Flow Loop Simulator

ME 430: Senior Project

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Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

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1 Executive Summary

PG&E's Diablo Canyon Power Plant has requested a full-sized flow process system for training of technicians by providing them a hands-on experience in a controlled environment. The basic design requirements were established to determine the scope of the project. An initial system layout was selected from a variety of concepts after similar system schematics, components, and processes had been researched. The resulting schematic was flexible to suit several needs of the control aspect while remaining simple.

Design efforts resulted in a system capable of many configurations; allowing for implementation of three training experiments. These experiments involve control of tank level and heat transfer (via temperature drop across a heat exchanger) as well as a vortexing experiment. Analysis supports the effectiveness of these experiments in meeting the desired specifications. Without a completed system, installation and testing of the controls system was impossible. PG&E and the professors of Cal Poly will determine what future projects need to be started to finish the simulator.

Note that this report is for the control team and does not communicate many of the design associated with the main system.

2 Introduction

Law requires the technicians at PG&E's Diablo Canyon Power Plant to go through a complete training process before they are cleared to work inside the power plant. This training involves many hours of training to learn the maintenance procedures will be used in the plant. Due to the nature of the technicians' job, a hand on experience is imperative to their training. This experience is cut short without training on a working, full-sized system in a relatively safe and controlled environment.

3 Background

The Diablo Canyon Nuclear Power Plant Learning Center currently has an inoperable, full-scale flow loop simulator comprised of numerous pumps, multiple feed water tanks, a heat exchanger, a lube oil system, a chemical injection system, and numerous valves and controllers of various types. The 16' by 8' unit is currently inoperable due to oversized pumps coupled with incorrect piping sizes. A mismatch of pump outlet and inlet diameters also causes cavitation of the high-flow pumps which severely damages the impellers. These problems render the system completely inoperable.

A detailed system schematic of the old flow loop simulator illustrating the various loops with main components and control valves was provided and is included as Appendix B. This full scale system will be a valuable resource because it serves 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, NE was also provided and is included as Appendix C. The schematic details two pumps to 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.

In addition, the 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 piping is used instead of 4” stainless steel pipe to transport the working fluid.

A database of available materials and components in the plants large warehouse has also 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 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 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 main 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, all in an environment that is safer and less critical than within the plant.

3.2 Engineering Specifications:

1) System must be built on structures capable of being transported without the need for special permits pertaining to weight, length, height or width.
2) System must replicate the plant environment by:
    a. Using as many possible components and subsystems commonly found in the plant environment:
        - Valves (flow control, check, isolation)
        - Controls (temperature, flow, pressure, tank level)
        - Instrumentation (temperature, flow, pressure, level, flow metering)
        - Heat exchangers
        - Pumps
        - Tanks (1200 – 1600 gallons)
        - Piping (4”-6”)
        - Boiler/heater
        - Snubbers
        - Chemical add tank
        - Injection pump
    b. Replicating common procedures performed in plant maintenance and operation
    c. Possibly replicating common scenarios for technicians and operators such as:

        - Pump Vortexing
        - 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
3) System must operate on available utilities
    a. Compressed air (110psi)
    b. Electricity (480VAC and 120VAC)
    c. Potable Water
4) Primarily use components commonly stocked by the plant
5) System shall stay within safe operating conditions
    a. Maximum allowable pressure: 110psi
    b. Maximum allowable Temperature: 120°F

4 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 designing the main system and is responsible for the selection of all pumps, heat exchanger, tanks, piping, heating elements and skid design. The controls team is responsible for selecting all instruments, valves, control valves, and controllers, as well as setting up a controls interface and operation procedures.

4.1 *Controls Team Management Plan*

The controls team is composed of Kevin Rehm, Matt Starbuck, and Tyler Ista. This team is responsible for the design and implementation of the flow loop simulators instrumentation, and controls. Tyler, the team leader, will conduct most of the systems analysis and focus on valves. Matt will be in charge of choosing appropriate instrumentation for the system and in charge the controllers. Kevin will be in charge of motor and heater electrical as well as in charge of keeping the team on task and on schedule. Everyone on the controls team will conduct research, support the building of the skid, and help with all experiment testing.

The team shared information with both the system and controls groups using Google Groups. The team met two to three times a week with the agenda shown in Appendix D.

5 Controls Design Considerations

5.1 *Method of Approach for Controls*

The controls team aims to provide proper instrumentation, control valves, controllers, power, alarms and interlocks to the system, as well as a set of experiments to demonstrate the control system. To do this, a system layout must be developed. Both subsections of the team worked together to develop a piping system layout. It was important to keep both sub-teams' criteria in mind during development.

The research began with the old PG&E Flow Loop Simulator and other similar systems. A detailed system schematic of the inoperable PG&E simulator illustrating the various loops with main components and control valves was provided by PG&E, and is included as Appendix B. 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 schematic from a flow loop simulator used by Cooper Nuclear Station in Brownville, Nebraska was provided by PG&E, and is included as Appendix C. 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 assisted in development of the initial piping layout. One of the aims of the controls team in the design was to have the system capable of producing three experiments: a heat transfer, a tank level control, and a vortexing experiment. The two teams worked together on the system design; ensuring all of the controls team's considerations were included and no reiterations of the 2-D piping schematic would be necessary for in the future development of the project.

The experiments were the main driving force behind the controls design. The experiments demonstrate how controls can be used can be used in a plant environment as well as how the components of the system can be used. Considerable thought went into determining which characteristics of the system would be controlled and how.

Additionally, the control system needed to provide control of the pumps and heater for safety purposes. The heater needs to be turned off when the water level was too low and when the temperature became too high. The pumps need to be turned off when the water levels were close to cavitation and when the vented tanks are close to overflowing. A secondary system of interlocks was also developed for redundant safety precautions on high safety risks.

Analysis needed to be conducted on the heat transfer and level control experiments to confirm feasibility, determine controller gains, and give an approximate time response to each experiment. System dynamics was used to analyze the response of each experiment.

5.2 Piping Layout

All major system layouts are in the attached System Figures in Appendix I.

The piping layout dictates how controls and instrumentation will be implemented. The systems team has developed the design with some input from the controls team. System Figure 1 displays the system that has been developed. The points of interest for controls are the instruments and valves as well as the general layout of the system.

6 Experiments

6.1 Experiment Development

Once the piping system was finished the goal was to configure it for controlling system parameters. This led to the development of three experiments. PG&E desired a demonstration of vortexing; making it the first experiment. One of the main purposes of the system was to transfer heat, making a control system around this concept became the second experiment. Tank level became the last experiment because the system could easily be set up to change the levels of the tanks and tank level control is a very visual use of a control system.

6.1.1 Vortex Experiment

Goal:

The vortex experiment provides an experiment where the trainee can experience the effects of a vortex.

Configuration:

To achieve vortexing the water surface needs to be within 2.5 ft. from the suction outlet. To get the pipe outlet closer to the surface of the water the outlet of the cold tank will be switch from outlet B to outlet A shown in Figure 6-1. The cold tank inlet needs to be under the water surface to prevent disruption in the vortex.

For the vortex experiment all other parts of the system will be excluded. The water on the cold side will not pass through the heat exchanger or the radiator. Also the outlets are switched via opening and closing valves. The system configuration for the vortex experiment is shown in System Figure 4.

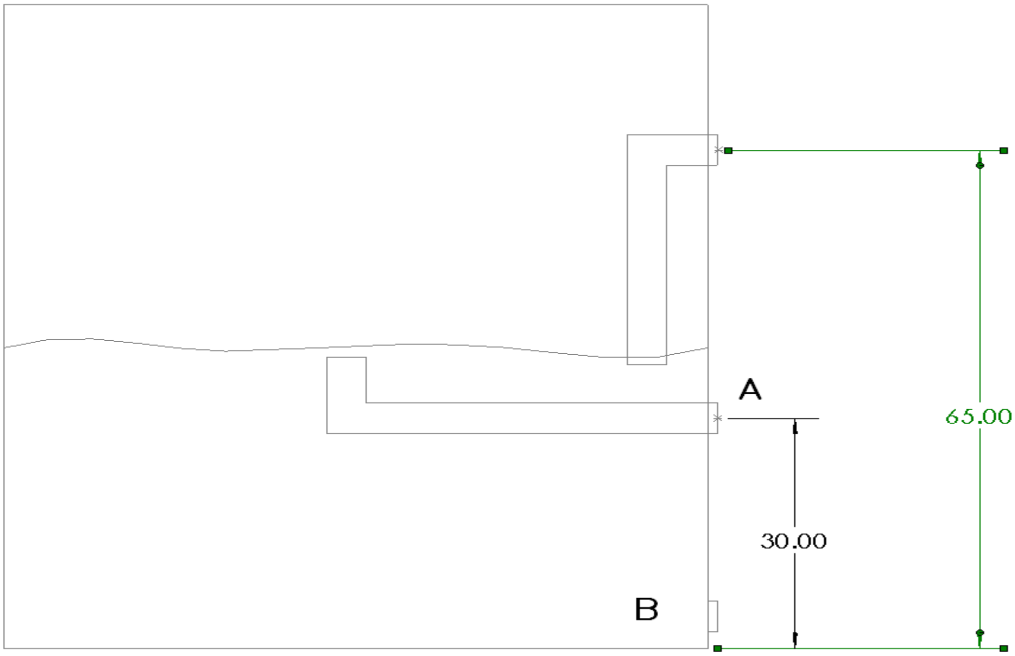


Figure 6-1. The internal piping configuration of the cold tank for creating vortexes. (Dimensions are in inches.)

Analysis Results:

Based on information from Gould's Pumps, in Figure for 200GPM and a 4 inch diameter pipe, the inlet needs to be less than 2.5 feet from the surface of water to start vortexing.

Experiment Development:

The vortex must be created in one of the tanks because it is the only part of the system where there is a water surface and the ability to suck air into the pump. The hot loop tank was not selected because of the heating elements inside it will disrupt the vortex and prevent it from occurring. Therefore, the cold loop was selected to conduct the experiment. To create the effect the pump needs to pull water closer to the surface of the water in the tank or increase the flow rate by a large amount. Since it is difficult to increase flow rate, changing the tank outlet level was chosen.

6.1.2 Heat Transfer Experiment

Goal:

The heat transfer experiment provides a controls experiment where the controlled parameter is temperature.

Configuration:

The valves will be open and shut as shown in System Figure 2. The flow of the hot loop is highlighted in red and the cold loop in blue. The controlled temperature is the temperature gradient between TI-03 and TI-04. The control valves (CV-22 and CV-23) control the flow rate on each side of the loop, which affects the heat transfer between the two loops.

The PAC controls the entire process, and will additionally have to maintain a constant hot tank temperature. The temperature is to be maintained by turning individual heaters on and off based upon need.

Analysis Results:

The results seen below in Figure 6-2 show that the following analysis is supported by the systems teams' analysis. The heat-up time for the system is 1452 seconds (~24 minutes). This is with both control valves nearly closed in the model to prevent any heat transfer between sides.

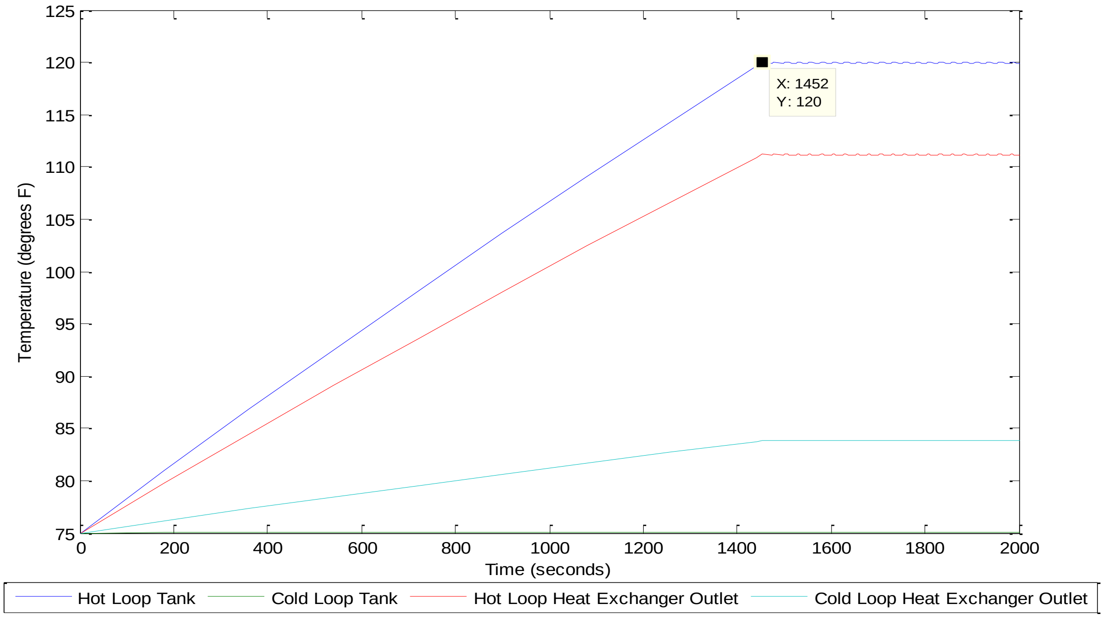


Figure 6-2. Temperature response of the system during heat up of the hot tank.

Following the confirmation of accuracy of the model, it was important to determine the range of temperatures that could be chosen as a set point. The results can be seen below in Figure 6-3, a 3D plot of the effect of both control valve positions on the differential temperature drop across the heat exchanger.

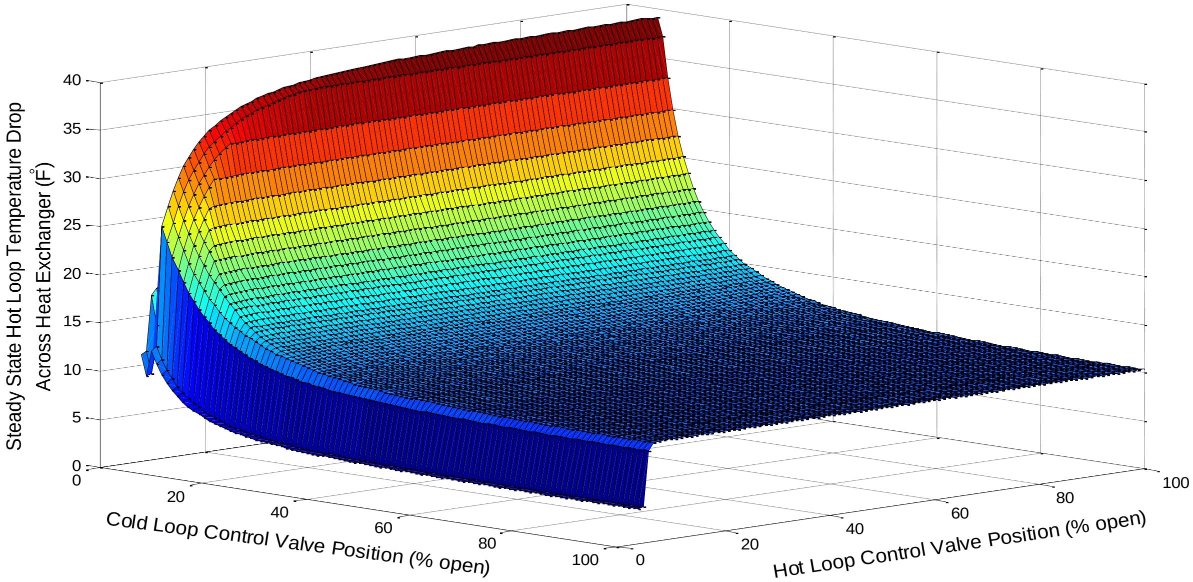


Figure 6-3. The temperature drop across the heat exchanger versus the control valves' positions.

The above figure shows that the range of setpoints for the temperature drop across the heat exchanger can be from nearly zero degrees Fahrenheit to almost 40 degrees Fahrenheit. This is the best case scenario of a 60°F ambient temperature. Figure 6-3 also shows that the cold loop control valve has a much greater effect on the differential temperature drop across the hot side of the heat exchanger. It is important to notice the high sensitivity of the cold loop control valve position on the differential temperature. The valve is only operating within 20% of its total throw. This sensitivity will only present a problem if the temperature across the heat exchanger is capable of changing too rapidly. With the current model an instantaneous change is possible because the effectiveness-NTU method used to model the heat exchanger does not take into account the thermal capacitance of the metal of the heat exchanger. For these reasons the controllability of the system is still in question.

The details of the analysis can be found in Appendix H.

Experiment Development:

The main purpose of the flow loop simulator is to expose technicians to as many components as possible and related processes. With the heat exchanger being one of the main components in the system, it was necessary to provide the process of controlling temperature drop across the heat exchanger.

In Figure 6-4 two different positions were considered for the control valves. A control valve in position B with a gate valve in position A was chosen due to its common occurrence in real systems and its ability to control the flow rate from full throttle to no flow.

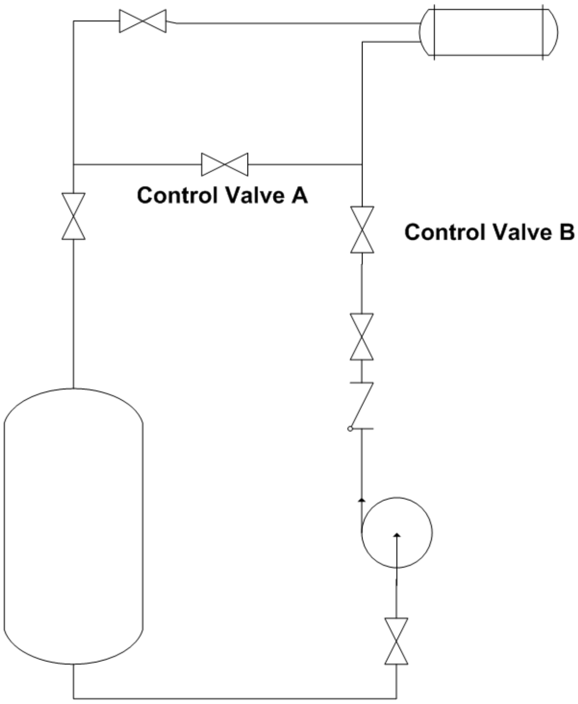


Figure 6-4: Positions considered for the control valves for the heat transfer experiment.

6.1.3 Level Control

Goal:

The objective of a level control experiment is to provide an example of a controls system in which tank level is controlled. The benefit of this experiment is the tangibility of tank level and the ease of observation of its operation.

Configuration:

Flow will be provided via two pumps both pulling water from their respective tank. The outlets of these pumps are connected to each other and the control valves. Therefore the control valves will determine how much of the combined flow from both pumps enters each tank. This configuration can be seen in System Figure 3. It should also be noted that the placement of the valves between the control valve outlet and the tanks would allow a disturbance to be added to the control system. Such a disturbance would allow observance of the system's response to varying conditions.

Analysis Results:

As seen below in Figure 6-3, all of the water from one 6 foot diameter 7 foot tall tank can be transferred to the other in 175 seconds. Meaning the tank heights can be changed by a foot in 50 seconds. Therefore, making it easy to observe the effects of a change in set point or a disturbance added to the system.

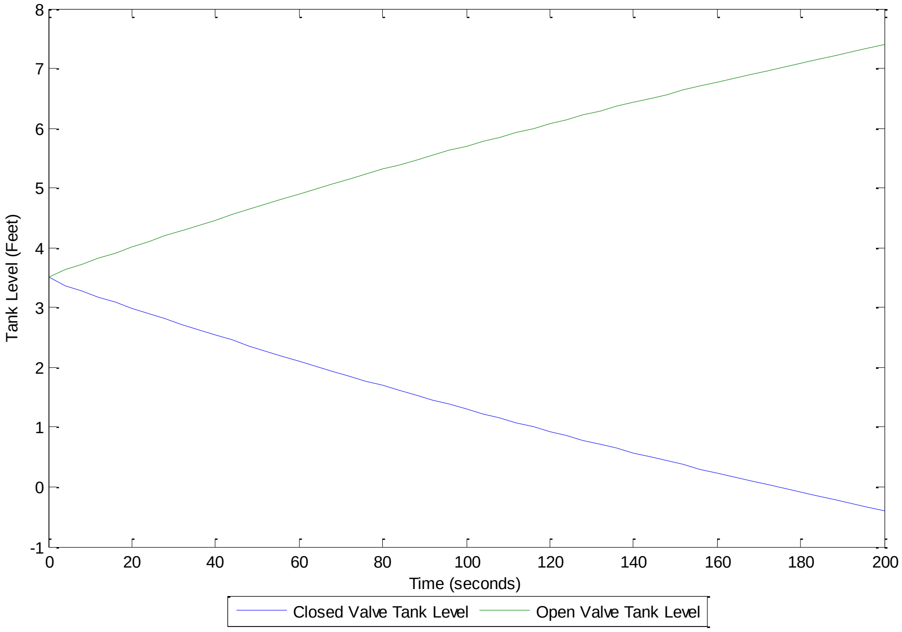


Figure 6-5. Tank level response for a four foot change in tank level for each tank.

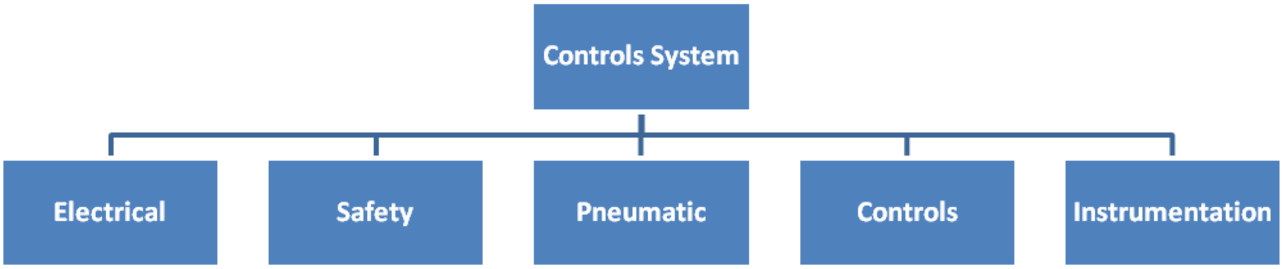
Experiment Development:

This experiment went through many iterations. First, many different concepts were considered. These concepts varied by placement of the control valves. Some of the concepts would have required separate control valves for the two different experiments. Cost of control valves was considered and a configuration of System Figure 1 was chosen. Following analysis of this configuration led to a number of iterations due to slow system response. This analysis can be referred to in Appendix H. The final configuration that was determined is in System Figure 3.

