process was followed. The sub-teams conducted research to learn more about similar systems and the various components used in the system, brainstormed ideas for different piping schematics and system layouts, and performed appropriate analysis to verify the design.

The research began with finding out more about the old Flow Loop Simulator and other similar systems. A detailed system schematic of the inoperable simulator illustrating the various loops with main components and control valves was provided by PG&E, and is included as Appendix C. This full scale system was a valuable resource because it served as an appropriate example of the common materials used, methods of attachment and support, piping layout, valve and controller placement, as well as typical component sizes technicians will see in the power plant.

Similarly, a sample schematic from a flow loop simulator used by Cooper Nuclear Station in Brownville, Nebraska was provided by PG&E as well, and is included as Appendix D. In the schematic, two pumps circulate water through a sophisticated system of piping, controllers, and various valves. The complicated controls and instrumentation devices allow for numerous bypass loops and related features helpful for technician operation and maintenance training.

These schematics formed an initial starting point and basis for the design of the new Flow Loop Simulator. These piping schematics coupled with the engineering specifications helped direct the research of the individual components of the system such as the heat exchanger, pumps, and valves. The

piping schematics and the engineering specifications also helped with brainstorming several new piping schematics connecting the system's major components.

The two-dimensional piping schematic was then turned into a three-dimensional system layout of the Flow Loop Simulator using SolidWorks modeling software. The three-dimensional model was constructed to provide an accurate visual representation of how the components will be laid out and how the manual valves will be arranged with respect to the surrounding components. The three-dimensional model was also beneficial for designing the skid and allowed a more complete analysis of the system. For example, knowing the lengths, heights, turns, and valves of the piping was necessary to calculate the head needed by the pump for the determined flow rate for optimal design.

In addition to the development of the piping schematic and system layout, system characteristics were also created to bridge the design requirements and overall function of the simulator. These characteristics can be found in the section that follows. Characteristics of note include a maximum fluid temperature of 100°F and maximum working pressure of 110 psi. These were developed to ensure operator safety in the possible event of a failure. Also, a reasonable fill and drain time for a tank was established to eliminate the possibility of a dry running pump during draining or tank level control. With this in mind, a prospective drain time of seven minutes was chosen.

With a drain time established, a flow rate could then be determined based on tank capacity. Initially, the tanks to be used for the new simulator would be from the old simulator which each had a capacity of 350 gallons. Assuming a full tank and a drain time of seven minutes, a flow rate of 50 gpm was determined. The flow rate was then used to analyze the pump specifications according to principles of fluid mechanics and used to analyze the heat transfer required by the heat exchanger, heating component, and cooling component based on the respective temperature differences.

Unfortunately, several problems arose based on the design flow rate. First, a pump designed for a 50 gpm flow rate is very small compared to the pumps used in the power plant. For example, the pumps used in the old simulator were considered full-sized and were capable of outputting approximately 700 gpm. Second, 50 gpm pumps and other components have inlets and exits much smaller than the 4 in. nominal size, which was the smallest diameter pipe used in the plant that maintains a full size feel. This would require numerous expansion and contraction couplings. Third, the economic fluid velocity range for 4 in. pipe is approximately 4 - 8 ft/sec and a flow rate of 50 gpm produces a flow velocity of approximately 1 ft/sec.

Possible solutions were explored in attempt to use a full-size pump, but reduce the flow down to 50 gpm. One solution consisted of the implementation of a pressure reducer immediately after the pump outlet. In addition, significantly trimming down the pump impeller diameter was also researched as a possible solution to decrease flow rate of a full-size pump. Lastly, reducing the nominal piping size was also consideration, but would cause the simulator to lose the desired full-size feel.

Finally, it was decided to simply increase the design flow rate of the system to employ the full capabilities of a full-size pump and increase the fluid velocity into the economic fluid velocity range. A new design flow rate of 200 gpm was chosen, yielding an average fluid velocity of approximately 5 ft/sec for 4 in. nominal pipe. In addition, the larger pumps also typically have 3 and 4 in. inlets and exits, which is more appropriate for the desired piping size to be used throughout.

To the effect of increasing the design flow rate required, the remaining components also grew in overall capacity. Re-evaluating the drain time criteria, a tank size of approximately 1000 gallons was determined appropriate, as the fill and drain time remained reasonable at approximately five minutes.

5.2 System Characteristics

The Flow Loop Simulator has specific characteristics that describe the system which are designed to ensure the system meets the PG&E engineering specifications. The system characteristics are as follows:

1) Water is the working fluid
2) Two loops
    a. Maximum temperature in the hot loop = 100°F
    b. Minimum temperature in the cold loop = Room temperature
3) 200 gallon per minute flow rate
4) 3 pumps
5) 2 tanks (1000 – 1600 gallons)
6) 4 in. nominal pipe diameter
7) Reasonable drain and fill time (2 - 10 minutes)
8) System shall stay within safe operating conditions
    a. Maximum allowable Temperature: 100°F
    b. Maximum allowable pressure: 110psi

6.0 Piping Schematic

6.1 Functional Description of Schematic

The selected piping schematic on the following page illustrates the overall piping layout chosen for the Flow Loop Simulator. The piping connects three pumps, two holding tanks, a shell and tube heat exchanger, and a cooling component to circulate water through a hot loop (red) and a cold loop (blue) comprised of 4 in. steel pipe.

Individually, the hot loop begins at the first holding tank where it is filled with water from a potable source. Inside the tank, the water is heated to 100°F using immersion type heating elements. From the hot holding tank, the water is sucked off the bottom of the tank by one of three centrifugal pumps and sent through the tube side of the shell and tube heat exchanger. The heat exchanger removes heat from the hot fluid thus reducing the fluids temperature to 90°F at the tube side outlet. Completing the hot loop, the fluid flows back to the holding tank where the fluid is reheated.

Similar to the hot loop, the cold loop begins with filling the second tank. Inside the tank, the water is to remain room temperature, assumed to be approximately 70 °F. The second of three centrifugal pumps draws water from the bottom of the large holding tank. The water is then sent through the shell side of the heat exchanger, where it exits with a temperature of approximately 80 °F. A cooling component is implemented after the heat exchanger to bring the cold fluid back to room temperature before returning back into the cold tank. Both tanks are vented to the atmosphere to eliminate the need for pressure vessels.

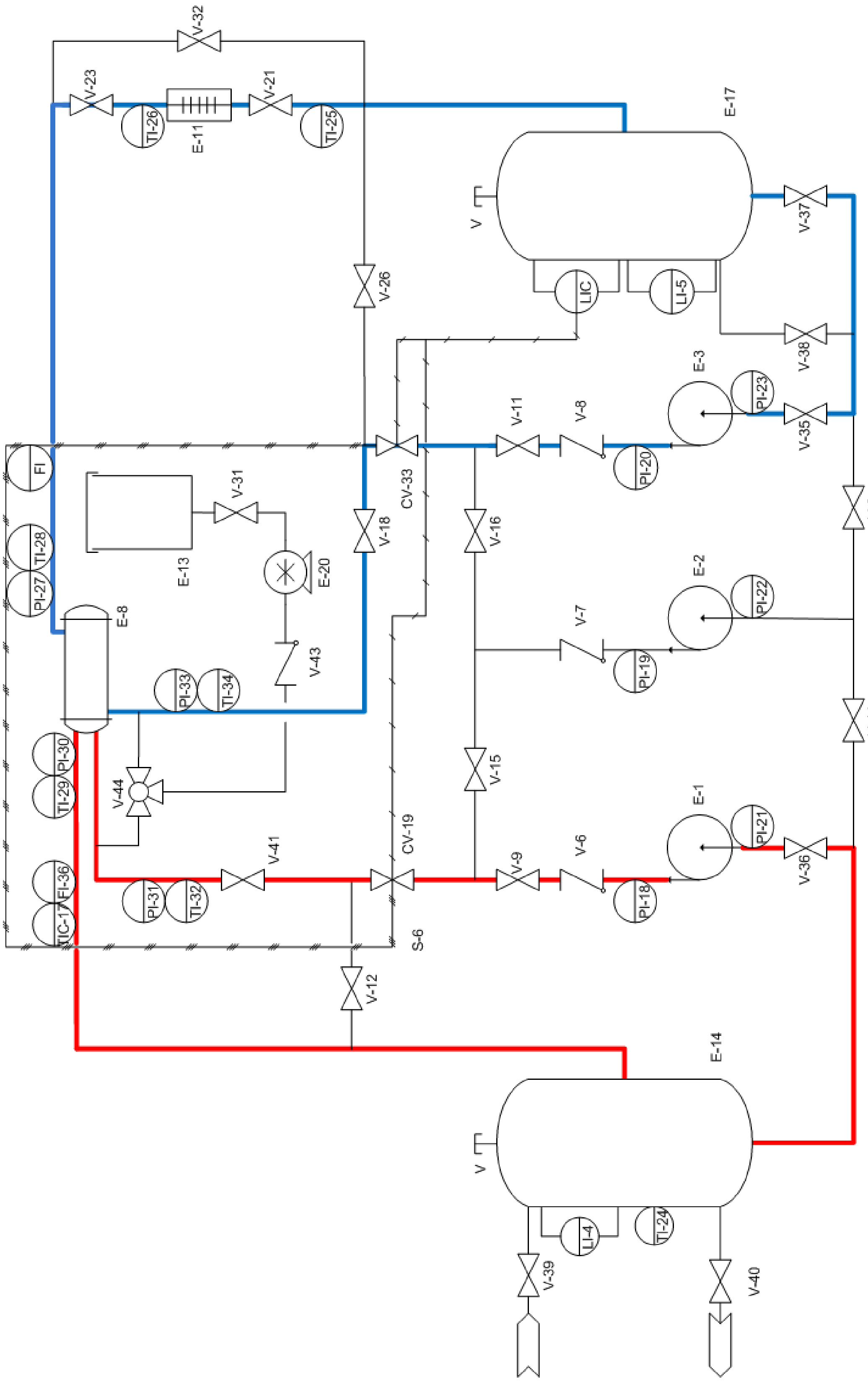

Figure 1: Piping Schematic

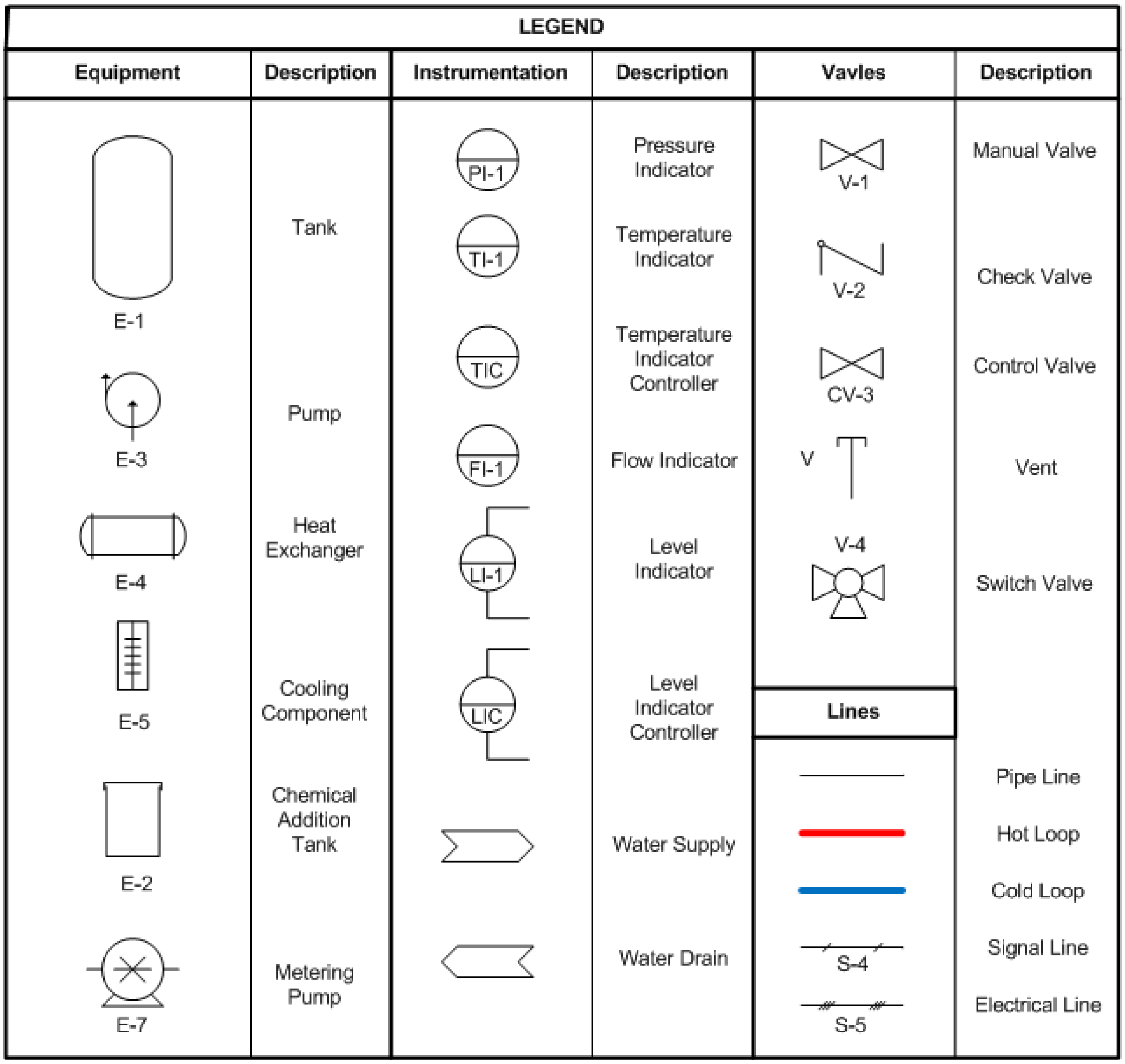

Figure 2: Piping Schematic Legend

A chemical injection system will be implemented to prevent corrosion in the piping and the various components with the chemical treatment of the water. Chemicals can be injected into either hot or cold loop via the chemical addition tank and metering pump. The chemicals would be injected just after the pumps and before the inlet of the heat exchanger. The switch valve connecting the chemical injection tank to the system can be manually adjusted to direct chemicals into the hot loop, cold loop, or both. Anytime a significant amount of new water is added to the system, the manual valve below the tank can be opened to inject the chemicals into the system.

Also depicted in the schematic is a third pump plumbed in parallel with the others and is designed to function as a spare pump for use when the other pumps require maintenance. The third pump may also be used to demonstrate system problems such as vortexing which can have damaging effects and should only be run under this condition for short periods of time.

6.2 Schematic Selection Process

The process for selecting the system piping schematic illustrated in Figure 1 involved several steps. First, several different concepts were brainstormed, each accomplishing the various tasks required. The concept schematics are shown in Appendix E. Analyzing each schematic revealed the desirable and less-desirable elements of each design. A final schematic was then compiled based on the desirable elements from each elementary concept as well as the flexibility in fluid path to perform maintenance and provide system control. Various piping bypasses allow for the ease of maintenance of different piping branches, and provide the capability of continuous operation if one pump was removed. The implementation of system controls also drove the schematic design to allow for proper operation of the simulator as well as offer experiments to enhance technician training.

7.0 System Layout Design

After a detailed system schematic had been developed, a three-dimensional piping layout was constructed using SolidWorks modeling software to provide an accurate representation of the size of the simulator, the packaging of components, and piping networks.

Sections 7.1 – 7.3 below describe the first elementary system concepts developed. An illustration of each layout is provided along with a short description. Similar to the schematic selection process, the final system layout is a combination of the three initial designs. Several illustrations and a detailed description of the final system layout follow in Section 7.4.

7.1 Layout Concept 1

The first system concept shown below is a basic layout with a majority of the piping and components in a single vertical plane that closely resembles the piping schematic. The benefit of the shared resemblance is that translation from the actual system layout to the piping schematic may be easier to comprehend amongst technicians. In addition, mounting the piping is simplified due to the majority of the piping lying in one plane. The open section between the two vertical tanks suggests an entrance point for a technician to access the floor mounted pumps as well as the controls components within the piping network. The disadvantage of this system is that the heat exchanger is placed relatively high which may make it more difficult to access or service.

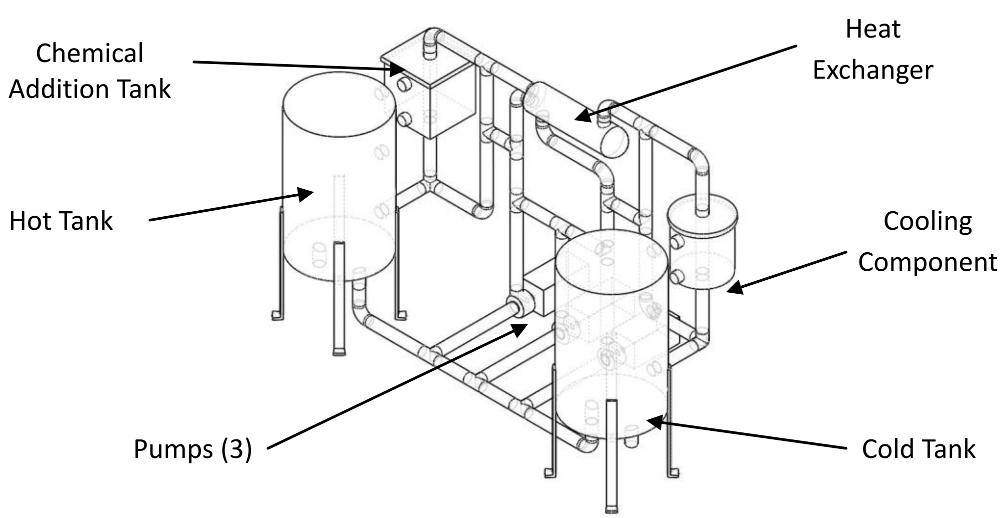

Figure 3: Layout Concept 1

7.2 Layout Concept 2

The second layout concept shown below is similar to the first in component location and overall layout. The piping network, however, is oriented differently by placing numerous sections overhead, rather than vertically. This configuration uses less piping than the first. Unfortunately, the layout obtains a more cramped feel due to the overhead piping sections. In addition, the heat exchanger mounted directly over the pumps obstructs overhead access of a service hoist.

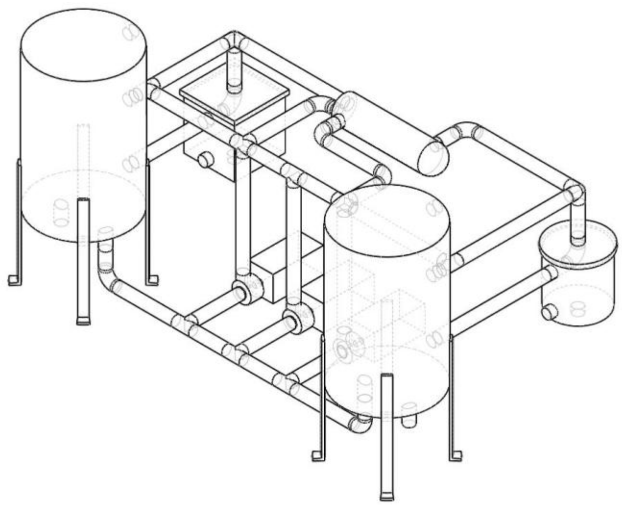

Figure 4: Layout Concept 2

7.3 Layout Concept 3

The third layout concept shown below is a more compact version of Layout Concept 1. This layout has the potential to take up less space by re-orienting the pumps and reducing the total depth of the assembly. The piping network is reworked to place everything in a single vertical plane, making proper mounting possible. In addition, this layout uses the least amount of piping of the three concepts. Accessibility of the pumps, however, may suffer by reducing the overall footprint of the assembly.

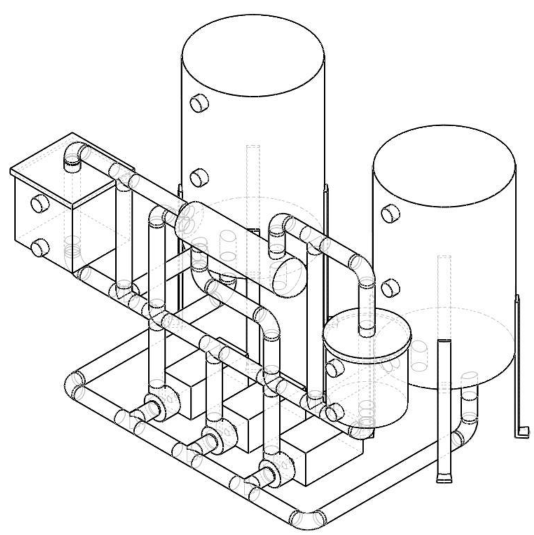

Figure 5: Layout Concept 3

7.4 Final Layout

The fourth and final layout concept developed is displayed in Figure 6. The large variation in appearance compared to the previous three layouts is a result of the increased component sizes. Increased component sizes were a result of quadrupling the design flow rate from 50 gpm to 200 gpm to utilize the capacity of a full-sized pump and 4 in. nominal piping. This final design incorporates some of the advantages from each of the three initial concepts such as, overhead accessible pumps, single plane piping network, and easily accessible controls components. All system components used for the fourth layout meet the design requirements of the system and represent specific products of true size and shape available through PG&E or other outside vendors.

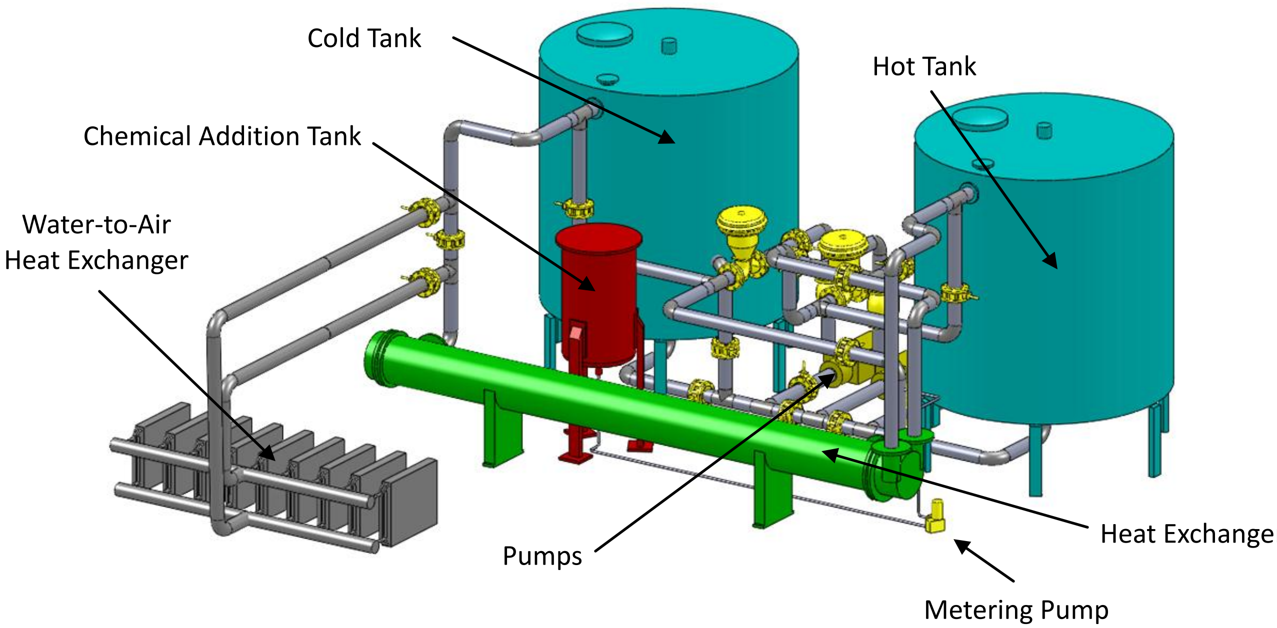

Figure 6: Final Design

Figure 7 below illustrates the front view of the simulator observed when entering the Human Performance Center. This gives the best access to the pumps as well as a clear view of the levels in each of the tanks.

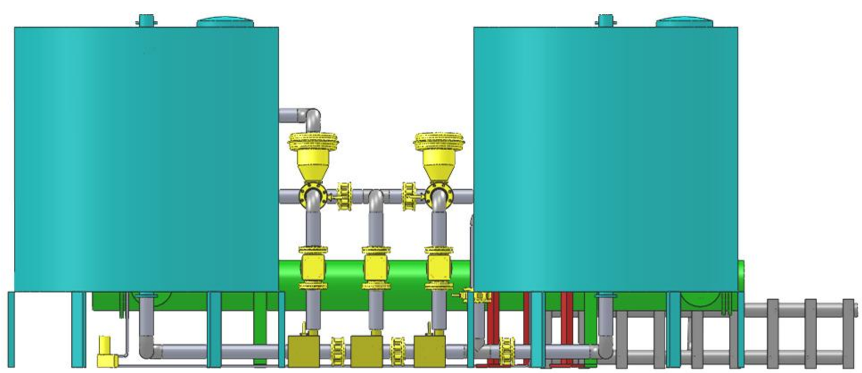

Figure 7: Front View

Figure 8 below shows the top view of the final system layout. Note the absence of any obstructions over top of the pumps. This will allow an overhead hoist to be used if a pump requires removal from the system for maintenance. In addition, the top view also shows the orientation of the piping network. The piping in the upper left hand corner of the figure is actually three separate piping sections that share a vertical plane to simplify pipe mounting and support. Lastly, the series of water-to-air heat exchangers are to be mounted and plumbed outside the Human Performance Center to reduce the systems thermal impact inside the building. Therefore, the heat exchanger sub assembly was modeled away from the simulator.

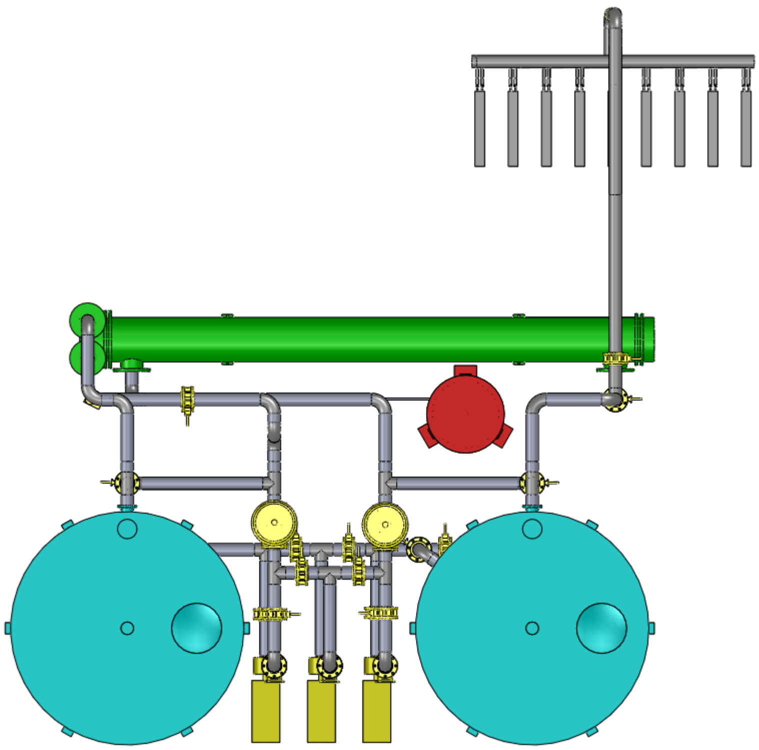

Figure 8: Top View

The side view of the simulator is illustrated on the following page in Figure 9. Due to the 8 ft wide by 10 ft high doorway that the simulator must pass through to get into the Human Performance Center, it was necessary to split the system into two sub assemblies each having their own mounting skid: a primary skid and a secondary skid. The primary skid holds the two tanks and three pumps and some piping. The secondary skid will carry the heat exchanger, the chemical addition tank, and the remainder of the piping. The skids as well as all piping will be flanged at the plane of intersection of the two skids. The water-to-air heat exchangers will mount to an independent skid outside the building.

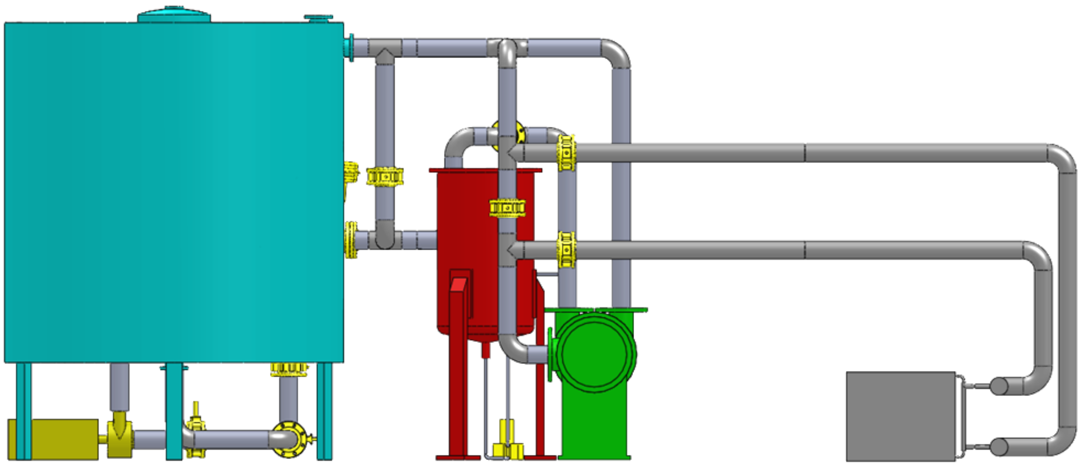

Figure 9: Front View

Figure 10 below shows a frontal isometric view of the completed system with the skid assembly. Note the seam between the primary and secondary skids just after each of the tanks. Also, the accessibility of the pumps is preserved with the absence of structural members in the center opening on the front face of the primary skid. The design of the primary skid places support for the piping system directly above the main piping for the heat exchanger on both the hot and cold loops. Assembly drawings with a complete bill of materials can be found in Appendix F and G.