7 Control System Design

7.1 Control System Overview

The diagram below illustrates the division of the system into 5 key parts. Each of these subsystems has specific components with specifications based off of other components or based off of the design of the fluid/thermal system.



7.2 Instrumentation Subsystem Design

7.2.1 Instrumentation Subsystem Requirements

The goal behind instrumentation is to provide electrical and mechanical instrumentations for the system. The electrical will be used to run the PACs and provide a central display for all of the system characteristics. Mechanical gauges are for displaying locally were the characteristic is being measured.

7.2.2 Instrumentation Subsystem Overview

There are four properties being measured in the system: temperature, pressure, flow rate, and tank level. All four are to be done electrically, but flow rate will not be done for the gauges. All of the locations to be observed are shown in the piping diagram System Figure 1.

7.2.3 Instrumentation Component Specification

Temperature instrumentation at seven points to be measured with:

- 7 RTDs
- 32°F – 150°F
- The RTDs need to be mounted into a thermowell, as shown in Figures G-3 in Appendix G.

Pressure instrumentation at ten points to be measured with:

- Ten pressure transducers
  - Milliamp signal
  - 0 – 50 psig
- Ten redundant pressure gauges
  - 0 – 50 psig
- A maintenance tap can be used for both the gauge and transducer at each location, making a total of ten maintenance taps needed as shown in Figure G-2 in Appendix G.

Flow rates are to be measured with:

- Differential pressure transducer across an orifice plate
  - Milliamp signal
  - 0 – 5psi differential pressure
  - Mounting and the additional piping needed is shown in Figure G-1 in Appendix G

Tank levels are to be monitored with:

- Pressure transducers
  - A pressure range of 0 – 5psi (Eight feet of water produces 3.5psi)
  - Milliamp signal
  - Mounting shown in Figure G-4 in Appendix G.
- Sight glasses
  - Approximately 4 – 5 feet tall.

7.3 Controls Subsystem Design

7.3.1 Controls Subsystem Requirements

The controller is to read all electrical signals and control the heaters and pump power switches, as well as the control the valves positioners proportionally. Each experiment has particular characteristics to control.

The heat transfer experiment is to control a temperature difference across the heat exchanger by manipulating the flow rate with the configuration shown in System Figure 2.

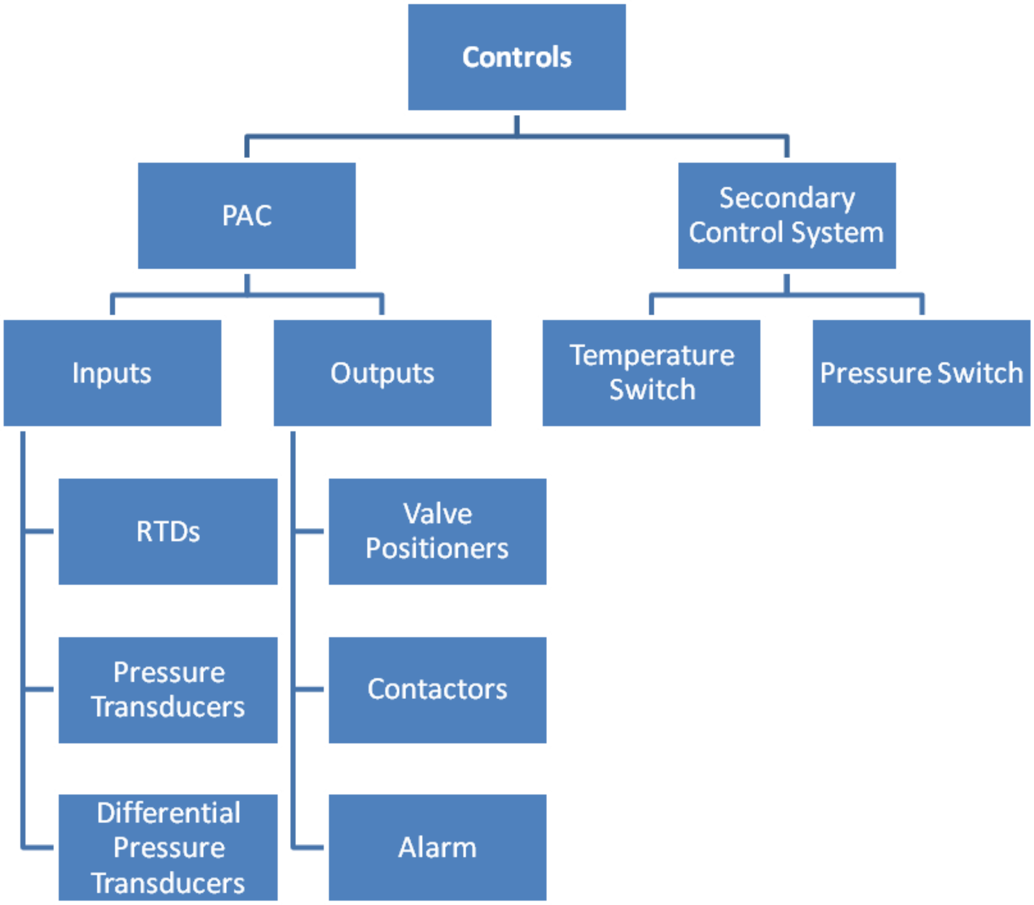
- Temperature difference of 10°F across TI-03 and TI-04
- Control flow rate with CV-22 and CV-23

The tank level experiment is to control the level of the cold tank by moving water between the two tanks using the configuration shown in System Figure 3.

- LI-9 use for control feedback
- Flow between tanks controlled by CV-22 and CV-23

7.3.2 Controls Subsystem Overview

The primary control unit of basic operations, alarms, and interlocks is the PAC. The secondary control system is the back up for the interlocks only. The alarms and interlocks are discussed in detail in the safety section. This section focuses on the basic operations.



7.3.3 Controls Component Specification

The inputs that the PAC needs to read are:

- 14 4-20 milliamp signals for pressure transducers
- 7 RTD signals
- Input diagram is shown in System Figure 5. (Legend is System Figures 11 and 12).

The outputs for the PAC are:

- 9 120VAC for toggling pumps, heater, and alarm on/off
- 2 4-20 milliamp signals for valve positioners
- Output diagram is shown in System Figures 7 and 8. (Legend is System Figures 11 and 12).

The following components have been made available for the project:

- 1756-L63 Series A PAC
- 1756-OW16I Relay Module
- 1756-PA72C Power Supply
- 1756-IF16 Analog Input Module (need 2 modules)
- 1756-OF8 Analog Output Module
- 10.4" Panel View Plus Touch Screen Monitor in a 16" x 16" x 9" enclosure

These components take care of the PAC, all of the milliamp inputs and outputs modules, and the 120VAC module, as well as a power supply. The additional equipment needed are one chassis, communication module, an RTD module, and slot fillers. The following have also been recommended:

- 1756-A7 – Seven Slot Chassis
- 1756-IR6I – Six channel RTD input module (need 2 modules)
- 1756-EN2T – Communication module

7.3.4 Controller I/O Setup

The specific module to instrument/component is as shown in Appendix F.

7.4 Electrical Subsystem Design

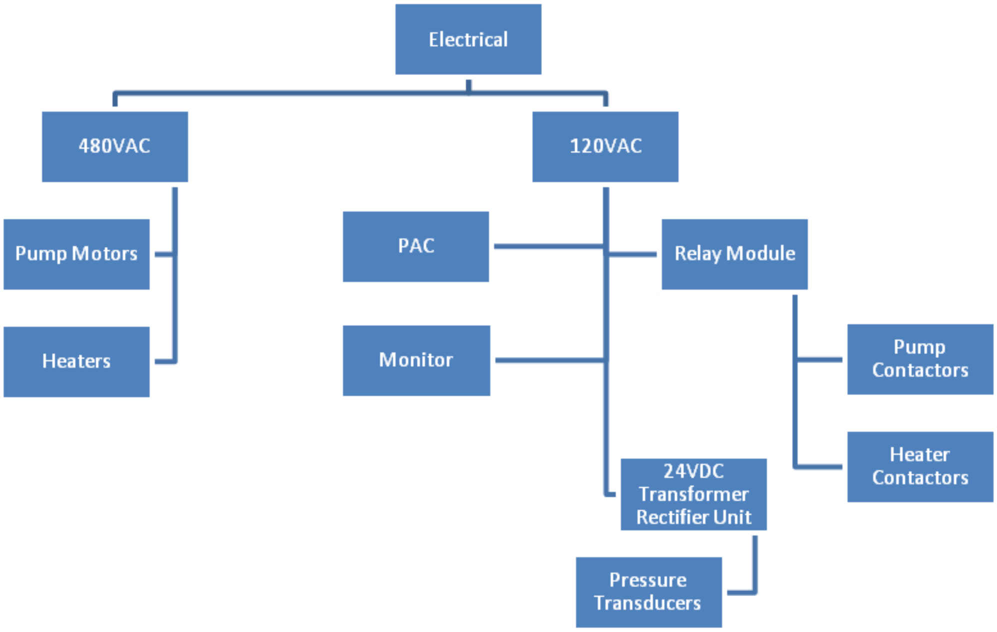
7.4.1 Electrical Subsystem Requirements

- Operation: Provide power to components
- **480VAC (648.3 Amps)**
    - (3) Pump motors
        - 3-phase
        - 5hp (3.73kW) each
        - 7.77 Amps each
        - Total: 11.2kW (23.3 Amps)
    - (5) Emersion Heaters
        - 3-phase
        - 60kW each
        - 125 Amps each
        - Total: 300kW (625 Amps)
- **120VAC (10.42Amps)**
    - 24VDC Transformer Rectifier Unit
        - Estimating from Omega PN: PSS-D12B
            - Output Voltage: 24VDC
            - Max current output: 240mA
            - Assuming 50% efficient

    - Total: <<1 Amp
  - PAC
    - 100W (0.83 Amps)
  - PanalView Plus Touch Screen Monitor
    - 70W (0.59 Amps)
  - Contactors (heaters and Pumps)
    - <1 Amp per contactor
    - Total: <8 Amps

7.4.2 Electrical subsystem Overview

There are a variety of voltage and power needs to be accommodated in the system. These requirements are looked at in this section as well as the support equipment necessary.



7.4.3 Electrical Subsystem Component Specification/Selection

Relay Output Module

- Quantity required: 1
- Position on System Figure 8 and 9.
- Operation: Switch 120VAC to turn on and off contactors
- Specs:
  - Relays Required: 8
- **Selection:** 1756-OW16I (recommended by Kris Jentzsch)

Pump Contactors

- Quantity Required: 3
- Positions of PC-29, PC-30 and PC-31 on System Figure 8, 9 and 10.
- Operation: Turn on and off each 5hp pump via relay module
- Specs:
  - Primary Voltage: 480VAC 3-phase (7.77Amps)
  - Secondary Voltage: 120VAC
  - Maximum Coil Power Rating: 250VA

Heater Contactors

- Quantity Required: 5
- Positions of HC-24, HC-25, HC-26, HC-27, and HC-28 on System Figure 8, 9 and 10.
- Operation: Turn on and off each heater via relay module
- Specs:
  - Primary Voltage: 480VAC 3-phase (125 Amps)
  - Secondary Voltage: 120VAC
  - Maximum Coil Power Rating: 250VA

24VDC Transformer Rectifier Unit

- Quantity Required: 2
- Positions of PS-32 and PS-33 on System Figure 6.
- Operation: Convert 120VAC to 24VDC for pressure transducer supply
- Specs:
  - Pressure transducer max current pull: 20mA
  - Number of Transducers: 10
  - Total: 200mA

7.5 Pneumatic Subsystem

7.5.1 Pneumatic Subsystem Requirements

- Provide pneumatic supply to system
- (2) Control valves
  - Model # 667-ED-35821
  - Serial Numbers:
    - CVS090935A
    - CVS090935B
  - Max pressure supply: 65 psi
  - Regulator
    - Type: 67CFR-224
    - Max Pressure: 250 psig
    - Spring Range: 0 - 35psi

7.5.2 Pneumatic Overview

Pneumatic is used to operate the control valves. Pneumatic diagram on System Figure 11.

7.5.3 Pneumatic Component Specifications

The only remaining component for the pneumatics is the pneumatic lines. The length need will need to be determined by the location the flow loop simulator.

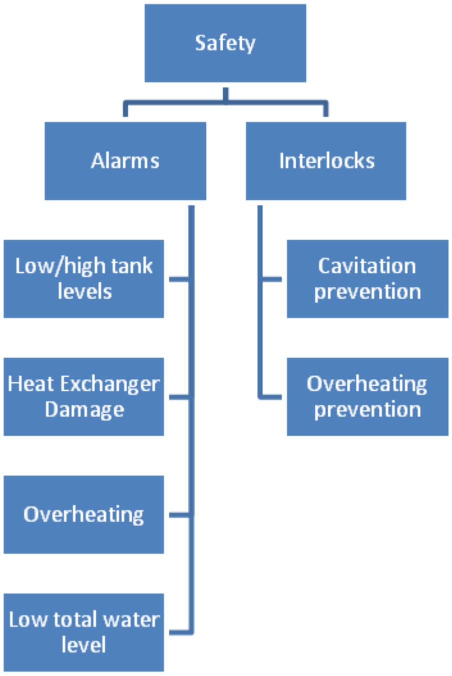
7.6 Safety Subsystem Design

7.6.1 Safety Subsystem Specifications

- Maximum system temperature: 120°F
- Prevent component damage:
    - Heater operating out of water
    - Pump cavitation
    - Preventing overflow
- Expose failing components
    - Leaking heat exchanger
    - Fouling of heat exchanger

7.6.2 Safety Subsystem Overview

The alarms and interlocks are taken care of by the PAC and secondary control system. This section goes into what conditions the alarms and interlocks each system will run.



7.6.3 Interlock System Design

The interlocks exist for serious safety and system damage prevention. For this reason redundancy will be implemented. The PAC will be primarily responsible for implementing the interlocks. There will also be secondary systems of pressure and temperature switches to absolutely prevent the conditions of cavitations and overheating. A description of how each system will be implemented is below.

Overheating Prevention Interlock

Purpose	Prevent water temperature from exceeding the maximum system temperature
	PAC Interlock
Sensors Used	RTD TI-01. System Figure 1.
Set Point	120°F
Operation	This interlock is already built into the temperature controller for the heater and can be seen in the Controls subsystem design.
	Secondary Interlock
Switch/Sensor Used	Temperature Switch TS-51. System Figures 8 and 9.
Switch Set Point	125°F
Operation	This interlock will operate by switching the 120VAC input to the relay module of the PAC for switching the heater contactors. If the temperature is above the setpoint the switch will shut off the 120VAC supply, preventing power from reaching the heaters.

Cavitation Prevention Interlock

Purpose	Prevent pumps from running when water level in tanks is below the safe limit for cavitation.

PAC Interlock

Sensors Used	Pressure transducers TI-8 and TI-9. System Figure 1.
Set Point	3ft
Operation	If the water level drops below the setpoint then the system will respond by maintaining water level at that setpoint by means of the control valve. Another option is to impose a lower limit on the user input tank level setpoint.

Secondary Interlock

Switch/Sensor Used	Pressure switch PS-52 and PS-54. System Figures 8 and 9.
Switch Set Point	2.75ft
Operation	This interlock will operate by switching the 120VAC input to the relay module of the PAC for switching the pump contactors. If the tank level is below the set point, then the switch will shut off the 120VAC supply therefore preventing power from reaching the pumps.

7.6.4 Alarm System Design

The system of alarms will be implemented within the PAC. These alarms will operate off of the existing pressure transducers and temperature indicators. A description of the operation of each alarm is below.

Tank Level

Purpose	Alert user of dangerously high or low tank levels
Input Parameter	Tank Level
Sensors Used	Pressure transducers TI-8 and TI-9. System Figure 1.
Set Point(s)	42inches and 76inches
Desired Response	Set alarm if tank levels are not within the set points.

Heat Exchanger

Purpose	Alert user of heat exchanger failure
Input Parameter	Pressure drop across heat exchanger
Sensors Used	Pressure Transducers pairs: PI-16, PI-17, and PI-18 , PI-19. System Figure 1.
Set Point(s)	TBD
Desired Response	Set alarm if the pressure drops across both sides of the heat exchanger are not within the set points.

High Temperature

Purpose	Alert user if the system is exceeding the maximum temperature
Input Parameter	Hot tank water temperature
Sensors Used	RTD TI-01. System Figure 1.
Set Point(s)	120°F
Desired Response	Set alarm if the hot tank water temperature is greater than the setpoint.

Low Total Water Level

Purpose	Alert user of a low total system water level
Input Parameter	Tank levels
Sensors Used	Pressure Transducers TI-8 and TI-9. System Figure 1.
Set Point(s)	7ft between both tanks
Desired Response	Set the alarm if the sum of the tank levels is less than the set point.

7.6.5 Safety Component Specification

Due to the interlocks being a redundant system it operation requires a few more components. Specification of these components and the alarm are listed below.

Temperature Switch

Quantity Required	1	
Position in System	TS-51. System Figures 8 and 9.	
Operation(s)	Turn off all heaters if maximum temperature is exceeded	
Specifications	Switching Temperature	125°F
	Current Rating	<5 amps
Suggested Model	Omega Adjustable Temperature Switch (PN: TSW-45)	

Pressure Switch

Quantity Required	3	
Position in System	PS-52, PS-53, and PS-54. System Figures 8 and 9.	
Operation(s)	Turn off heaters if exposed above water surface	
	Turn off pumps if NPSHA approaches NPSHR due to low water level in tanks	
Specifications	Switching Pressure	Heater operation: 40 in H_2O Cavitation Operation: 36 in H_2O
	Current Rating	<1 amp
	Deadband	<2 in H_2O
Suggested Model	Omega General Purpose Pressure Switch (PN: PSW-138)	

Alarm

Quantity Required	1	
Position in System	A-50. System Figures 8 and 9.	
Operation(s)	Notify user of system malfunctions	
Specifications	Operating Voltage	120VAC
	Minimal Decibel Level	80dB
	Others	Moisture tolerant
Suggested Model	Omega 70 series Audible Alarm Annuciator (PN: 70A-4)	

8 Verification of Engineering Specifications

The goal of the controls team is to provide proper instrumentation, control valves, controllers, power, alarms and interlocks to the system. The controls team also needs a set of experiments to demonstrate the controller system.

The system contains temperature instruments, pressure instruments, tank level instruments, flow meters, control valves, and a programmable automation controller with interface.

A set of experiments are designed and analyzed to be practical examples of a control system.

A design has been constructed to provide alarms and interlocks for the PAC's equipment operations. A back up set of interlocks have also been designed to insure no damage to the equipment.

Due to the scope of the project verification through testing will not be achievable at this point, but will be taken on my future projects.

9 Building Plans

The system team and controls team collaboratively work on the build of the main skid, installation of major components , and installation of the piping. The construction, of the previously mentioned items, is detailed in the system team's design report.

Due to the size of the project, instrumentations and controls will be implemented by future project groups. There are strict codes on electrical design and implementation, so PG&E will review the electrical requirements and finish the design and be responsible for the implementation of the electrical system.

10 Future Project Plans

The future of the project for the controls team is to present the design to PG&E and clarify where we have left off. The flow loop simulator has already been deemed to be large enough for future Cal Poly senior projects to continue working on and expanding the design and finish construction.

Instrumentation, wiring and the PAC will need to be ordered and installed by future teams. Coding of the PAC and testing of its algorithms will need to be done. The vortex experiment needs to be tested to confirm the design and make any needed modifications. Assuming the power and pneumatic needs can be accommodated, testing of the heat transfer and tank level experiments need to be tested and proper PID gains need to be determined for each experiment. If the proper testing conditions cannot be met by Cal Poly, PG&E will need to do testing of the full system.

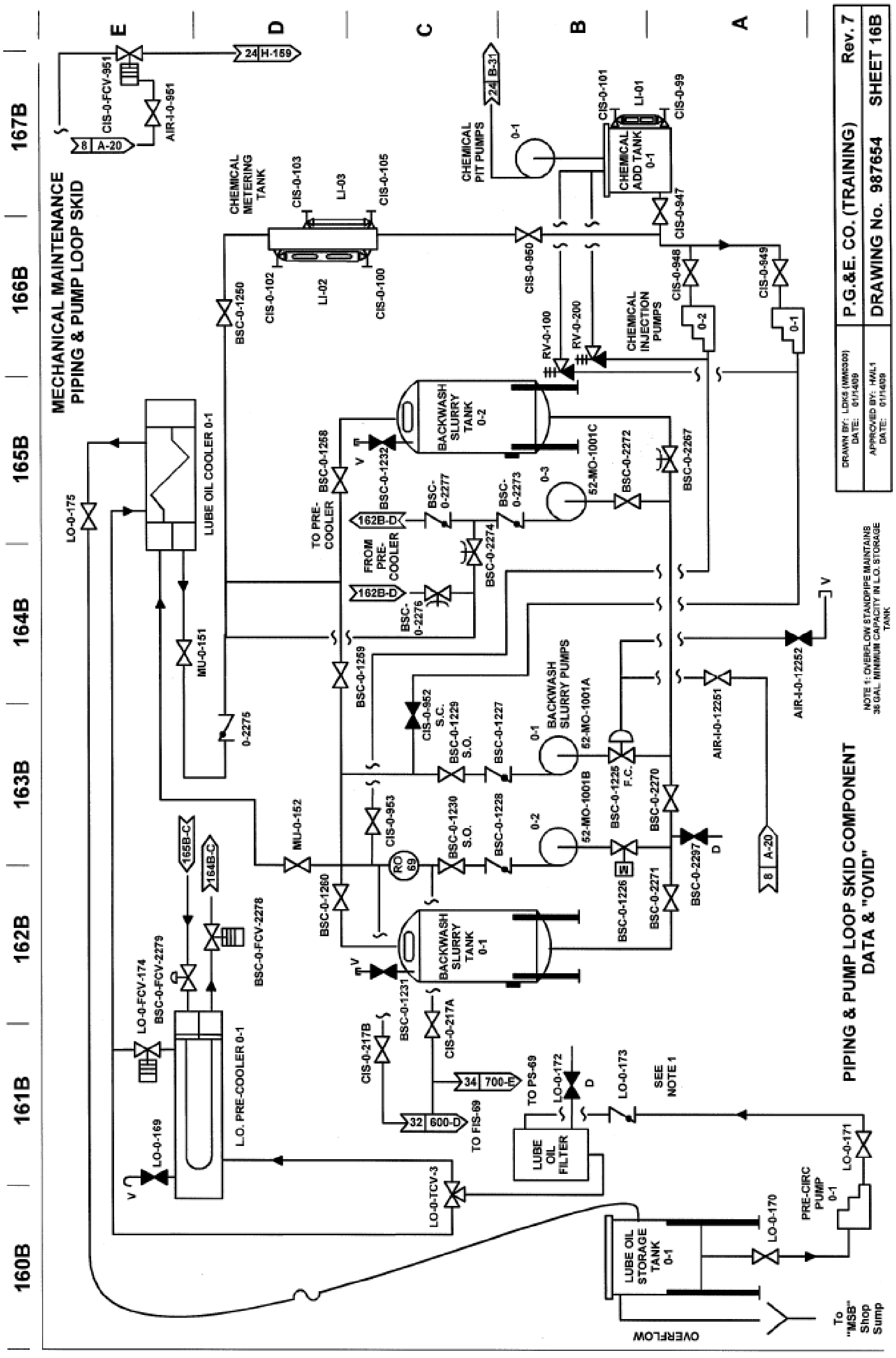
11 Appendices

Appendix A: Bibliography
Appendix B: PG&E Flow Loop Simulator Schematic
Appendix C: Cooper Nuclear Station Flow Loop Simulator Schematic
Appendix D: Control Team Gantt Chart
Appendix E: Bill of Materials
Appendix F: Controller I/O Configuration
Appendix G: Instrument Mounting
Appendix H: Analysis
Appendix I: System Diagrams
Appendix J: Hardware Documentation

Appendix A: Bibliography

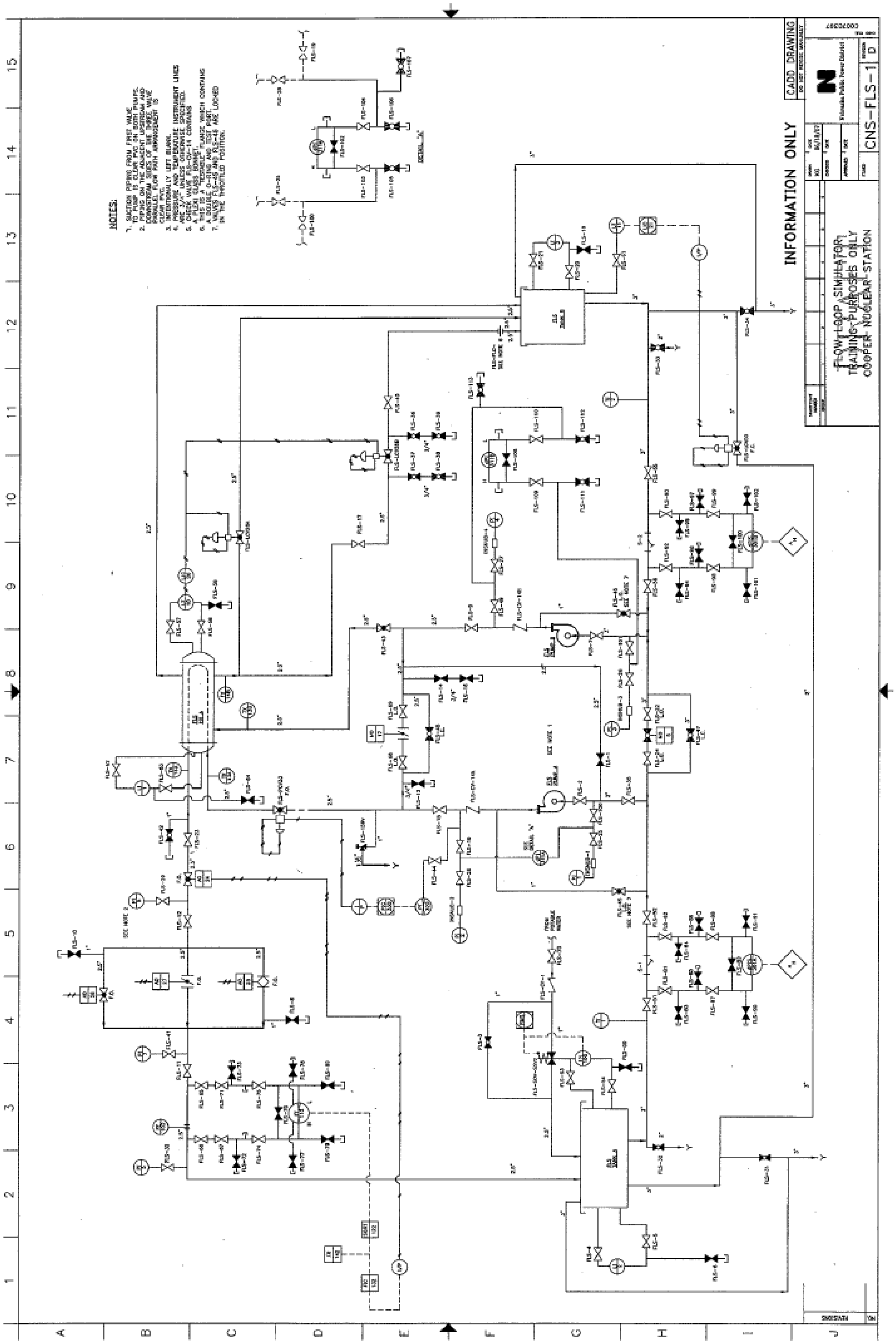
1. "Pumps in pits." *Mc Nally Institute*. Web. 15 Nov. 2009. <http://www.mcnallyinstitute.com/14-html/14-12.htm>.
2. “Piping Design Section 02.” Goulds Pumps. <http://www.gouldspumps.com/pag_0006.html>.
3. “Pump Control Panel Data Sheet” Byron Wilson, Allen Bradley. February 24, 2010.

Appendix B: PG&E Flow Loop Simulator Schematic

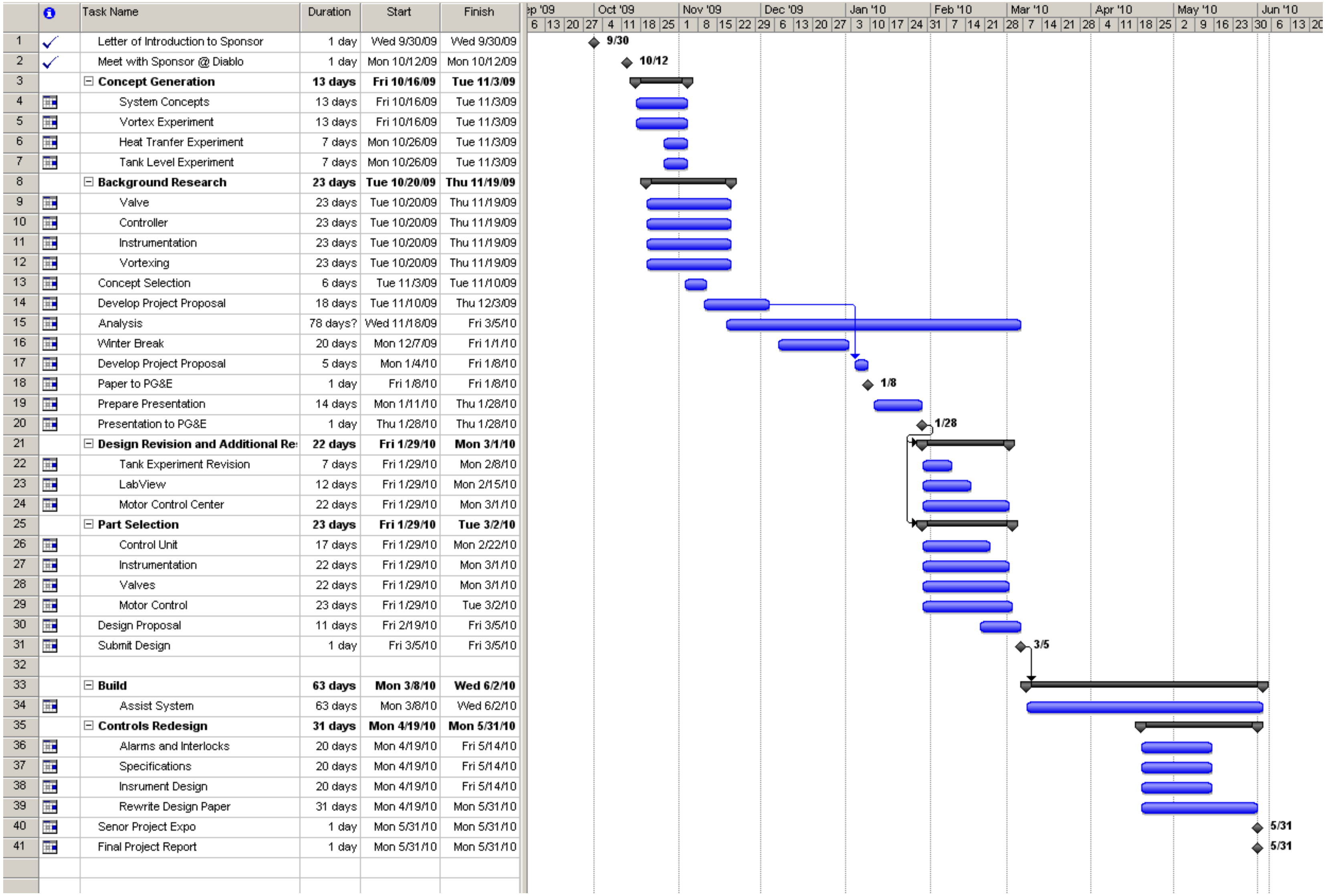


MM0300-01 (11x17)

Appendix C: Cooper Nuclear Power Station



Appendix D: Controls Team Gantt Chart



	ℹ	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		⊟ **Concept Generation**	**13 days**	**Fri 10/16/09**	**Tue 11/3/09**
4	▦	System Concepts	13 days	Fri 10/16/09	Tue 11/3/09
5	▦	Vortex Experiment	13 days	Fri 10/16/09	Tue 11/3/09
6	▦	Heat Tranfer Experiment	7 days	Mon 10/26/09	Tue 11/3/09
7	▦	Tank Level Experiment	7 days	Mon 10/26/09	Tue 11/3/09
8		⊟ **Background Research**	**23 days**	**Tue 10/20/09**	**Thu 11/19/09**
9	▦	Valve	23 days	Tue 10/20/09	Thu 11/19/09
10	▦	Controller	23 days	Tue 10/20/09	Thu 11/19/09
11	▦	Instrumentation	23 days	Tue 10/20/09	Thu 11/19/09
12	▦	Vortexing	23 days	Tue 10/20/09	Thu 11/19/09
13	▦	Concept Selection	6 days	Tue 11/3/09	Tue 11/10/09
14	▦	Develop Project Proposal	18 days	Tue 11/10/09	Thu 12/3/09
15	▦	Analysis	78 days?	Wed 11/18/09	Fri 3/5/10
16	▦	Winter Break	20 days	Mon 12/7/09	Fri 1/1/10
17	▦	Develop Project Proposal	5 days	Mon 1/4/10	Fri 1/8/10
18	▦	Paper to PG&E	1 day	Fri 1/8/10	Fri 1/8/10
19	▦	Prepare Presentation	14 days	Mon 1/11/10	Thu 1/28/10
20	▦	Presentation to PG&E	1 day	Thu 1/28/10	Thu 1/28/10
21		⊟ **Design Revision and Additional Re**	**22 days**	**Fri 1/29/10**	**Mon 3/1/10**
22	▦	Tank Experiment Revision	7 days	Fri 1/29/10	Mon 2/8/10
23	▦	LabView	12 days	Fri 1/29/10	Mon 2/15/10
24	▦	Motor Control Center	22 days	Fri 1/29/10	Mon 3/1/10
25		⊟ **Part Selection**	**23 days**	**Fri 1/29/10**	**Tue 3/2/10**
26	▦	Control Unit	17 days	Fri 1/29/10	Mon 2/22/10
27	▦	Instrumentation	22 days	Fri 1/29/10	Mon 3/1/10
28	▦	Valves	22 days	Fri 1/29/10	Mon 3/1/10
29	▦	Motor Control	23 days	Fri 1/29/10	Tue 3/2/10
30	▦	Design Proposal	11 days	Fri 2/19/10	Fri 3/5/10
31	▦	Submit Design	1 day	Fri 3/5/10	Fri 3/5/10
32					
33		⊟ **Build**	**63 days**	**Mon 3/8/10**	**Wed 6/2/10**
34	▦	Assist System	63 days	Mon 3/8/10	Wed 6/2/10
35		⊟ **Controls Redesign**	**31 days**	**Mon 4/19/10**	**Mon 5/31/10**
36	▦	Alarms and Interlocks	20 days	Mon 4/19/10	Fri 5/14/10
37	▦	Specifications	20 days	Mon 4/19/10	Fri 5/14/10
38	▦	Insrument Design	20 days	Mon 4/19/10	Fri 5/14/10
39	▦	Rewrite Design Paper	31 days	Mon 4/19/10	Mon 5/31/10
40	▦	Senor Project Expo	1 day	Mon 5/31/10	Mon 5/31/10
41	▦	Final Project Report	1 day	Mon 5/31/10	Mon 5/31/10

Appendix E: Bill of Materials

Electrical					
Pump Contactor	XTMC9A10A	Eaton	$48.65	3	$145.95
Heater Contactor	LC1D80G7	Schneider Electric	$412.00	5	$2,060.00
			Sub Total:		$2,205.95

Controller					
Programable Automation Controller	1756-L63	Allen Bradley	$0.00	1	$0.00
Relay Module	1756-OW16I	Allen Bradley	$0.00	1	$0.00
Power Supply	1756-PA72C	Allen Bradley	$0.00	1	$0.00
Analog Input Module	1756-IF16	Allen Bradley	$0.00	2	$0.00
Analog Output Module	1756-OF8	Allen Bradley	$0.00	1	$0.00
Seven Slot Chassis	1756-A7	Allen Bradley	$451.00	1	$451.00
RTD Input Module	1756-IR6I	Allen Bradley	$1,920.00	2	$3,840.00
Communication Module	1756-EN2T	Allen Bradley	$2,652.00	1	$2,652.00
Touch Screen	Panel View Plus Touch		$0.00	1	$0.00
			Sub Total:		$6,943.00

Instrumentation					
RTD	RTD-NPT-72-E	Omega	$64.00	7	$448.00
Pressure Transducer	PX209-100GI	Omega	$215.00	12	$2,580.00
Snubbers	PS-4E	Omega	$12.75	16	$204.00
Wet/Wet Pressure Transducer	PX409-005DWUI	Omega	$840.00	2	$1,680.00
			Sub Total:		$4,912.00

Gauges					
Sight Glass	Build Our Own	McMaster-Carr	$695.89	2	$1,391.78
Sight Glass Valving	3700K14	McMaster-Carr	$522.73	1	
Sight Glass Tube	3724K33	McMaster-Carr	$42.04	1	
Sight Glass Guards	3713K149	McMaster-Carr	$131.12	1	
Pressure Gauge	PGC-20L-100	Omega	$18.00	10	$180.00
			Sub Total:		$1,571.78

Grand Total:	$15,633

Appendix F: Controller I/O Configuration

Table 1. RTD Module 1 to Temperature Indicator

Ports	Channel	Connected to
IN-0/A IN-0/B RTN-0/C	0	TI-3
IN-1/A IN-1/B RTN-1/C	1	TI-4
IN-2/A IN-2/B RTN-2/C	2	TI-5
IN-3/A IN-3/B RTN-3/C	3	TI-6
IN-4/A IN-4/B RTN-4/C	4	TI-7
IN-5/A IN-5/B RTN-5/C	5	-

Table 2. RTD Module 2 to Temperature Indicators

Ports	Channel	Connected to
IN-0/A IN-0/B RTN-0/C	0	TI-1
IN-1/A IN-1/B RTN-1/C	1	TI-2
IN-2/A IN-2/B RTN-2/C	2	-
IN-3/A IN-3/B RTN-3/C	3	-
IN-4/A IN-4/B RTN-4/C	4	-
IN-5/A IN-5/B RTN-5/C	5	-

Table 3. Milliamp Input Module 1 to Pressure, Flow and Tank Level Indicators

Ports	Channel	Connected to
IN-0(+) IN-1(-) iRTN-0	0	LI-8
IN-2(+) IN-3(-) iRTN-2	1	LI-9
IN-4(+) IN-5(-) iRTN-4	2	PI-10
IN-6(+) IN-7(-) iRTN-6	3	PI-11
IN-8(+) IN-9(-) iRTN-8	4	PI-12
IN-10(+) IN-11(-) iRTN-10	5	PI-13
IN-12(+) IN-13(-) iRTN-12	6	PI-14
IN-14(+) IN-15(-) iRTN-14	7	PI-15

Table 4. Milliamp Input Module 2 to Pressure, Flow and Tank Level Indicators

Ports	Channel	Connected to
IN-0(+) IN-1(-) iRTN-0	0	PI-16
IN-2(+) IN-3(-) iRTN-2	1	PI-17
IN-4(+) IN-5(-) iRTN-4	2	PI-18
IN-6(+) IN-7(-) iRTN-6	3	PI-19
IN-8(+) IN-9(-) iRTN-8	4	FI-20
IN-10(+) IN-11(-) iRTN-10	5	FI-21
IN-12(+) IN-13(-) iRTN-12	6	-
IN-14(+) IN-15(-) iRTN-14	7	-

Table 5. Output Module to Control Valves

Ports	Channel	Connected to
IOUT-0 RTN	0	CV-22
IOUT-1 RTN	1	CV-23
IOUT-2 RTN	2	-
IOUT-3 RTN	3	-
IOUT-4 RTN	4	-
IOUT-5 RTN	5	-
IOUT-6 RTN	6	-
IOUT-7 RTN	7	-

Table 6. Relay Module to Pump and Heater Contactors

Port	Channel	Supply Port	Supply Voltage	Connected to
Out-0	0	L1-0	120VAC	HC-24
Out-1	1	L1-1	120VAC	HC-25
Out-2	2	L1-2	120VAC	HC-26
Out-3	3	L1-3	120VAC	HC-27
Out-4	4	L1-4	120VAC	HC-28
Out-5	5	L1-5	120VAC	PC-29
Out-6	6	L1-6	120VAC	PC-30
Out-7	7	L1-7	120VAC	PC-31
Out-8	8	L1-8	120VAC	A-50
Out-9	9	L1-9	-	-
Out-10	10	L1-10	-	-
Out-11	11	L1-11	-	-
Out-12	12	L1-12	-	-
Out-13	13	L1-13	-	-
Out-14	14	L1-14	-	-
Out-15	15	L1-15	-	-

Appendix G: Instrument Mounting

ITEM NO.	PART NUMBER	QTY.
1	Orifice plate 4" diameter pipe	1
2	4" diameter pipe	2
3	Wet/Wet Differenetial Pressure Transducer 1/4" NPT	1
4	Snubber 1/4" NPT	2
5	1/2" NPT ball valve	3
6	1/2" diameter pipe	16
7	1/2" diameter tee	2
8	1/2" elbow	2
9	1/4"F 1/2"M NPT pipe adaptor	2
10	Weld-o-let	2

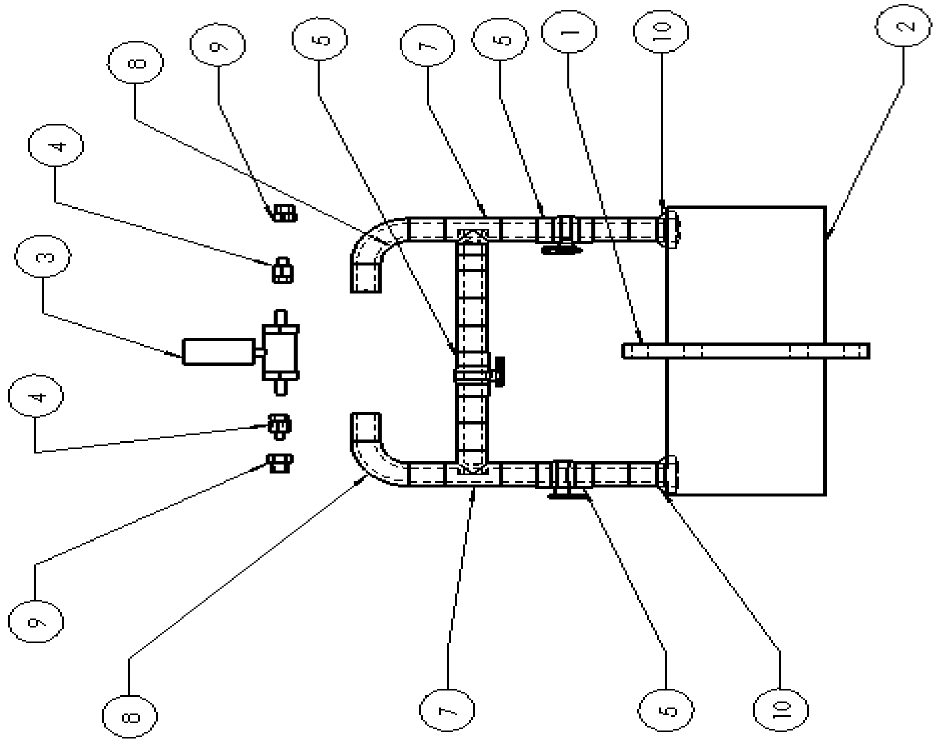
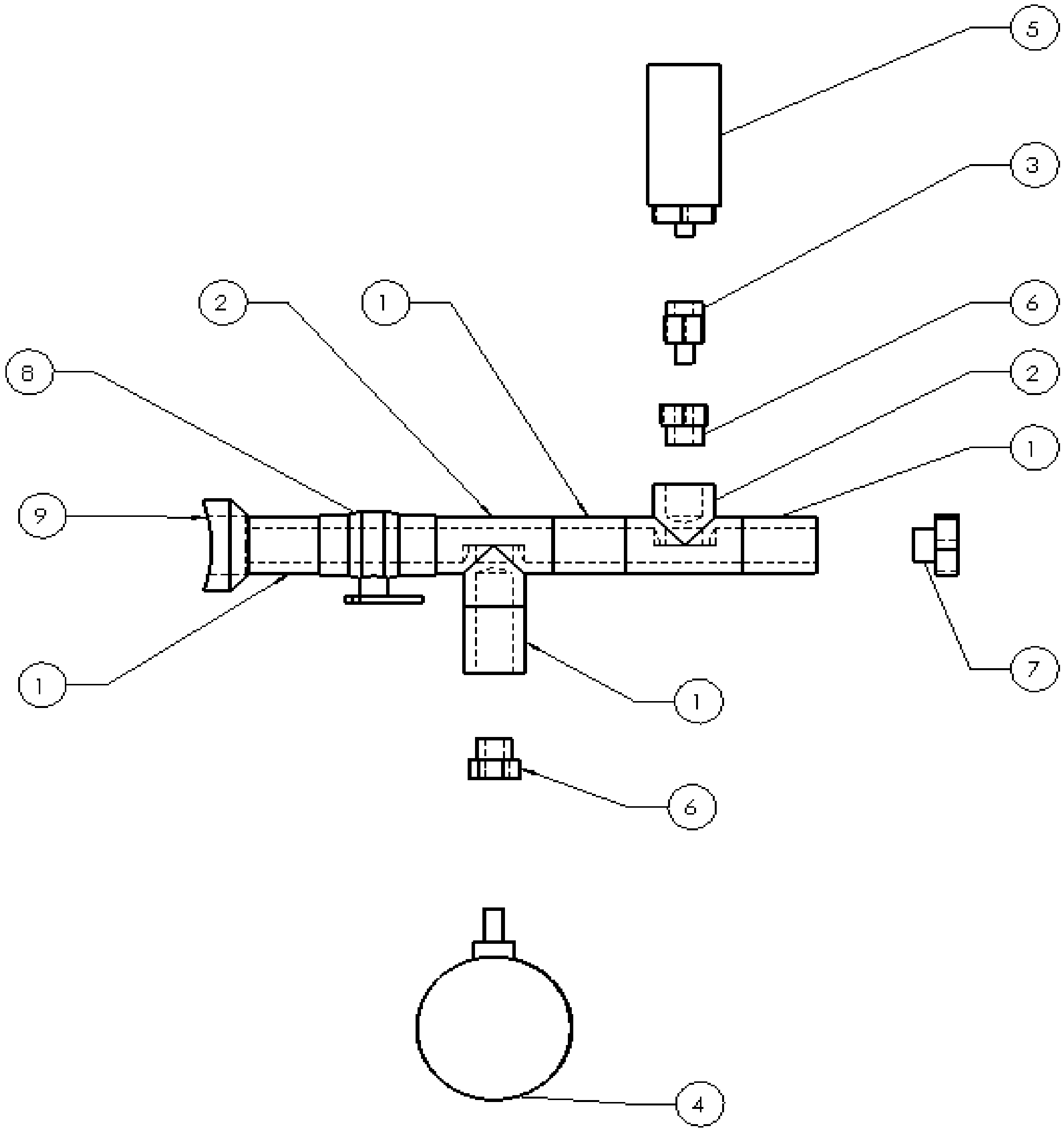


Figure G-1. Differential pressure transducer across an orifice plate.