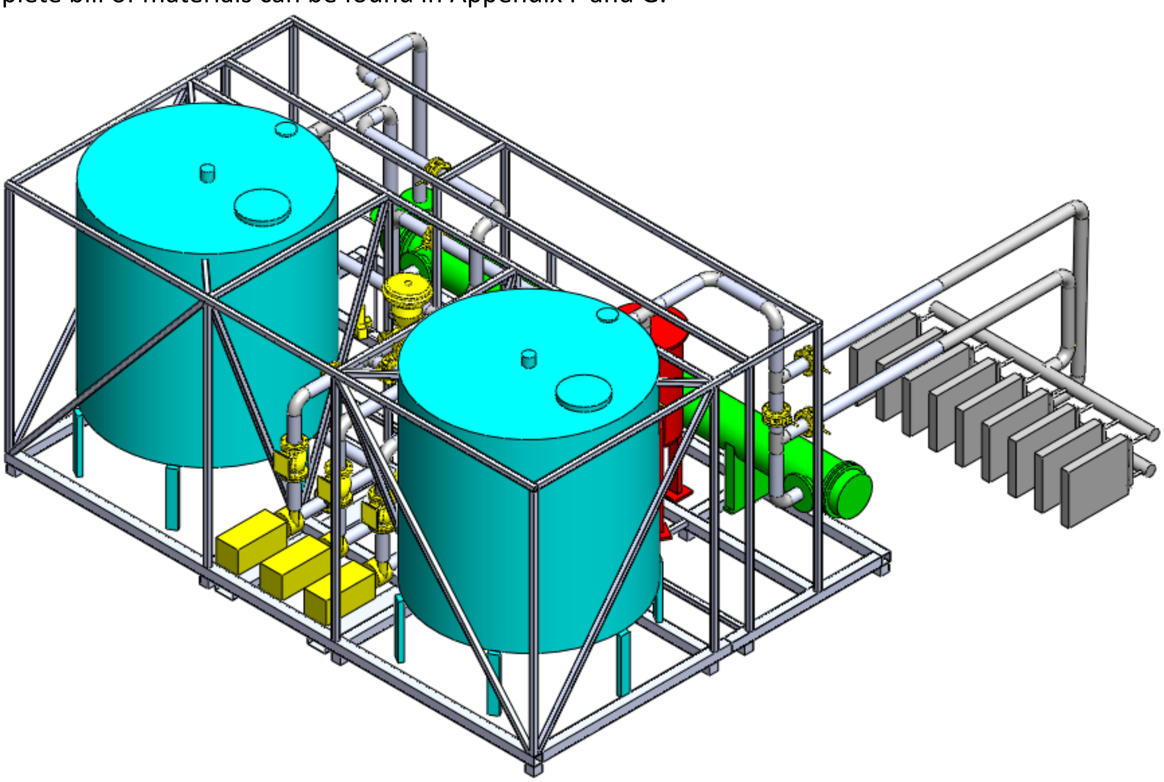

Figure 10: Frontal Isometric View

8.0 System Components

There are several major components desired in the Flow Loop Simulator to accurately simulate the environment a technician will experience in the power plant. The main components are a pump, heat exchanger, water heater, and cooling component. To aid the selection process a cost analysis for each of the components was developed to measure the advantages and disadvantages of the various options as well as to keep track of manufacturers. The complete cost analysis is listed in Appendix H.

8.1 Pumps

8.1.1 Background

Several different types of pumps are used throughout the Diablo Canyon plant. All pumps that handle water as the working fluid are known as centrifugal pumps, and come in two main configurations: horizontal and vertical, with each available as single stage or multi-stage pumps. Horizontal centrifugal pumps can either be end-suction or split case. End-suction pumps have the fluid inlet centered and normal to the pump impeller/motor and discharge the fluid vertically through an outlet in the volute. Split case pumps have a different configuration in that both the fluid inlet and outlet are in line, placing the impeller and motor in between, and perpendicular to the fluid flow path. For the flow loop simulator, a horizontal, end-suction centrifugal pump is ideal for its intended use and packaging configuration.

8.1.2 Analysis

An engineering analysis was required to determine the correct pump based on the system requirements. Sizing a pump for any given system or loop is based on three main characteristics, volumetric flow rate, head, and net positive suction head (NPSH). Head is defined as the total mechanical energy per unit weight of the fluid for a system measured in units of length. Total head at any location in a system is a combination of the head due to static pressure, dynamic pressure, and elevation. For the interest of describing the performance of a system, it is desirable to know the total head loss of the system as a whole. Therefore, it is the job of the pump to overcome the total losses of the system with a given volumetric flow rate. NPSH available is the amount of head available at the pumps suction based on tank height and losses in between the water surface and the pump inlet. This characteristic of the system is to be compared to the NPSH required of the particular pump of interest. It is critical that the available suction head exceeds the required suction head of a pump to prevent cavitation inside the volute.

Similar to total head, total head loss is composed of the total static pressure drop, dynamic pressure drop, and elevation changes of a system as well as major and minor losses. Major losses are due to the friction between the flowing fluid and the internal pipe surface which cause a pressure drop over straight lengths of piping. Minor losses combine all other losses in the system experienced in pipe bends, entrances and exits, valves and fittings, expansions and contractions of the pipes cross-section, as well as anything else that causes a pressure drop.

As discussed earlier, in the case of this system, the flow rate of 200 gpm was determined based on the desire to drain a full 1000 gallon tank in a reasonable five minutes allowing appropriate response time in the event of an unexpected change in the operation of the system. Determining the total head loss of the system, or head to be provided by the pump, was more difficult and required a more extensive engineering analysis.

Engineering Equation Solver (EES) was the computer program of choice to conduct the analysis for its overall simplicity and functionality. Formatted EES equations can be found in Appendix I. The use of EES makes altering specific parameters and recalculating desired solutions easy.

The total head loss analysis first began by generating a simple three-dimensional piping layout involving all components. The three-dimensional layout was necessary to get a general idea of not only how the system will look, but also provide an accurate estimate for how many elbows and tees will be needed for each loop, total length of straight piping, elevation changes, and other parameters which contribute to total head loss. The engineering analysis then proceeded with the application of several principles derived from fluid mechanics. Figure 11 below illustrates the analysis assumptions, control volume, and state properties used. A total head of approximately 35 ft is required by the pump by solving the resulting energy equation from state 1 to state 2. Losses include piping elbows, tees, valves, entrances, straight lengths of pipe, and pressure drops in heat exchangers (water-water and water-air). Interestingly, most of the losses were due to the pressure drops in the heat exchanger and air-to-water heat exchangers. The losses associated with the piping were relatively small, as expected with the overall small size of the simulator. The complete analysis can be found in the Appendix I.

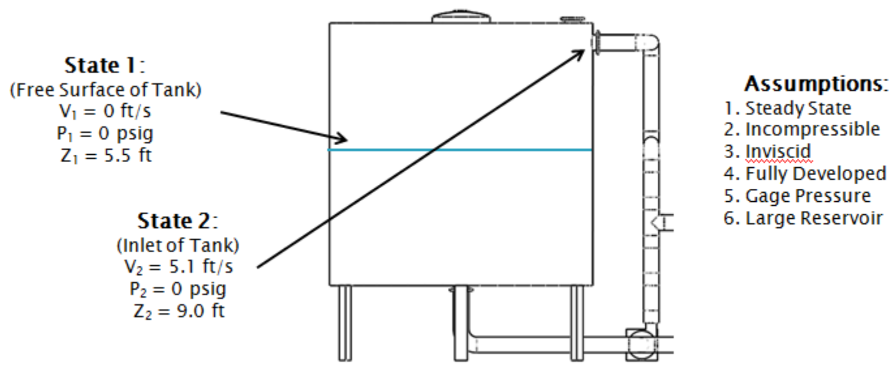

Figure 11: Schematic Used for Total Head Loss Analysis

The NPSH analysis was performed similarly to the total head loss analysis. Figure 12 below illustrates the analysis assumptions, control volume, and state properties used. A positive suction head of approximately 30 ft was determined by solving the modified energy equation. The complete analysis can be found in the Appendix I as well.

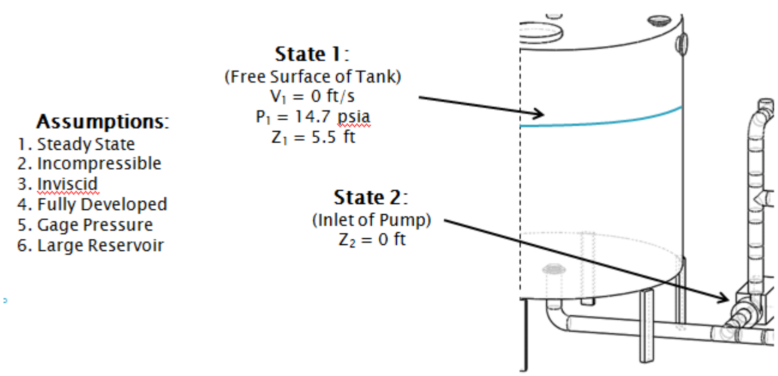

Figure 12: Schematic Used for NPSH Analysis

8.1.3 Selection

Based on the total head loss and NPSH analyses, the system requires the pump to provide approximately 35 ft of head with approximately 30 ft of inlet suction head with a volumetric flow rate of 200 gpm. A Goulds 3656M&L, 3 x 4 – 8 (D impeller) horizontal, end-suction pump is recommended to properly overcome the system losses and operate safely above the required suction head of 4 ft. Figure 13 below illustrates the pump curve for the recommended Goulds pump. Note the estimated operating point.

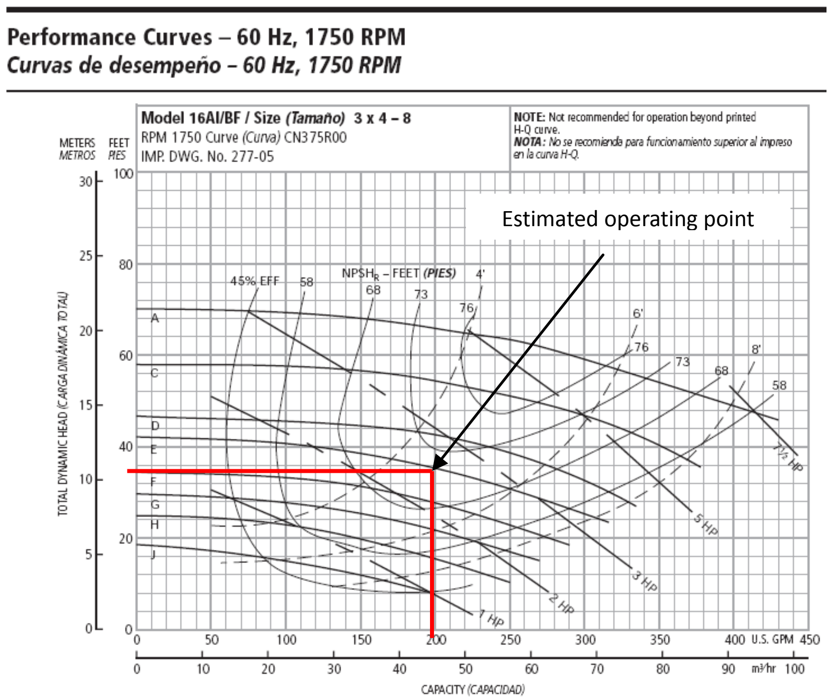

Figure 13: Pump Curve for Goulds 3656 M&L Pump

8.2 Heat Exchanger

8.2.1 Background

Heat exchangers are devices used to transfer heat between two fluids. In most cases, heat is transferred from a higher temperature working fluid to a separate, lower temperature fluid. The resulting heat transfer evacuates a limited amount of heat from a given system. In this case, the "working fluid" is the water circulating throughout the hot loop. The cold loop will contain the cooling fluid, used to transfer the heat out the hot loop.

Several types of heat exchangers were considered when selecting the proper unit for this system. The first type considered was a simple counter flow heat exchanger, which configures the flow paths opposite of one another. Counter flow exchangers have the advantage of being the most efficient in design. The disadvantage is that heat exchangers are often large units requiring lots of space. Another type of heat exchanger considered was a plate and frame heat exchanger. These offer excellent performance in a very small package. The disadvantage, however, is the potential for mixing between the two fluids. While this would not be a significant issue in the system with two water loops, it is also a poor representation of what is commonly found in the plant. The final heat exchanger type considered was the shell and tube heat exchanger. This type offers excellent performance as well, and has the ability to

operate at nearly the same efficiency as the counter flow heat exchanger without taking up the same amount of space. In addition, the shell and tube heat exchanger configuration is commonly used in industry as well as the plant.

In general heat exchanger selection is based on a combination of several key parameters dictating the overall size of the unit, such as the rate needed to transfer heat from the hot loop of the system (q), the overall heat transfer coefficient (U), and the overall heat transfer area (A). Knowing these parameters will allow for the correct heat exchanger for this application to be determined.

8.2.2 Analysis

To determine the key parameters of the shell and tube heat exchanger, Engineering Equation Solver (EES) was used to perform the required analysis. Expanding upon the engineering specifications previously determined, the system is designed to operate with a temperature difference of 10°F across the hot side of the heat exchanger. With a maximum temperature of 100 °F entering the inlet of the tube-side of the heat exchanger, the temperature exiting the tube side is 90 °F. Similarly the inlet of the shell-side is estimated to be 70 °F based on an assumed room temperature. The analysis was conducted based on this temperature difference to determine the necessary heat transfer, q, as well as the temperature at the exit of the shell-side.

The amount of energy to be transferred to maintain a temperature change of 10 °F in the hot loop can be calculated using the equation:

$$q = \dot{m} c_p (T_{h,i} - T_{h,e})$$

Where q is the rate at which energy is transferred from the working fluid, $\dot{m}$ is the fluid flow rate in lb_m/s, $T_{h,i}$ is the tube-side inlet temperature, $T_{h,e}$ is the tube-side outlet temperature, and C_p is the specific heat of water evaluated at the average of the inlet and outlet temperatures. The rate of heat transfer was calculated to be approximately 1,000,000 Btu/hr based on the flow rate and temperature drop specified. This heat transfer rate was used to determine the overall size of the heat exchanger.

8.2.3 Selection

The Westinghouse 16A8149 shell and tube heat exchanger is recommended based on the engineering analysis described above. This particular model is suggested for use in the simulator because the unit is already owned by the plant but is not currently used. To verify the Westinghouse exchanger was in fact suitable for the simulator, additional calculations were performed.

The log mean temperature difference method was used to evaluate the exchanger's actual behavior. This method uses an effectiveness factor to scale the unit's performance relative to a true cross flow heat exchanger. In addition, the effects of fouling were evaluated by adjusting the overall heat transfer coefficient to ensure that as the heat exchanger ages; its performance will still meet the heat transfer requirements of the system. Finally, the effectiveness NTU method was used to ensure that the actual temperature differences meet initial predictions. The resulting analysis from EES can be found in Appendix J.

8.3 Heating Component

8.3.1 Background

To generate the elevated temperature of the hot loop, a heating component was required. The simulator was designed to incorporate a large holding tank for room temperature water to be heated to the target temperature of 100 °F. To achieve this design requirement, two heating options were explored, commercial water heaters and immersion type heating elements submerged in the tank body.

Commercial water heaters are commonly found in residential dwellings and operate off natural gas or electricity. Unfortunately, these water heaters are designed for flow rates of about 3 - 5 gpm, which is much slower than the desired design flow rate of 200 gpm. The other heating option considered was immersion type heating elements. Immersion heaters are basically resistance heaters that protrude inward into the contents of the tank. The immersion heaters can be attached to the tank body by either a threaded mount or flange mount. These heaters are 3-phase and capable of running on 480 VAC.

8.3.2 Analysis

The size of the heating element required can be determined based on the steady state operating conditions and initial start up time of the simulator. Steady state operating conditions require the heaters to maintain a tank exit temperature of 100 °F with 90°F water continuously returning from the heat exchanger. For any closed system operating at steady state with a negligible change in height and velocity and no work being done on the fluid, the following equation can be used to describe the system:

$$\dot{Q}_{cv} = \dot{m}_{H20}(h_{exit} - h_{inlet})$$

This equation relates the required heat transfer rate, $\dot{Q}_{cv}$, to the mass flow rate, $\dot{m}_{H20}$ (200 gpm), and the difference between the enthalpy, h, of the water at the exit (100°F) and inlet (90°F) of the tank at atmospheric pressure. The calculated required heat transfer rate based on these parameters is approximately 1,000,000 Btu/hr, or 292 kW.

Initial start up time was considered to estimate the total time the heaters require to heat an entire tank of room temperature water to 100°F. The startup time resulting from this heat transfer capacity was calculated using another form of the same equation:

$$t = m_{H20} * (h_{final} - h_{initial})/\dot{Q}_{cv}$$

An immersion heater configuration heating 500 gallons of water from an initial temperature of 50°F to a final temperature of 100°F at a rate of 1,000,000 Btu/hr will take thirteen minutes, which is a reasonable wait time. The complete EES file for the immersion heater analysis can be found in Appendix K.

8.3.3 Selection

There are several different immersion heater configurations available. The output capacity of an immersion heater is based on its diameter and length. A few manufacturers offer industrial sized heaters that would be appropriate for our system considering the amount of heat transfer required. These immersion heaters can cost a few thousand dollars. A comparison of these options can be seen in the Cost Analysis in Appendix K. Two 150 kW Gaumer Process immersion heaters, model number 6F15N40M2U, are recommended.

8.4 Cooling Component

8.4.1 Background

A cooling component is required to maintain the water temperature of the cold loop by rejecting heat to the environment. Without the cooling component the cold loop would eventually heat up to the hot loop temperature due to the heat transferred by the heat exchanger. This problem would eliminate the function of the heat exchanger and cease to provide technicians with an experience that simulates real power plant conditions. Possible options for the cooling component include a radiator, cooling tower, and water-to-air heat exchanger.

8.4.2 Analysis

The cooling component required basic analysis to determine the heat transfer rate need to cool the water from 80°F back down to 70°F. This analysis used methodology very similar to the analysis performed for the heating component and resulted in a heat transfer rate of 1,000,000 Btu/hr needed. The complete cooling component analysis can be found in Appendix L.

The complete cooling component analysis also includes an over estimation of the analysis for the radiator heat transfer rate as well as analysis for the design of the configuration of the nine water-to-air heat exchangers. The distance between the water-to-air heat exchangers needed to be analyzed to insure that the thermal plume of hot air rising near the heat exchanger is less than half the distance between the heat exchangers so that the plumes do not coincide, which would reduce the heat transfer rate. Although the calculation is for the moving air, the Prandtl number, relating momentum diffusivity to thermal diffusivity, is approximately 1 for air. Because of this, the thickness of the thermal boundary layer can be assumed to be the same as the thickness of the air plume.

The piping configuration also needed to be checked to determine whether the pressure drop difference between the path of least resistance and the path of most resistance would cause a considerable velocity difference. Although the pressure drop difference was relatively insignificant compared to the entire system, the pressure drop was enough to significantly decrease the water velocity through the path with the most resistance. This means that if the heat exchangers have a piping configuration that has different flow paths with slightly different resistances, or losses, then the heat exchangers with the most resistive path will not experience the same flow rates as the least resistive paths, thereby decreasing their effectiveness.

8.4.3 Selection

Part availability in the warehouse is still currently being looked to as a possible solution to cool the cold loop. If PG&E does not have any available parts with the required capacity other possible solutions include a radiator, cooling tower, and water-to-air heat exchanger from external suppliers.

The first option is a Trantech radiator available in the warehouse that is designed for oil and would do a poor job of rejecting heat from water. Basic calculations for the radiator were done assuming greater heat transfer capacity characteristics, however, the total heat transfer rate of the radiator was still substantially less than the required heat transfer rate. A large number of the transformer radiators would be required to transfer heat from the system making the radiator a poor selection.

One option for the cooling component is a set of nine water-to-air heat exchangers in parallel. The heat exchangers, made by CT Wood Furnace, each dissipate over 100,000 Btu/hr at a flow rate of over 20 gpm. However, these heat exchangers are made of copper tubing and would have an unacceptably short

life if used outdoors as intended. Another option is aluminum car radiators with fans. The feasibility of this option is uncertain because the heat conductance of car radiators is specified by the capacity of the engine which is not useful for this application.

The current best option for the cooling component is a set of nine water-to-air heat exchangers in parallel, each dissipating over 100,000 Btu/hr at a flow rate of over 20 gpm. These heat exchangers are manufactured by CT Wood Furnace and provide the most cost effective, simple solution.

8.5 Tanks

8.5.1 Background

Two water storage tanks are required for the system to supply the fluid for each of the two loops. The two tanks will be able to hold at least 1000 gallons. However, while the system is being run at normal operating conditions the tanks will only be partially filled. With the tanks partially filled, technicians can observe water level. Also, the tanks will be vented to the atmosphere to reduce safety concerns with a pressurized vessel as well as reducing the complexity of the system by eliminating the need for an expansion tank. The tanks will be slightly raised to ensure that there is enough NPSH available to the pumps as discussed in the pump analysis section.

Ideally the inlet to the tanks will be just below the water level. This is dependent on the inlet/exit configuration of the tank selected. It is important for the inlet to be below the water level to reduce the amount of mixing in the tank and eliminate the chance of air entrainment. However, in the case of water entering the tanks at the top, the problems associated with air entrainment will be reduced due to the size of the tank. The exit from the tank will be at the center of the bottom of the tank. The tank material will preferably be stainless steel to provide enough support for the immersion heaters and to be easily welded with pipe.

8.5.2 Selection

There are many different tanks available online with a large range of sizes and pricing. Each option will be considered to make sure the optimum tanks are used for the design. A 1480 gallon tank from Aaron Equipment Company, stock number 42196001, is recommended. A complete list of the tanks considered can be found in the Cost Analysis in Appendix H.

8.6 Chemical Addition Tank

8.6.1 Background

A chemical addition tank is a necessary component of the system that provides chemicals to treat the water eliminating the effects of corrosion as well as eliminating any culture growth in the system. The tank will have a bolted cover that can be removed to manually add chemicals to the tank and only have one exit at the bottom from which the metering pump will draw the chemicals out.

8.6.2 Selection

The recommended chemical addition tank is a type 304 stainless steel tank available through McMaster.com. The recommended tank has a 16 gauge wall thickness, a 1 in. outer diameter drain tube, and an 80 gallon capacity, but smaller size options are available. McMaster-Carr offers an option for standard or sanitary tanks of the same specifications. The standard tank has part number 3772K74 and cost $1815.56. The sanitary tank has part number 3772K64 and cost $2061.28. The internet site

Machinery & Equipment, Inc. also offers another possible chemical addition tank with part number S735176.

8.7 Chemical Metering Pump

8.7.1 Background

The chemical metering pump is used to draw the chemicals from the chemical addition tank and inject them into the system. The chemicals will be injected into the system after the pumps and before the heat exchanger inlets in a similar location as the old Flow Loop Simulator. The water will have high pressure at these locations relative to the rest of the system which is typical for many types of chemical injection. The metering pump uses a diaphragm to control the fluid inside the pump and inject chemicals repeatedly in small amounts.

8.7.2 Selection

The chemical metering pump recommended for the Flow Loop Simulator is the Milton Roy model A. This metering pump is commonly used in the power plant giving technicians valuable hands on experience. The pump will also be made available through the PG&E warehouse.

8.8 UV Filter

8.8.1 Background

A UV filter functions as an additional water sanitizing process to the chemical addition tank. The UV filter operates by running water through a thin tube across a UV light which shines light in the 10-400nm wavelength range. This range is special because it eliminates 99.9% of bacteria.

8.8.2 Selection

The UV filter would be implemented within either the hot loop, cold loop, or both loops of the Flow Loop Simulator. This means that the UV filter would have to be designed to handle a flow rate of 200 gpm. Research on UV filters to this point shows that these UV filters are very expensive, costing as much as $17,150. UV filters also require continual maintenance and replacement of the UV light bulbs to maintain effectiveness. This combination of factors indicates that the UV filter will have more costs then benefits. The Flow Loop Simulator is recommended to rely on the chemical injection system alone for preventing corrosion and bacteria growth.

8.9 Skid

8.9.1 Background

The flow loop simulator is intended to operate as a stand-alone system requiring nothing more than connection to simple utilities (electricity and water supply) to function. The simulator is also to be manufactured at a remote build site and transported to the plant facility. To achieve this, all components must be mounted to a single structure or frame, known as a skid, which complements the systems functionality as well as maintains the systems rigidity when transportation is required. Due to the large size of the simulator and transportation constraints, the system and mounting skid will split into two skids, primary and secondary. The main skid will house holding tanks, three centrifugal pumps, and some piping as well as several valves, including the two control valves. The heat exchanger, chemical additional tank, and the remaining piping comprise the secondary skid.

Each component of the system will be rigidly mounted to the skid in the proper location according to the system design and then the skid may be mounted to the shop floor if desired. Several different types of mounting methods will interface between the system components and the skid frame, such as, bolted connections, mounting plates, u-bolts, and snubbers. For components such as the tanks and heat exchanger, bolted connections will be primarily used to mount to the skid. The pumps will sit on a thick mounting plate to allow alignment of the pump impeller and the motor shaft. Numerous piping flanges will be used in between system components, valves, and piping lengths. To support long lengths of piping, u-bolts, spring cans, and other rigid mounts will be employed to prevent deflection and failure of piping joints.

Being that the flow loop simulator will be built on Cal Poly campus, the ability to easily transport the simulator is mandatory. Due to the large size of many of the components, the overall size and weight of the system presents a concern for the stiffness of the skid when transportation is required. Skid design focuses primarily to resist overall deflection of the skid structure when lifted for transportation. This becomes extremely important due to the large runs of piping that are welded together.

8.9.2 Analysis

As discussed above, the overall skid design is driven by the need to limit deflection when transportation of the system is required. When on flat ground, the skid does not require large boxed steel members or a truss frame to support the weight of the systems components. However, when the system is to be lifted by a forklift in transportation, deflection becomes a major issue. Of the two skids, the primary skid receives most of the focus due to its long length of approximately 20 ft, a tank weight of approximately 2000 lbs each, and the use of a forklift to transport the assembly.

A simple analysis was performed to calculate deflection based on an estimated material size. The schematic illustrated in Figure 14 below displays the overall design of the primary skid and includes the major applied loads.

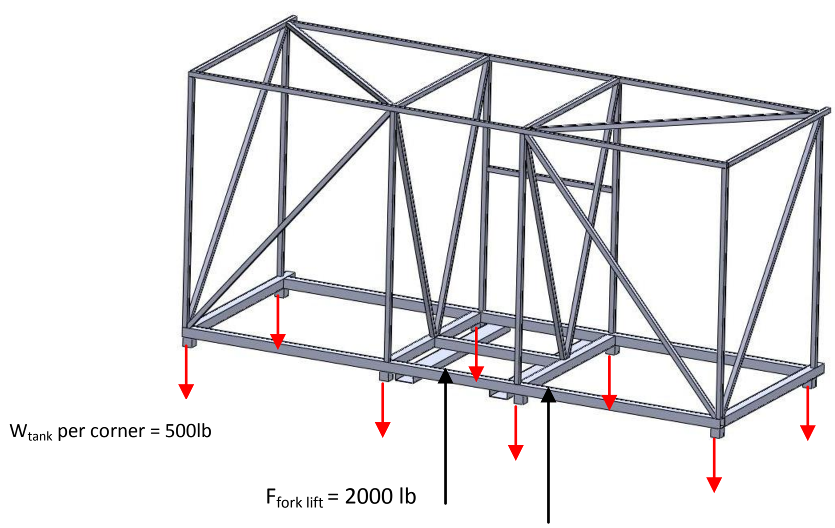

Figure 14: Primary Skid Design with Applied Loading When Lifted

In an effort to predict deflection, a simplified finite element model was developed in Abaqus/CAE. To verify the accuracy of the resulting deflection, a closed form analysis calculating axial stress in selected

members was performed and then compared with the model results. The closed form analysis consisted of a simple statics analysis to calculate the axial force in each member of the truss. Axial stress was then calculated for the members with the highest axial load based on the same estimated material sizes used in the model. Comparing the two methods resulted in less than 5% difference in stress, therefore, the deflection predicted by the finite element model is considered accurate. The resulting maximum stress was also compared against the material's (steel) yield strength and revealed that failure in each member due to stress is not a concern.

Using the finite element model, material profiles were then iterated to minimize material size, as well as minimize total deflection. Model results and a deformed plot are displayed in Figure 15 below. A maximum vertical deflection of approximately 0.04 in. was predicted. Note that the model represents only half of the primary skid's profile, and symmetry constraints were assigned to obtain deformation behavior of the entire structure. The sharp deformation seen on the lower right hand corner of the deformation plot is a result of the offset reaction load of the fork lift and the tank load. Note that a large scale factor is used on the plot to amplify distortion.

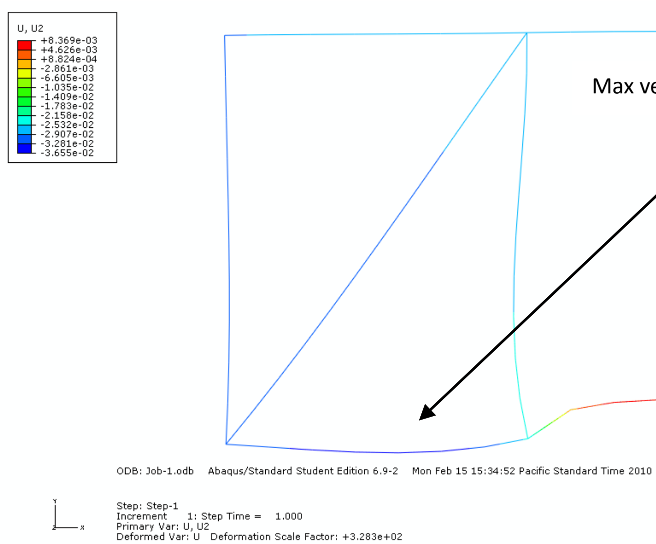

Figure 15: FEA Analysis

8.9.3 Overall Design

After analysis had been performed on a basic concept to verify design and finalize material size, a detailed solid model was drawn in SolidWorks. The materials consist of 4 in. x 0.188 in. wall square steel main beams and 2 in. x 0.120 in. wall square steel truss members. As discussed earlier, the system requires the use of two skids, a primary skid and secondary skid. The two skids will attach to each other via splice plates at four locations. The figures below illustrate the each skid independently as well as an assembly.