ITEM NO.	PART NUMBER	QTY.
1	1/2" diameter pipe	4
2	1/2" diameter tee	2
3	Snubber 1/4" NPT	1
4	Pressure Gauge 1/4" NPT	1
5	Pressure Transducer 1/4" NPT	1
6	1/4"F 1/2"M NPT pipe adaptor	2
7	End cap for 1/2" pipe	1
8	1/2" NPT ball valve	1
9	Weld-o-let	1

Figure G-2. Pressure gauge and transducer tap.

ITEM NO.	PART NUMBER	QTY.
1	RTD (with 1/4" NPT fitting)	1
2	Thermowell (similar to Ashcroft # 10W0162SM260)	1
3	.25F .5M NPT pipe adaptor	1

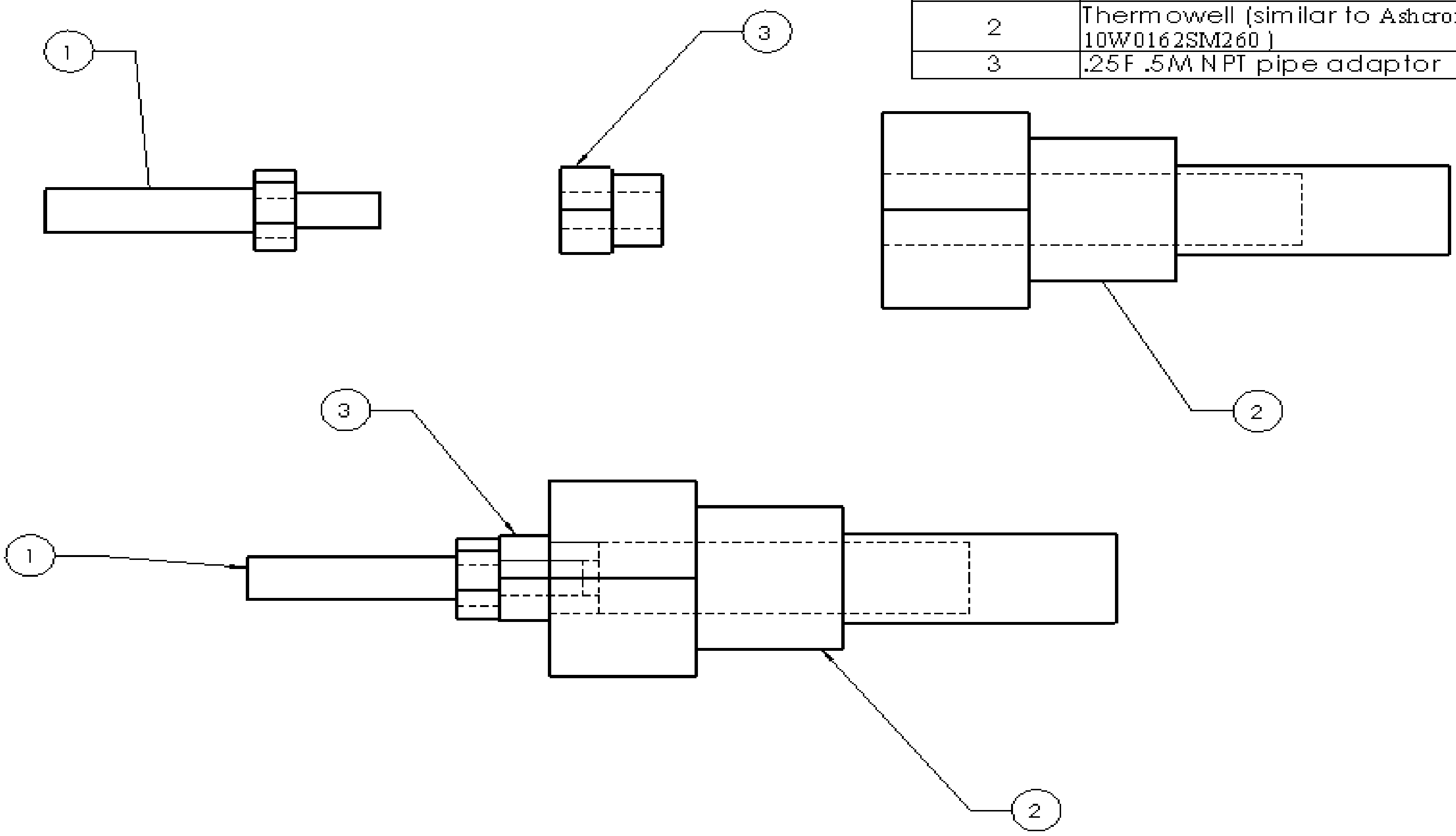


Figure G-3. RTD and thermowell

ITEM NO.	PART NUMBER	QTY.
1	1/2" NPT Bung	1
2	Pressure Transducer	1
3	Snubber 1/4" NPT	1
4	.25F .5M NPT pipe adaptor	1

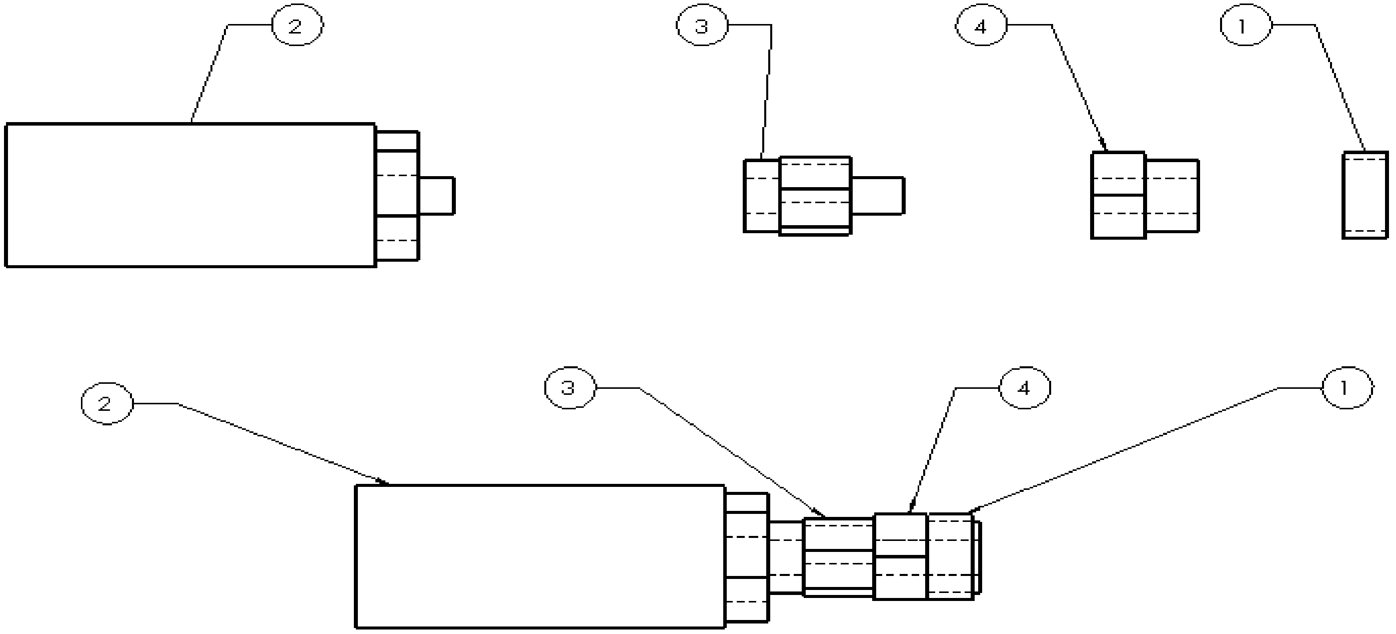


Figure G-4. Tank level pressure transducer.

Appendix H: Analysis

Vortexing Analysis

Background

There are two key parts of creating a vortex: flow rate to outlet submersion relation and geometry of the tank and outlet. Most information about vortexes is on how to prevent a vortex.

Typical designs to prevent vortexing include using diffuser screens, using floating rafts around the pump column to break up the vortices, floating large spheres on the surface to break up vortices, increasing the size of the inlet piping, reducing the inlet velocity by spreading the flow over a larger area, or changing the direction and velocity of the flow with the use of baffles, keeping the inlet flow to the pit below 2 ft/s, keeping the flow in the pit below 1 ft/s, and using any type of a logical flow straightener will reduce vortexing [1].

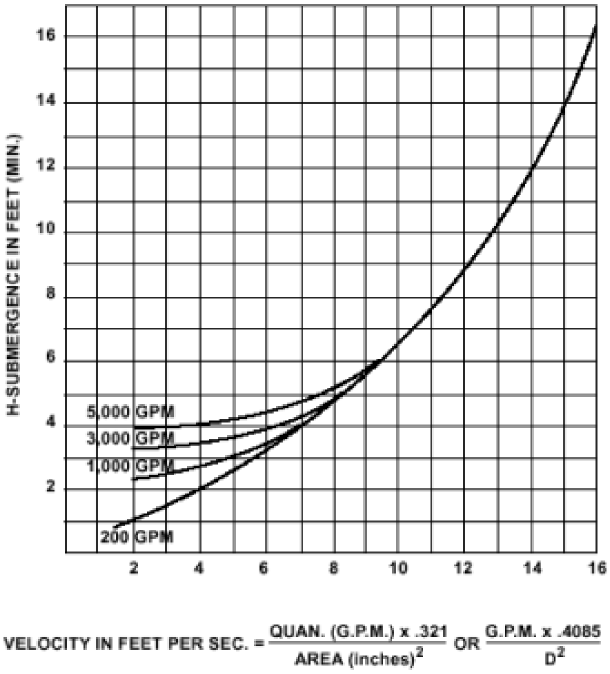


Figure H-1: Gould's Pump Minimum Vortex Height [2]

A common means of preventing a vortex is by submerging the pump line deep under the water surface. The proper depth for the line is determined by the flow rate the pump requires. Figure H-1 gives the recommended minimum depth for the pump line based on the velocity of the fluid[2].

Analysis

Geometry plays a key role in preventing vortexing. The outlet is to be placed centered in the tank with a slightly funneled opening. By deliberately avoiding the common designs to prevent vortexes the task of producing a vortex becomes more likely.

Based on information from Gould's Pumps, in Figure for 200GPM and a 4 inch diameter pipe roughly 2.5 feet of water is needed for the minimum depth to avoid vortexing. Since the desire is to create a vortex the minimum height of water above the vortex outlet will intentionally be below the threshold. Testing will be needed to confirm a height that consistently provokes vortexing, as well as to create the ideal outlet geometry.

Heat Transfer and Tank Level Experiments

Purpose

There were a few different purposes for completing analysis on this system. The first purpose is to confirm that the system will behave as intended. For instance, analysis will insure that the system won't take excessive amounts of time to respond. This analysis will also assure that the controlled parameter could be changed substantially by our inputs. Another benefit of the analysis is to confirm the analysis of the systems team and therefore assure that the components have all been sized properly.

Theory

The analysis was completed by means of system dynamics. System dynamics is a means of determining the behavior of a system. Any system can be within one or many different energy domains such as, mechanical translational, mechanical rotational, fluid, electrical and thermal. System dynamics makes all of these energy domains analogous to the electrical domain, with components that behave like voltage sources, current sources, resistors, capacitors, and inductors.

In this fluid system there are components that cause resistance to flow such as: heat exchangers, valves elbows, and friction in piping. These components behave much like a resistor in the electrical domain. They are an energy dissipation device. It is important to note that the relationship between voltage, current and resistance in an electrical system is linear. In a fluid system, the relationship between the volumetric flow rate, pressure drop and fluid resistance (the flow coefficient) is non-linear. The pressure drop is a function of the flow rate squared. This leads to an assumption: *The pressure drop across a fluid resistance is a linear function of the flow rate.* This allows easier modeling of a fluid system, but not the most accurate modeling but it allows an approximation of the response of the system.

At times this approximation of the pressure drop across a fluid resistance as a linear function of the flow rate led to an error in the numerical modeling of the system in the heat transfer experiment. There was a compatibility error due to the control valve being modeled accurately and the other fluid resistances being approximations. This error was improved upon by the resistances in the system to be modeled as true fluid resistances rather than linear approximations. It must be noted that the valves in the model are still not able to fully close without causing this error.

The system also contains a couple tanks. Tanks behave very much like capacitors in the electrical domain. Tanks are a device that stores energy by means of pressure. The change in height of water in a tank is technically a change in pressure at the bottom of the tank. This is true whether the tank is vented or not. Therefore a tank is a means of storing energy by pressure. This is exactly analogous to a capacitor which stores energy by means of storing a charge as an electric potential (voltage). In order to model a tank an equation similar to that found in the electrical domain is used. This relates the pressure drop across a tank to the flow rate into that tank based on the capacitance of the tank (which is based on the area of the surface of the fluid).

$$\frac{dP}{dt} = \frac{q}{C} \qquad C = \frac{A}{\rho g}$$

Another very important component in this system is the pump. There are a few different options for modeling a pump. A pump can be modeled as an ideal source such as a flow source or a pressure source. If it was an ideal pressure source the pressure across the pump would be constant. If it was an ideal flow source the flow across the pump would be constant. Neither of these are the case. The reality is that the flow through the pump is dependent on the head that is being pumped against. In order to create this relationship we must create a Norton (or Thevenin) equivalent source. A Norton equivalent source can be seen circled below in Figure . This shows a resistance(R_n) in parallel with the flow source(Q_s).

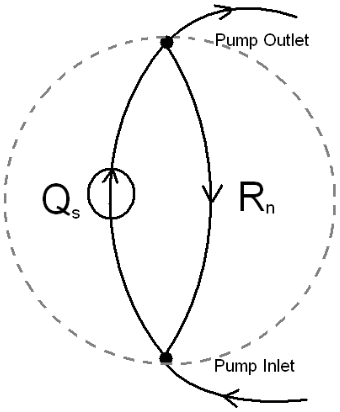


Figure H-2: Linear Graph of Pump Model (Norton Equivilant Source)

The combination of a resistance and a constant flow source results in a combined source whose output is now dependent on the head across it. This is because the greater the pressure across the pump, the greater the flow through the resistance. The result is that while the flow through the source stays constant, the flow out of the Norton equivalent source is now dependent on the pressure across it. This relationship between the head seen by the pump and the flow through it is determined by the value of the resistance, R_n. The value of R_n is determined by the slope of the pump curve in its operational area. This leads to another assumption: a Norton equivalent source is used as a linear approximation of the pump curve. The portion of the pump curve being approximated will depend on the experiment modeled. This is due to the pump operating in different portions of the curve for the different experiments.

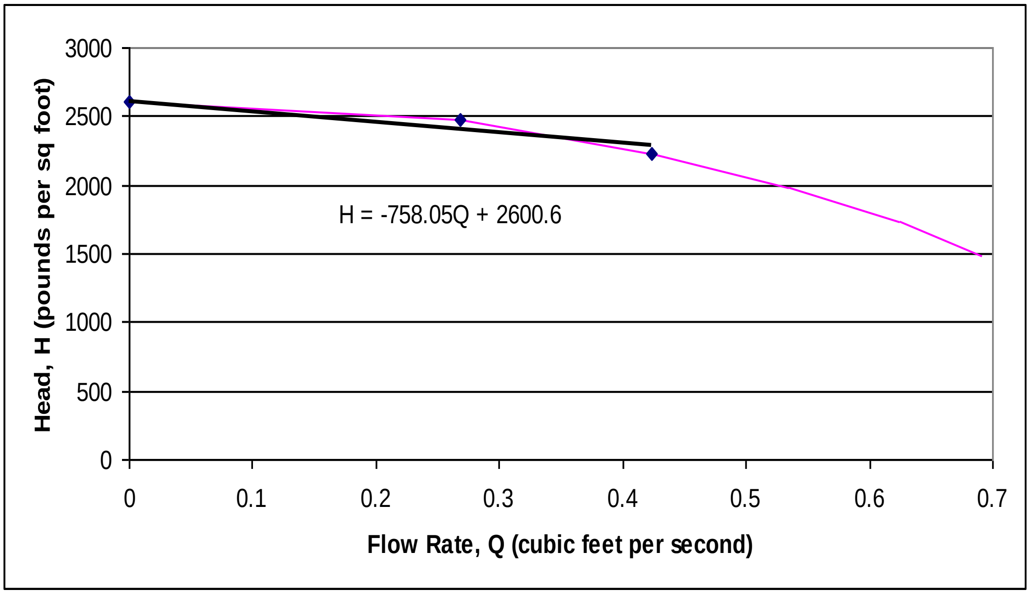


Figure H-1: Heat Transfer Experiment's Pump Curve Approximation.

For the heat transfer experiment, the minimum head the pump will see is that of the heat exchanger at the design flow rate (200GPM/.44CFS). The maximum head the pump will see is at the no flow condition. For this reason, the y-intercept is forced to go through that point on the curve. This leads to a Norton Equivalent resistance (R_n) value of 758 and a flow source of 2600.6/R_n (1.485CFS).

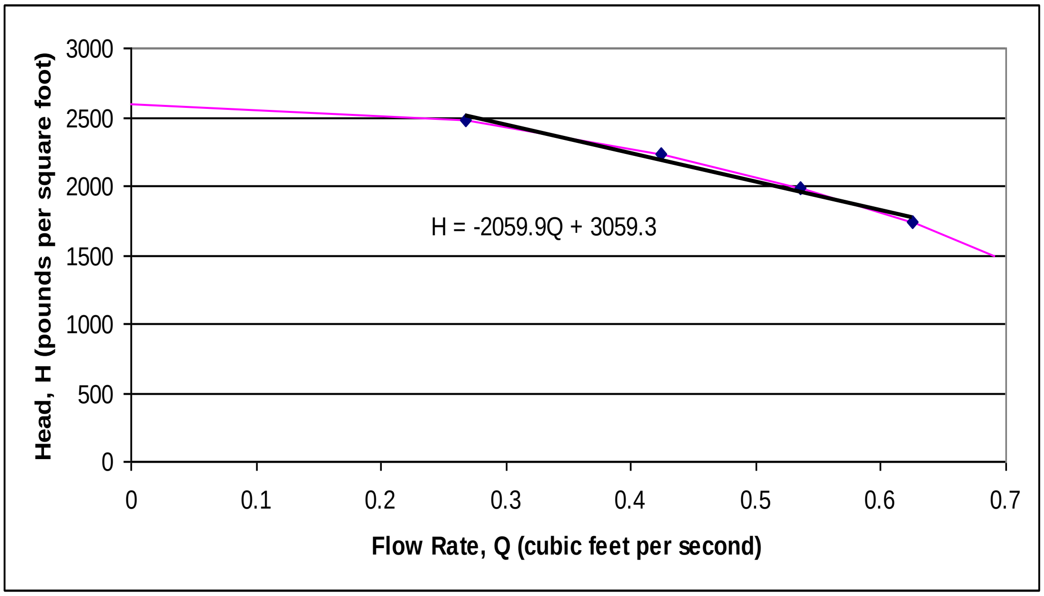


Figure H-2: Tank Level Experiment's Pump Curve Approximation.

For the tank level experiment, it is unlikely the pumps will ever operate near the no flow condition. It is more likely that the pumps will only operate around their design point of 200GPM(.44 CFS) and 35 feet of head (2181 lb/ft^2). This leads to a Norton Equivalent resistance (R_n) value of 2059.9 and a flow source of 3059.3/R_n (1.485CFS).

Due to the control valve being the only input to the system, it is important to accurately model the effect of position of the control valves on the pressure drop across (P) and fluid flow through it (q). The data that is provided for a valve at different positions is the flow coefficient, C_v. The flow coefficient is to be used with this equation:

$$q = C_v \sqrt{\frac{P}{SG}}$$

This is the non-linear equation that was assumed linear for other restrictions, but will not be assumed here. In order to model a control valve a valve position (0-100%), and flow through (or pressure drop) must be input in order to get pressure drop (or flow trough). This will allow a control valve to simply be input into the model as another element. In order to make this step it was important to figure out the relationship between the flow coefficient and the valve position. The following relationship was determined using data for a Fisher GX control valve with a linear plug:

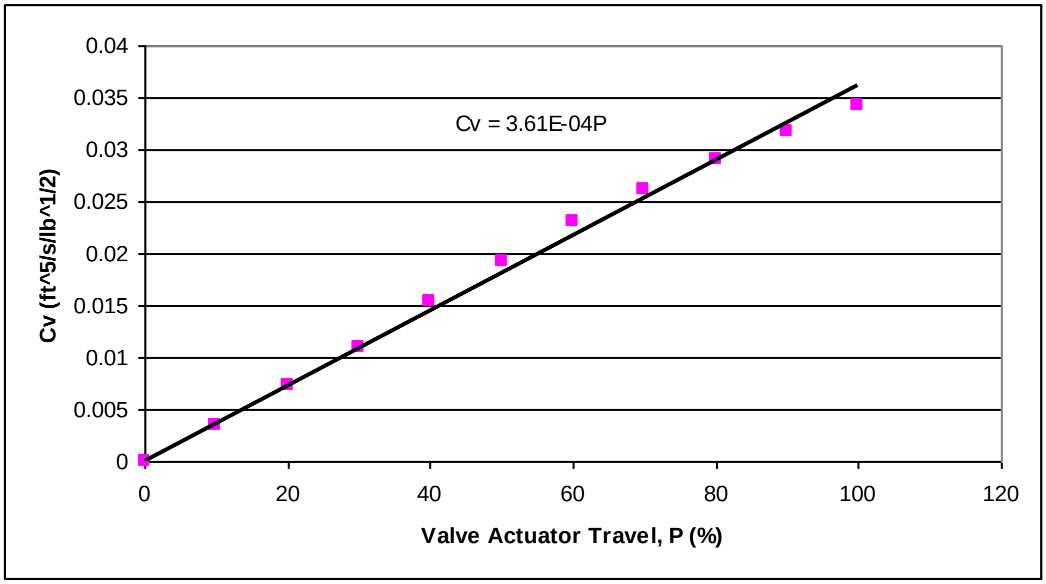


Figure H-3: The Relationship Between Flow Coefficient and Valve Actuator Position of Fisher GX Control Valve.

Above (in Figure H-3) the true relationship is not exactly linear but very accurately be approximated as linear. It can be seen that the slope is 3.61x10^{-4} and a y-intercept of zero because there obviously is no flow when the valve is completely closed.

System dynamics was once again used for the heat transfer analysis but they were only used to determine the relationship between the flow through each side of the heat exchanger and the valve positions. Once this was determined the analysis was completed using standard thermodynamic analysis such as energy balance and mass balance. The energy balance equations account for the thermal capacitance of the fluid (the fact that it will take time for the fluid to absorb heat by means of temperature change). In order to link the thermal and fluid system, it was important to model the heat exchangers.

The key goal in modeling the heat exchangers is to relate the fluid flow and amount of heat transferred to the fluid. This was accomplished using the effectiveness-NTU method. Some difficulties are associated with this. The computation of the convection coefficient on the shell side of the shell and tube heat exchanger is not easy. Therefore in order to simplify the calculations for the shell and tube heat exchanger the convection coefficient for the shell side was assumed to be the same as the tube side at any given flow rate. This should be accurate at the design flow rate for a well designed heat exchanger. It may not be true away from the designed flow rate but it is the best way to estimate the performance of our system.

The cooling component was modeled as a cross-flow heat exchanger that was designed from scratch to be able to transfer 1 million BTU/hr of heat at the maximum cold loop flow rate. This heat transfer capability was determined by the systems team and is based off of our heater size. The heater size was determined by the systems team based on the desired time for the system to get to an operating temperature. The Air flow rate through the heat exchanger was kept constant.

Summary of Assumptions

- Minor Losses are negligible
- All heat transfer occurs at the heat exchangers and the heater
    - Other components are insulated: piping, tanks, valves
    - Fluid friction at pump and piping does not contribute to heating of fluid
- Pressure drop and fluid flow relationship of restrictions will be assumed linear unless it is deemed necessary to model more accurately
- Relationship between valve flow coefficient and valve position (%) will be approximated by a linear curve fit
- Pump curve will be approximated as linear by means of a Norton equivalent source
- Heat transfer due to radiation is negligible
- Changes in pressure due to elevation changes in piping are neglected unless otherwise noted.

Level Control Procedure

To analyze the system response of the level control configuration, the governing equations were determined using system dynamics and the resulting differential equations were solved using Simulink.

The first step in the process of system dynamics analysis is to develop the linear graph and normal tree. The normal tree is used to put equations in the proper form to minimize algebraic manipulation. The Linear graph and normal tree can be seen in Figure H-6 below.

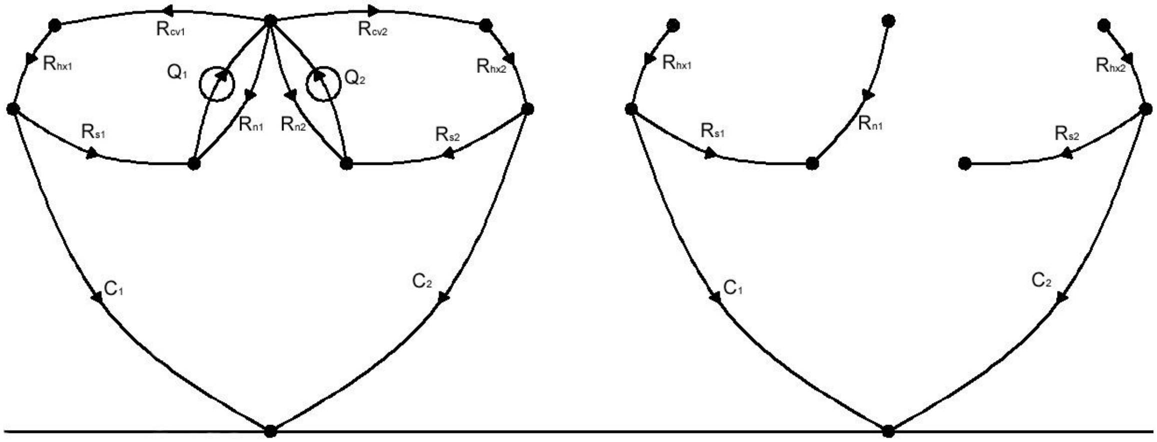


Figure H-6: The linear graph and normal tree for the level control configuration.

These two diagrams are used to determine the governing equations. The first set of governing equations is called the elemental equations. Elemental equations are derived from the behavior of a specific element and if the element is on the normal tree, the equation is written in terms of the through variable(flow). These equations are below.

$$\frac{dP_{C1}}{dt} = \frac{1}{C_1} q_{C1} \qquad (1)$$

$$\frac{dP_{C2}}{dt} = \frac{1}{C_2} q_{C2}$$

$$P_{RS1} = R_{S1} q_{RS1}$$

$$P_{RS2} = R_{S2} q_{RS2}$$

$$P_{Rn1} = R_{n1} q_{Rn1}$$

$$P_{Rhx1} = R_{hx1} q_{Rhx1}$$

$$P_{Rhx2} = R_{hx2} q_{Rhx2}$$

$$P_{Rhx2} = R_{hx2} q_{Rhx2}$$

$$q_{Rn2} = \frac{P_{Rn2}}{R_{n2}}$$

$$q_{Rcv1} = \frac{P_{Rcv1}}{R_{cv1}}$$

$$q_{Rcv2} = \frac{P_{Rcv2}}{R_{cv2}}$$

The remaining equations are determined through continuity and compatibility requirements. Continuity requires that the flow into a node equal the flow out of a node. Compatibility requires that the pressure drop along any path between two nodes be equal. These equations are written in terms of the elements on the normal tree. These two sets of equations are seen below.

$$q_{Rs2} = Q_2 - q_{Rn2}$$

$$q_{Rn1} = Q_1 + Q_2 - q_{Rcv1} - q_{cv2} - q_{Rn2}$$

$$q_{Rs1} = -Q_1 + q_{Rcv1} + q_{Rcv2} + q_{Rn2}$$

$$q_{Rhx1} = q_{Rcv1}$$

$$q_{Rhx2} = q_{Rcv2}$$

$$q_{C1} = Q_2 - q_{Rn2} - q_{Rcv2}$$

$$q_{C2} = -Q_2 + q_{Rn2} + q_{Rcv2}$$

$$P_{Rcv1} = P_{Rn1} - P_{Rs1} - P_{Rhx1}$$

$$P_{Rn2} = P_{Rn1} - P_{Rs1} + P_{C1} - P_{C2} + P_{Rs2}$$

$$P_{Rcv2} = P_{Rn1} - P_{Rs1} + P_{C1} - P_{C2} + P_{Rhx2}$$

These equations were then symbolically represented in Simulink and solved for.

Heat Transfer Experiment Procedure

The heat transfer experiment required the use of system dynamics to determine the governing equations for the two fluid loops. These loops were modeled in Simulink and were used to determine the relationship between valve position and flow through the heat exchanger. The flow was then fed into a thermal system that was also modeled in Simulink. The governing equations for the thermal system were determined using classic thermodynamics (mass and energy balance).

Using system dynamics, the following linear graph and normal tree in Figure H-7 were developed for a single flow loop.

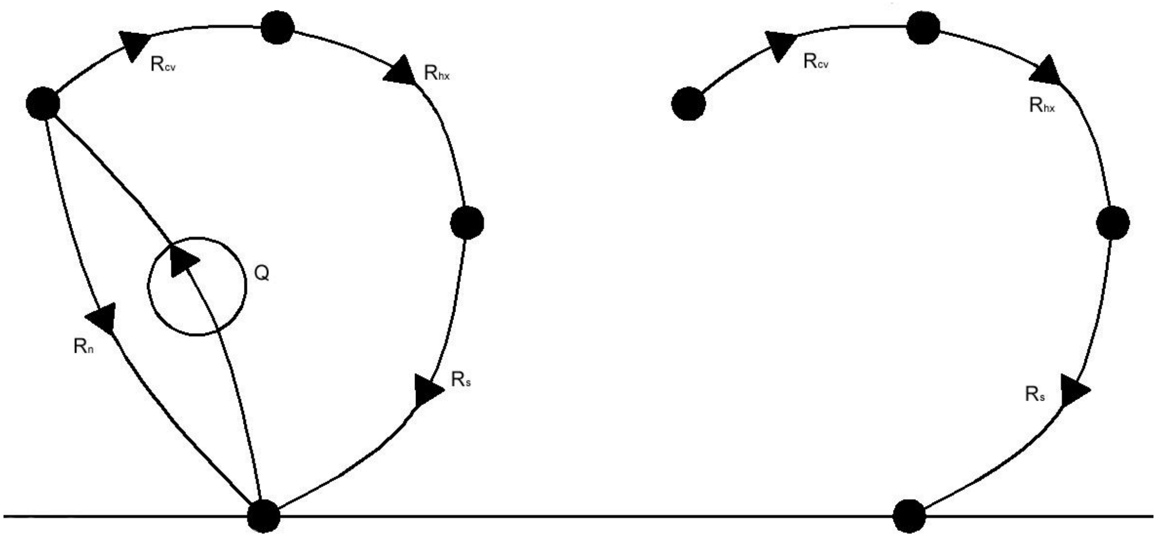


Figure H-7: The linear graph and normal tree for the temperature control configuration.

These were then used to determine the equations below.

$$P_{Rcv} = R_{cv} q_{Rcv}$$

$$P_{Rhx} = R_{hx} q_{Rhx}$$

$$P_{RS} = R_S q_{RS}$$

$$q_{Rn} = \frac{P_{Rn}}{R_n}$$

$$q_{Rcv} = Q - q_{Rn}$$

$$q_{Rhx} = Q - q_{Rn}$$

$$q_{Rs} = Q - q_{Rn}$$

$$P_{Rn} = P_{Rcv} - P_{Rhx} - P_{Rs}$$

Using these equations in Simulink to determine flow at a specific valve position, it was then necessary to determined the relationship between the temperature drop across the hot side of the heat exchanger with respect to flow through it. The schematic in Figure H-8 was developed to complete this analysis. The locations labeled with numbers identifying points of unique temperature within the system.

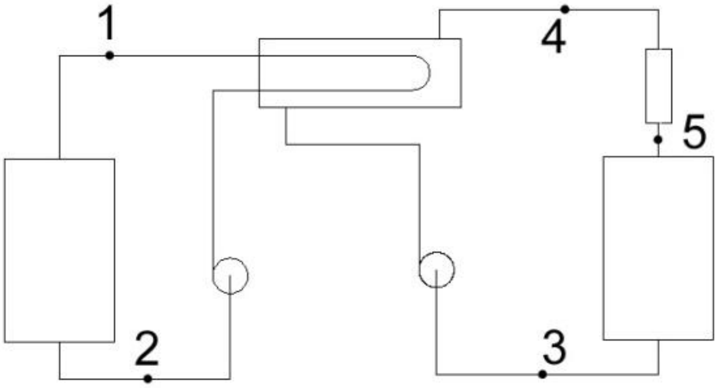


Figure H-8: Schematic used for thermal analysis.

Using this system schematic and the principles of mass balance and energy balance, the following equations were developed.

HOT LOOP MASS BALANCE

$$\dot{m}_2 = \dot{m}_1 = \dot{m}_h$$

HOT LOOP TANK ENERGY BALANCE

$$Q_{heater} + \dot{m}_h C_p (T_1 - T_2) = m_h C_p \frac{dT}{dt}$$

HOT LOOP HX ENERGY BALANCE

$$\dot{m}_h C_p (T_2 - T_1) - Q_{hx1} = 0$$

COLD LOOP MASS BALANCE

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_5 = \dot{m}_c$$

COLD LOOP TANK ENERGY BALANCE

$$\dot{m}_c C_p (T_5 - T_3) = m_c C_p \frac{dT}{dt}$$

COLD LOOP HX1 ENERGY BALANCE

$$\dot{m}_c C_p (T_3 - T_4) + Q_{hx1} = 0$$

COLD LOOP HX2 ENERGY BALANCE

$$\dot{m}_c C_p (T_4 - T_5) - Q_{hx2} = 0$$

Combining these equations, the following differential equations were developed for the hot loop and cold loop.

$$\frac{dT_2}{dt} = \frac{1}{m_h C_p} (Q_{heater} - Q_{hx1})$$

$$\frac{dT_3}{dt} = \frac{1}{m_c C_p} (Q_{hx1} - Q_{hx2})$$

In these equations, T_3 and T_2 are embedded in the Q_{HX1} and Q_{HX2} terms by the Effectiveness-NTU equations:

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

$$q = \varepsilon C_{\min} (T_{h,i} - T_{c,i})$$

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

For the shell and tube heat exchanger

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

For the crossflow heat exchanger

$$\varepsilon = 1 - \exp\left[\frac{1}{C_r}\left(NTU\right)^{.22}\left\{\exp\left[-C_r\left(NTU\right)^{.78}\right] - 1\right\}\right]$$

Results

Following the determination of how each component was going to be modeled and determining the equations that represented these components they were all combined into a Simulink model for each experiment. This model allows us to observe the flow rate and pressure at all locations in our level control system. For our temperature control system we could also observe all temperatures in our system.

Level Control

Below you will find results from both original and revised setups of the level control experiment. Through analysis, it was discovered that the original setup did not respond in adequate time. The results of original setup have been included to provide insight into the complexity of this system’s behavior.

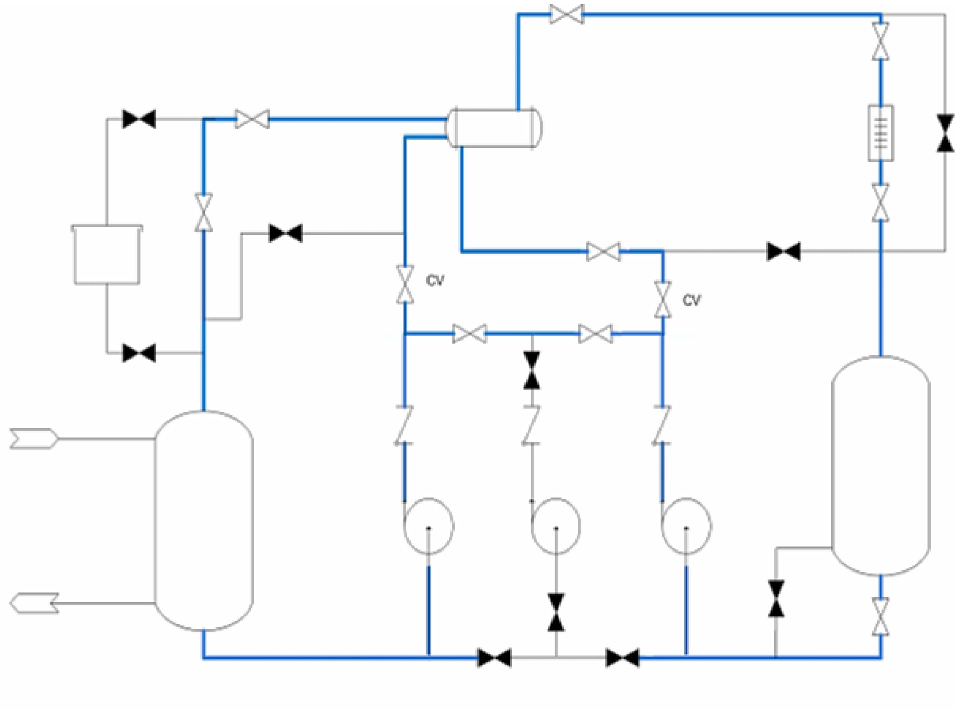


Figure H-9: The original systems configuration with flow routed through the heat exchangers.

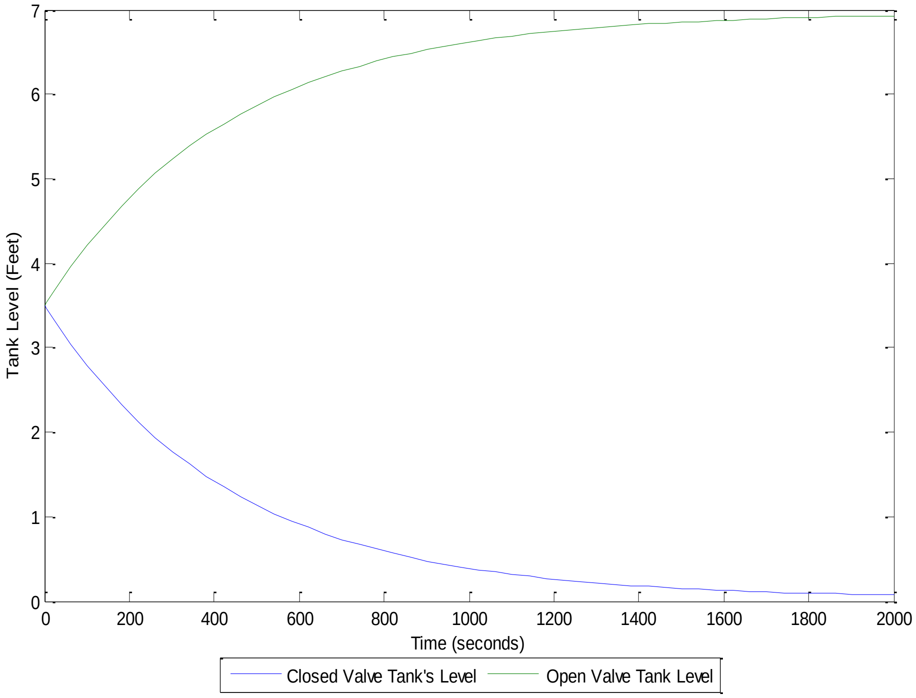


Figure H-10: Transient response of original tank level experiment.

Figure H- above shows the unexpected results of the originally tank level setup. This setup ran the water trough the heat exchanger(s) prior to dumping into the tank. The hope was that the cold loop's two heat exchangers would naturally off balance the flow resulting in a more interesting and dynamic system.

The results show that it takes too long to fill one tank by draining the other. This is due to the pumps being in parallel. When running pumps in parallel it doubles the possible flow rate but has no affect on the maximum head that the two pumps can provide. With one valve closed, it was expected that one pump would circulate fluid at 200GPM and the other pump would transfer fluid between the loops at 200GPM. This is not the case. The increased flow rate through the heat exchanger results in an increase in the dynamic head loss (pressure loss due to friction of flow). This means that the pumps need to push against more pressure and flow is reduced.

The reason that the pumps can only pump the fluid to a height of 7 feet is similarly due to the effect of the two pumps being in parallel. As the height in one tank increases and the other decreases, the pumps start working against each other. The output pressure of the pump pulling from the tank with a greater height becomes larger than the output pressure of the pump that pulls from the lower tank. This result in the lower tank's pump reaching its maximum head sooner and therefore it stops contributing to the flow. At this point the other pump gets to its normal operating point and circulates fluid at 200GPM through its loop. After confirming these problems, it was determined that the best solution would be to bypass the heat exchangers as shown below.

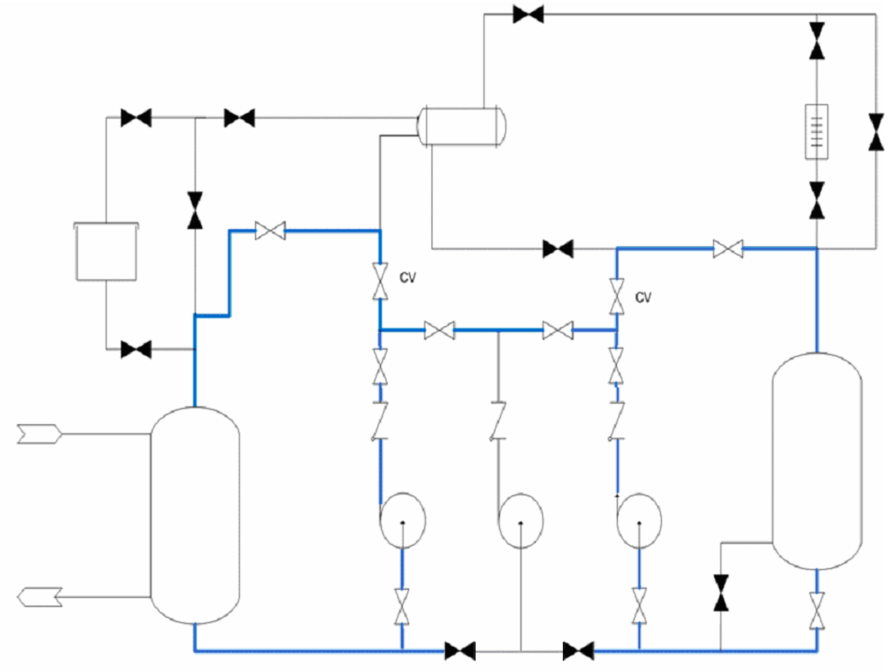


Figure H-11: The revised tank level experiment configuration with fluid bypassing the heat exchangers.