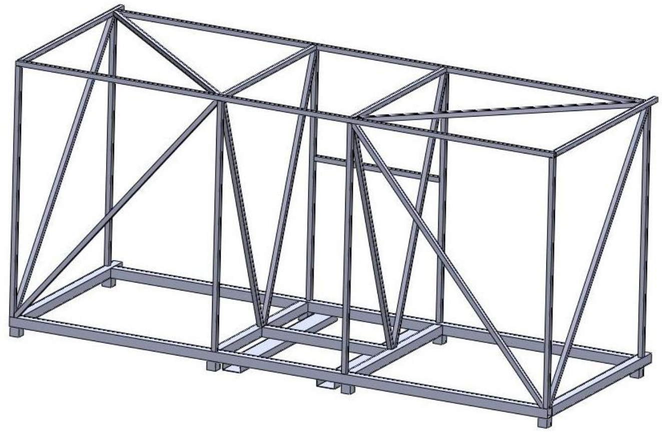

Figure 16: Front Isometric View of Primary Skid

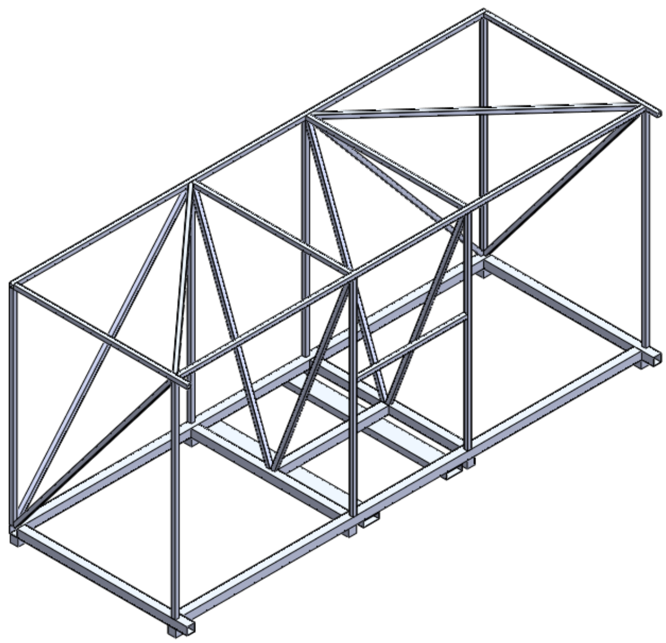

Figure 17: Rear Isometric View of Primary Skid

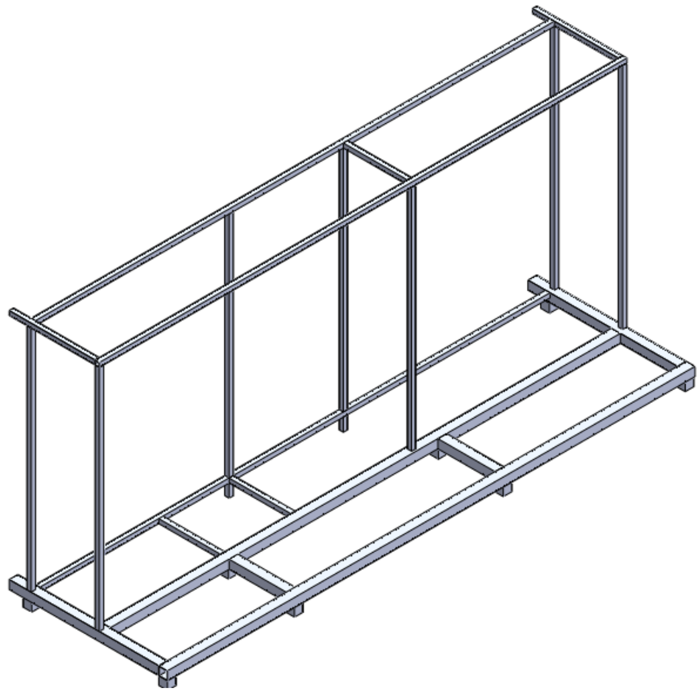

Figure 18: Isometric View of Secondary Skid

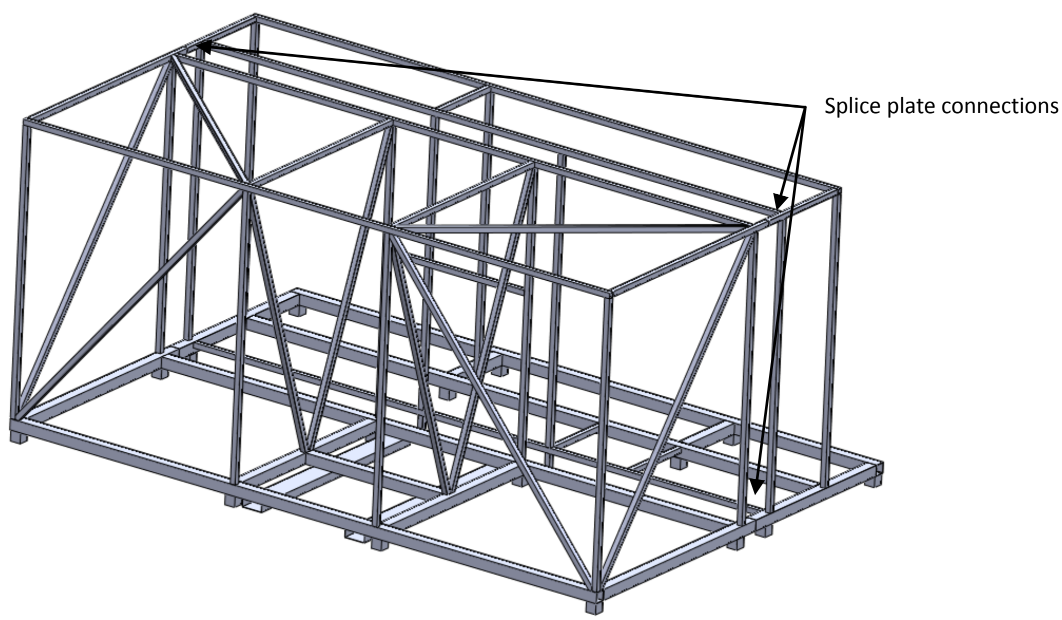

Figure 19: Isometric View of Skid Assembly

All joints on the skid are to be fully welded with plate gussets where appropriate.

9.0 Verification of Engineering Specifications

The selected concept has the desired system components: two flow loops (a hot loop and a cold loop), heat exchanger, tanks, pumps, instrumentation, and controls. The two tanks will be installed with level controllers. The heat exchanger is to be installed and instrumented as specified. There are also many places throughout the system for different types of isolation, check, and control valves essential to exposing the technicians to multiple valve technologies. The simulator also has several locations throughout the system for pressure, temperature, flow, and control instrumentation which is also beneficial for technician training.

10.0 Testing Plans

There are several aspects of the system that must be tested to ensure that the system will operate as designed and to verify that the system meets the engineering specifications of the project. The systems team will test for leaks in the system while also testing the ability of the system to hold pressure up to the specified maximum allowably pressure. The team will also test the cooling component to determine its performance.

10.1 Leak Testing

10.1.1 Objective

The object of testing the piping system for leaks before operation is to ensure the system can be operated safely. The system will be tested for leaks using pressurized air before putting water into the system. Air is safer to work with and also does not require clean up if system leaks are found. Leak testing will follow the Process Industry Practices standard PNE00012. Following this standard, the system, or an isolated portion of the system, is pressurized to 25 psig or half of test pressure. A bubble formation solution is then applied to all applicable welds and fittings. Any leaks found are to be repaired. The test is then repeated at increasing pressure increments of 25% of maximum test pressure or 25 psig until the final pressure is reached. Although our system will only have approximately 15 psi, the system will be tested to 100 psi since this is the maximum allowable pressure in the engineering specifications.

10.1.2 Procedure

1. Isolate section to be tested by installing blank plates or closing gate valves.
2. Fill the system with 25 psig air.
3. Apply the bubble formation solution at all fittings and welds in the test section. Caution must be taken to not form bubbles in solution due to application.
4. Observe solution. If bubbles begin to form make note of leak.
5. Release pressure if leaks are present and repair welds and fittings as necessary.
6. Repeat at the same pressure until no leaks are present.
7. Once no leaks are found at 25 psig, increase the air pressure in 25psig increments and repeat steps 3-6 until 100 psi is reached.

10.1.3 Test Outcomes

This test should allow all system leaks to be identified and insure that the system can safely hold the specified 100 psig. This test will need to be performed for all pipe sections that are fitted together or welded that are not assembled by the manufacturer. Once this test has been successfully completed for the entire system, the system will be considered safe.

10.2 Cooling Component Testing

10.2.1 Objectives

The object of testing the cooling component is to determine its heat transfer capabilities. Understanding the capability of the cooling component will aid in determining the required number of air-to-water heat exchangers required to properly reject the heat produced by the flow loop simulator. This test will require pumping hot water through each heat exchanger while an external fan blows air across. To determine the heat transfer between the water and the air, the inlet and outlet temperature of the water, the flow rate of the water, the flow rate of the air and the inlet temperature of the air will be measured, resulting in the heat rejection capabilities of the subsystem.

10.2.2 Procedure

1. Install cooling component on test stand.
2. Connect cooling component inlet to boiler water using flexible tubing.
3. Connect cooling component outlet to drain using flexible tubing.
4. Install thermocouples in-line with water inlet and outlets.
5. Install rotometer between boiler water supply and cooling component inlet.
6. Install thermocouple between the fan and the cooling component.
7. Connect the power to the fan.
8. Open boiler water supply.
9. Monitor the water temperature at the outlet of the cooling component until it reaches a constant value.
10. When outlet temperature becomes steady take a reading of all temperatures and flow rates.
11. Turn off fan.
12. Close boiler water supply.

10.2.3 Test Outcomes

The result of this experiment is the heat transfer capacity of the cooling component which can be determined based on the following equation.

$$\dot{q} = \dot{m}C_p\left(T_{H_2O,inlet} - T_{H_2O,outlet}\right)$$

The mass flow rate must be calculated from the measured volumetric flow rate and the density of water at the average temperature. Knowing the flow rate and temperature of the air is important to ensure that the radiator will have the same performance when the system is in operation.

11.0 Preliminary Construction Plans

The skid and simulator assembly will be built outside of the Mustang ’60 shop in the Bonderson Engineering Project Center at Cal Poly. This shop has the equipment needed to build the system and also has the advantage of offering more storage space than the hanger, another shop on campus. The Mustang ’60 shop has the latest in welding equipment which will be beneficial when assembling the system.

Construction of the flow loop simulator will begin with the fabrication of both the primary and secondary skids. The implementation of major components will take place simultaneously. For example, due to the large size of the tanks, a forklift will be used to position them into place on the primary skid floor before the vertical members and upper halo are constructed. This will prevent the need for a crane to hoist the tanks in from the top of the skid. Construction is estimated to take place in the following order:

1. Primary skid
2. Tank mounting
3. Pump mounting and laser alignment
4. Secondary skid
5. Heat exchanger mounting
6. Fabrication and mounting of piping network
7. Valve and Electronic component wiring

At this time, the construction plan pertaining to the piping is still in development. Initially, it was desired to have the complete stainless steel piping network TIG welded by a combination of the senior project students and certified pipe fitters from PG&E. Due to the low pressure and low temperatures of the system, thin walled Schedule 10 ASTM 304 stainless is a likely option. Thinner walled piping is more difficult to weld due to the inherent limitation of heat input, but requires less overall passes to complete each joint. An additional option being explored at this time is to use threaded elbows, flanges, and couplings rather than welding. This will dramatically save time as there are an estimated over 100 joints that would require approximately 5 hours each of welding.

12.0 Transportation

The system will be transported from Cal Poly campus to the Human Performance Center on site at the Diablo Canyon Plant. Each skid will be lifted by forklift and placed on to a flat bed trailer. Due to the weight of the primary skid, a large telescoping forklift will be required to successfully place the skids on and off the trailer. A Gradall telescoping forklift with an estimated load capacity of 10,000 lbs is recommended. Once on site, multi-ton rollers will be used to transport the two skids inside the Human Performance Center.

13.0 Manufacturing

Manufacturing of the flow loop simulator proved to be both time consuming and labor intensive on the build team throughout the 9 week build period. Faced with a heavy work load, little previous metal fabrication experience, and limited access time to the Mustang '60 machine shop, the team worked relentlessly, and took advantage of every opportunity to work. The large size of the main framework material required multiple hands to move, cut, position, and fit-up, therefore requiring extra time to achieve the high quality fit-up the build team desired. It was estimated that over 500 man hours were invested to complete the major fabrication of the simulator in approximately 9 weeks.

Both the primary and secondary skid halves were fabricated in similar form, beginning with assembling the base of each upside down, flipping over, then mounting the roof and vertical members (built separate). The skid bases were built upside down to provide the ability to weld each tube joint completely and with proper technique, and allow the mounting of the feet and fork runners. Square and straightness of the skids was achieved through the use of careful measuring, patient tube fit-up, and systematic welding methods. The figures below show the completed progress of the simulator.

Figure 20: Completed progress of primary skid.

Figure 21: Completed progress of secondary skid.

For the most part, the framework was built to the dimensioned design of the engineering models. Some modifications took place mostly in areas that were left still to be determined at the time of the final design report submission. One modification implemented included tank type and overall tank mounting methods. In the search for hot and cold water holding tanks, the availability for existing stainless steel tanks built to the dimensions and capacity designed for became difficult, and revealed a large purchase price for used tanks and expensive shipping costs. Therefore, a change was made to use a plastic tank for the cold water holding tank, which proved cost effective, and in general easier to work with. A schematic was developed to outsource a custom built tank to accommodate the several immersion heaters, and inlet and outlet flanges present on the hot tank. Due to the flat-bottom and absence of mounting feet on the cold tank, a design change was made to place thick gauge steel sheet for the base of the tank to sit on. The hot tank was also to use the same mounting method as the cold tank. Bracing was added under the steel sheet to support the weight of the water during operation. Figure 20 below shows the

In addition to tank mounting modifications, the vertical members of the skid frame were also modified to allow the installation and removal of the tanks. As mentioned earlier, the hot tank design has several flanges protruding outward of the tank body to support the immersion heaters. Due to the large tank diameter and protruding flanges, it was necessary to modify the skid framework to be removable for the tank installation and removal. Using numerous bolted connections, 2 of the four corners of the primary skid (including diagonal bracing) were made removable to allow unobstructed installation of the oversized tanks. The figure below shows the fabricated flanges used. Figure 22 below shows one of four bolted connections implemented.

Figure 22: Bolted connection.

14.0 Testing

14.1 Radiator Test

The radiator test was conducted by filling an arbitrary tank with a mixture of hot and cold water. The water mixture was gravity fed from the tank into the radiator with a shrouded fan. The hot water was discharged from a boiler outside the Cal Poly Thermal Science Lab and cold water was fed using a garden hose. The tank height was approximately 5.5 ft above ground level, the steady state water height was approximately 3 ft from ground level, and the radiator was lifted approximately 1 ft from ground level. The fan was supplied with 12 volts and 11 amps. TCI Auto reports on their website that the 14 in. reversible fan kit used in this experiment operates at 1750 rpm and develops air flow rates between 1250 cfm and 1350 cfm depending on if the air is being pushed or pulled.

In order to measure flow rate, the water was drained continuously into 3 large buckets. The time to fill the buckets was recorded and the weight of the buckets with and without water was also recorded. Data for the mass flow rate through the radiator is recorded below. A total bucket weight of 5.5 lb was subtracted to determine the water weight. It should be noted that minimal, but unavoidable, spilling occurred during trials 2 and 3 and that noticeable spilling occurred during trial 1.

Table 1. Mass Flow Rate Data

Trial	Bucket and Water Weight			Time	Mass Flow Rate		
-	lb	lb	lb	s	lb/hr	lb/s	gpm
1	40.1	40.9	43.8	77	5579	1.55	11.1
2	38.1	37.9	35.2	62	6132	1.70	12.3
3	36.4	39.4	34.2	62	6081	1.69	12.2

Water temperature was measured at the inlet and exit of the radiator. The ambient air temperature going into the radiator was also measured to be approximately 66°F. All temperature measurements were taken using Type-K thermocouples. In the table below, T1 and T2 represent the radiator inlet and exit temperatures respectively. These temperatures were taken at the same time flow measurements were being recorded. Trials 1 through 14 were recorded during the second flow rate measurement and trials 15 through 28 were recorded simultaneously with the third flow rate measurement. The effectiveness-NTU method for heat exchangers was used to analyze the radiator. The effectiveness of the radiator was determined based on the maximum heat transfer rate possible which is based on the following equation:

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

The equation above uses an expression for the minimum heat capacity rate defined by the following equation for the fluid with minimum value of C:

$$C_{min} = \dot{m}c_p$$

The NTU, or Number of heat Transfer Units, can then be determined based on an equation for single pass, cross-flow heat exchangers with both fluids unmixed. The equation for this relationship between effectiveness and NTU is as follows:

$$\varepsilon = 1 - \exp\left[\left(\frac{1}{C_r}\right)(NTU^{0.22})\{exp[-C_r(NTU^{0.78})] - 1\}\right]$$

The overall heat transfer coefficient was then determined by the equation below:

$$NTU = \frac{UA}{C_{min}}$$

Table 2. Temperature Data and NTU Calculations

Trial	T1	T2	E	NTU	UA
-	**°F**	**°F**	**-**	**-**	**Btu/hr-°R**
1	118	110.5	0.4516	0.6741	1318
2	119.8	105.1	0.8556	2.677	5235
3	120.8	105.1	0.8971	3.326	6505
4	120.2	105.4	0.8551	2.670	5222
5	116.0	105.0	0.6889	1.432	2800
6	115.6	111.9	0.2336	0.2822	551
7	115.7	112.4	0.2079	0.2458	480
8	115.4	112.8	0.1648	0.1880	367
9	116.1	112.1	0.2500	0.3063	599
10	115.3	111.8	0.2223	0.2660	520
11	115.2	111.9	0.2100	0.2487	486
12	114.6	112.0	0.1675	0.1915	374
13	115.2	112.0	0.2037	0.2399	469
14	116.7	112.6	0.2532	0.3112	608
15	120.9	105.5	0.8784	2.997	5861
16	121.5	105.1	0.9253	4.007	7836
17	121.6	106.3	0.8617	2.756	5389
18	120.4	105.3	0.8692	2.859	5592
19	121.9	105.0	0.9467	4.809	9403
20	116.3	113.3	0.1868	0.2169	424.2
21	116.5	112.6	0.2418	0.2942	575.3
22	115.2	112.3	0.1846	0.2140	418.5
23	115.1	112.2	0.1850	0.2145	419.4
24	115.3	111.9	0.2160	0.2570	502.6
25	115.1	111.6	0.2232	0.2673	522.7
26	115.4	111.7	0.2345	0.2836	554.5
27	117.5	111.2	0.3831	0.5316	1040
28	113.7	111.5	0.1444	0.1621	317

The data gathered from the test is hard to interpret. For both tests the inlet temperature seems to be generally decreasing. The trend may be due to possible fluctuation in boiler water discharge temperature. All trials were taken sequentially without turning off the boiler or cutting off water supply

to the radiator, but the time gap between the 14th and 15th trials may have been enough time for the boiler to cycle between pulses of hot discharge water. Another unexpected trend is that the exit temperature seems to increase while the inlet temperature is decreasing. This trend is harder to explain and may be due to air flow being blocked by the person recording data from the thermocouples.

All radiator data should also be considered to have some error in the data. A single thermocouple read from a hand held meter measured air to the accuracy of plus or minus 2°F. The difference between two thermocouples in the same device measuring the same air temperature was observed to be as much as 5 °F.

The effectiveness for the radiator was determined to be greater than one for certain measurement points based on the air mass flow rate given by TCI Auto's website. In order for the calculations to be reasonable the air mass flow rate was raised to 1800 cfm. The maximum temperature difference across the radiator resulted in an overall heat transfer coefficient of 9,403 Btu/hr-R and a heat transfer rate of 100,600 Btu/hr. Using the max overall heat transfer coefficient requires 4 radiators to be connected in series to drop the radiator temperature from 110°F to 75°F. In order to keep the flow rate through the radiators similar to the rate observed during the test, 16 set of the series connected radiator need to be connected in parallel. This results in a total of 64 radiators assuming optimal conditions of 66°F air temperature but does not account for losses in the system.

More testing of the radiator may be necessary to yield more steady state results. In order to improve the test a better method for measuring temperature accurately is suggested. Also, a greater steady state tank height should be used to decrease the effect of any fluctuation of boiler temperature. Further testing should be done to determine if connecting radiators in series or parallel yields the predicted results. Another option to improve radiator performance is to select a radiator designed for greater horsepower dissipation.

14.2 Transportation Test

Both the primary and secondary skids were transported from where the skid was constructed for the design expo. The frame was moved using a pallet jack at one end and a forklift on the other end. Both skids passed a preliminary transportation test without failing. Deflection in the primary skid was unnoticeable. Deflection in the secondary skid, however, was significant due to the extreme weight of the heat exchanger. This deflection should be considered when implementing more supports for the piping as a future senior project.

15.0 Final Piping Layout

The final piping layout displayed below is the most accurate design that takes into account the dimensions of the actual components used in the system. The piping is dimensioned in the Appendices for several different critical views. Drawings display the piping dimensions to the faces of flanges, tees, and elbows, however the true length of the pipe adds 1.09 in. for each threaded end. This thread length is the hand tightened distance plus the wrench make-up for 4 in. nominal pipe. A common pipe dimension of 5.91 in. (which is a true length of 8.09 in. if threaded on both ends) is used often because it is the shortest length of pipe that can be threaded using a 4 in. pipe threader. Although piping dimensions are shown accurately in drawings, pump location as well as other components need to be measured as the piping network is being completed.

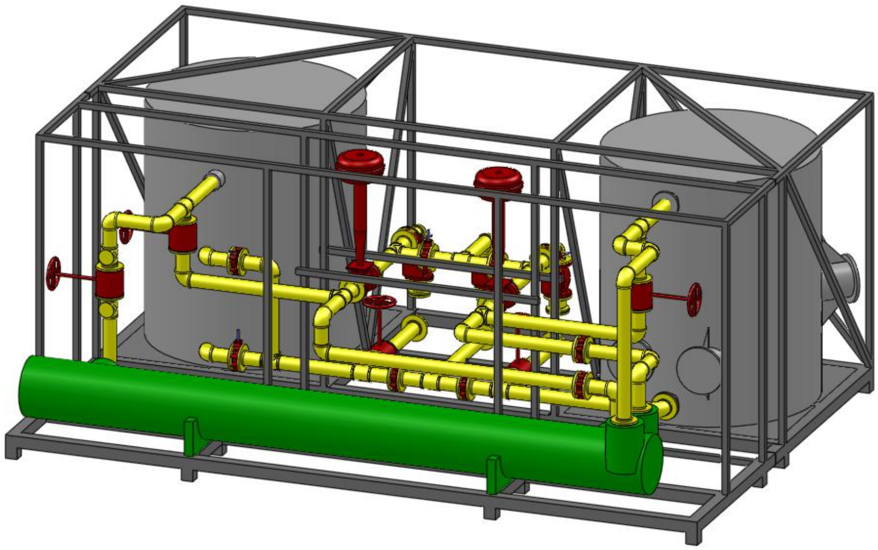

Figure 23: Final Piping Layout

Piping dimensions of 4 in. nominal pipe determined from the piping views (not including thread length) are Found in Appendix S.

The placement of the control valves in the system is difficult due to their size and weight and to ensure that they can be supported. The control valves were placed in between the two skids so that structural beams are close and can provide support. This location would require the control valves to be removed when the skid is transported, however the flanges are then in a good location so that the piping for each skid can be developed independently. The piping layout designed for the pump outlet is still not finalized due to the transition from 3 in. to 4 in. piping which requires a reducer and possibly some welding. This section may change which can be critical because it will change the location of the control valves and may lead to interference with the skid frame.

Additional supports need to be added to the system design to provide the piping support. The chemical addition tank and injection pump piping is not shown in this figure because the the components were not purchased or dimensioned. The radiator component is not shown in this figure either because the design has not been finalized to assure the appropriate heat transfer rate.

The hot tank should be stainless steel and manufactured to the design developed for the system shown below. Instrumentation thermo wells are included in the dimensions. The dimensions for the tank are displayed in the Appendix. The angled flanges are designed to clear the cross-brace supports on the skid frame.

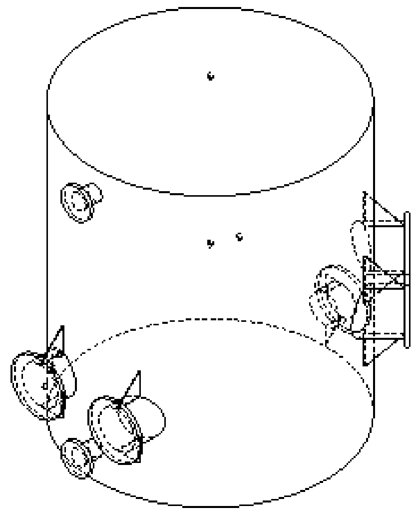

Figure 24: Hot Tank

Heat exchanger flanges still need to be made to go from 4 in. piping to the tube and shell flange sizes. Important dimensions for the tube and shell flanges are as follows:

2 Shell Flanges (Tube Turn 8" 304 SS H7580 DWG 9-H-332)

- OD = 13 1/2"
- ID = 8 3/4"
- Step diameter = 10 1/2"
- Step size = 1/16"
- Bolt circle diameter = 11 3/4"
- Bolt hole diameter = 7/8"
- Flange thickness = 1 1/16"
- Number of bolts = 8

2 Tube Flanges (6" 00 Tube-Line A 181 HCE)

- OD = 12.5"
- ID = 6 3/4"
- Step diameter = 8 1/2"
- Step size = 1/16"
- Bolt circle diameter = 10 1/2"
- Bolt hole diameter = 7/8"
- Flange thickness = 1 7/16"
- Number of bolts = 12

The bolts, nuts, washers, and gaskets required to hold the flanges are as follows:

- 96 Nuts
- 96 Bolts (with length of 2 1/8" + Nut + 2 Washers)
- 352 Washers (160+96x2)
- 160 Bolts (2")
- 24 Gaskets (4" ID, 6 5/8" OD)

16.0 Requirements for Future Completion

Due to the scope and scale of the simulator, there are several things that still need to be done for it to be fully complete. There are several portions of the project that require more detailed analysis to finish the design of the system The system will also require additional fabrication followed by functional testing. Below is a detailed outline of areas requiring additional attention.

16.1 Design and Analysis

- Finish detailed piping layout for use in fabricating piping network. Incorporate drains
- Seismic analysis and design of piping network mounting system
- Additional research and design of water treatment system including a chemical analysis to predict the effects of additives on the stainless steel piping
- Analysis and design of electrical systems and wire routing for major components (heaters and pumps, and valves)

16.2 Manufacturing

- Pumps
    - Weld nuts for motor mounts on underside of motor bases
    - Align pumps and motors on mounting plate. Mark hole locations for each pump
    - Drill holes for pump mounting hardware. Weld nuts on underside of mounting plate for pump mounting hardware
    - Stitch weld pump mounting plate to skid
    - Stitch weld motor mounts to pump mounting plate (Match weld length on top side of motor bases)
    - Fasten pumps and motors
- Tanks
    - Drill holes in cold-tank plates for eye bolts. Tank is to be secured to skid via steel cabling (may require analysis)
    - Hot tank mounting still to be determined
    - Mount heaters in hot tank
- Heat Exchanger
    - Adjust heat exchanger position relative to supports according to piping dimensions or adjust piping dimensions so heat exchanger is balanced of the center of the skid
    - Clean, straighten, and re-install heat exchanger u-bolts (New u-bolts may be required)

    - Replace seals on heat exchanger
    - Re-install end caps on heat exchanger
    - Explore the use of piping reducers going from heat exchanger flanges to 4 in. piping
- Piping
    - Cut and thread piping according to detailed piping layout
    - Mount piping and valves according to analysis
- Instrumentation
    - Attach mounts for instrumentation
    - Install instrumentation
    - Wire instrumentation, pumps and heaters
- Chemical Injection System
    - Fabricate water treatment system and Milton-Roy pump according to design
- Skid
    - Drill secondary skid side of splice plates
    - Attach feet to eventually bolt to the floor in the Learning Center
    - Paint skid

16.3 Testing

- Pressure/leak test of piping network
- Functional test of pumps
- Testing of instrumentation
- Testing of heaters

Appendices

Appendix A: Bibliography

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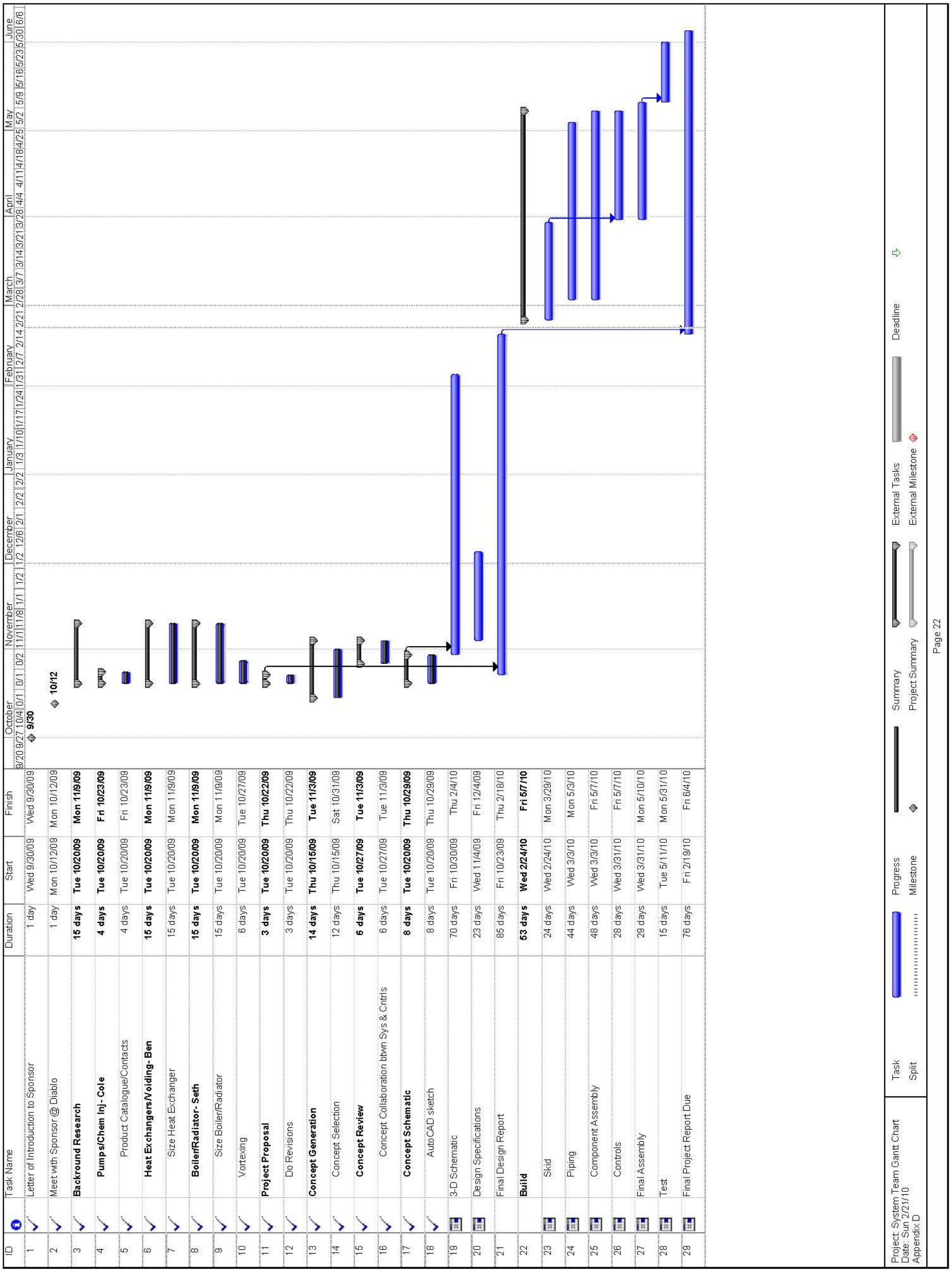
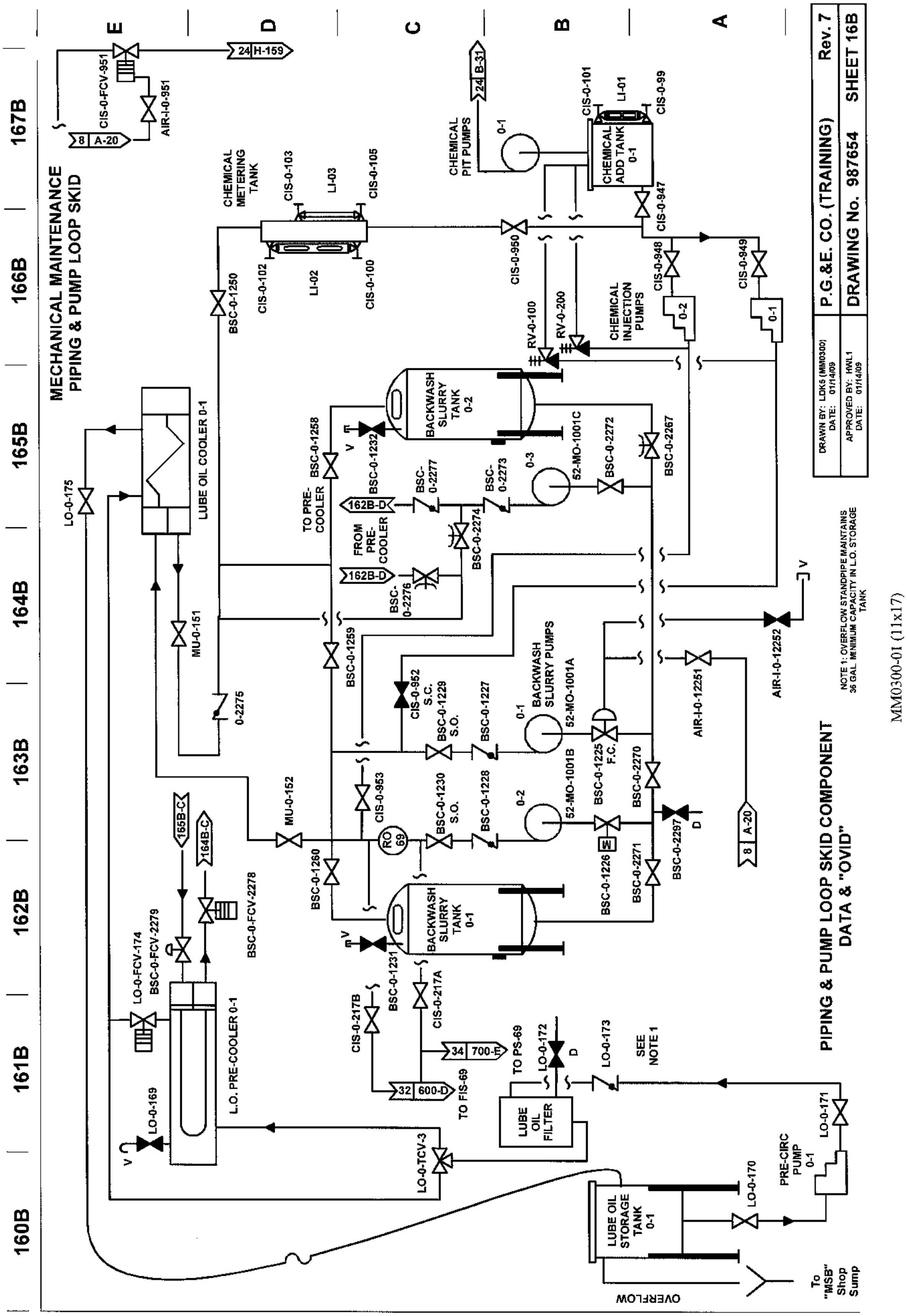
Appendix B: System Team Gantt Chart

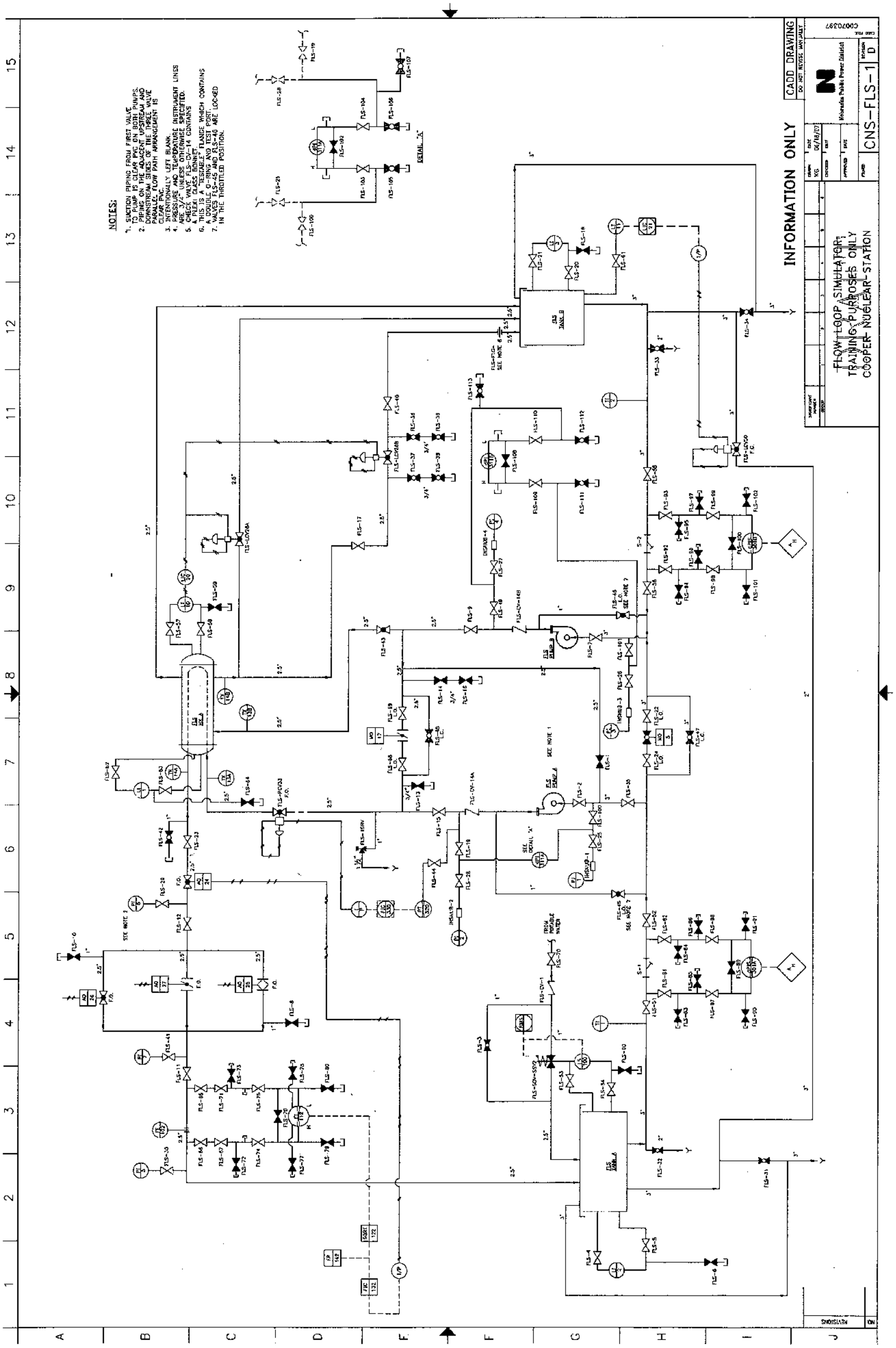


ID	Task Name	Duration	Start	Finish
1	Letter of Introduction to Sponsor	1 day	Wed 9/30/09	Wed 9/30/09
2	Meet with Sponsor @ Diablo	1 day	Mon 10/12/09	Mon 10/12/09
3	**Backround Research**	**15 days**	**Tue 10/20/09**	**Mon 11/9/09**
4	**Pumps/Chem Inj- Cole**	**4 days**	**Tue 10/20/09**	**Fri 10/23/09**
5	Product Catalogue/Contacts	4 days	Tue 10/20/09	Fri 10/23/09
6	**Heat Exchangers/Voiding- Ben**	**15 days**	**Tue 10/20/09**	**Mon 11/9/09**
7	Size Heat Exchanger	15 days	Tue 10/20/09	Mon 11/9/09
8	**Boiler/Radiator- Seth**	**15 days**	**Tue 10/20/09**	**Mon 11/9/09**
9	Size Boiler/Radiator	15 days	Tue 10/20/09	Mon 11/9/09
10	Vortexing	6 days	Tue 10/20/09	Tue 10/27/09
11	**Project Proposal**	**3 days**	**Tue 10/20/09**	**Thu 10/22/09**
12	Do Revisions	3 days	Tue 10/20/09	Thu 10/22/09
13	**Concept Generation**	**14 days**	**Thu 10/15/09**	**Tue 11/3/09**
14	Concept Selection	12 days	Thu 10/15/09	Sat 10/31/09
15	**Concept Review**	**6 days**	**Tue 10/27/09**	**Tue 11/3/09**
16	Concept Collaboration btwn Sys & Cntrls	6 days	Tue 10/27/09	Tue 11/3/09
17	**Concept Schematic**	**8 days**	**Tue 10/20/09**	**Thu 10/29/09**
18	AutoCAD sketch	8 days	Tue 10/20/09	Thu 10/29/09
19	3-D Schematic	70 days	Fri 10/30/09	Thu 2/4/10
20	Design Specifications	23 days	Wed 11/4/09	Fri 12/4/09
21	Final Design Report	85 days	Fri 10/23/09	Thu 2/18/10
22	**Build**	**53 days**	**Wed 2/24/10**	**Fri 5/7/10**
23	Skid	24 days	Wed 2/24/10	Mon 3/29/10
24	Piping	44 days	Wed 3/3/10	Mon 5/3/10
25	Component Assembly	48 days	Wed 3/3/10	Fri 5/7/10
26	Controls	28 days	Wed 3/31/10	Fri 5/7/10
27	Final Assembly	29 days	Wed 3/31/10	Mon 5/10/10
28	Test	15 days	Tue 5/11/10	Mon 5/31/10
29	Final Project Report Due	76 days	Fri 2/19/10	Fri 6/4/10

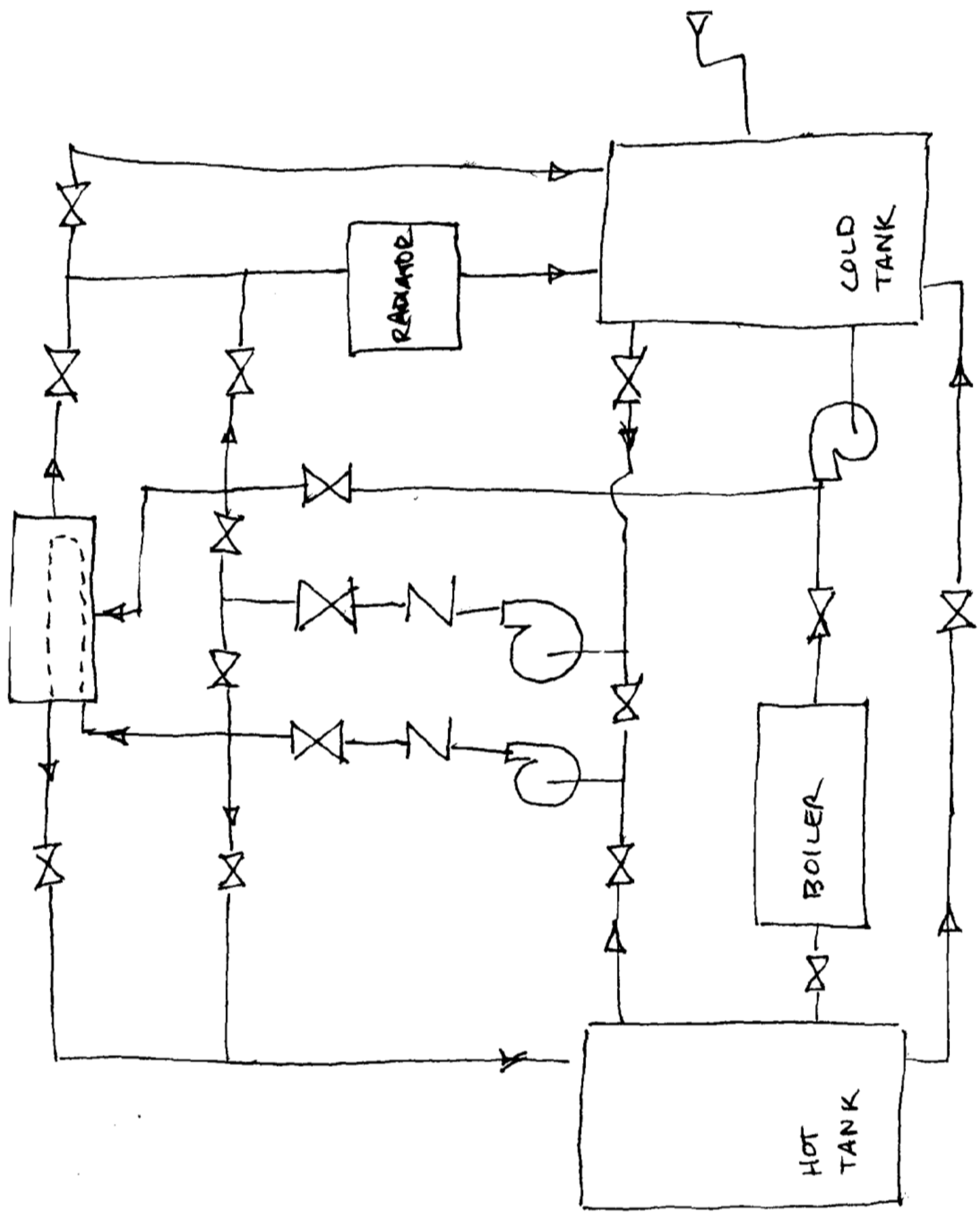
Appendix C: Original PG&E Flow Loop Simulator Schematic

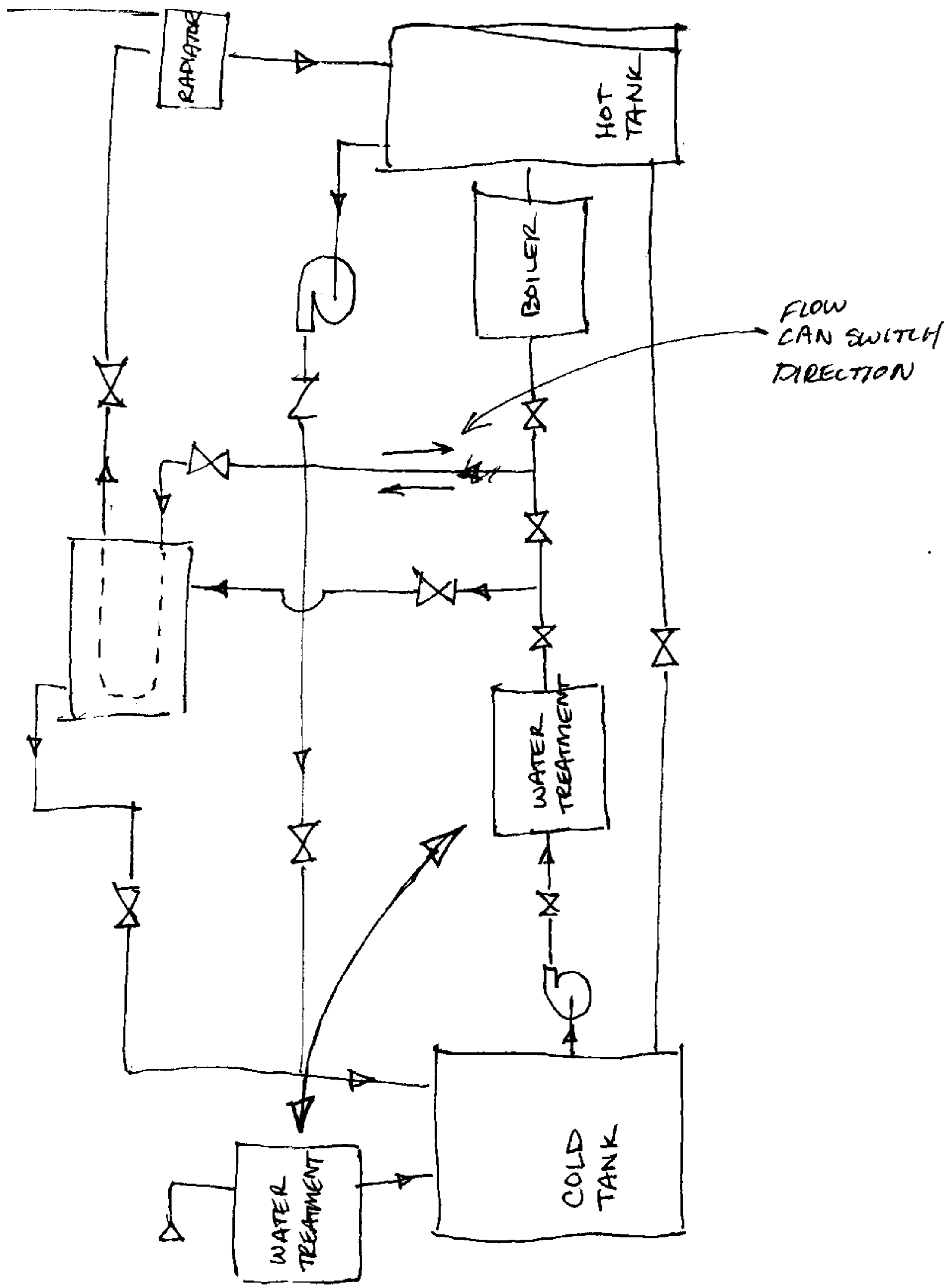


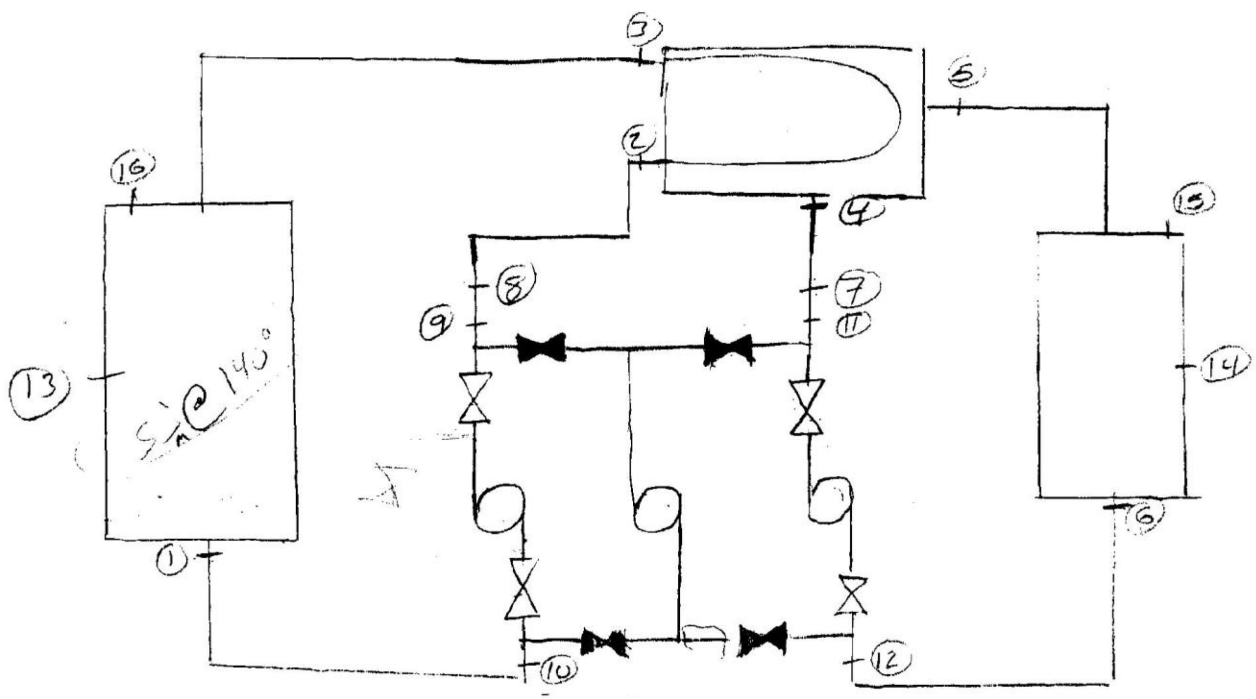
Appendix D: Cooper Nuclear Station Flow Loop Simulator Schematic