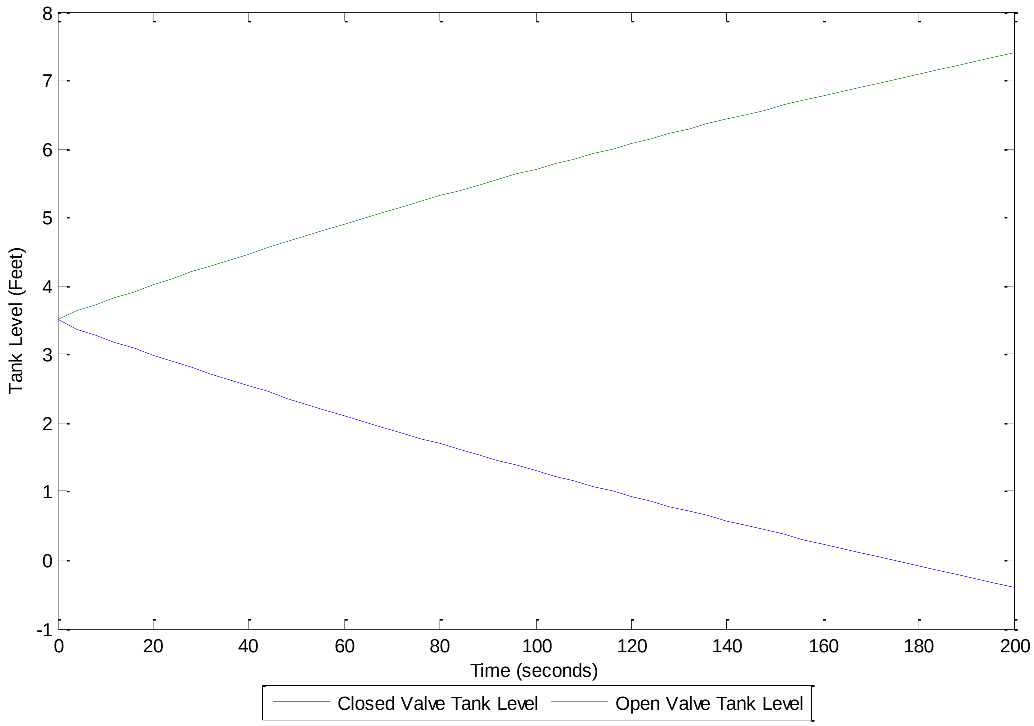


Figure H-12: Revised Tank Level Experiment's Behavior.

As seen above in *Figure H-*, all of the water from one 6 foot diameter 7 foot tall tank can be transferred to the other in 175 seconds. Meaning the tank heights can be changed by a foot in 50 seconds. Therefore, making it easy to observe the effects of a change in set point or a disturbance added to the system.

Heat Transfer Experiment

The analysis for the heat transfer experiment led us to determine that the set point temperature of our heater (maximum system temperature) is too low. The explanation of how this was determined is explained in this section and a revised maximum temperature is proposed.

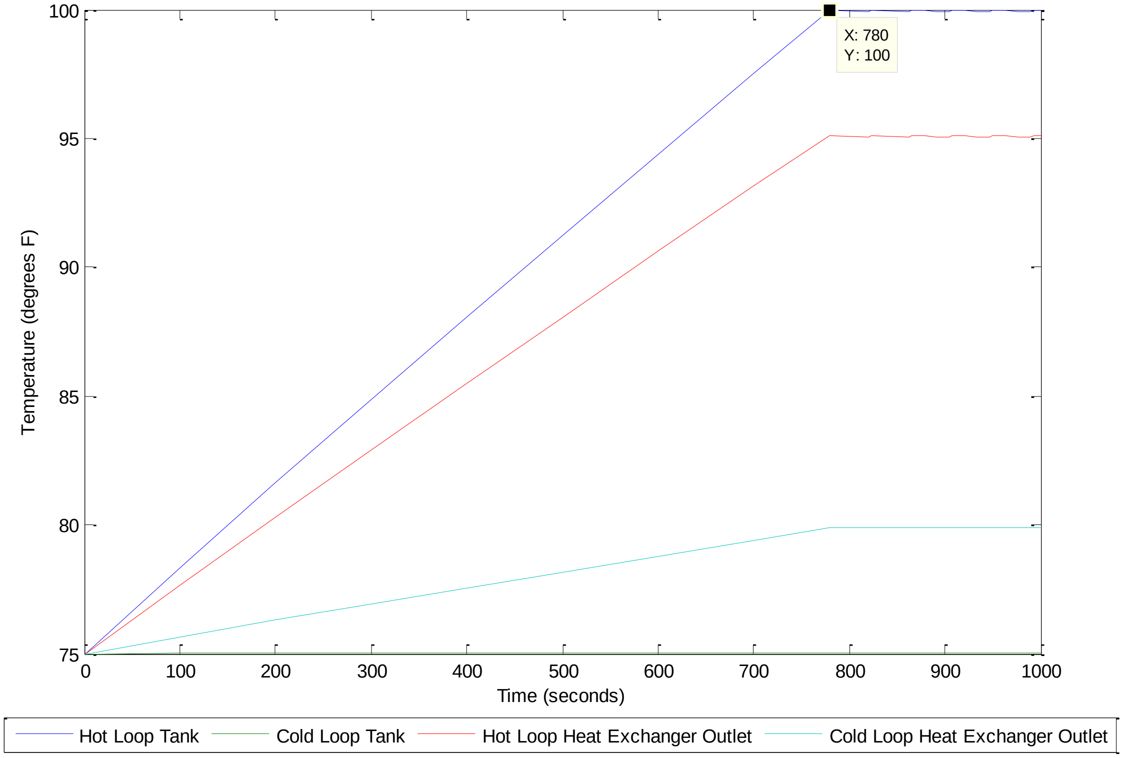


Figure H-13: Original Hot Loop Warm Up Time.

Figure H- shows the warm up time for the hot loop is 780 seconds (13 minutes) with an ambient temperature of 75°F. This is achieved by closing both valves or with pumps turned off. With an ambient temperature of 60 degrees this warm up time is increased to about 1275 seconds (21.5 minutes).

While this warm up time is plenty fast and confirms the system team's analysis, other factors determined that maximum temperature needs to be increased. The goal of this experiment is to control the shell and tube heat exchanger's hot loop outlet temperature. The maximum temperature we can achieve is the set point of our heater, currently 100°F. The minimum temperature that we can achieve is shown below in Figure X.

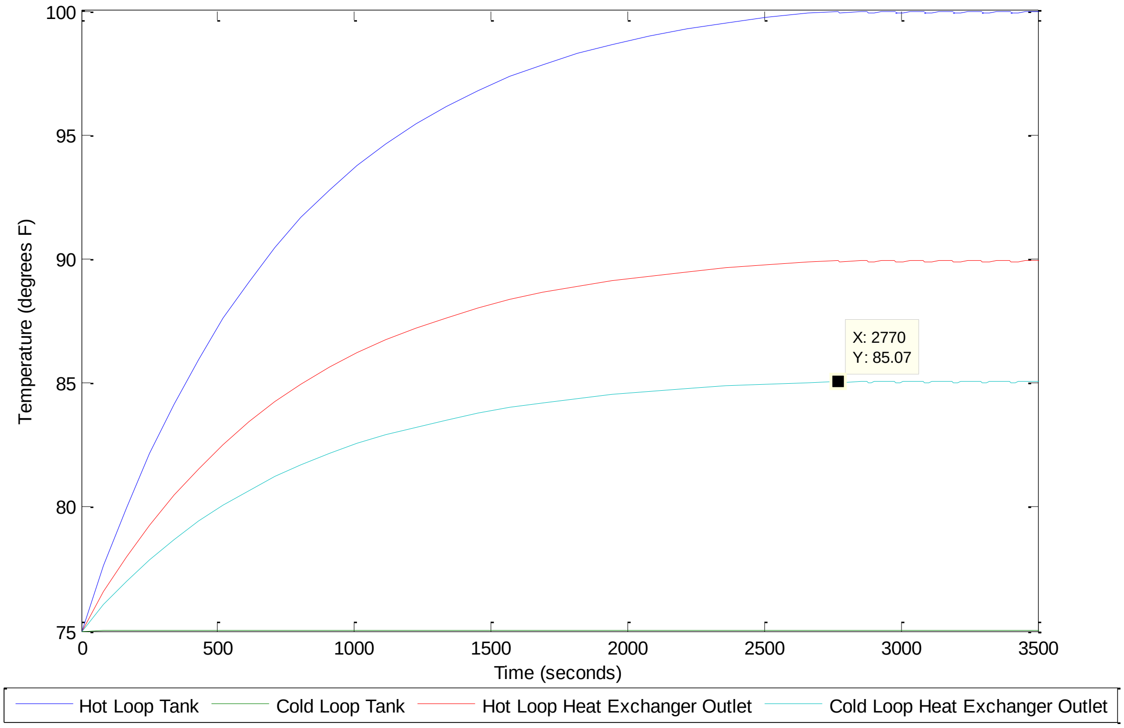


Figure H-14: Minimum Hot Loop Heat Exchanger Outlet Temperature.

Figure H- shows a minimum temperature of 90°F can be achieved at the hot loop heat exchanger outlet. This is with an ambient temperature of 75°F. If the ambient is 60°F, the minimum temperature is 75°F. With an ambient of 80°F the minimum is 92 °F.

The problem associated with this minimum temperature is that we can only control the temperature to a set point between 90°F and 100°F (if the ambient temperature is 75°F). If the ambient temperature is lower there is a larger range of temperature control. The problem is that the use of this device shouldn't have to be postponed based on the ambient temperature. Therefore, a change needs to be made.

Another problem is associated with the minimum temperature being so low. A low minimum temperature puts a huge demand on the cooling component. This requires the cooling component to dissipate 1 million BTU/hr of heat between two fluids which have a temperature difference of only 10 degrees. This temperature difference can be seen in Figure X as the difference between the two bottom curves. In order to achieve this, the heat exchanger had to be sized rather large (7'x4'X5") and it required a ridiculous flow rate of 2000 ft^3/s. That is a 50mph flow through the heat exchanger, which is unreasonable. The unrealistic nature of this can be confirmed by the bottom curve in Figure X. It can be seen that the cold loop's temperature does not increase noticeably. It is completely unrealistic to be able to cool a liquid to air temperature with a cross-flow heat exchanger.

One option to solve this problem would be to increase the size of the heat exchanger to allow more heat transfer between the air and the water. This is nearly impossible though because the heat exchanger size has already reached the point of diminished return. Increasing any dimension of the heat exchanger does very little to increase its heat transfer capabilities. Even if the heat exchanger is doubled in size, the heat transfer capabilities increase only by a small percentage. If doubled again, its heat transfer abilities increase by a fraction of the previous percentage.

With all of this in mind it was determined that the max temperature of the hot loop had to be raised. Keeping in mind that 140° is a low threshold of what can burn somebody, the temperature of 120°F was chosen. This new maximum temperature changes the warm up time because it will now require more heat in to raise the temperature of the hot loop.

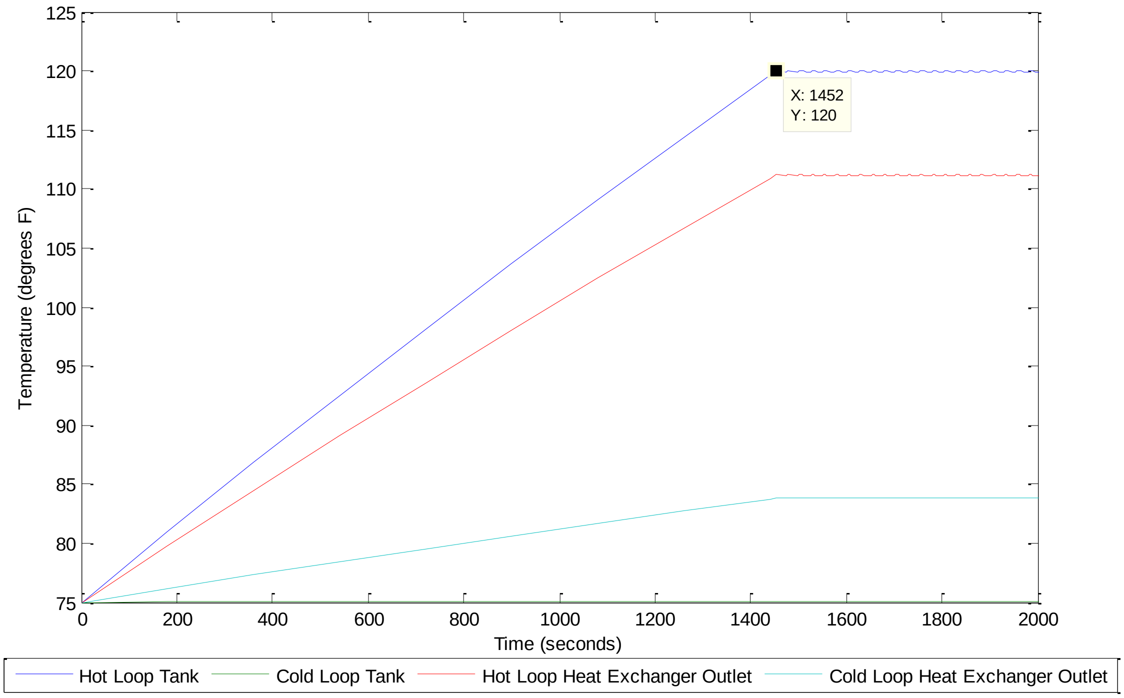


Figure H-15: New Maximum Temperature Warm Up Time.

Figure H- *shows that the* time to warm up with an ambient temperature of 75°F is approximately 1450 seconds (24 minutes). This will increase to approximately 2000 seconds (33 minutes) for an ambient temperature of 60°F.

With the valves nearly closed we should be able to achieve no significant temperature drop across the heat exchanger and therefore have a maximum hot loop heat exchanger outlet temperature of 120°F. Using a new heat exchanger design, with larger dimensions of (14'x4'x5") and a reasonable air flow rate of 800CFS. We are able to achieve a new low temperature.

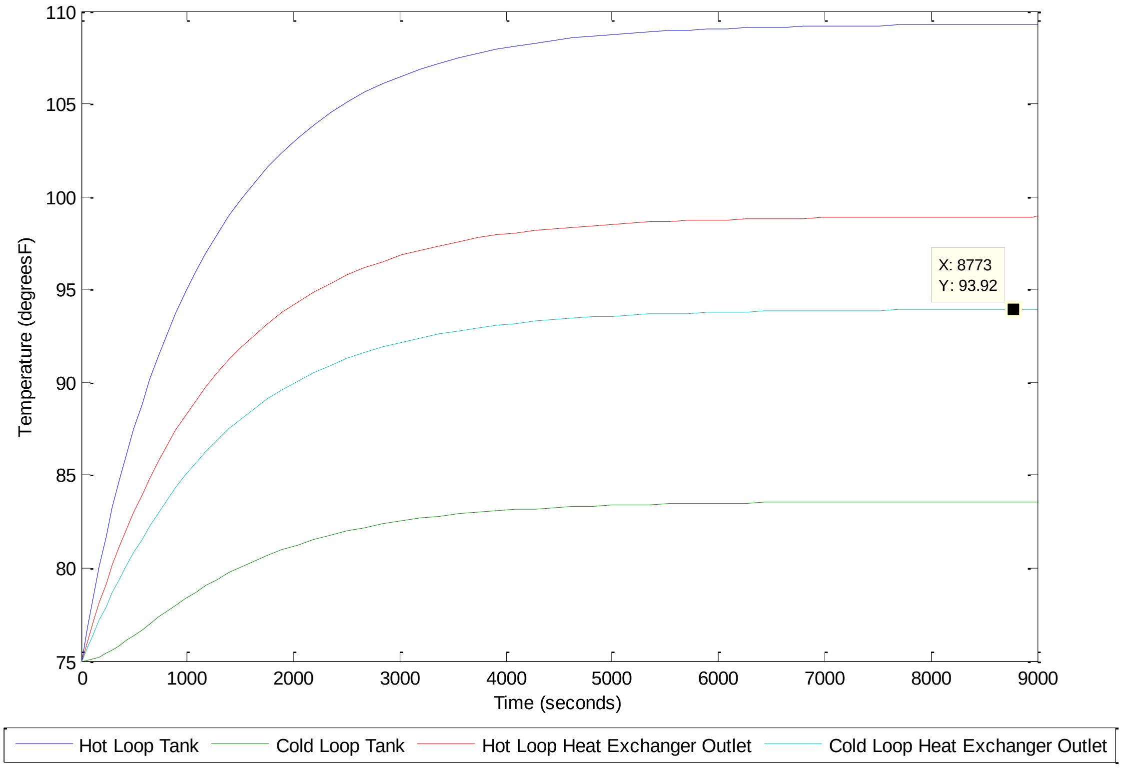
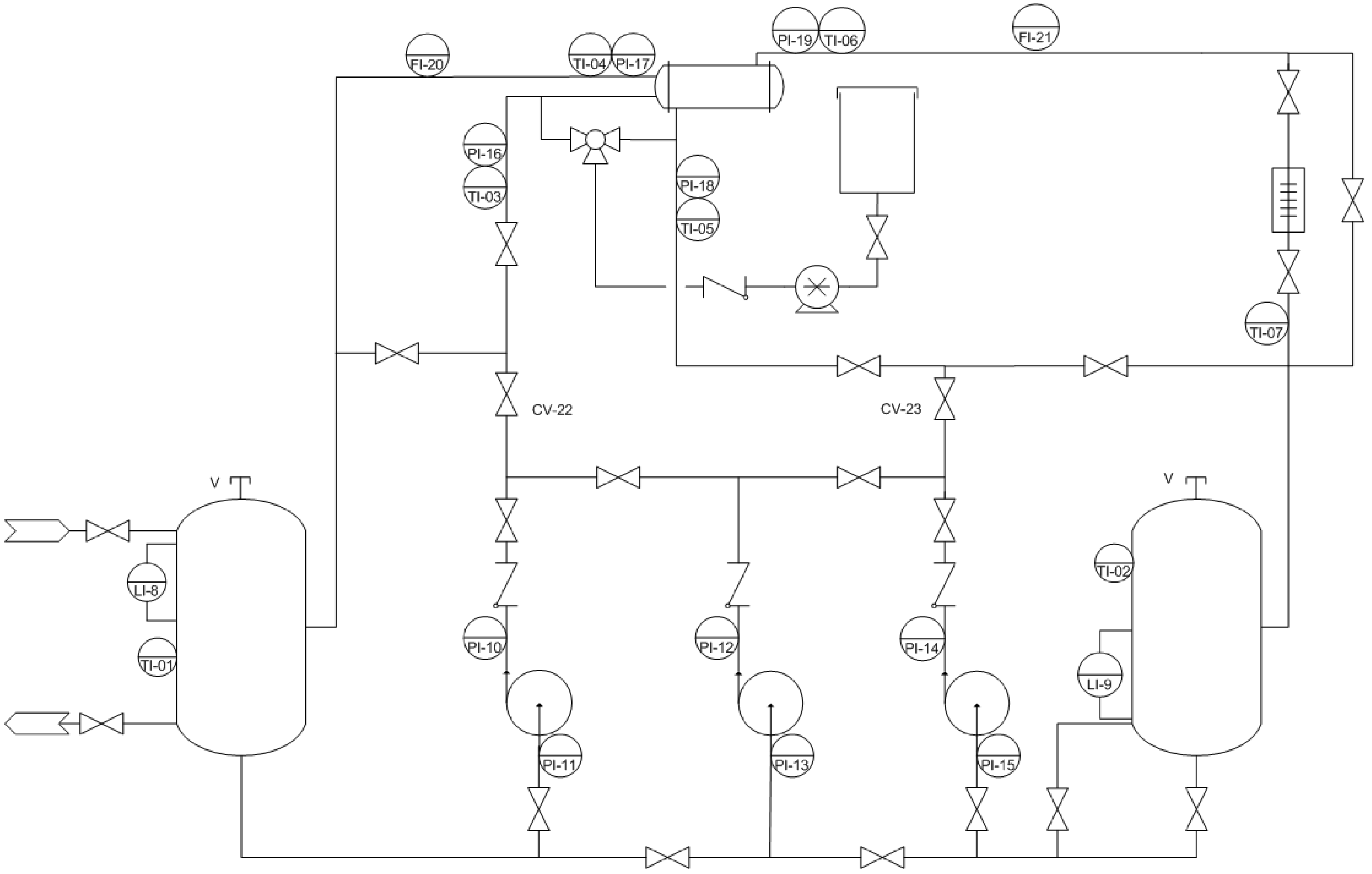


Figure H-16: Minimum Achievable Hot Loop Heat Exchanger Outlet Temperature.