Appendix E: Concept Schematics




RADIATOR
HOT TANK
BOILER
FLOW CAN SWITCH DIRECTION
WATER TREATMENT
COLD TANK
WATER TREATMENT



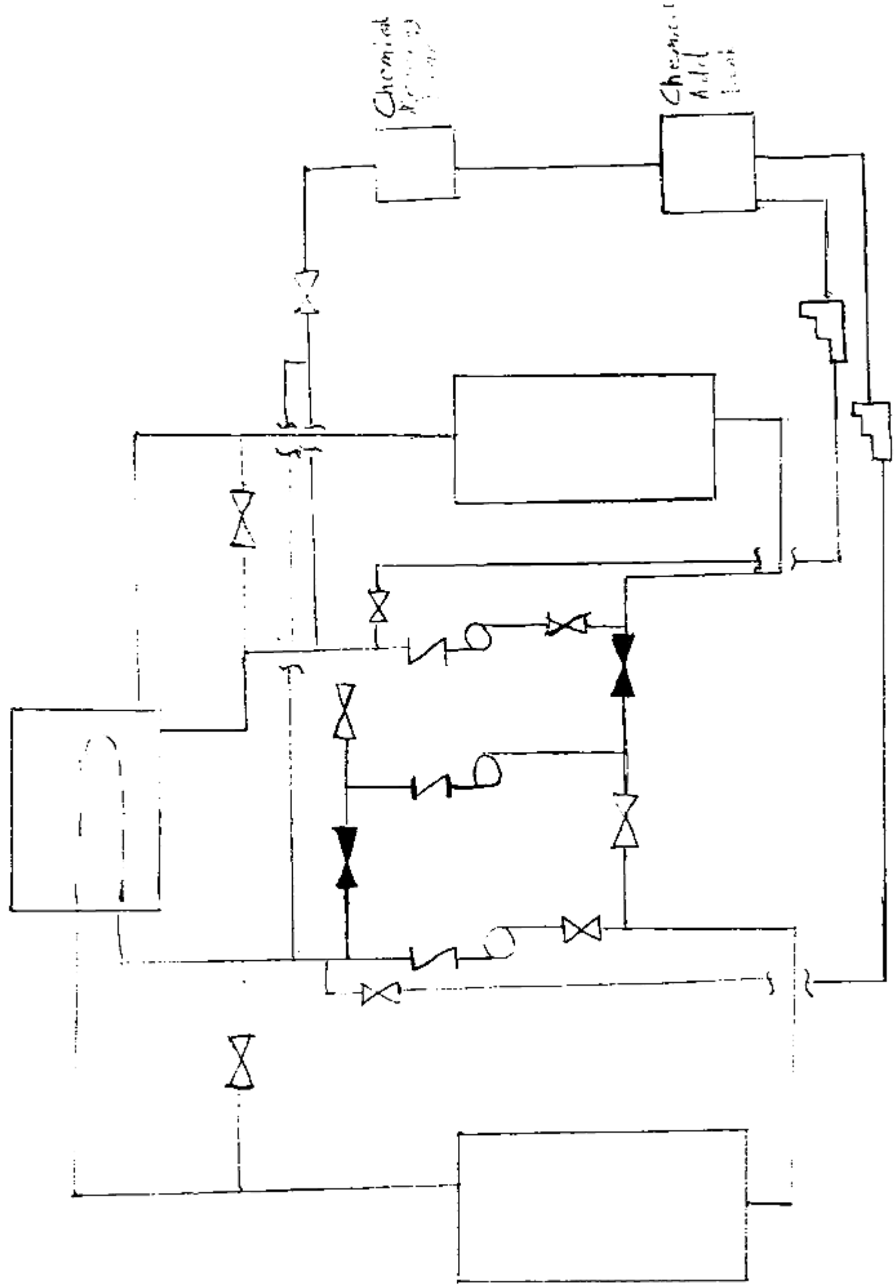
Temps
1 - 6

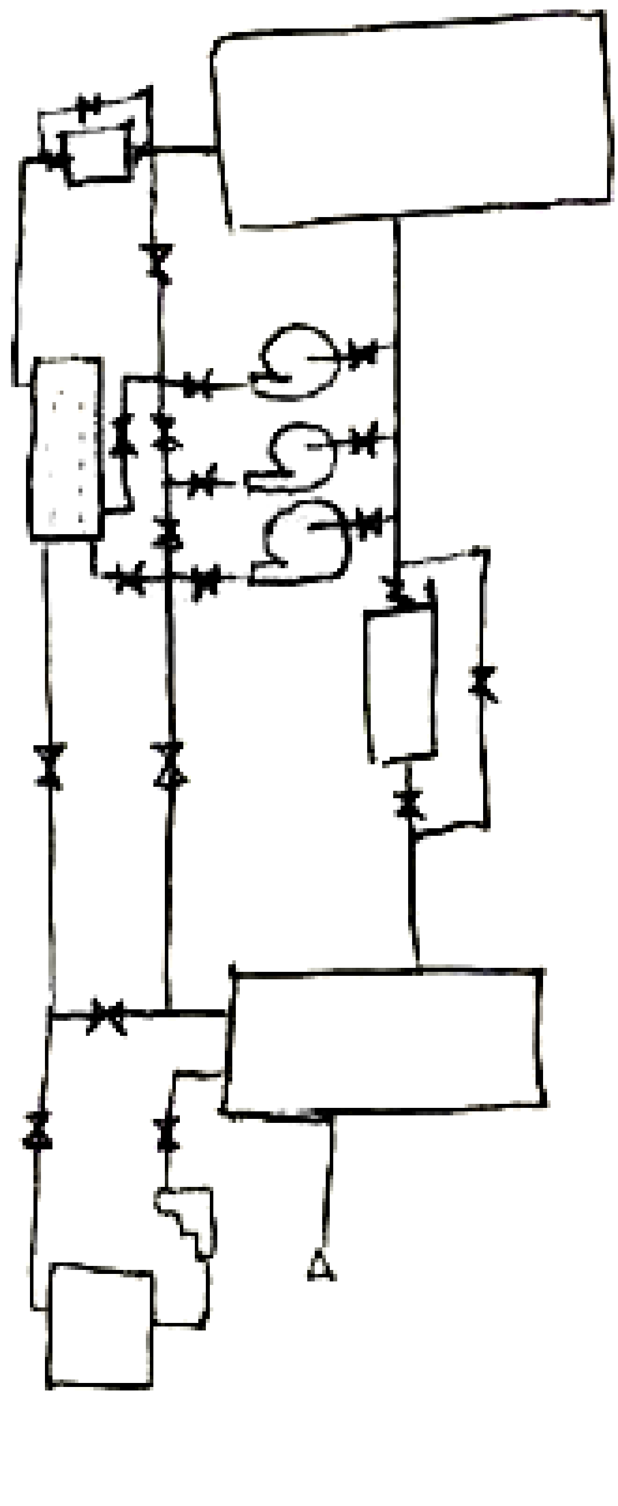
Flow Control Valve
7, 8

Pressure
9 - 12

Tank Levels *
13 - 14

Level Control Valve
15, 16

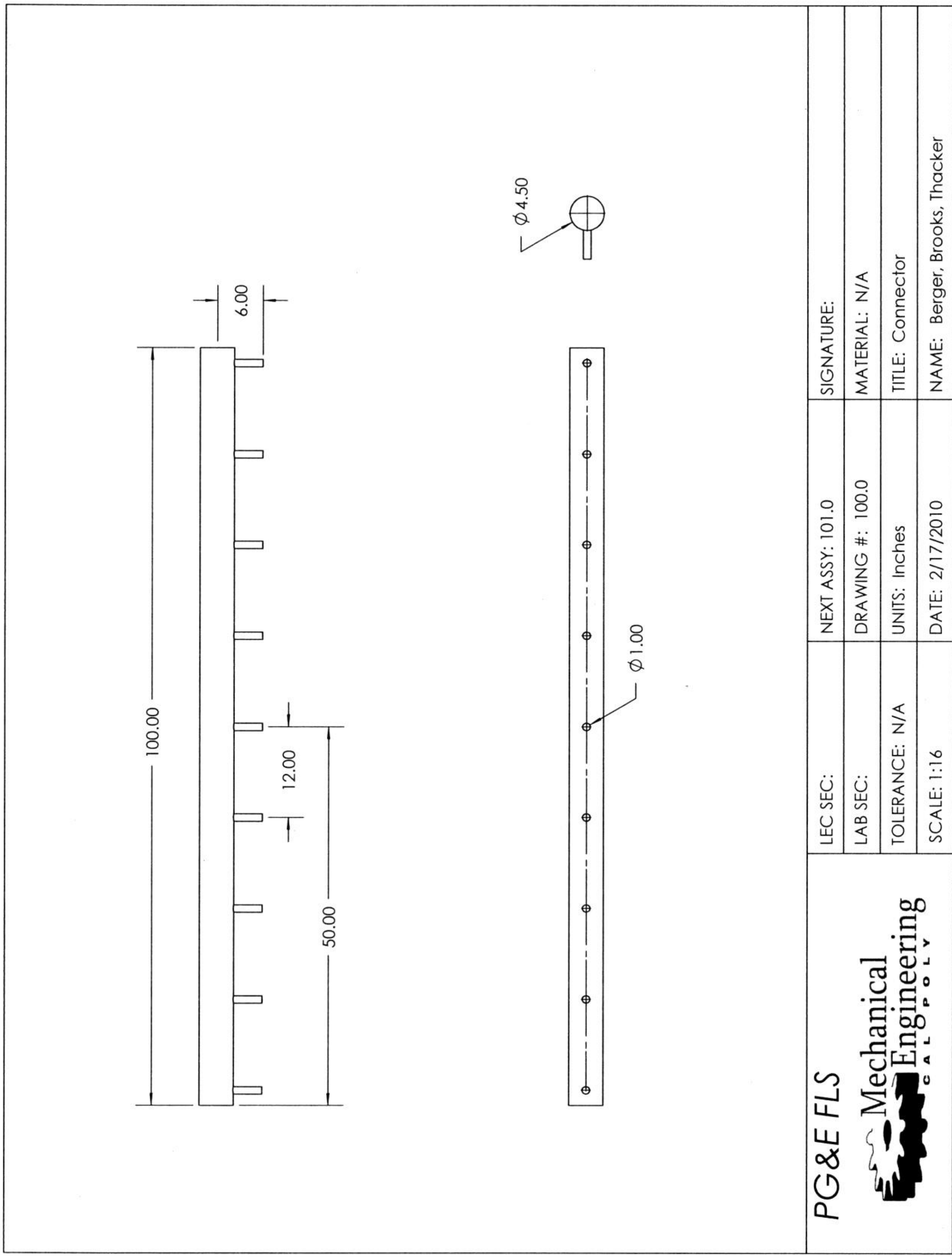

Chemical
Chemical
Add



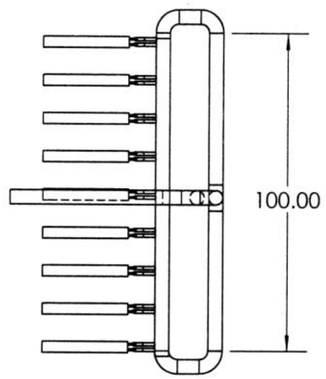
Appendix F: Bill of Materials

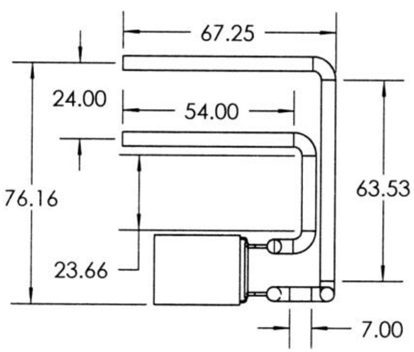
	Major Components	Quantity
1	Pump	3
2	Immersion Heater	2
3	Tank	2
4	Heat Exchanger	1
5	Water-to-Air Heat Exchanger	9
6	Chemical Addition Tank	1
7	Metering Pump	1
	V**alves**	
8	Butterfly Valves (4")	17
9	Check Valve (4")	3
10	Check Valve (0.75")	1
11	Control Valve (4")	2
12	Switch Valve (0.75")	1
	Piping	
13	4" Nom. Dia. Pipe	160 ft
14	1" Nom. Dia. Pipe	10 ft
15	0.75" Nom. Dia. Pipe	25 ft
16	Elbows (4")	31
17	Elbows (1")	4
18	Elbows (0.75")	4
19	Tees (4")	14
20	4"-3" Pipe Contractions	3
21	Flanges	12
	Skid	
22	4" x 4" x 0.188" Square Tube	150 ft
23	2" x 2" x 0.120" Square Tube	400 ft
24	3" x 8" x 0.188" Square Tube	30 ft
25	Plate	TBD
26	Mounting	TBD

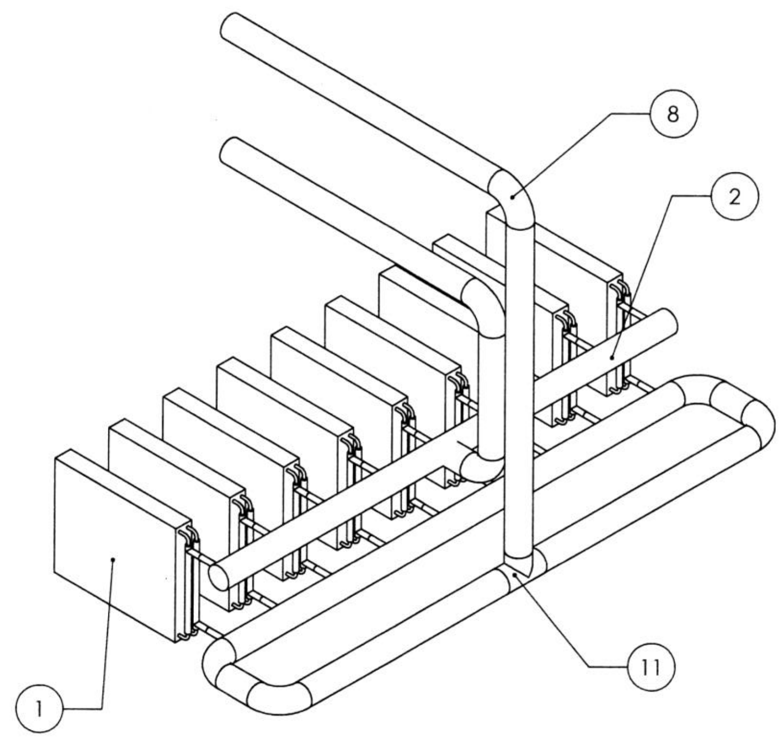
Appendix G: Assembly Drawings



ITEM NO.	PART NUMBER	QTY.
1	Water-To-Air Heat Exchanger	9
2	Connector	2
8	4 Inch Bend	7
11	4 Inch Tee	1







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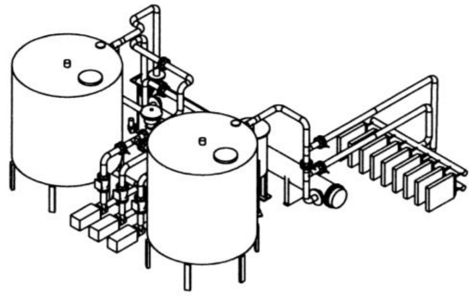
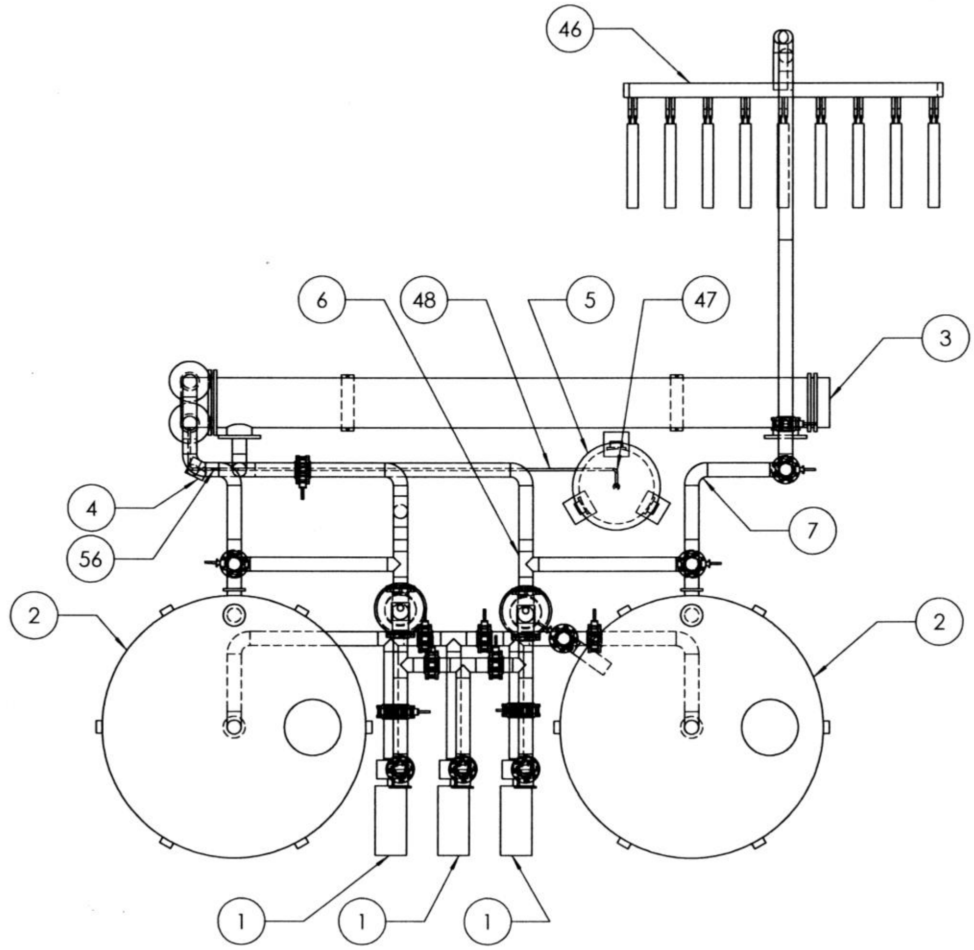
Mechanical Engineering CAL POLY	LAB SEC:	DRAWING #: 101.0	MATERIAL: N/A
	TOLERANCE: N/A	UNITS: Inches	TITLE: Cooling Component Assembly
	SCALE: 1:50	DATE: 2/17/2010	NAME: Berger, Brooks, Thacker

5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	3656 Goulds Pump	3
2	Perma-san 1600 gallon Tank	2
3	Westinghouse 16A8149-1	1
4	Milton Roy Model A Metering Pump	1
5	Chemical Addition Tank	1
6	4 Inch Tee	13
7	4 Inch Bend	24
46	Cooling Component Assembly	1
47	0.75 Inch Elbow	4
48	0.75 Inch Piping	1
56	0.75 Inch 3-Way Valve	1



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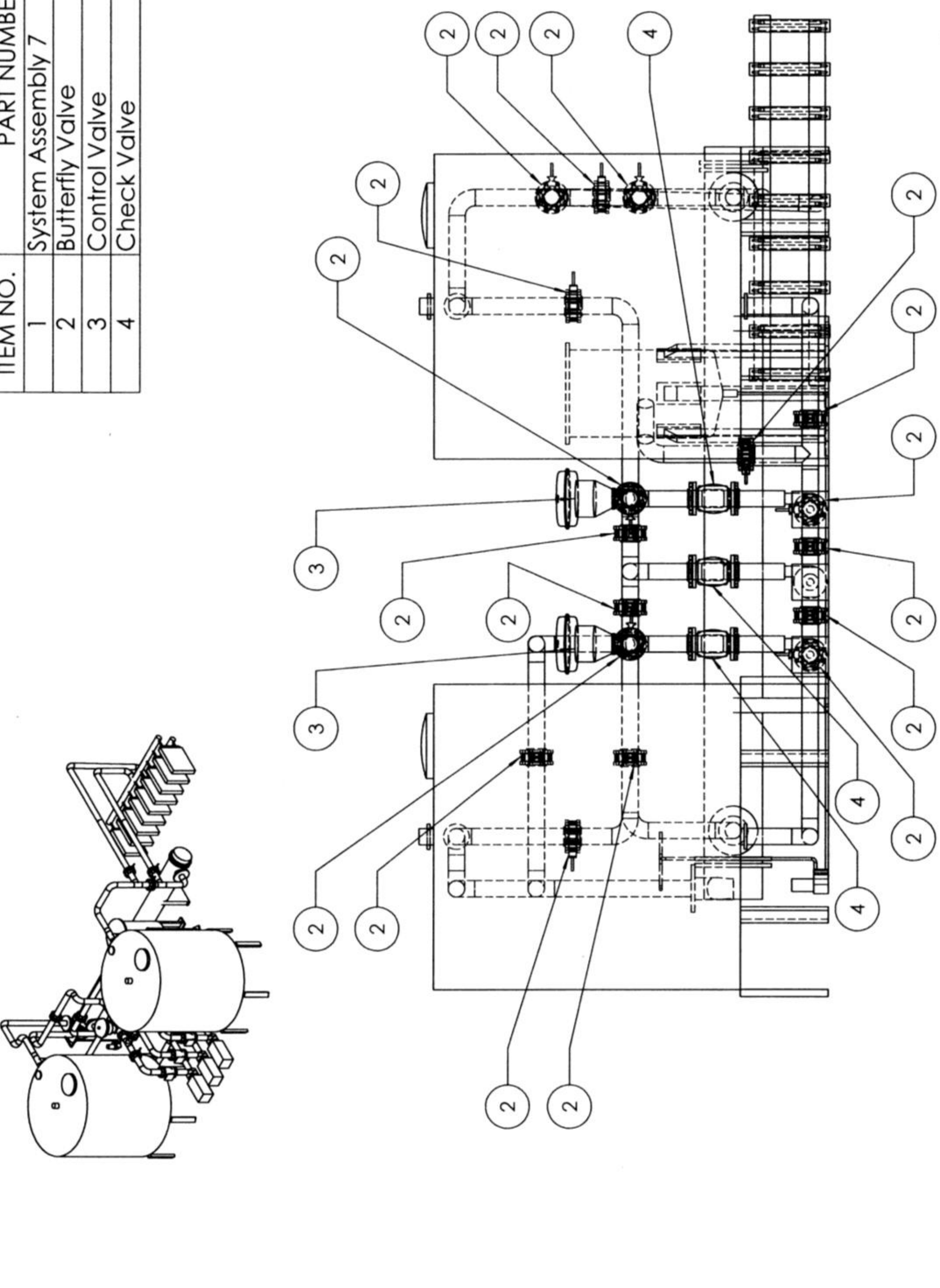
Mechanical Engineering CAL POLY	TOL: N/A	UNITS: Inches	TITLE: System 7
	SCALE: 1:50	DATE: 2/17/2009	NAME: Berger, Brooks, Thacker

ITEM NO.	PART NUMBER	QTY.
1	System Assembly 7	1
2	Butterfly Valve	17
3	Control Valve	2
4	Check Valve	3



PG&E FLS

Mechanical Engineering CAL POLY

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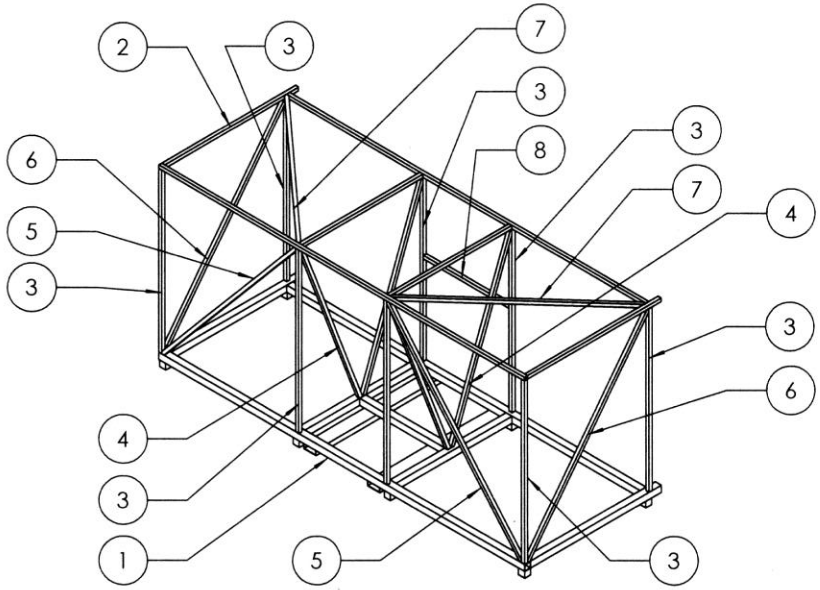
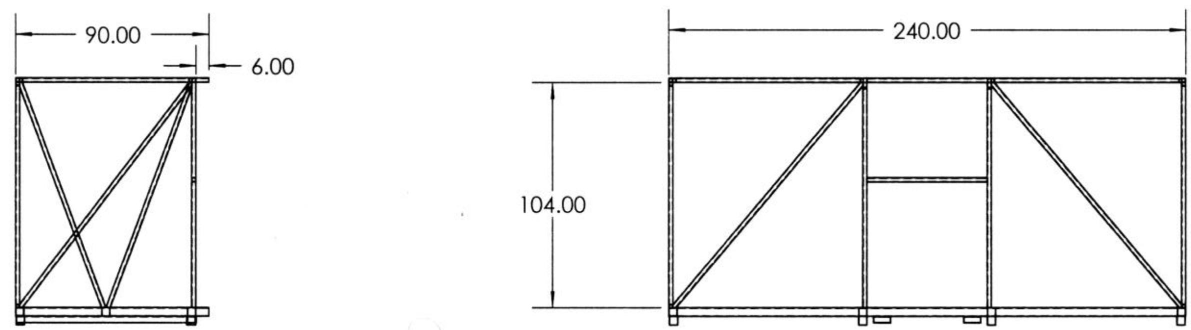


ITEM NO.	PART NUMBER	QTY.
1	Frame Bottom	1
2	Frame Top	1
3	2_x_2,104in	8
4	2_x_2,111.42_diagonal_1in	4
5	2_x_2,136.24in	2
6	2_x_2,131.21in	2
7	2_x_2,118.93in	2
8	2_x_2,56in	1

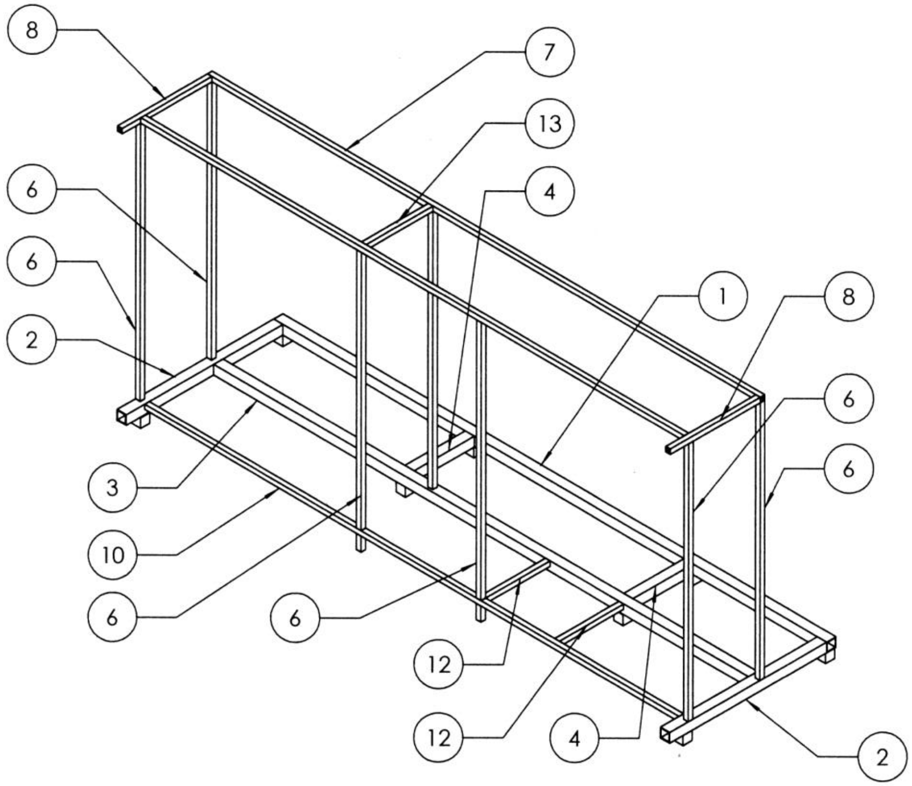


PG&E FLS

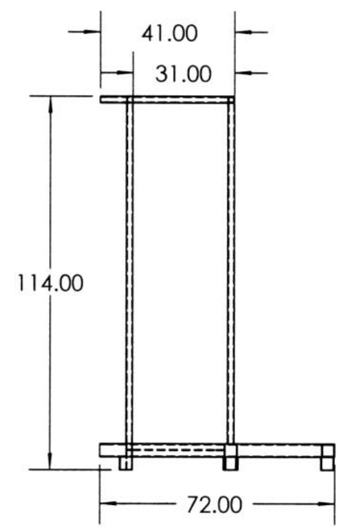
Mechanical Engineering
CAL POLY

LEC SEC:	NEXT ASSY: 103.0	SIGNATURE:
LAB SEC:	DRAWING #: 102.0	MATERIAL: N/A
TOLERANCE: N/A	UNITS: Inches	TITLE: Main Frame
SCALE: 1:75	DATE: 2/17/2010	NAME: Berger, Brooks, Thacker

5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	4_x_4,240in	1
2	4_x_4,68in	2
3	4_x_4,232in	1
4	4_x_4,26in	2
5	4_x_4,4in	8
6	2_x_2,104in	7
7	2_x_2,240in	1
8	2_x_2,39in	2
9	2_x_2,236in	1
10	2_x_2,232in	1
11	2_x_2,6in	2
12	2_x_2,28in	2
13	2_x_2,29in	1



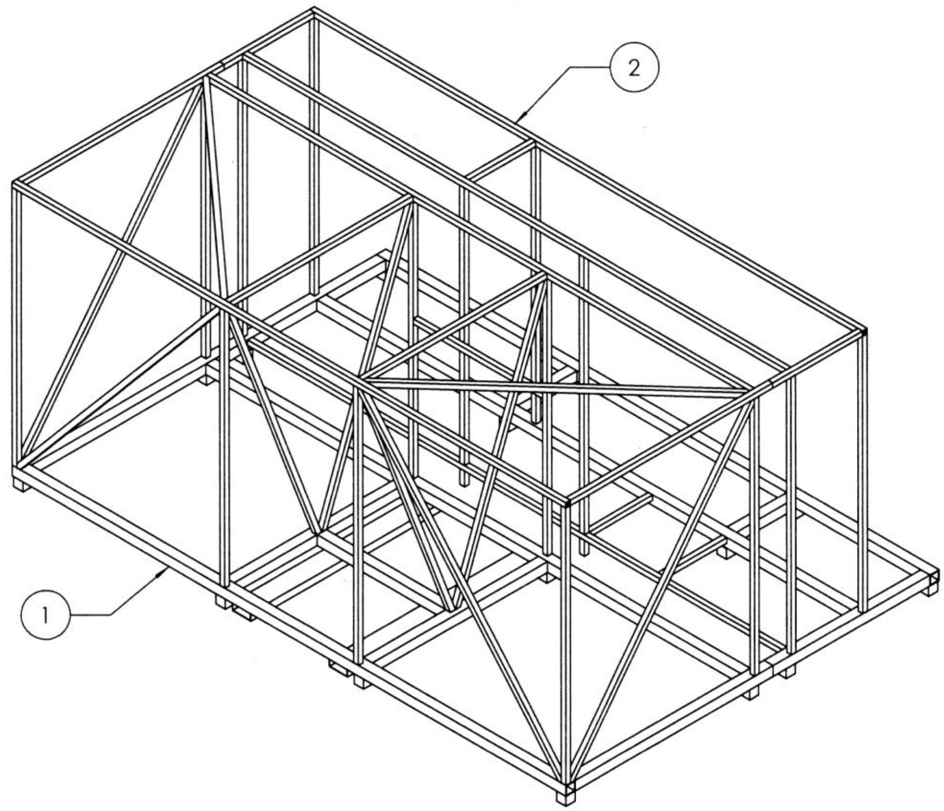
PG&E FLS

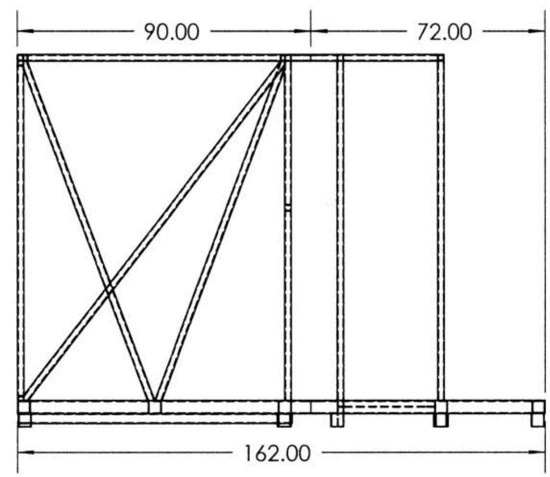
Mechanical Engineering
CAL POLY

LEC SEC:	NEXT ASSY: 103.0	SIGNATURE:
LAB SEC:	DRAWING #: 102.1	MATERIAL: N/A
TOLERANCE: N/A	UNITS: Inches	TITLE: Secondary Frame
SCALE: 1:50	DATE: 2/16/2010	NAME: Berger, Brooks, Thacker

5 4 3 2 1

ITEM NO.	PART NUMBER	QTY.
1	Main Frame	1
2	Secondary Frame	1

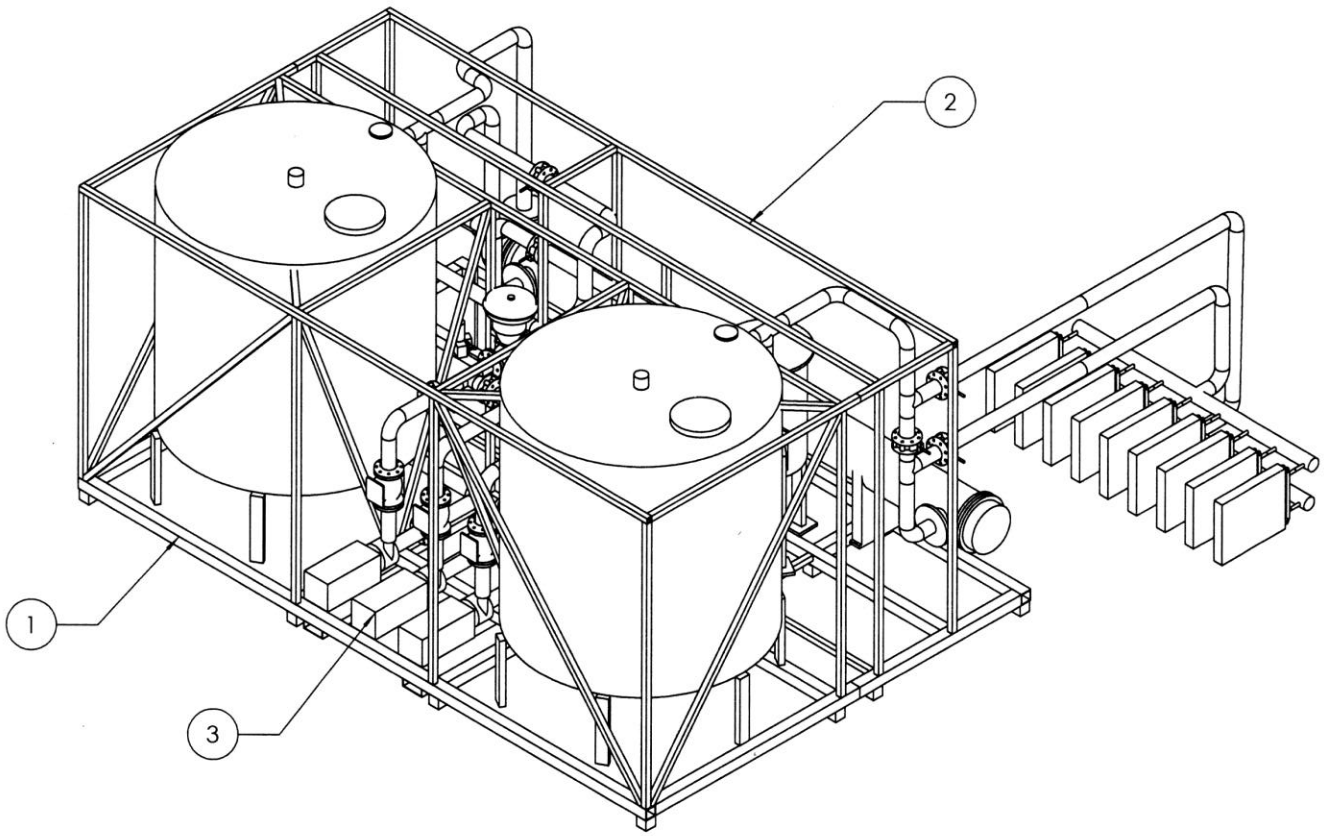




PG&E FLS	LEC SEC:	NEXT ASSY: 104.0	SIGNATURE:
Mechanical Engineering CAL POLY	LAB SEC:	DRAWING #: 103.0	MATERIAL: N/A
	TOLERANCE: N/A	UNITS: Inches	TITLE: Skid Assembly
	SCALE: 1:75	DATE: 2/17/2010	NAME: Berger, Brooks, Thacker

5 4 3 2 1

ITEM NO.	PART NUMBER	QTY.
1	Main Frame	1
2	Secondary Frame	1
3	System Assembly 7.1	1



PG&E FLS	LEC SEC:	NEXT ASSY: N/A	SIGNATURE:
Mechanical Engineering CAL POLY	LAB SEC:	DRAWING #: 104.0	MATERIAL: N/A
	TOLERANCE: N/A	UNITS: Inches	TITLE: FLS Final Design
	SCALE: 1:50	DATE: 2/17/2010	NAME: Berger, Brooks, Thacker

5 4 3 2 1

Appendix H: Cost Analysis

Part	Company	Capacity	Model	Size	Description	Cost	Weight	Qty.	Phone Number
Immersion Heater	Omega	150 kW			TM Series, Flanged, 480 VAC, 3-Phase,	>$3,500		2	(888) TC-OMEGA
	McMaster-Carr	18 kW		47-3/8"	Flanged, 480 VAC, 3-Phase,	539.72		17	(562) 463-4277
	McMaster-Carr	15 kW		39-7/8"	Flanged, 480 VAC, 3-Phase,	526.72		20	(562) 463-4277
	Watlow Industries	Up to 1MW			Flanged, 480 VAC, 3-Phase,			1	(573) 221-2816
	Warren Electric Corporation	Up to 800 kW			Flanged, 480 VAC, 3-Phase,			1	(877) 399-4328
	Gaumer Process (Houston, Texas)	300 kW	6F15N77M2U	6" Dia. x 77"	Flanged, 480 VAC, 3-Phase,		112 lb	1	Call for pricing: (800) 460-5200
Cooling Component	CT Wood Furnace	220,000Btu/hr, 23gpm	HTL 22x25	22"x25"x3.5"	Water-to-Air Heat Exchanger	232.76		9	(203) 881-1602
	Alternative Heating Supplies	220,000Btu/hr, 23gpm	HTL 22x25	22"x25"x3.5"	Water-to-Air Heat Exchanger	232.76		9	(888) 881-1602
	Whaley Products, Inc.	75 ton/330 kW, 225 gpm, 1,000,000 Btu/hr,	WP155075	60"x60"x113"	Cooling Tower	8720	911 lbs	1	
Pump	PG&E-Gould			3655S 4" x 4" - 7"	Missing Pump Curve			3	
	Gould	40 ft. Head, 200 gpm			3656 M&L series "D" Implellar			3	
Tank	Machinery & Equiment Company, Inc.	1600 gallon	S730115	7' Dia. x 7' Straight Side	304 SS			2	
	Aaron Equipment Company Inc.	1480 gallon	42196001	72" Dia. x 84" Straight Side	2 1/2" NPT center bottom outlet, 316 Stainless Steel	4000		2	630-238-7536
	Bid on Equipment	1250 gallon	59006		Stainless Steel, Dented, Doesn't leak	1050		2	
	EquipNet	1,000 gallon	61099	60" Dia. x 72" High	304 SS, Tennessee facility	2600	2100 lbs	2	
	EquipNet	1,321 gallon	64929	5' Dia. x 8' High	304 SS	2500	2,000 lbs	2	
	EquipNet	871 gallon	64970	5' Dia. x 5' High	304 SS	2500	1727 lbs	2	
	EquipNet	1,000 gallon	217044	5.5' Dia. x 98" High	Mixer, Stainless Steel	1500	1250 lbs	2	
	EquipNet	1,000 gallon	232757	60" Dia. x 144" High	Unused, 304 SS	4000	2,000 lbs	2	
	EquipNet	800 gallon	81512	5' Dia. x 8' High	304 Stainless Steel	3500	1530 lbs	2	
	Bid on Equipment	1000 gallon	61213	66" Dia. x 70" Straight Side	Stainless Steel, 85" Overall height	5000		2	
Heat Exchanger	Westinghouse PG&E	1,000,000 Btu/hr	16A8149-1	16" Dia. X 18' Length	Surface Area: 610 sqft. Design Press: Shell 200 psi Tube 250 psi			1	
Chemical Addition Tank	Machinery & Equiment Company, Inc.	75 gallons	S735176	24" Dia. x 38" Straight Side	Stainless Steel, Bolted cover, Agitator			1	
	McMaster-Carr	80 gallons	3772K73	32" Dia. x 45" Height	Standard, 1" OD Drain, 304 Stainless Steel	1628.59		1	
	McMaster-Carr	80 gallons	3772K74	32" Dia. x 45" Height	Standard, 1" OD Drain, 304 Stainless Steel	1815.56		1	
	McMaster-Carr	80 gallons	3772K64	32" Dia. x 45" Height	Sanitary, 1" OD Drain, 304 Stainless Steel	2061.28		1	
Chemical Injection Pump	PG&E				Milton Roy Model A			1	
4" x 4" x 0.188" Square Tube	B&B Steel Supply, Santa Maria, Ca	150 ft		*Must be 20 ft sticks	$5.80/ft on 2/19/2010	870	1440		(805)349-9991
2" x 2" x 0.120" Square Tube		400 ft		*Must be 20 ft sticks	$2.30/ft on 2/19/2010	920	1065		
3" x 8" x 0.188" Square Tube		30 ft			$10.00/ft on 2/19/2010	300	345		
Piping	PG&E	100'			Stainless Steel	$91.00/ft (costworks)		1	
	PG&E	100'			Carbon Steel	$18.10/ft (costworks)		1	

Appendix I: Pump Analysis

Total Head Loss Analysis

Valves and Fittings Equivalent Length L_e/D

$$\frac{L_{e,GateValve}}{D} = 8$$

$$\frac{L_{e,GlobeValve}}{D} = 340$$

$$\frac{L_{e,AngleValve}}{D} = 150$$

$$\frac{L_{e,BallValve}}{D} = 3$$

$$\frac{L_{e,LiftCheckValve,globelift}}{D} = 600$$

$$\frac{L_{e,LiftCheckValve,anglelift}}{D} = 55$$

$$\frac{L_{e,FootValve,poppetdisk}}{D} = 420$$

$$\frac{L_{e,Footvalve,hingeddisk}}{D} = 75$$

$$\frac{L_{e,Elbow,90}}{D} = 30$$

$$\frac{L_{e,Elbow,45}}{D} = 16$$

$$\frac{L_{e,ReturnBend,closepattern}}{D} = 50$$

$$\frac{L_{e,StandardTee,throughrun}}{D} = 20$$

$$\frac{L_{e,StandardTess,throughbranch}}{D} = 60$$

$D = 1$

K Factor for Entrance Types

$K_{SquareEdged} = 0.5$

General System Properties

$$\dot{Q} = \frac{200}{60 \cdot 7.48} \quad ft^3/sec$$

$e = 0.00015 \quad ft$

$$D_{pipe} = \frac{4}{12} \quad \textit{ft}$$

$$A_{cs} = \frac{\pi \cdot D_{pipe}^{\ 2}}{4} \quad \textit{ft}^2$$

$$V = \frac{\dot{Q}}{A_{cs}} \quad \textit{ft/s}$$

Friction Factor
For Re < 2300, f = 64/Re
For Re < 10^5, f = 0.316/($Re^{0.25}$)
*For Re > 2300, 1/($f^{0.5}$) = -2.0*log10(((e/D_{pipe})/3.7)+(2.51/(Re*($f^{0.5}$))))*

----HOT LOOP----

Properties of Water at T = 100 deg F

$$\rho = 1.93 \quad \textit{Slug/ft}^3$$

$$\mu = 0.0000143 \quad \textit{lbf*s/ft}^2$$

$$\nu = 0.00000738 \quad \textit{ft}^2\textit{/s}$$

$$P_\nu = 0.95 \quad \textit{psia}$$

$$Re = \frac{\rho \cdot V \cdot D_{pipe}}{\mu}$$

$$f = \frac{0.316}{Re^{0.25}}$$

Minor Losses

$$h_{l,m} = K_{SquareEdged} \cdot \frac{V^2}{2} + f \cdot \frac{L_{e,fitting}}{D} \cdot \frac{V^2}{2} \quad \textit{ft}^2\textit{/s}^2$$

$$\frac{L_{e,fitting}}{D} = n_{elbows} \cdot \frac{L_{e,Elbow,90}}{D} + n_{gatevalves} \cdot \frac{L_{e,GateValve}}{D} + n_{tees} \cdot \frac{L_{e,StandardTee,throughrun}}{D}$$

$$n_{elbows} = 6$$

$$n_{gatevalves} = 8$$

$$n_{tees} = 6$$

Major Losses

$$h_l = f \cdot \frac{L_{straight}}{D_{pipe}} \cdot \frac{V^2}{2} \quad \textit{ft}^2\textit{/s}^2$$

$$L_{straight} = 43 \quad \textit{ft} \quad \textit{Sum of all straight lengths}$$

Loss in Heat Exchanger

$P_{drop,hx} = 10$ *psia*

$H_{l,hx} = \dfrac{P_{drop,hx} \cdot 144}{\rho \cdot g}$ *ft*

Loss in Radiator

$P_{drop,rad} = 2.7$ *psia*

$H_{l,rad} = \dfrac{P_{drop,rad} \cdot 144}{\rho \cdot g}$ *ft*

Energy Equation

$$\frac{P_1 \cdot 144}{\rho \cdot g} + \alpha_1 \cdot \frac{V_1^{\,2}}{2 \cdot g} + z_1 - \left[\frac{P_2 \cdot 144}{\rho \cdot g} + \alpha_2 \cdot \frac{V_2^{\,2}}{2 \cdot g} + z_2\right] = \frac{h_{l,m}}{g} + \frac{h_l}{g} + H_{l,hx} + H_{l,rad} - \Delta_{H,pump} \quad ft$$

$\alpha_1 = 1$

$\alpha_2 = 1$

$V_1 = 0$ *ft/s*

$V_2 = V$ *ft/s*

$P_1 = 0$ *Psig, free surface @ water surface*

$P_2 = 0$ *Psig, free surface @ tank inlet*

$z_1 = 5$ *ft*

$z_2 = 6$ *ft*

$g = 32.174$ *ft/s²*

SOLUTION

Unit Settings: [F]/[psia]/[lbm]/[degrees]

$\alpha_1 = 1$
$\alpha_2 = 1$
$A_{cs} = 0.08727$
$D = 1$
$\Delta_{H,pump} = 33.94$
$D_{pipe} = 0.3333$
$e = 0.00015$
$f = 0.01443$
$g = 32.17$
$h_l = 24.28$
$H_{l,hx} = 23.19$
$h_{l,m} = 75.02$
$H_{l,rad} = 6.261$
$K_{SquareEdged} = 0.5$

$L_{e,AngleValve}$ = 150
$L_{e,BallValve}$ = 3
$L_{e,Elbow,45}$ = 16
$L_{e,Elbow,90}$ = 30
$L_{e,fitting}$ = 364
$L_{e,Footvalve,hingeddisk}$ = 75
$L_{e,FootValve,poppetdisk}$ = 420
$L_{e,GateValve}$ = 8
$L_{e,GlobeValve}$ = 340
$L_{e,LiftCheckValve,anglelift}$ = 55
$L_{e,LiftCheckValve,globelift}$ = 600
$L_{e,ReturnBend,closepattern}$ = 50
$L_{e,StandardTee,throughrun}$ = 20
$L_{e,StandardTess,throughbranch}$ = 60
$L_{straight}$ = 43
μ = 0.0000143
ν = 0.00000738
n_{elbows} = 6
$n_{gatevalves}$ = 8
n_{tees} = 6
P_1 = 0
P_2 = 0
$P_{drop,hx}$ = 10
$P_{drop,rad}$ = 2.7
P_v = 0.95
$\dot{Q}$ = 0.4456
Re = 229736
ρ = 1.93
V = 5.107
V_1 = 0
V_2 = 5.107
z_1 = 5
z_2 = 6

No unit problems were detected.

NPSH Analysis

Valves and Fittings Equivalent Length L_e/D

$$\frac{L_{e,GateValve}}{D} = 8$$

$$\frac{L_{e,GlobeValve}}{D} = 340$$

$$\frac{L_{e,AngleValve}}{D} = 150$$

$$\frac{L_{e,BallValve}}{D} = 3$$

$$\frac{L_{e,LiftCheckValve,globelift}}{D} = 600$$

$$\frac{L_{e,LiftCheckValve,anglelift}}{D} = 55$$

$$\frac{L_{e,FootValve,poppetdisk}}{D} = 420$$

$$\frac{L_{e,Footvalve,hingeddisk}}{D} = 75$$

$$\frac{L_{e,Elbow,90}}{D} = 30$$

$$\frac{L_{e,Elbow,45}}{D} = 16$$

$$\frac{L_{e,ReturnBend,closepattern}}{D} = 50$$

$$\frac{L_{e,StandardTee,throughrun}}{D} = 20$$

$$\frac{L_{e,StandardTess,throughbranch}}{D} = 60$$

$$D = 1$$

K Factor for Entrance Types

$$K_{SquareEdged} = 0.5$$

General System Properties

$$\dot{Q} = \frac{200}{60 \cdot 7.48} \quad \mathit{ft^3/sec}$$

$$e = 0.00015 \quad \mathit{ft}$$

$$D_{pipe} = \frac{4}{12} \quad ft$$

$$A_{cs} = \frac{\pi \cdot D_{pipe}^{2}}{4} \quad ft^2$$

$$V = \frac{\dot{Q}}{A_{cs}} \quad ft/s$$

Friction Factor

For Re < 2300, f = 64/Re

For Re < $10^{5,}$ f = 0.316/(Re$^{0.25)}$

*For Re > 2300, 1/(f$^{(0.5)}$) = -2.0*log10(((e/D$_{pipe}$)/3.7)+(2.51/(Re*(f$^{(0.5)}$))))*

----NPSH----

Properties of Water at T = 100 deg F

$$\rho = 1.93 \quad Slug/ft^3$$

$$\mu = 0.0000143 \quad lbf{*}s/ft^2$$

$$\nu = 0.00000738 \quad ft^2/s$$

$$P_{\nu} = 0.95 \quad psia$$

$$Re = \frac{\rho \cdot V \cdot D_{pipe}}{\mu}$$

$$f = \frac{0.316}{Re^{0.25}}$$

Minor Losses

$$h_{l,m} = K_{SquareEdged} \cdot \frac{V^2}{2} + f \cdot \frac{L_{e,fitting}}{D} \cdot \frac{V^2}{2} \quad ft^2/s^2$$

$$\frac{L_{e,fitting}}{D} = n_{elbows} \cdot \frac{L_{e,Elbow,90}}{D} + n_{ballvalves} \cdot \frac{L_{e,BallValve}}{D} + n_{tees} \cdot \frac{L_{e,StandardTee,throughrun}}{D}$$

$$n_{elbows} = 1$$

$$n_{ballvalves} = 2$$

$$n_{tees} = 1$$

Major Losses

$$h_l = f \cdot \frac{L_{straight}}{D_{pipe}} \cdot \frac{V^2}{2} \quad ft^2/s^2$$

$$L_{straight} = 5 \quad ft \quad \textit{Sum of all straight lengths}$$

Energy Equation

$$NPSHA = \frac{P_1 \cdot 144}{\rho \cdot g} + z_1 - \frac{h_{l,m}}{g} - \frac{h_l}{g} - \frac{P_v \cdot 144}{\rho \cdot g} \quad \textit{ft}$$

$V_2 = V$ *ft/s*

$P_1 = 14.7$ *Psia, free surface @ water surface*

$z_1 = 1$ *ft*

$z_2 = 0$ *ft*

$g = 32.174$ *ft/s²*

SOLUTION
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]
$A_{cs} = 0.08727$
$D = 1$
$D_{pipe} = 0.3333$
$e = 0.00015$
$f = 0.01443$
$g = 32.17$
$h_l = 2.823$
$h_{l,m} = 17.06$
$K_{SquareEdged} = 0.5$
$L_{e,AngleValve} = 150$
$L_{e,BallValve} = 3$
$L_{e,Elbow,45} = 16$
$L_{e,Elbow,90} = 30$
$L_{e,fitting} = 56$
$L_{e,Footvalve,hingeddisk} = 75$
$L_{e,FootValve,poppetdisk} = 420$
$L_{e,GateValve} = 8$
$L_{e,GlobeValve} = 340$
$L_{e,LiftCheckValve,anglelift} = 55$
$L_{e,LiftCheckValve,globelift} = 600$
$L_{e,ReturnBend,closepattern} = 50$
$L_{e,StandardTee,throughrun} = 20$
$L_{e,StandardTess,throughbranch} = 60$
$L_{straight} = 5$
$\mu = 0.0000143$
$NPSHA = 32.27$
$\nu = 0.00000738$
$n_{ballvalves} = 2$
$n_{elbows} = 1$
$n_{tees} = 1$
$P_1 = 14.7$
$P_v = 0.95$
$\dot{Q} = 0.4456$
$Re = 229736$
$\rho = 1.93$
$V = 5.107$

V_2 = 5.107
z_1 = 1
z_2 = 0

No unit problems were detected.

Appendix J: Heat Exchanger Analysis

Heat Transfer Area

$$d = \frac{0.54 \quad [in]}{12 \quad [in/ft]}$$

$$l = \frac{190.5 \quad [in]}{12 \quad [in/ft]}$$

$$n_{tubes} = 118$$

$$A = \pi \cdot d \cdot l \cdot n_{tubes} \cdot 2$$

$$t = \frac{0.147}{12}$$

Heat Transfer Coefficient

$$k_{316ss} = \mathbf{k}\left[\text{'Stainless}_{AISI316}\text{'} \ , \ 0.5 \cdot \left(T_{hi} + T_{ci} \right) \right]$$

$$\mu_h = \mathbf{Visc}\left[\text{'Water'} \ , T = \frac{T_{hi} + T_{ho}}{2}, P = 14.7 \right]$$

$$\mu_c = \mathbf{Visc}\left[\text{'Water'} \ , T = \frac{T_{ci} + T_{co}}{2}, P = 14.7 \right]$$

$$Pr_h = \mathbf{Pr}\left[\text{'Water'} \ , T = \frac{T_{hi} + T_{ho}}{2}, P = 14.7 \right]$$

$$Pr_c = \mathbf{Pr}\left[\text{'Water'} \ , T = \frac{T_{ci} + T_{co}}{2}, P = 14.7 \right]$$

$$Re_{D,h} = 4 \cdot \dot{m}_h \cdot \frac{3600 \quad [s/hr]}{n_{tubes} \cdot \pi \cdot d \cdot \mu_h}$$

$$Re_{D,c} = 4 \cdot \dot{m}_c \cdot \frac{3600 \quad [s/hr]}{n_{tubes} \cdot \pi \cdot d \cdot \mu_c}$$

$$NuD_h = 0.023 \cdot Re_{D,h}{}^{[4 / 5]} \cdot Pr_h{}^{0.4}$$

$$NuD_c = 0.023 \cdot Re_{D,c}{}^{[4 / 5]} \cdot Pr_c{}^{0.4}$$

$k_h = 0.624 \quad [W/m*K] \cdot 0.5779 \quad [Btu/ft*hr*F/W/m*K]$ *From Table A.6*

$k_c = 0.606 \quad [W/m*K] \cdot 0.5779 \quad [Btu/ft*hr*F/W/m*K]$ *From Table A.6*

$$h_h = NuD_h \cdot \frac{k_h}{d}$$

$$h_c = NuD_c \cdot \frac{k_c}{d}$$

$$U = \left[\frac{1}{h_h} + \frac{1}{h_c} + \frac{t}{k_{316ss}} \right]^{-1}$$

$$U_{fouled} = \left[\frac{1}{U} + 0.001 \quad [\text{hr-ft}^2\text{-R/Btu}]\right]^{-1}$$

System Parameters

$$T_{hi} = 100 \quad [F]$$

$$T_{ho} = 86.33 \quad [F]$$

$$T_{ci} = 70 \quad [F]$$

$$\Delta T_1 = T_{hi} - T_{co}$$

$$\Delta T_2 = T_{ho} - T_{ci}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left[\frac{\Delta T_1}{\Delta T_2}\right]}$$

$$\rho_h = \rho\left[\text{'Water'}, T = \frac{T_{hi} + T_{ho}}{2}, P = 14.7\right]$$

$$\rho_c = \rho\left[\text{'Water'}, T = \frac{T_{ci} + T_{co}}{2}, P = 14.7\right]$$

$$cp_h = \mathbf{Cp}\left[\text{'Water'}, T = \frac{T_{hi} + T_{ho}}{2}, P = 14.7\right]$$

$$cp_c = \mathbf{Cp}\left[\text{'Water'}, T = \frac{T_{ci} + T_{co}}{2}, P = 14.7\right]$$

$$V_h = 200 \quad [gpm]$$

$$V_c = 200 \quad [gpm]$$

$$\dot{m}_h = \frac{V_h}{7.48 \quad [\text{gal/ft}^3] \cdot 60 \quad [\text{sec/min}]} \cdot \rho_h$$

$$\dot{m}_c = \frac{V_c}{7.48 \quad [\text{gal/ft}^3] \cdot 60 \quad [\text{sec/min}]} \cdot \rho_c$$

$$R = \frac{T_{ci} - T_{co}}{T_{ho} - T_{hi}}$$

$$P = \frac{T_{ho} - T_{hi}}{T_{ci} - T_{hi}}$$

$$F = 0.975 \quad \textit{Table 11S.1}$$

Heat Transfer

$$q = \dot{m}_h \cdot cp_h \cdot [T_{hi} - T_{ho}] \cdot 3600 \quad [s/hr]$$

$$q = \dot{m}_c \cdot cp_c \cdot [T_{co} - T_{ci}] \cdot 3600 \quad [s/hr]$$

$$q_{hx} = U_{fouled} \cdot A \cdot F \cdot \Delta T_{lm}$$

Operating Conditions

$$C_h = \dot{m}_h \cdot cp_h$$

$$C_c = \dot{m}_c \cdot cp_c$$

$$C_{min} = \textbf{Min}\left[C_h, C_c\right]$$

$$C_{max} = \textbf{Max}\left[C_h, C_c\right]$$

$$C_r = \frac{C_{min}}{C_{max}}$$

$$NTU = U_{fouled} \cdot \frac{A}{C_{min} \cdot 3600 \text{ [s/hr]}}$$

$$\varepsilon = 2 \cdot \left[1 + C_r + \left(1 + C_r^2\right)^{(1/2)} \cdot \left(\frac{1 + \textbf{exp}\left[-NTU \cdot \left(1 + C_r^2\right)^{(1/2)}\right]}{1 - \textbf{exp}\left[-NTU \cdot \left(1 + C_r^2\right)^{(1/2)}\right]}\right)\right]^{-1}$$

$$\varepsilon = C_h \cdot \left[\frac{T_{hi} - T_{ho1}}{C_{min} \cdot (T_{hi} - T_{ci})}\right]$$

$$C_r = \frac{T_{co1} - T_{ci}}{T_{hi} - T_{ho}}$$

SOLUTION

Unit Settings: [F]/[psia]/[lbm]/[degrees]

A = 529.6 [ft^2]
cp_c = 0.9991 [Btu/lbm-R]
cp_h = 0.9991 [Btu/lbm-R]
C_c = 27.71 [Btu/s-R]
C_h = 27.64 [Btu/s-R]
C_{max} = 27.71 [Btu/s-R]
C_{min} = 27.64 [Btu/s-R]
C_r = 0.9972
d = 0.045 [ft]
ΔT_1 = 16.37 [F]
ΔT_2 = 16.33 [F]
ΔT_{lm} = 16.35 [F]
ε = 0.4555
F = 0.975
h_c = 642.6 [Btu/hr-ft^2-R]
h_h = 706.9 [Btu/hr-ft^2-R]
k_{316ss} = 7.769 [Btu/hr-ft-R]
k_c = 0.3502 [Btu/hr-ft-R]
k_h = 0.3606 [Btu/hr-ft-R]
l = 15.88 [ft]
μ_c = 2.159 [lbm/ft-hr]
μ_h = 1.777 [lbm/ft-hr]
$\dot{m}_c$ = 27.74 [lbm/s]

$\dot{m}_h$ = 27.66 [lbm/s]
NTU = 0.9596
NuD_c = 82.57
NuD_h = 88.21
n_{tubes} = 118
P = 0.4557
Pr_c = 6.279
Pr_h = 5.044
q = 1.360E+06 [Btu/hr]
q_{hx} = 1.522E+06 [Btu/hr]
R = 0.9972
$Re_{D,c}$ = 11089
$Re_{D,h}$ = 13439 [-]
ρ_c = 62.25 [lbm/ft^3]
ρ_h = 62.08 [lbm/ft^3]
t = 0.01225 [ft]
T_{ci} = 70 [F]
T_{co} = 83.63 [F]
T_{co1} = 83.63 [F]
T_{hi} = 100 [F]
T_{ho} = 86.33 [F]
T_{ho1} = 86.34 [F]
U = 219.9 [Btu/hr-ft^2-R]
U_{fouled} = 180.3 [Btu/hr-ft^2-R]
V_c = 200 [gpm]
V_h = 200 [gpm]

No unit problems were detected.

Appendix K: Heating Component Analysis

Immersion Heater Calculations

By Seth Berger

,,,,,,,,,,,Start-Up,,,,,,,,,,,

$t_{min} = 30$

$P = 14.7$ [psi]

$T_1 = 50$ [F]

$T_3 = 100$ [F]

$$T_{avg} = \frac{T_1 + T_3}{2}$$

$$\dot{Q}_{Startup} = m \cdot \left[\frac{h_3 - h_1}{t_{hr}} \right]$$

$$\dot{Q}_{Startup,kW} = \dot{Q}_{Startup} \cdot \frac{0.293}{1000 \text{ [kW/Btu/hr]}}$$

$$t_{Startup} = m \cdot [h_3 - h_1] \cdot \frac{60 \text{ [min/hr]}}{\dot{Q}_{SteadyState}}$$

$m = \rho_{avg1} \cdot V$

$\rho_{avg1} = \rho[\text{'Water'}, T = T_{avg}, P = P]$

$V_{gal} = 500$ [gal]

$V = V_{gal} \cdot 0.1337$ [ft^3/gal]

$h_3 = \mathbf{h}[\text{'Water'}, T = T_3, P = P]$

$h_1 = \mathbf{h}[\text{'Water'}, T = T_1, P = P]$

$$t_{hr} = \frac{t_{min}}{60 \text{ [min/hr]}}$$

,,,,,,,,,Steady State,,,,,,,,,

$\dot{q}_{gpm} = 200$ [gpm]

$T_2 = 90$ [F]

$$T_{avg2} = \frac{T_2 + T_3}{2}$$

$$\dot{Q}_{SteadyState} = \dot{m} \cdot [h_3 - h_2]$$

$$\dot{Q}_{SteadyState,kW} = \dot{Q}_{SteadyState} \cdot \frac{0.293}{1000}$$

$\dot{q} = \dot{q}_{gpm} \cdot 0.1337 \cdot 60$ [ft^3/hr/gpm]

$\dot{m} = \rho_{avg2} \cdot \dot{q}$

$\rho_{avg2} = \rho\left[\text{'Water'}, T = T_{avg2}, P = P\right]$

$h_2 = \mathbf{h}\left[\text{'Water'}, T = T_2, P = P\right]$

SOLUTION

Unit Settings: [F]/[psia]/[lbm]/[degrees]

h_1 = 18.09 [Btu/lbm]
h_2 = 58.06 [Btu/lbm]
h_3 = 68.05 [Btu/lbm]
m = 4162 [lbm]
$\dot{m}$ = 99547 [lbm/hr]
P = 14.7 [psi]
$\dot{q}$ = 1604 [ft^3/hr]
$\dot{q}_{gpm}$ = 200 [gpm]
$\dot{Q}_{Startup}$ = 415829 [Btu/hr]
$\dot{Q}_{Startup,kW}$ = 121.8 [kW]
$\dot{Q}_{SteadyState}$ = 994507 [Btu/hr]
$\dot{Q}_{SteadyState,kW}$ = 291.4 [kW]
ρ_{avg1} = 62.26 [lbm/ft^3]
ρ_{avg2} = 62.06 [lbm/ft^3]
T_1 = 50 [F]
T_2 = 90 [F]
T_3 = 100 [F]
T_{avg} = 75 [F]
T_{avg2} = 95 [F]
t_{hr} = 0.5 [hr]
t_{min} = 30 [min]
$t_{Startup}$ = 12.54 [min]
V = 66.84 [ft^3]
V_{gal} = 500 [gal]

No unit problems were detected.