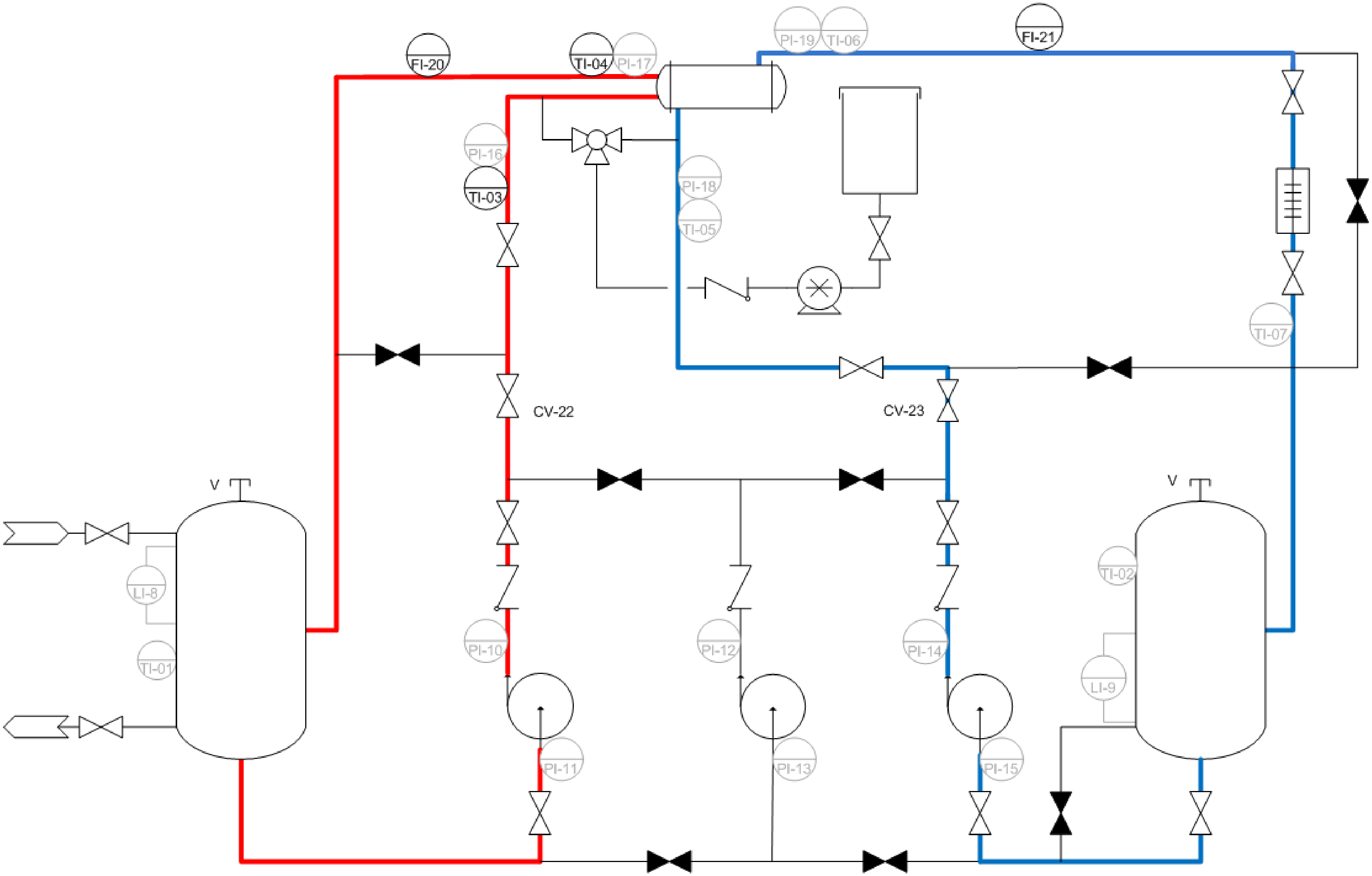
Figure H- shows that a minimum temperature of approximately 94°F can be achieved with an ambient temperature of 70°F. This is with both valves open completely for maximum flow rates through the heat exchangers. This temperature can be reduced to 84°F if the ambient temperature is 60°F.

The new heat exchanger and a maximum temperature of 120°F enable control of the temperature within 194°F to 120°F. This is a 26°F range and makes the system much more useable and realistic. The heat exchanger is still required to be large but now requires a reasonable flow rate. The system should have a startup time of less the 30 minutes.

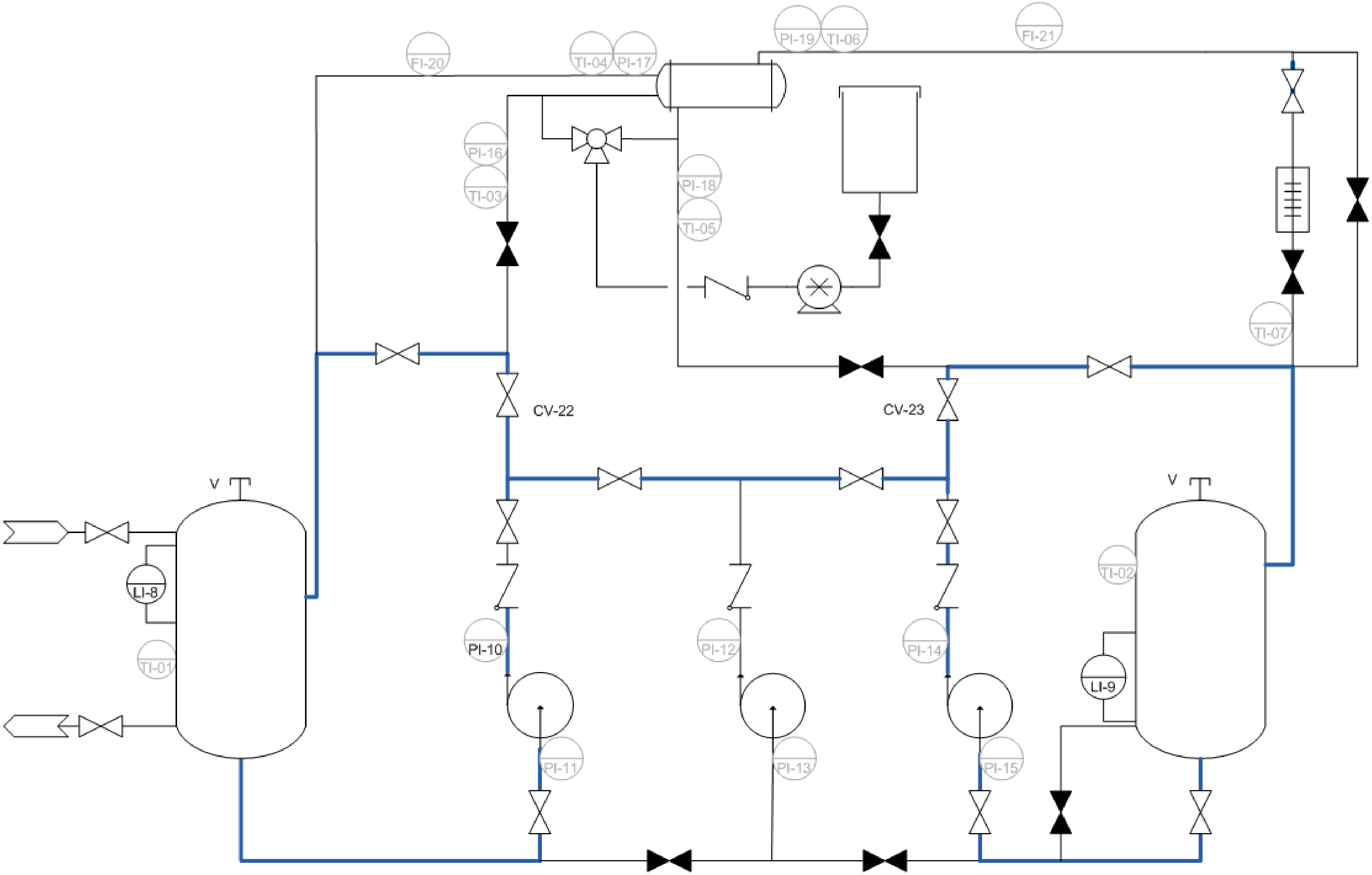
Appendix I: System Figures



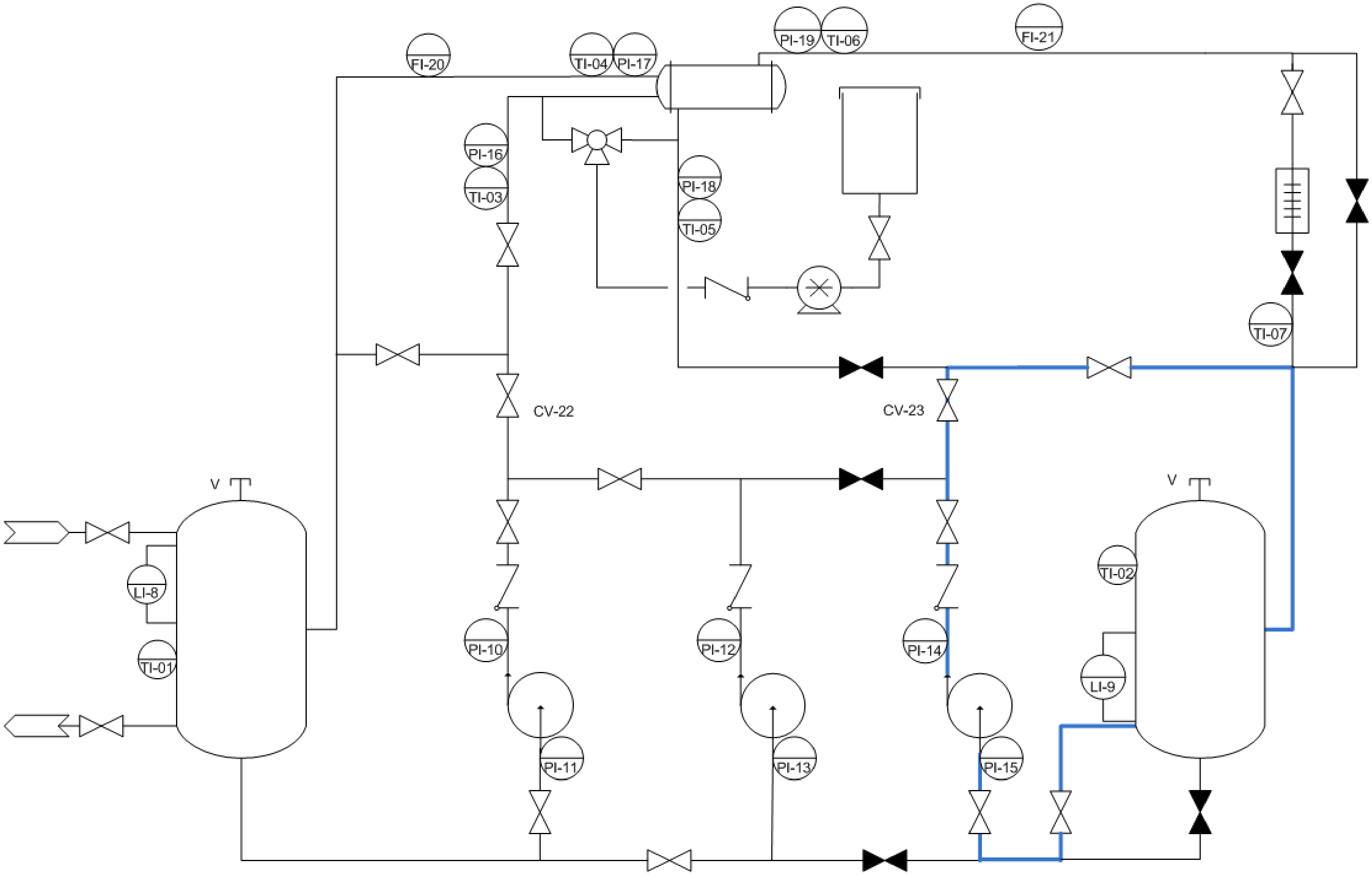
System Figure 4. Piping and instrumentation diagram with heat transfer configuration.



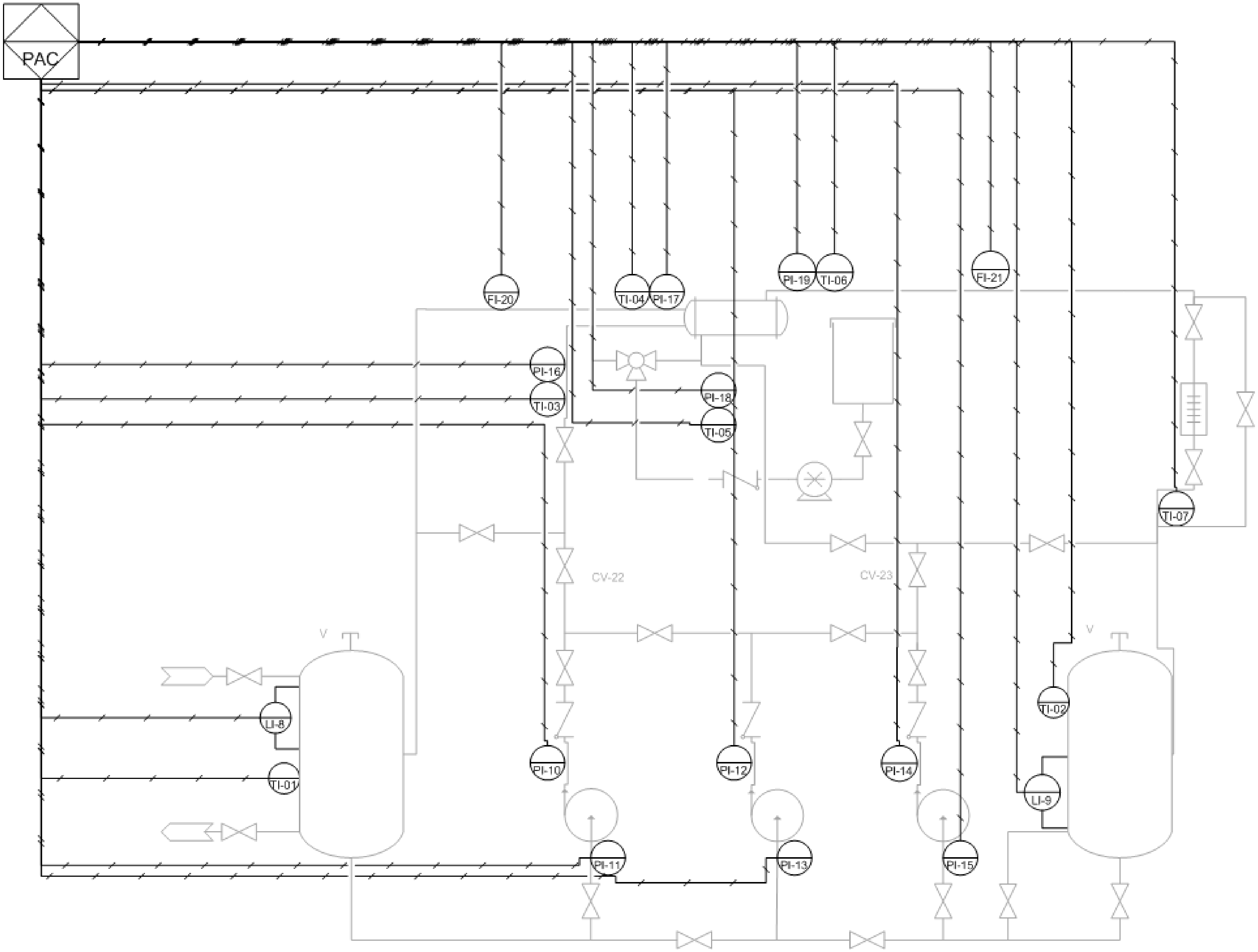
System Figure 5. Heat transfer configuration with important instrumentation highlighted.



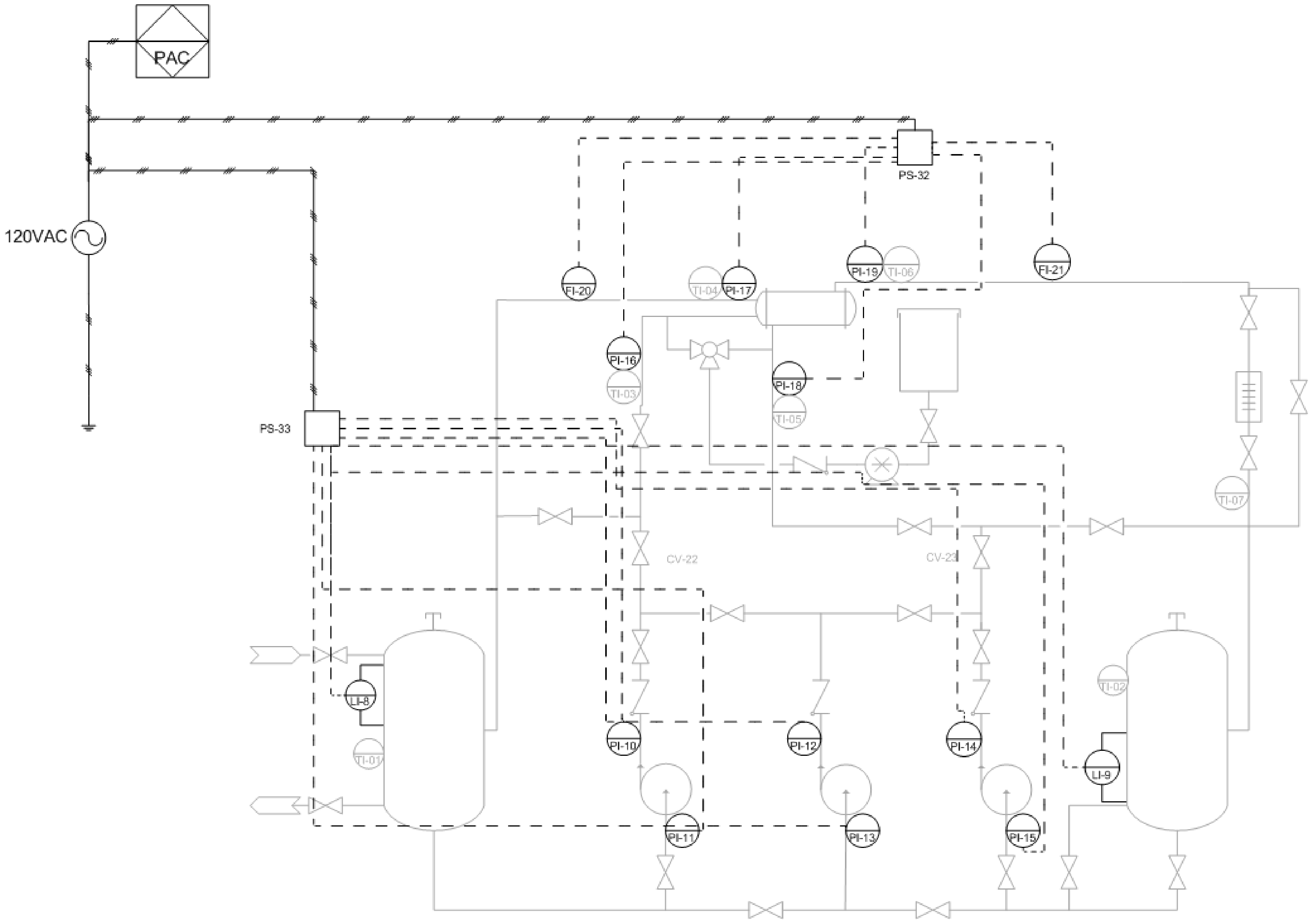
System Figure 6. Tank level configuration with important instrumentation highlighted.



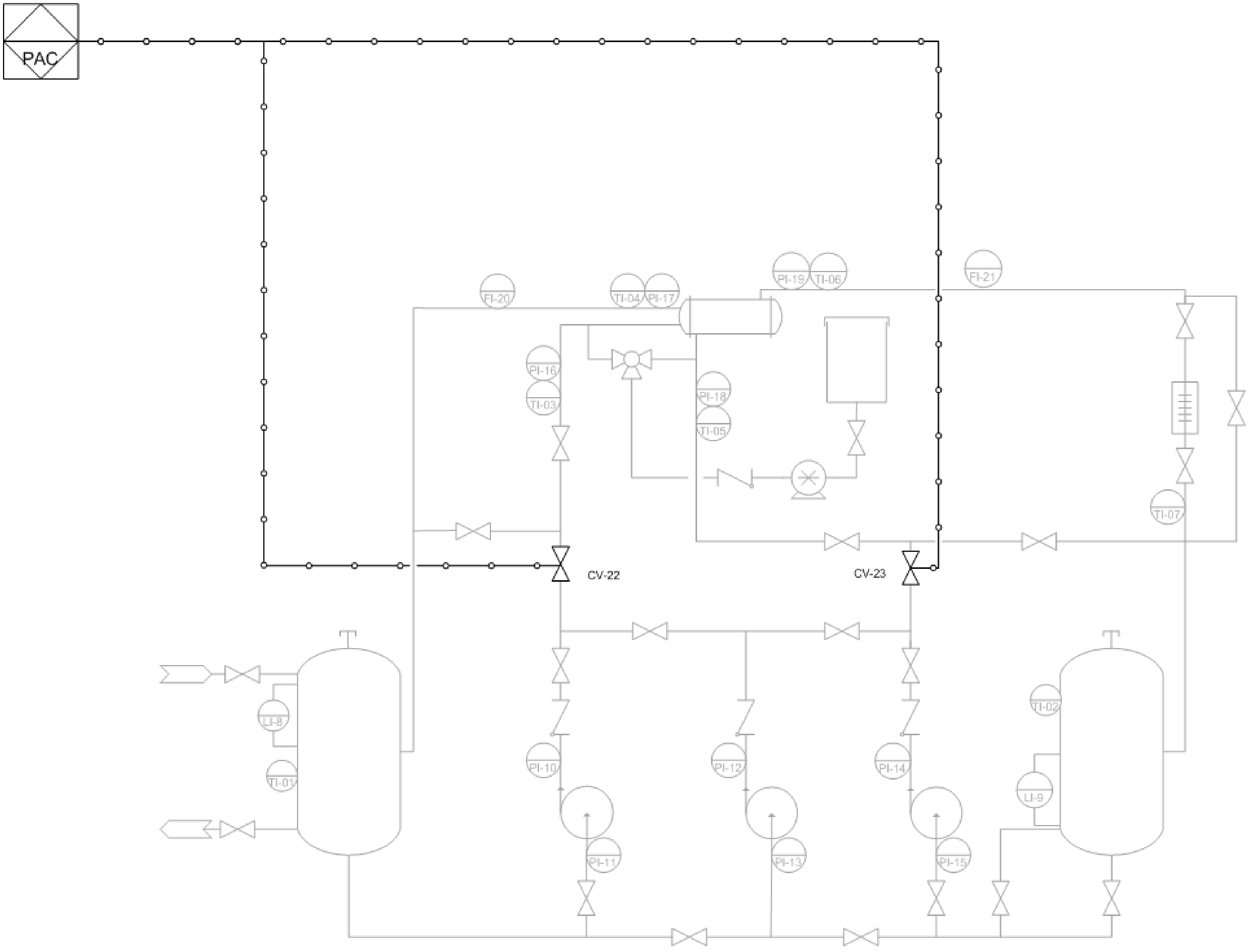
System Figure 12. Vortex configuration.