Appendix L: Cooling Component Analysis

Radiator Heat Transfer Calculations

By Seth Berger

Heat Transfer Required

$\dot{V}_{gpm} = 200$ [gpm]

$T_1 = 26.67$ [C] *80 deg F*

$T_2 = 21.11$ [C] *70 deg F*

$$T_{avg} = \frac{T_1 + T_2}{2}$$

$P = 101$ [kPa]

$\dot{Q}_{Req} = \dot{m} \cdot [h_2 - h_1]$

$$\dot{Q}_{Req,kW} = \frac{\dot{Q}_{Req}}{3600 \text{ [s/hr]}}$$

$\dot{V} = \dot{V}_{gpm} \cdot 0.003785 \cdot 60$ [m^3/hr/gpm]

$\dot{m} = \rho_{avg} \cdot \dot{V}$

$\rho_{avg} = \rho[\text{'Water'}, T = T_{avg}, P = P]$

$h_2 = \mathbf{h}[\text{'Water'}, T = T_2, P = P]$

$h_1 = \mathbf{h}[\text{'Water'}, T = T_1, P = P]$

Heat Transfer Through Radiator

Givens

$W = 15 \cdot 0.0254$ [m]

$L = 68.75 \cdot 0.0254$ [m]

$SA = W \cdot L$

$t = 0.018$ [m]

$D = 0.022$ [m] *This is an estimate*

$N_{Plates} = 33$

$A_{H2O} = W \cdot D$

$$Q_{H2O} = 50 \cdot 3.785 \cdot \frac{0.001}{60}$$

$T_{Air} = 21.11$ [C] *70 deg F*

$T_{H2O} = 26.67$ [C] *80 deg F*

$k_{Radiator} = 14.5$ *@T=300K=26.85 deg C*

$k_{Air} = 25.9 \cdot 10^{-3}$ *@T=295K=22 deg C*

$k_{H2O} = 613 \cdot 10^{-3}$ *@T=300K=27 deg C*

$P_{Air} = 101$ [kPa]

$P_{H2O} = 110$ [kPa] *This is an assumption*

$$Q_{Air} = \frac{1000}{60 \cdot 3.28^3}$$

$A_{Air} = 1.5 \cdot 1.5$ [m^2]

Convection from Water to Radiator

$$R_1 = \frac{1}{\overline{h}_{H2O} \cdot SA}$$

$$\overline{h}_{H2O} = \overline{\nu}_{H2O} \cdot \frac{k_{H2O}}{W}$$

Conduction through Radiator

$$R_2 = \frac{t}{k_{Radiator} \cdot SA}$$

Convection from Radiator to Air

$$R_3 = \frac{1}{\overline{h}_{Air} \cdot SA}$$

$$\overline{h}_{Air} = \overline{\nu}_{Air} \cdot \frac{k_{Air}}{W}$$

Resistance Network

$$R = \frac{R_1 + R_2 + R_3}{2}$$

Heat Transfer Equation

$$q_{Plate} = \frac{T_{H2O} - T_{Air}}{R}$$

$$q_{Total} = N_{Plates} \cdot q_{Plate}$$

--Air--

Nussel Number for Turbulent Air Flow over a Flat Plate

$$\overline{\nu}_{Air} = 0.68 \cdot Re_{Air}^{[1/2]} \cdot Pr_{Air}^{[1/3]}$$

Prandtl Number for the Air

$Pr_{Air} = \mathbf{Pr}\left[\text{'Air'}, T = T_{Air}\right]$

Reynold's Number for the Air

$$Re_{Air} = \rho_{Air,Avg} \cdot V_{Air} \cdot \frac{W}{\mu_{Air,Avg}}$$

$\rho_{Air,Avg} = \rho\left[\text{'Air'}, T = T_{Air}, P = P_{Air}\right]$

$$V_{Air} = \frac{Q_{Air}}{A_{Air}}$$

$\mu_{Air,Avg} = \mathbf{Visc}\left[\text{'Air'}, T = T_{Air}\right]$

--H2O--

Nussel Number for Turbulent H2O Flow over a Flat Plate

$$\overline{\nu}_{H2O} = 0.68 \cdot Re_{H2O}^{\left[1/2\right]} \cdot Pr_{H2O}^{\left[1/3\right]}$$

Prandtl Number for the H2O

$Pr_{H2O} = \mathbf{Pr}\left[\text{'Water'}, T = T_{H2O}, P = P_{H2O}\right]$

Reynold's Number for the H2O

$$Re_{H2O} = \rho_{H2O} \cdot V_{H2O} \cdot \frac{W}{\mu_{H2O}}$$

$\rho_{H2O} = \rho\left[\text{'Water'}, T = T_{H2O}, P = P_{H2O}\right]$

$$V_{H2O} = \frac{Q_{H2O}}{N_{Plates} \cdot A_{H2O}}$$

$\mu_{H2O} = \mathbf{Visc}\left[\text{'Water'}, T = T_{H2O}, P = P_{H2O}\right]$

SOLUTION

Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]

$A_{Air} = 2.25$ [m^2]
$A_{H2O} = 0.008382$ [m^2]
$D = 0.022$ [m]
$h_1 = 111.8$ [kJ/kg]
$h_2 = 88.57$ [kJ/kg]
$\overline{h}_{Air} = 3.007$ [W/m^2-K]
$\overline{h}_{H2O} = 141.3$ [W/m^2-K]
$k_{Air} = 0.0259$ [W/(m-K)]
$k_{H2O} = 0.613$ [W/(m-K)]
$k_{Radiator} = 14.5$ [W/(m-K)]
$L = 1.746$ [m]
$\mu_{Air,Avg} = 0.0000183$ [kg/m-s]
$\mu_{H2O} = 0.0008577$ [kg/m-s]

$\dot{m}$ = 45304 [kg/hr]
$\bar{\nu}_{Air}$ = 44.24
$\bar{\nu}_{H2O}$ = 87.81
N_{Plates} = 33
P = 101 [kPa]
Pr_{Air} = 0.729
Pr_{H2O} = 6.004
P_{Air} = 101 [kPa]
P_{H2O} = 110 [kPa]
Q_{Air} = 0.4723 [m^3/s]
$\dot{Q}_{Req}$ = -1.054E+06 [kJ/hr]
$\dot{Q}_{Req,kW}$ = -292.7 [kW]
Q_{H2O} = 0.003154 [m^3/s]
q_{Plate} = 21.71 [W]
q_{Total} = 716.3 [W]
R = 0.2562 [K/W]
Re_{Air} = 5225 [-]
Re_{H2O} = 5049 [-]
$\rho_{Air,Avg}$ = 1.196 [kg/m^3]
ρ_{avg} = 997.3 [kg/m^3]
ρ_{H2O} = 996.6 [kg/m^3]
R_1 = 0.01064 [K/W]
R_2 = 0.001866 [K/W]
R_3 = 0.4998 [K/W]
SA = 0.6653 [m^2]
t = 0.018 [m]
T_1 = 26.67 [C]
T_2 = 21.11 [C]
T_{Air} = 21.11 [C]
T_{avg} = 23.89 [C]
T_{H2O} = 26.67 [C]
V_{Air} = 0.2099 [m/s]
$\dot{V}$ = 45.42 [m^3/hr]
$\dot{V}_{gpm}$ = 200 [gpm]
V_{H2O} = 0.0114 [m/s]
W = 0.381 [m]

No unit problems were detected.

Cooling Component

Water-To-Air Heat Exchanger Calculations

,,,,,,, Thermal Plume Width,,,,,,,,,

To determine hx spacing

Grashof Number

$$Gr = \frac{g \cdot \beta \cdot [T_s - T_\infty] \cdot x^3}{\nu^2}$$

$g = 9.81$ [m/sec^2]

$T_s = 299.8$ [K]

$T_\infty = 294.3$ [K]

$\nu = 0.00001589$ [m^2/s]

$$x = \frac{22}{12 \cdot 3.28}$$ *Height*

$$\beta = \frac{1}{T_\infty}$$

$$\eta = \frac{y}{x} \cdot \left[\frac{Gr}{4}\right]^{[1/4]}$$

$\eta = 4$

$s = y \cdot 2 \cdot 3.28 \cdot 12$ [in/m]

y is the distance from one hx

s is the minimum distance between hxs

,,,,,,,, Need for Return Line,,,,,,,,,

If velocity through inner heat exchangers is much greater (10%) than the velocity through the outer heat exchanger, then a return line is necessary

Pressure Drop Through Longest Path, hl_{lp}

$hl_{hx} = 206.5$

$$hl_{lp} = \frac{f \cdot L \cdot V_1^2}{D} + hl_{hx}$$

$$D = \frac{4}{12}$$

$f = 0.019$

$L = 4 \cdot 2$

$V_1 = 5.1$ *Velocity at cooling component inlet*

Flow Rate Based On That Pressure Drop

$$\frac{V_1^2}{2} - \frac{V_2^2}{2} = hl_{lp} - hl_{hx}$$

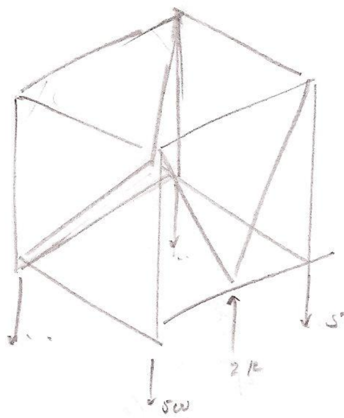
SOLUTION

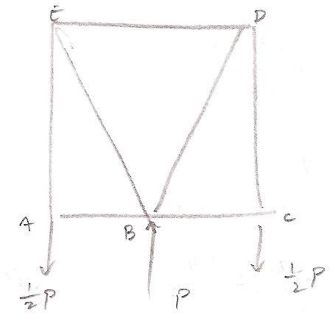
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]

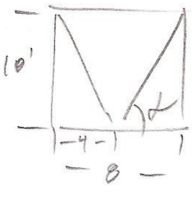
β = 0.003398 [1/K]
D = 0.3333 [ft]
η = 4
f = 0.019
g = 9.81 [m/sec^2]
Gr = 1.267E+08
hl_{hx} = 206.5
hl_{lp} = 218.4
L = 8 [ft]
ν = 0.00001589 [m^2/s]
s = 2.346 [in]
T_∞ = 294.3 [K]
T_s = 299.8 [K]
V_1 = 5.1
V_2 = 1.513
x = 0.5589 [m]
y = 0.0298 [m]

No unit problems were detected.

Appendix M: Skid Analysis



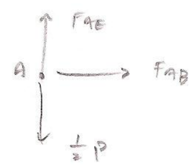




$\alpha = \tan^{-1}\left(\frac{10}{8}\right)$

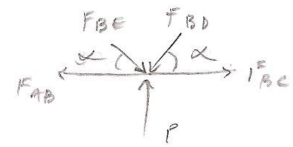
$\alpha = 51.34°$

Start @ A



$\therefore F_{AB} = 0$

Also, $F_{BC} = 0$



$\Sigma F_y: P - F_{BD}\sin\alpha - F_{BE}\sin\alpha = 0$

$\Sigma F_x: \cancel{F_{BC}}^{0} - \cancel{F_{AB}}^{0} + F_{BE}\cos\alpha - F_{BD}\cos\alpha = 0$

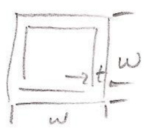
$F_{BE} = F_{BD}$

$P - F_{BD}\sin\alpha - F_{BD}\sin\alpha = 0$

$F_{BD} = \dfrac{P}{2\sin\alpha}$

$F_{BD} = 0.64\,P$

Axial Stress



$\sigma_A = \dfrac{F}{A_{cs}}$

$A_{cs}: A_o - A_i$

$W^2 - (W-2t)^2$

$\sigma_A = \dfrac{0.64\,P}{W^2 - (W-2t)^2}$

For $n_s = 2$, 1020 steel, $S_y = 32\,ksi$

$\sigma_A = \dfrac{S_y}{n_s}$

$\dfrac{0.64\,P}{W^2 - (W-2t)^2} = \dfrac{S_y}{n_s}$

$W^2 - W^2 + 4Wt - 4t^2$

$4t(W - t)$

$W = \dfrac{0.64\,P\,n_s}{S_y \cdot 4t} + t$

$W = \dfrac{0.64\,(2k\ lbs)\,2}{30\times10^3\,\frac{lb}{in^2} \cdot 4 \cdot .188\,in} + .188\,in$

$W = 0.30\ in$

✓ For Column Buckling.

$$P_{cr} = \frac{C\pi^2 EI}{l^2}$$

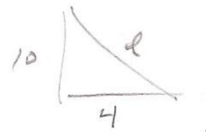
$C = 4$

$E = 30\times10^6$ ksi

$I = \frac{1}{12}\left((2)^4 - (2-2(.120))^4\right)$

$= 6.4 \text{ in}^4$

$l = 10.77$ in

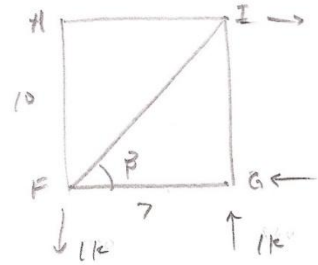


$l = \left[4^2+10^2\right]^{1/2}$

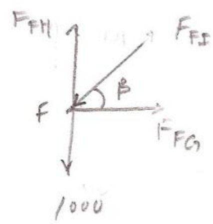
$l = 10.77$ in

$$P_{cr} = \frac{4\cdot\pi^2\cdot 30\times10^6 \frac{lbf}{\cancel{in^2}}\cdot 6.4\ \cancel{in^4}}{10.77^2\ \cancel{in^2}}$$

$P_{cr} = \underline{65 \text{ kips}} >>> 2k$



@ F



$\Sigma F_y = 0$

$-F_{FI}\sin\beta - 1000 + F_{FH} = 0$

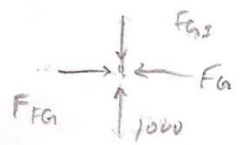
$\Sigma F_x = 0$

$F_{FG} - F_{FI}\cos\beta = 0$

$\beta = \tan^{-1}\left(\frac{10}{7}\right)$

$\beta = 55°$

@ G



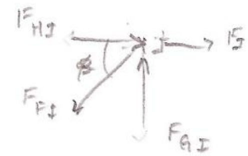
$\Sigma F_y = 0$

$F_{GI} = 1000$

$\Sigma F_x = 0$

$F_{FG} - F_G = 0$

@ I



$\Sigma F_y = 0$

$-F_{FI}\sin\beta + F_{GI} = 0$

$F_{FI} = \frac{F_{GI}}{\sin\beta}$

$F_{FI} = \frac{1000}{\sin(55°)}$

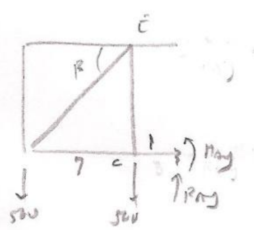
$F_{FI} = 1220.66\ lbf$

$\Sigma F_x = 0$

$F_{HI} - F_{FI}\cos\beta = 0$

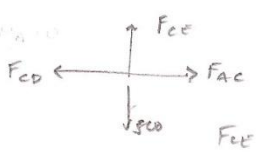
$F_{HI} = 1220.66\cos(55)$

$F_{HI} = 700\ lbf$

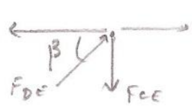


$\Sigma F_y = R_{Ay} + R_{By} - 1000 = 0$

$R_{Ay} = 1000$



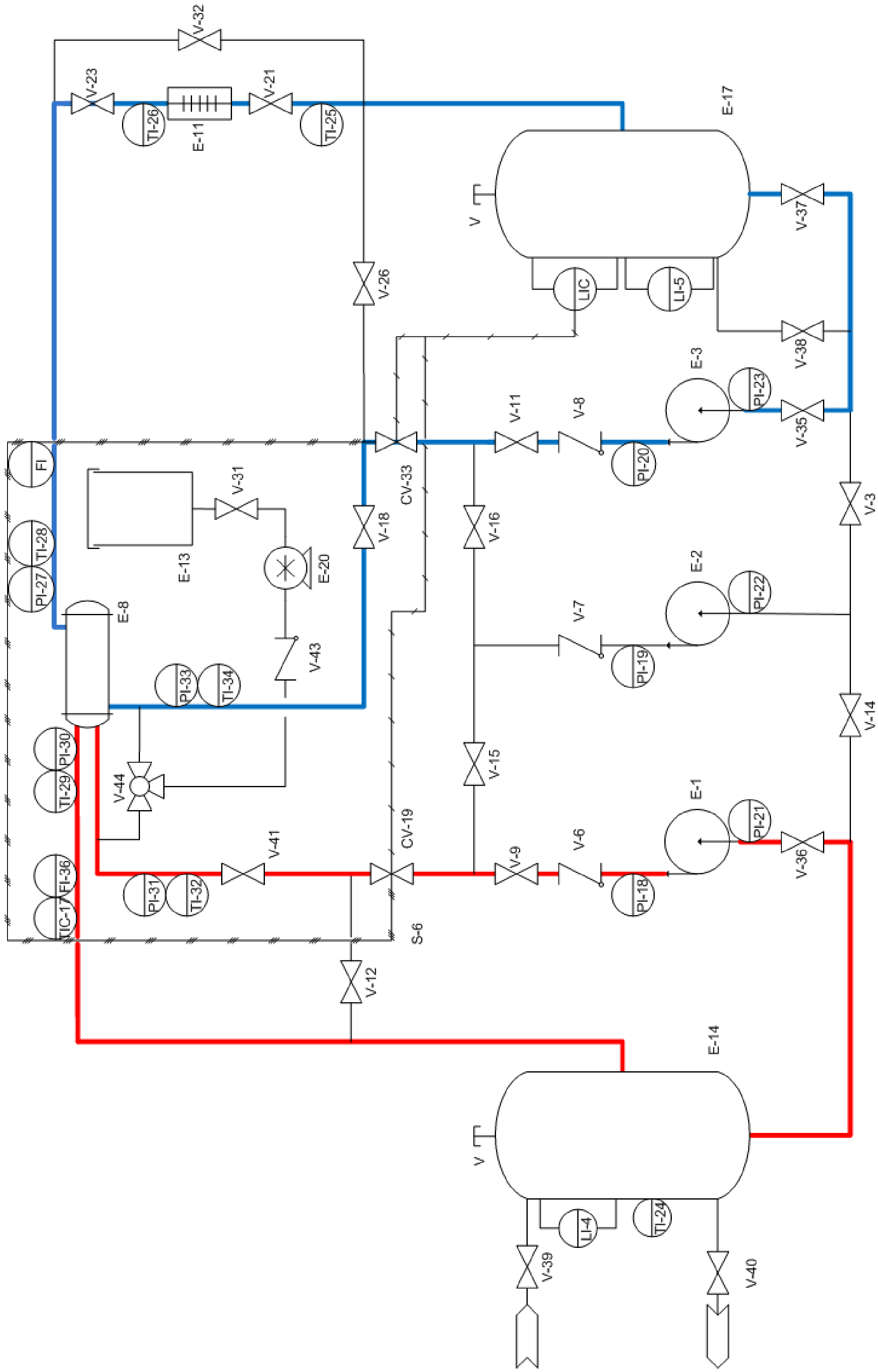
$F_{CE} = 500$



$F_{DE}\sin\beta = F_{CE}$

$F_{DE} = \frac{F_{CE}}{\sin\beta}$

Appendix N: New PG&E Flow Loop Simulator Schematic



Appendix O: Piping Materials

Main System				
Diameter	Length (in)	Quantity	Total (in)	Valve Configuration
4	34.19	2	68.38	**
4	34.19	1	34.19	
4	11.75	2	23.50	**
4	40.83	1	40.83	
4	18.32	2	36.64	
4	6.90	1	6.90	
4	31.67	1	31.67	**
4	12.25	2	24.50	
4	37.26	3	111.78	***
4	24.33	2	48.66	**
4	24.33	1	24.33	
4	11.75	2	23.50	**
4	24.00	2	48.00	*
4	36.00	1	36.00	**
4	12.00	1	12.00	
4	43.83	1	43.83	
4	38.37	2	76.74	**
4	3.75	4	15.00	
4	4.06	1	4.06	
4	3.30	1	3.30	
4	57.22	1	57.22	**
4	17.36	1	17.36	
4	3.83	2	7.66	
4	15.64	1	15.64	
4	4.27	1	4.27	
4	18.23	1	18.23	
4	59.25	1	59.25	
4	37.40	1	37.40	
4	4.85	1	4.85	
4	5.04	1	5.04	
4	18.26	1	18.26	
4	81.35	1	81.35	**
4	17.36	2	34.72	
4	43.83	1	43.83	
4	19.95	1	19.95	
	16.81	1	16.81	
	15.75	1	15.75	**
	16.69	2	33.38	
	5.04	1	5.04	
		Total (ft):	**100.82**	

*	= control valve
**	= butterfly valve
***	= check valve

System Total (ft)	100.82
Cooling Total (ft)	46.45
Injection Total (ft)	18.59

Cooling Component				
Diameter	Length (in)	Quantity	Total (in)	Valve Configuration
4	69.52	2	139.04	**
4	60.00	1	60.00	
4	54.00	1	54.00	
4	62.68	1	62.68	
4	23.66	1	23.66	
4	100.00	2	200.00	
4	6.00	1	6.00	
4	12.00	1	12.00	
		Total (ft):	**46.45**	

Chemical Injection System				
Diameter	Length (in)	Quantity	Total (in)	Valve Configuration
0.75	23.61	1	23.61	
0.75	3.48	1	3.48	
0.75	130.00	1	130.00	
0.75	2.00	1	2.00	
0.75	40.00	1	40.00	
0.75	6.00	2	12.00	
0.75	12.00	1	12.00	
		Total(ft):	**18.59**	

Appendix P: Skid Materials

4 x 4 x 0.188 Square Tube		
Width	4	in
Height	4	in
Thickness	0.188	in
A_{OUTER}	16	in^2
A_{INNER}	13.13	in^2
A_{STEEL}	2.867	in^2
ρ_{STEEL}	0.284	lb/in^3
W_{STEEL}	0.814	lb/in
W_{STEEL}	9.769	lb/ft
$W_{STEEL,primary}$	869.5	lb
$W_{STEEL,secondary}$	569.9	lb

Primary Skid		
Length (in)	# of Lengths	raw length (in)
240	2	480
88	2	176
78	2	156
56	4	224
4	8	32
	Total	1068
Secondary Skid		
Length (in)	# of Lengths	raw length (in)
240	2	480
68	2	136
26	2	52
4	8	32
	Total	700

Length	Sum
240	4
88	2
78	2
68	2
56	4
26	2

length	# ea length per	# 240's	# each lngth total
240	1	4	4
88	1		2
78	1	2	2
68	1		2
56	4	1	4
26	2	0.5	2
		7.5	Total Sticks (20 ft)
		150	**Total Feet Required**
		5.80	Price per foot
		870.00	**Total price**

2 x 2 x 0.120 Square Tube		
Width	2	in
Height	2	in
Thickness	0.12	in
A_{OUTER}	4	in^2
A_{INNER}	3.098	in^2
A_{STEEL}	0.902	in^2
ρ_{STEEL}	0.284	lb/in^3
W_{STEEL}	0.256	lb/in
W_{STEEL}	3.075	lb/ft
$W_{STEEL,primary}$	648.5	lb
$W_{STEEL,secondary}$	415.7	lb

Primary Skid		
Length (in)	# of Lengths	raw length (in)
240	2	480
136.24	2	272.48
131.21	2	262.42
118.93	2	237.86
111.43	4	445.72
104	8	832
	Total	2530.48
Secondary Skid		
Length (in)	# of Lengths	raw length (in)
240	3	720
104	7	728
39	2	78
28	3	84
6	2	12
	Total	1622

Length	Sum
240	5
136.24	2
131.21	2
118.93	2
111.43	4
104	15
39	2
28	3
6	2

length	# ea length per	# 240's	# each length total
240	1	5	5
136.2	1		2
39	1	2	2
28	2		4
131.2	1	2	2
104	1		2
118.9	1	2	2
111.4	1		2
111.4	1	2	2
104	1		2
104	2	7	14

20	Total Sticks (20 ft)
240	**Total Feet Required**
2.30	Price per foot
552.00	**Total price**

3 x 8 x 0.188 Rectangle Tube		
Width	8	in
Height	3	in
Thickness	0.188	in
A_{OUTER}	24	in^2
A_{INNER}	20.01	in^2
A_{STEEL}	3.995	in^2
ρ_{STEEL}	0.284	lb/in^3
W_{STEEL}	1.134	lb/in
W_{STEEL}	13.61	lb/ft
$W_{STEEL,\ primary}$	190.6	lb
$W_{STEEL,\ secondary}$	154.3	lb

Primary Skid		
Length (in)	# of Lengths	raw length (in)
84	2	168
	Total	168
Secondary Skid		
Length (in)	# of Lengths	raw length (in)
68	2	136
	Total	136

Length	Sum
84	2
68	2

length	# ea length per	# 240's	# each length total
84	2	1	2
68	1		1
68	1	0.5	1

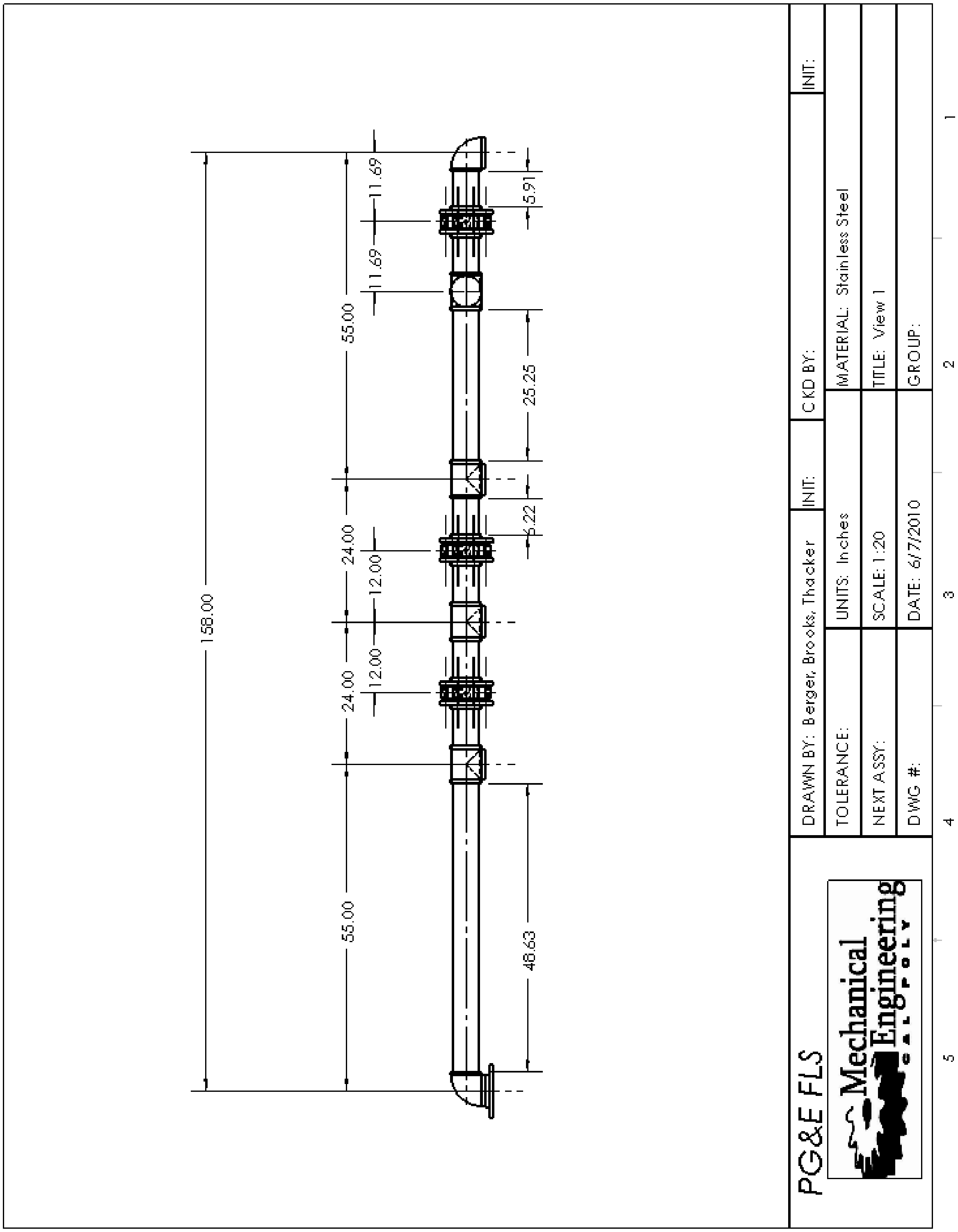
1.5	Total Sticks (20 ft)
30	**Total Feet Required**
10.00	Price per foot
300.00	**Total price**

Appendix Q: Radiator Test Calculations

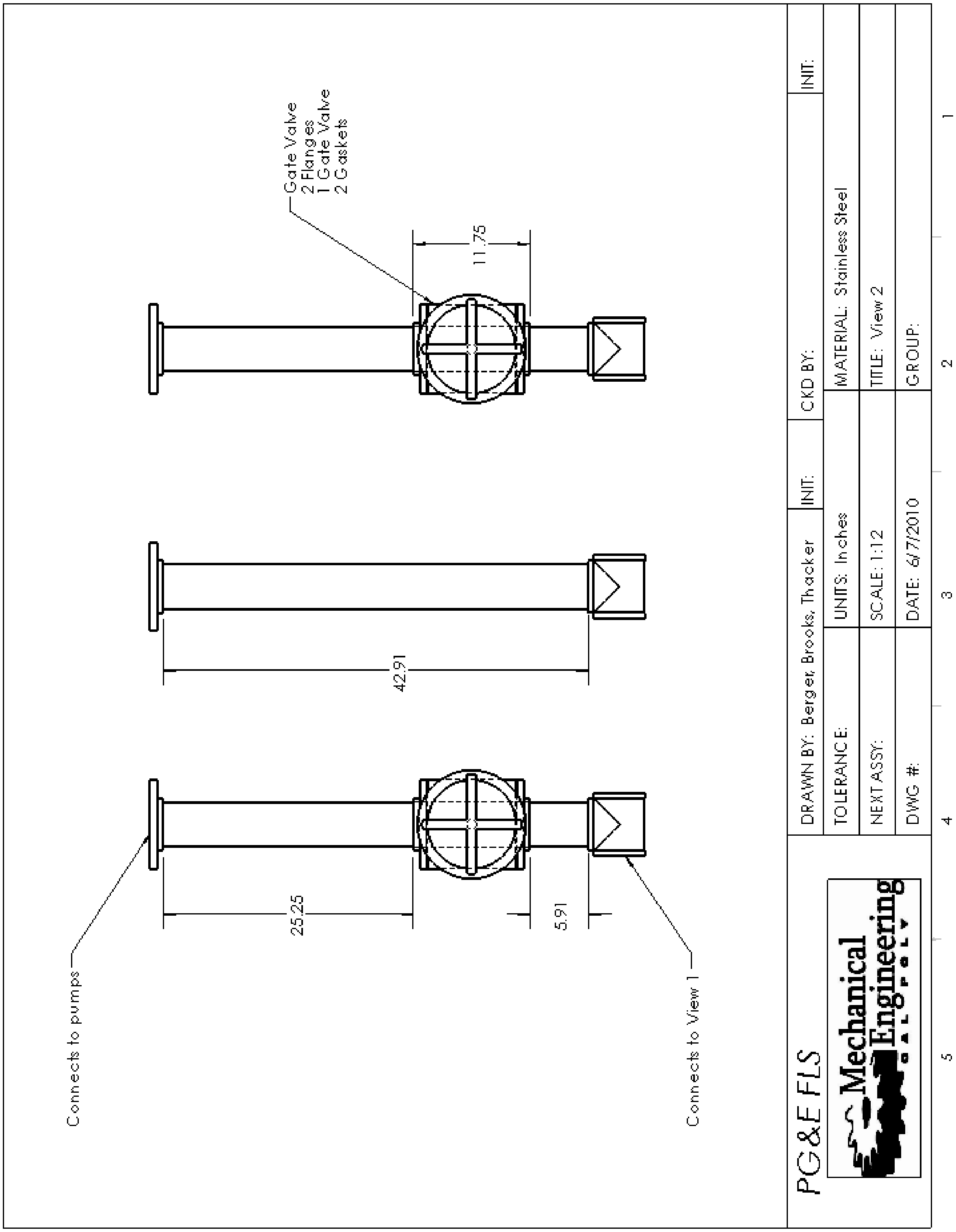
```
"Data"
T_h_i =80[deg F]          "Inlet Water Temperature"
{T_h_o = 106 [deg F] }  "Outlet Water Temperature"
T_c_i = 66 [deg F]         "Inlet Air Temperature"
m_dot_water = 6131 [lb/hr]        "Water Mass Flow Rate"
V_dot_air =1800 [cfm]   "Air Volume Flow Rate 1703"
m_dot_air =V_dot_air*rho_air*60           "Air Mass Flow Rate"
C_h=c_water*m_dot_water
c_water=Cp(Water,T=T_avg,P=P_atm)
T_avg=(T_h_i+T_h_o)/2
P_atm = 14.7 [psi]
C_min=c_air*V_dot_air*rho_air*60
c_air=Cp(Air,T=T_c_i)
C_r=C_min/C_h
rho_air=Density(Air,T=T_c_i,P=P_atm)

"q Max"
q_Max=C_min*(T_h_i-T_c_i)

"E = Effectiveness Must Be < 1"
E=(C_h*(T_h_i-T_h_o))/(C_min*(T_h_i-T_c_i))

"Number of Transfer Units"
E=1-exp((1/C_r)*(NTU^0.22)*(exp(-1*C_r*(NTU^0.78))-1))

UA=NTU*C_min
UA=9403
```

Appendix R: Piping Layouts

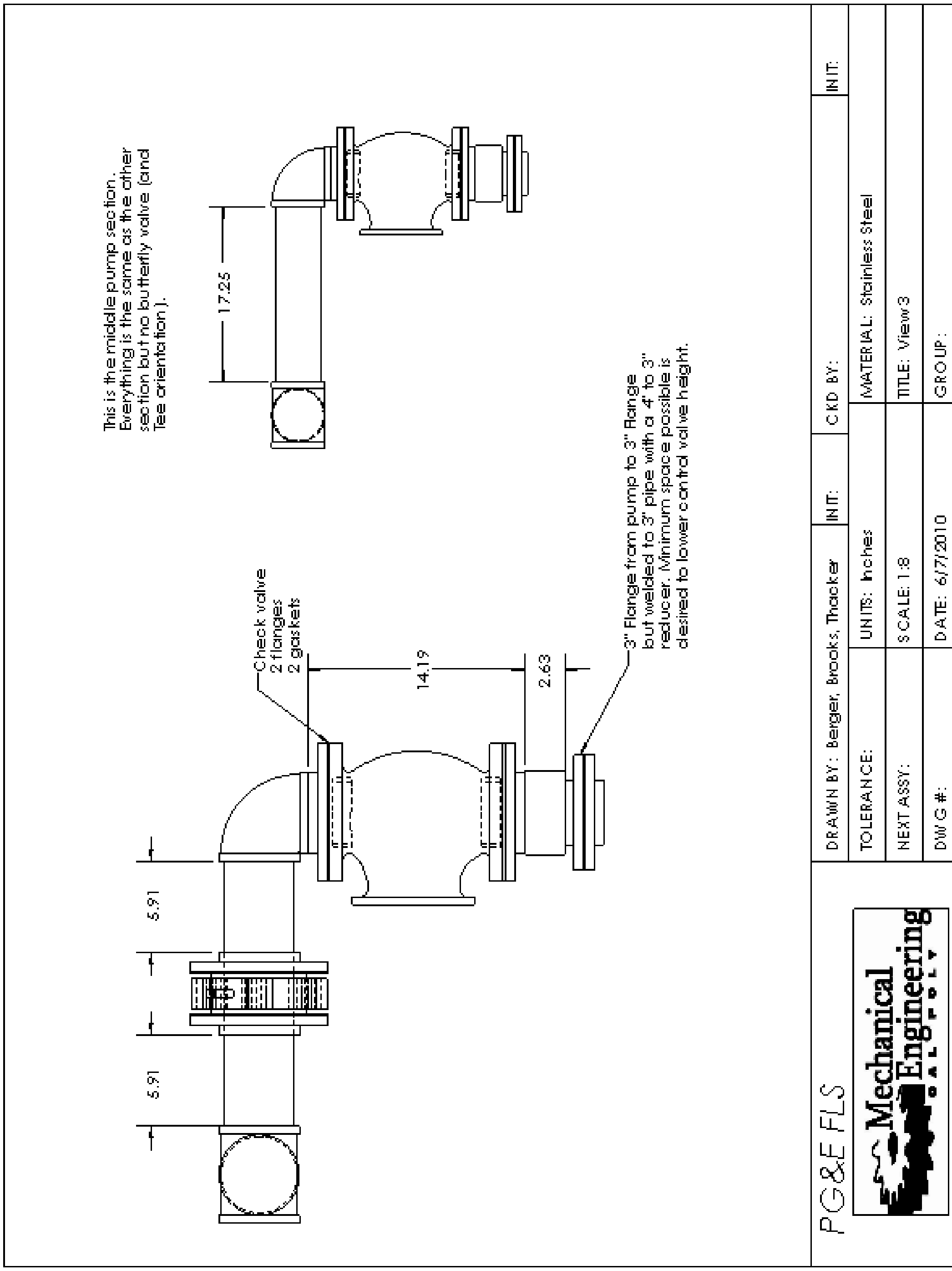
Piping View 1



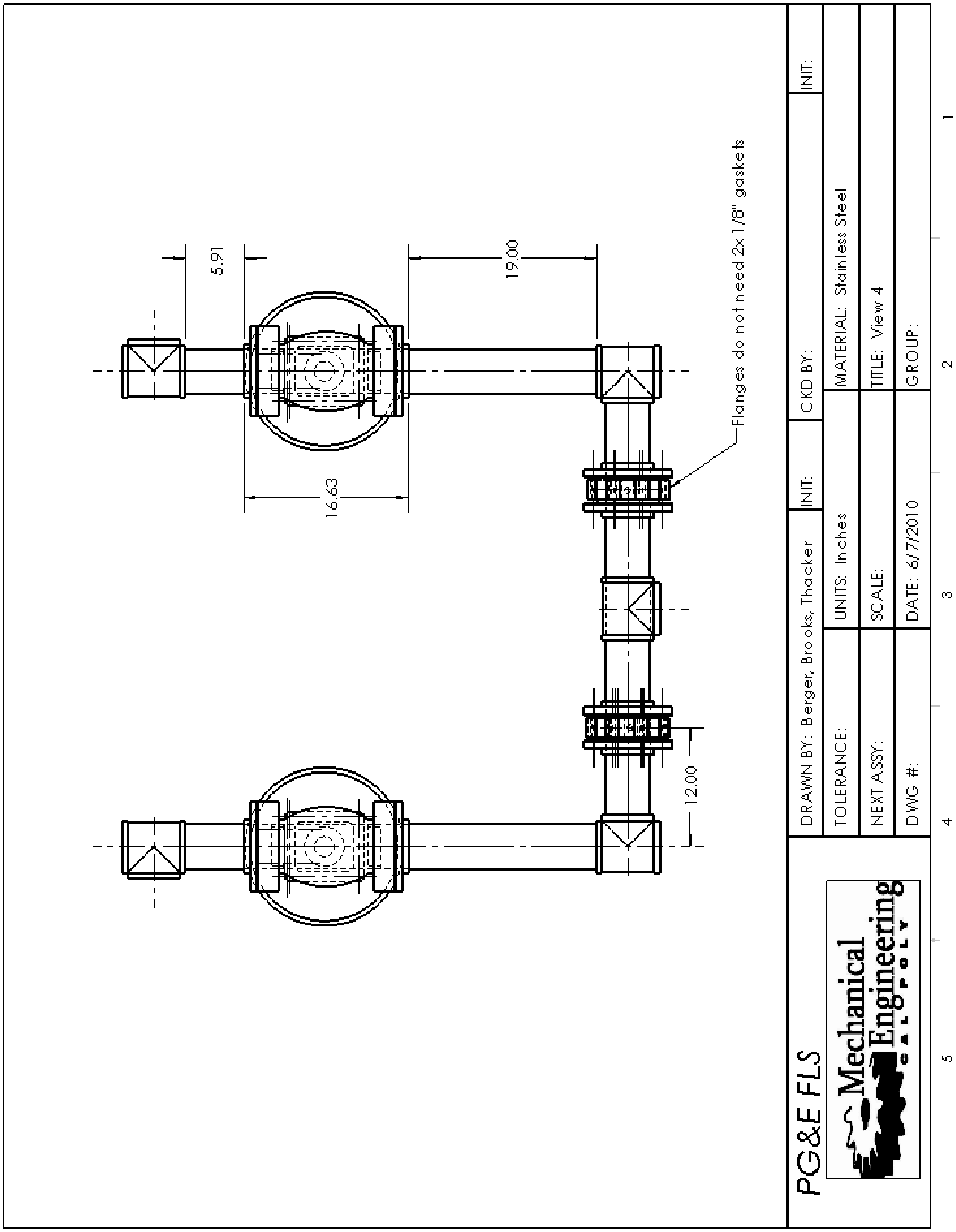
Piping View 2



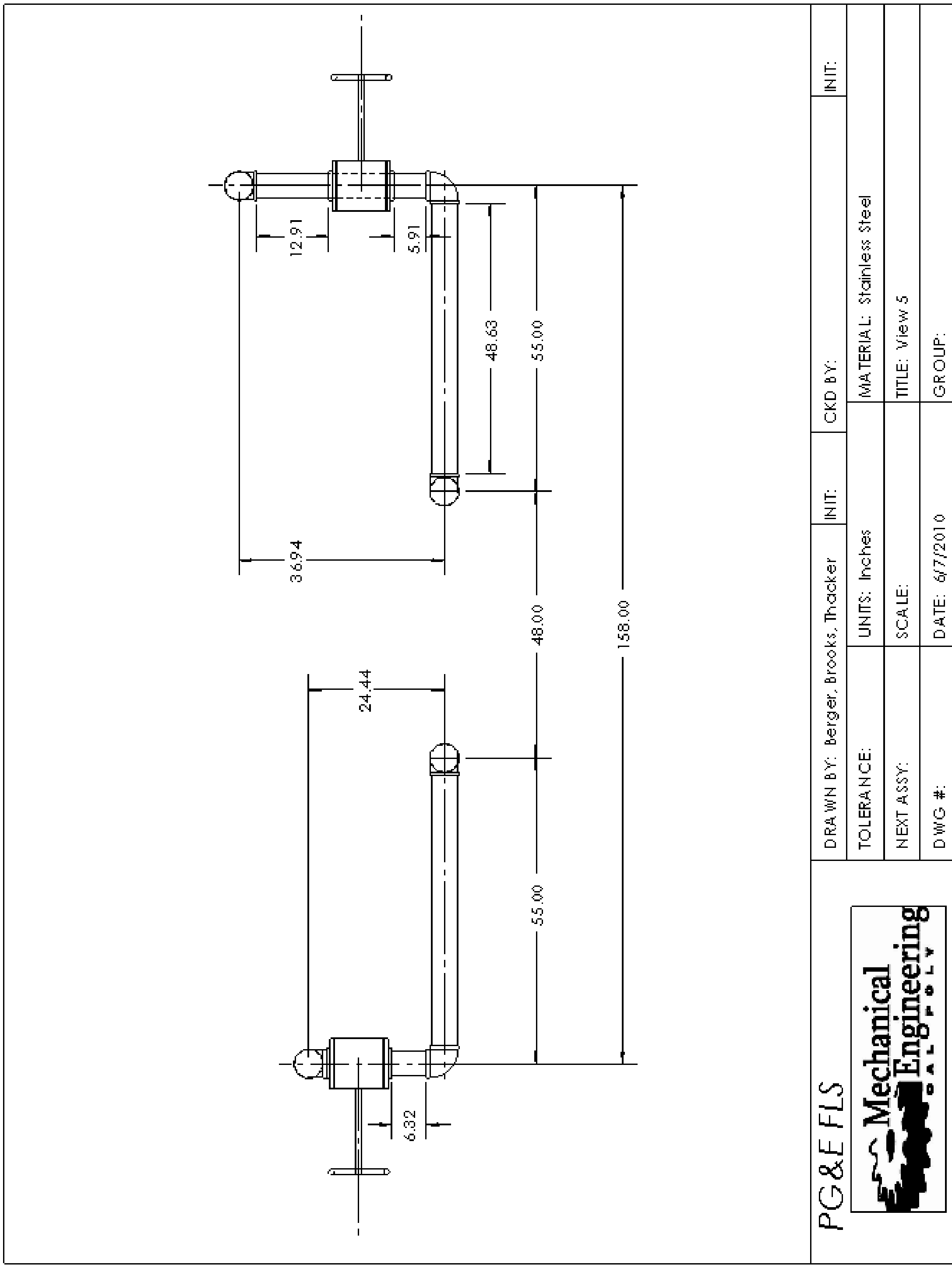
Piping View 3



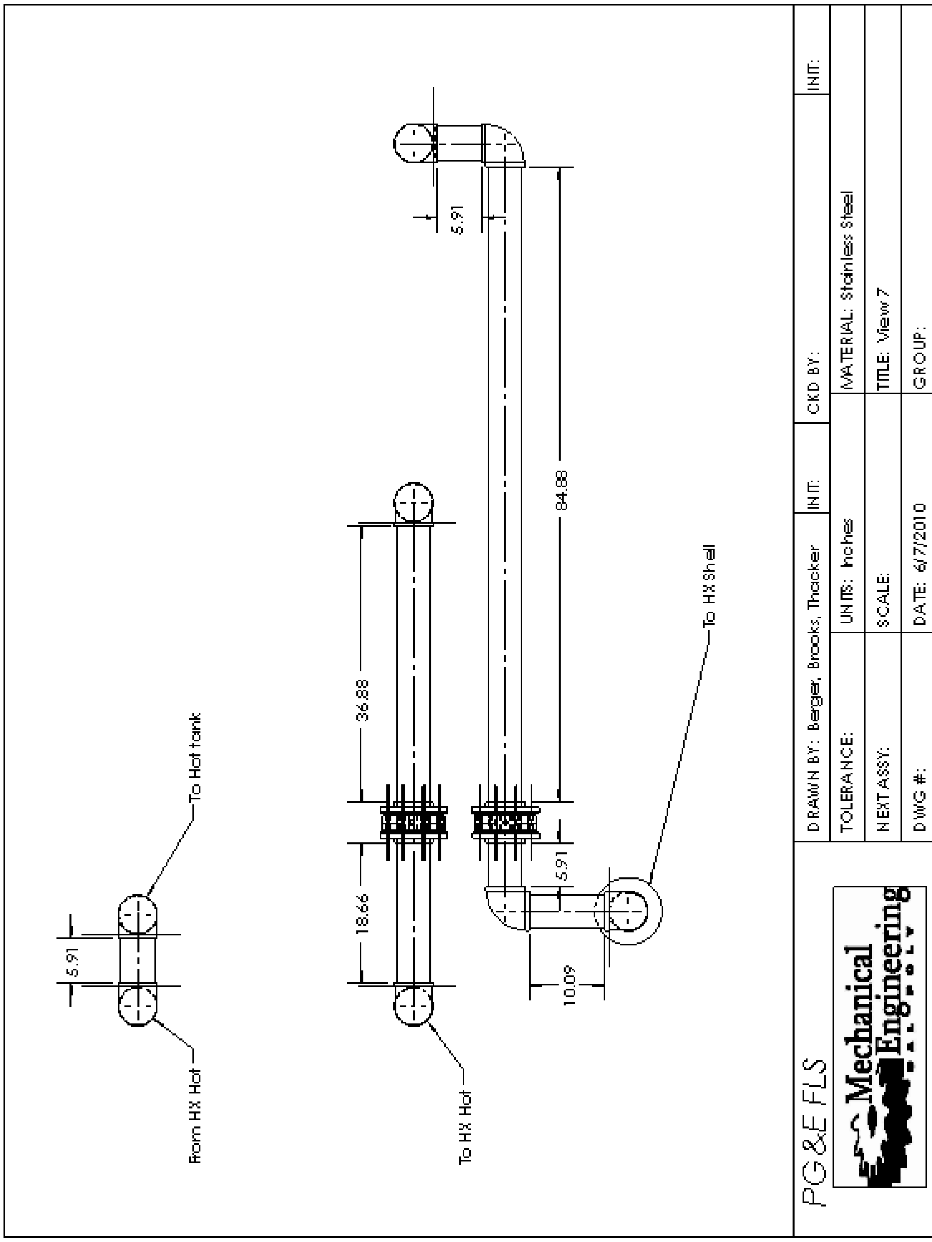
Piping View 4



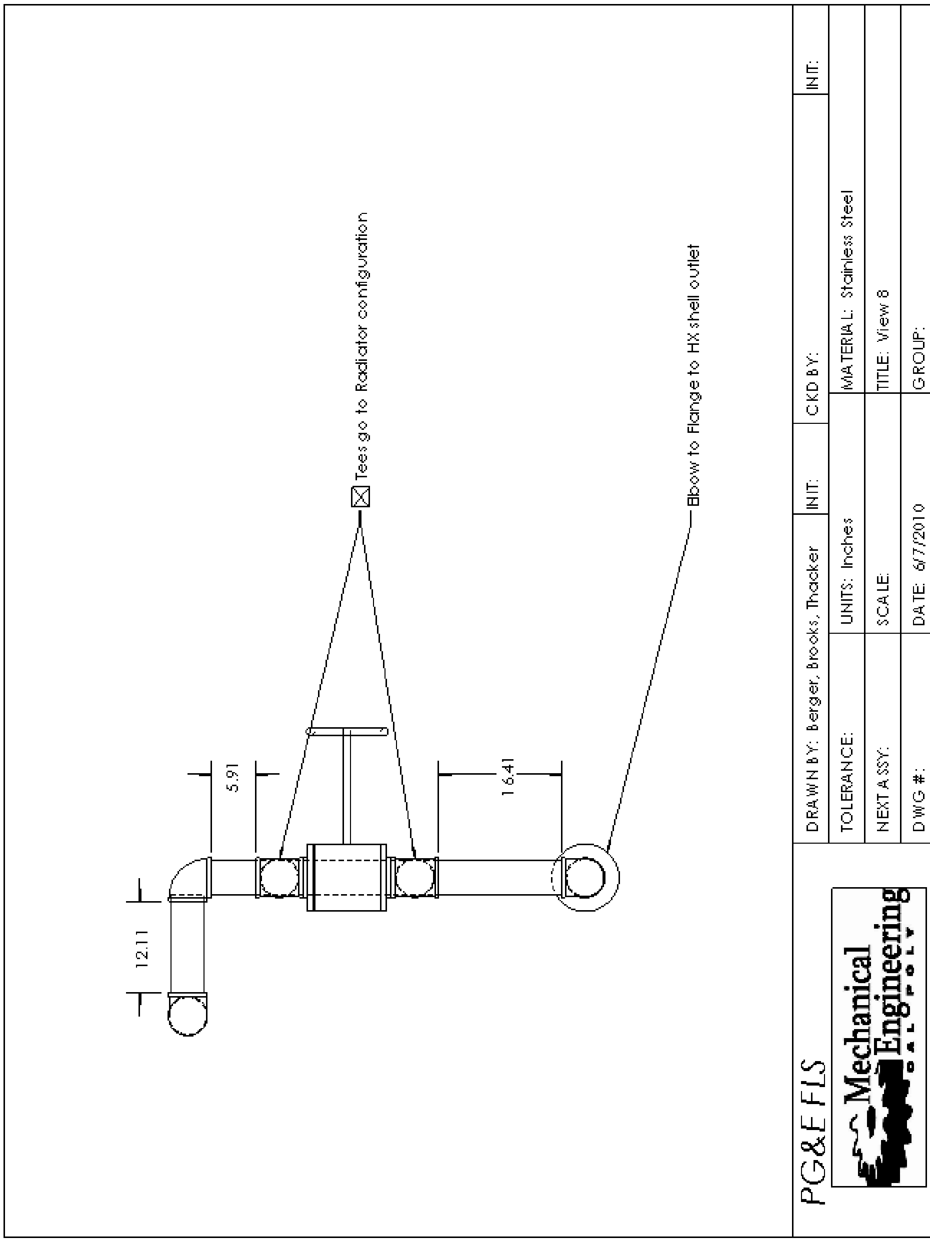
Piping View 5



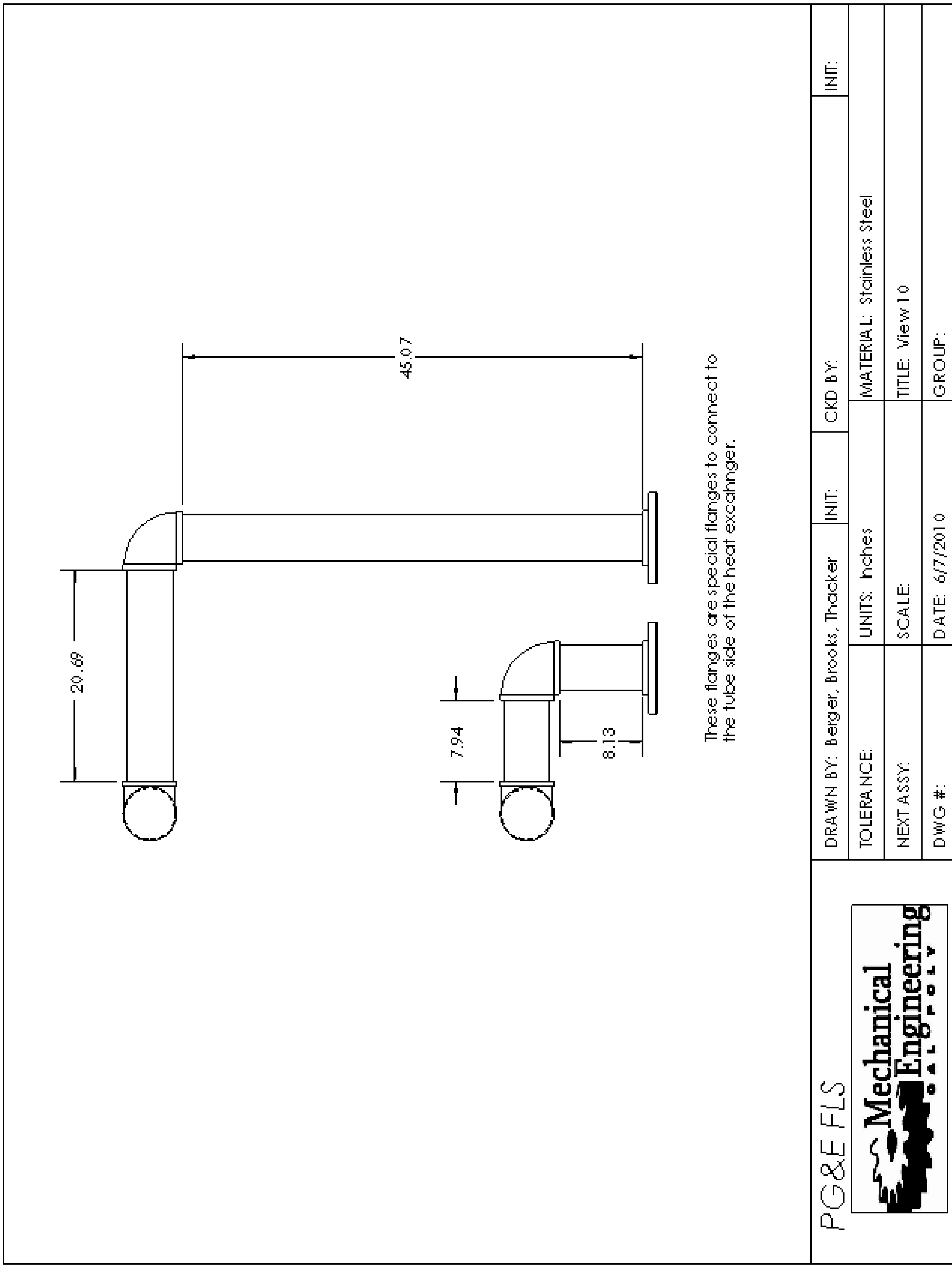
Piping View 7



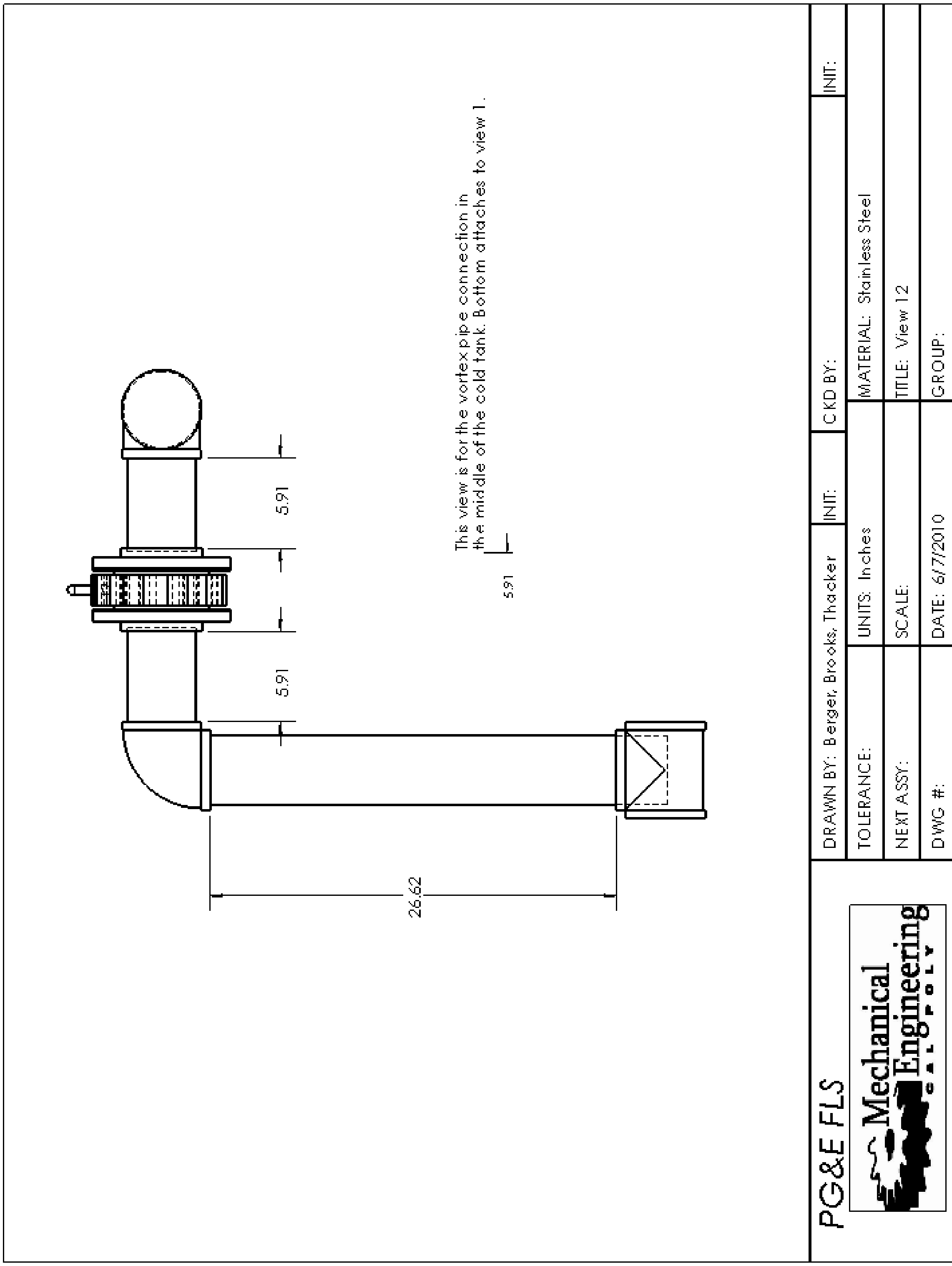
Piping View 8



Piping View 10



Piping View 12



Appendix S: Required Pipe Lengths

Length (in) *does not include thread length	Quantity
5.91	18
25.25	3
6.22	8
48.63	3
0	11
42.91	1
17.25	2
19	1
6.32	1
12.91	1
84.88	1
36.88	1
18.66	1
10.09	1
12.11	1
16.41	1
45.07	1
20.69	1
7.94	1
8.13	1
26.62	1

Appendix T: Hot Tank