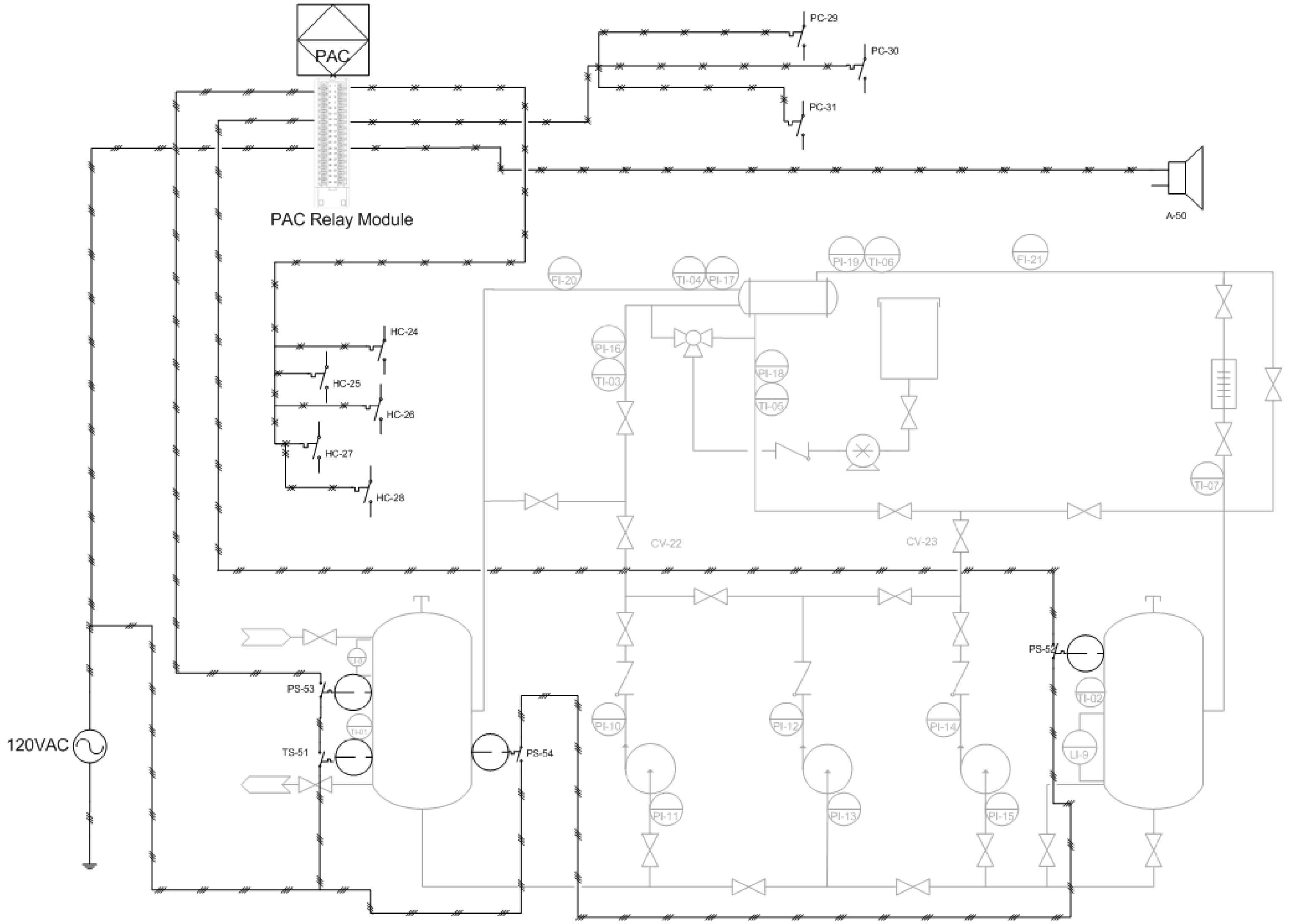
System Figure 9. Sensor to PAC wire diagram. Uses 2x Analog Input Module (1756-IF16) and 2x Six Channel RTD input modules (1756-IR6I).



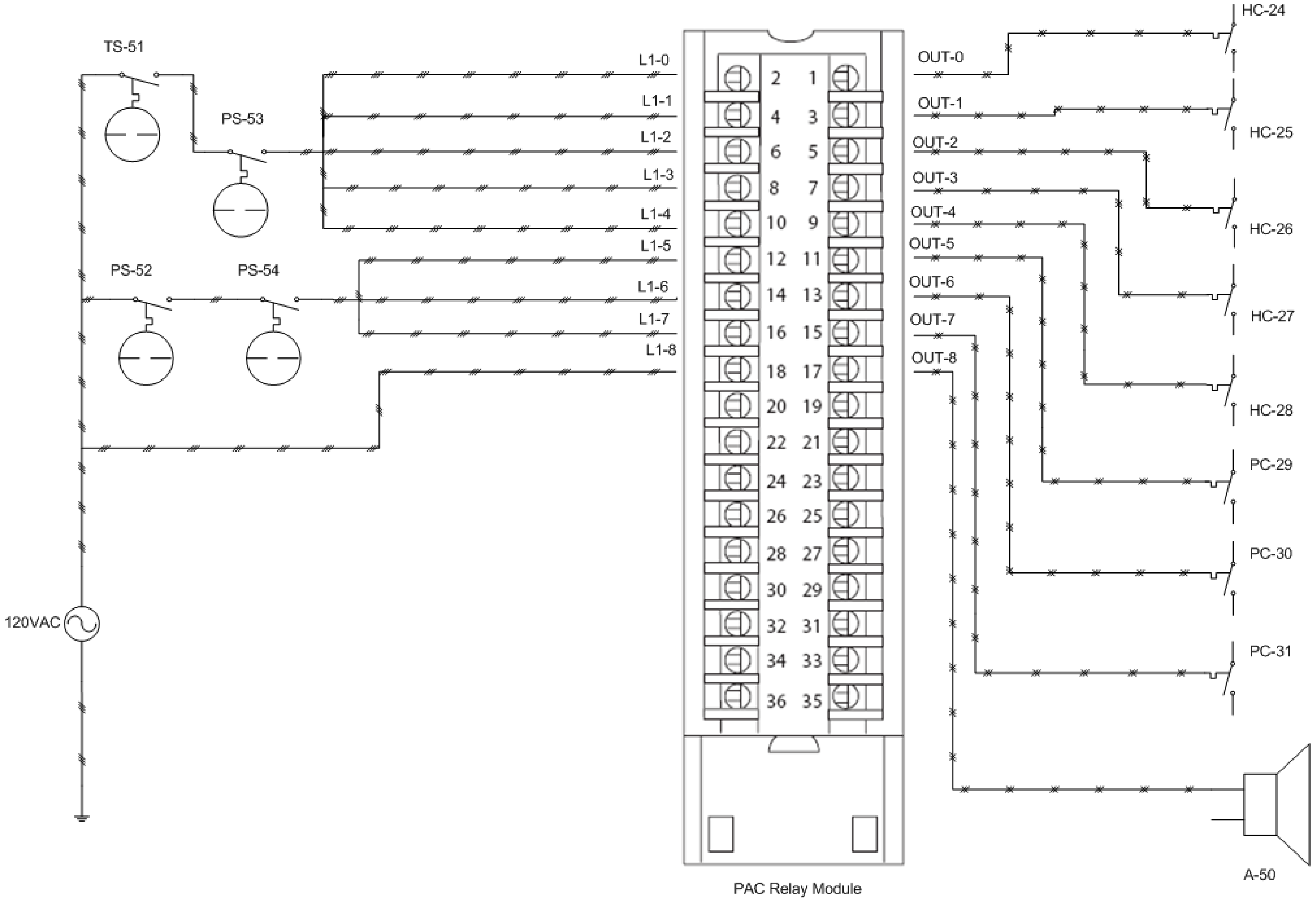
System Figure 6. 120VAC and 24VDC wire diagram.



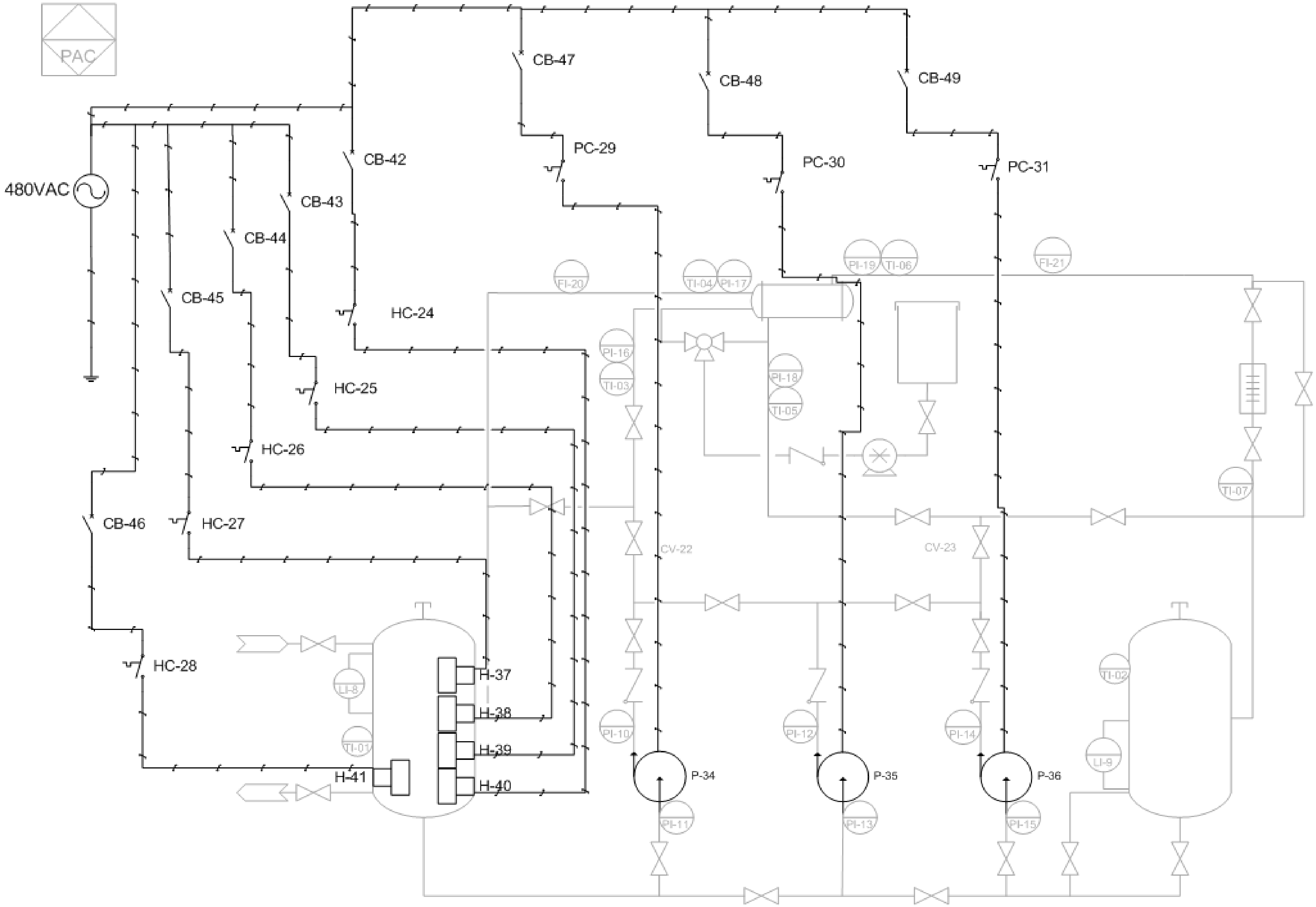
System Figure 7. PAC milliamp output wire diagram. Signals sent from the Analog Output Module (1756-OF8).



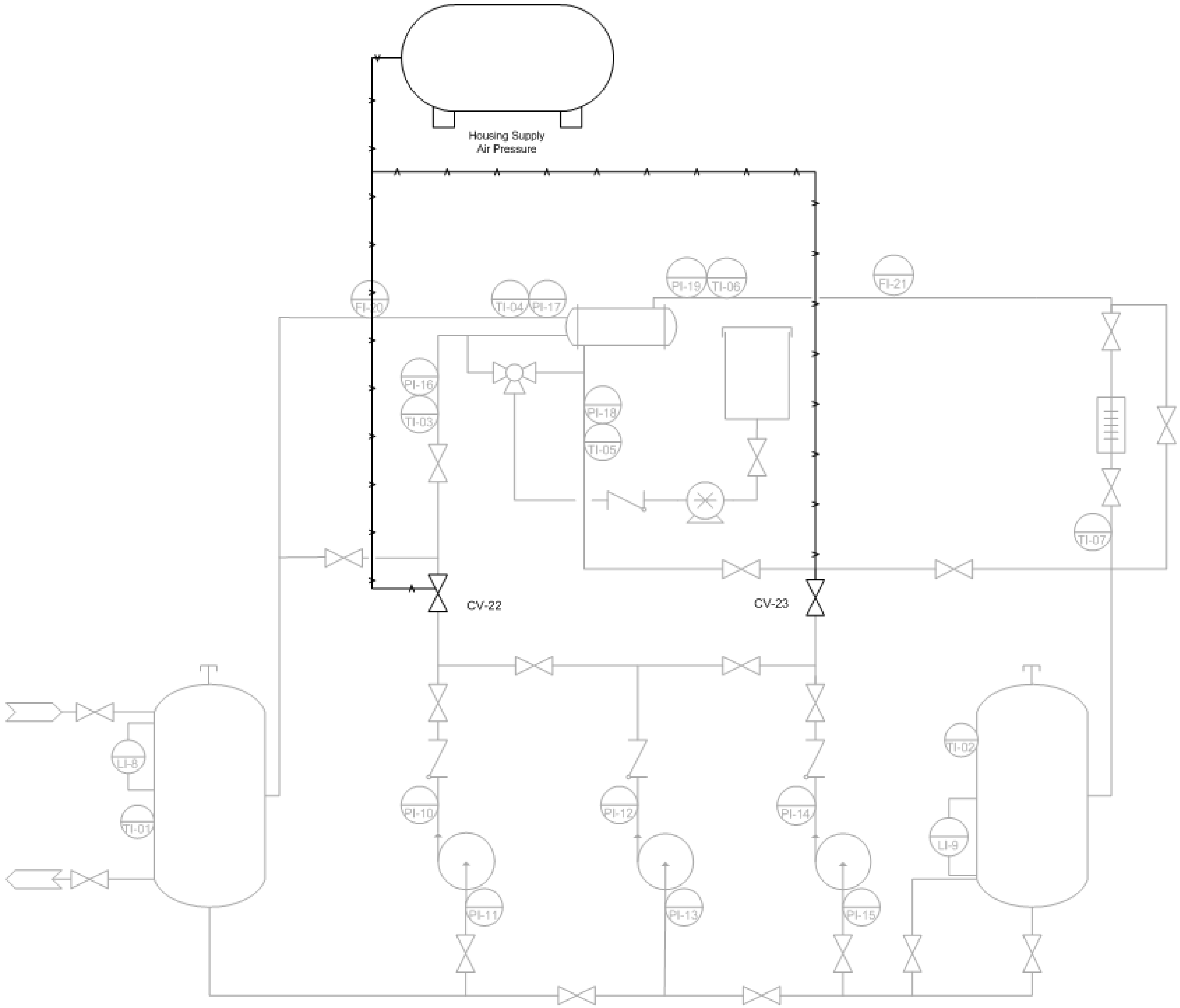
System Figure 8. 120VAC signal and signal supply. The 120VAC signal uses the Relay Module (1756-OW16I). Includes secondary interlock switches.



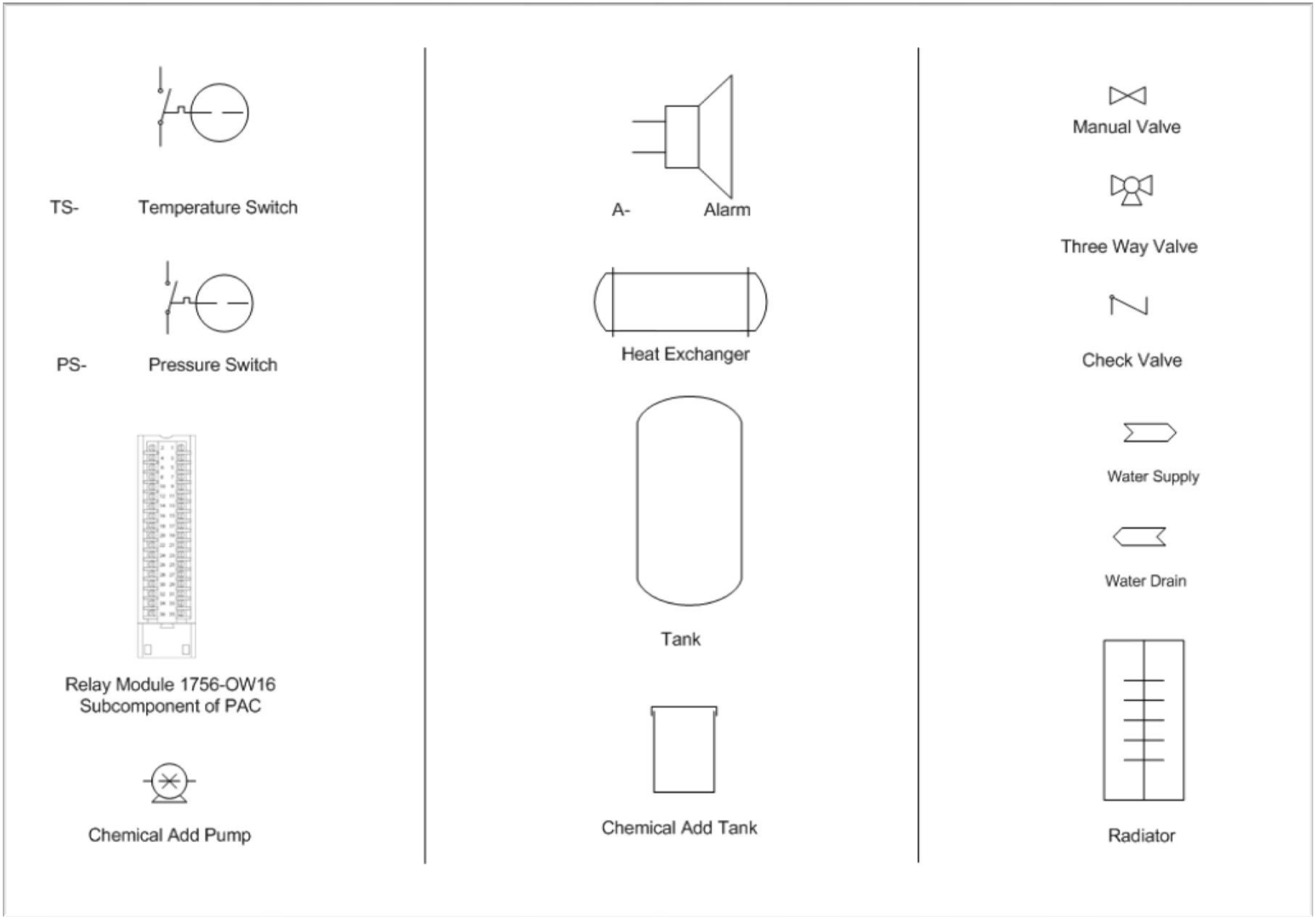
System Figure 9. Detailed diagram of Relay Modules (1756-OW16I) signal supply voltage, including secondary interlock switches.



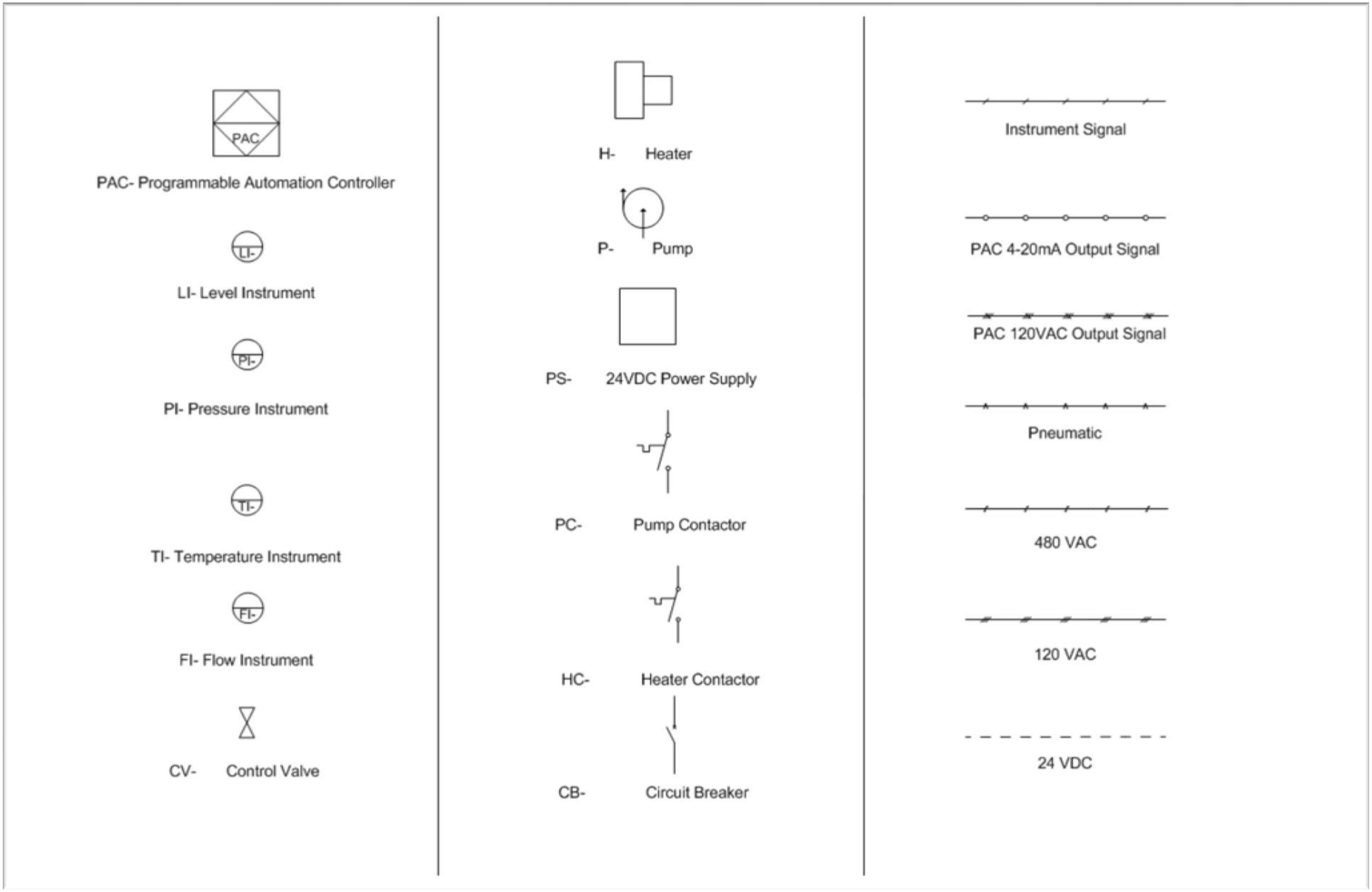
System Figure 1110. 480VAC wire diagram.



System Figure 11. Pneumatic diagram.



System Figure 12. System Figure Legend Page 1.



System Figure 13. System Figure Legend Page 2.