Summer 2021

JME 4110: Data Cooling Center

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Joint Engineering Program

University of Missouri–St. Louis ▪ Washington University in St. Louis

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At the current time there is a over reliance on digital data, algorithms and hardware. It became apparent that in order to decrease energy usage on reliable digital infrastructure that submerging the data centers in cooling dielectric fluid was the logical next step. The report presents the benefits of that next step to a large audience scientifically, technically as well as in report format

JME 4110 Mechanical Engineering Design Project

Data Center Cooling

Brennan Fogarty
Christopher Schmidt
Aryal Suruchi

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1 INTRODUCTION

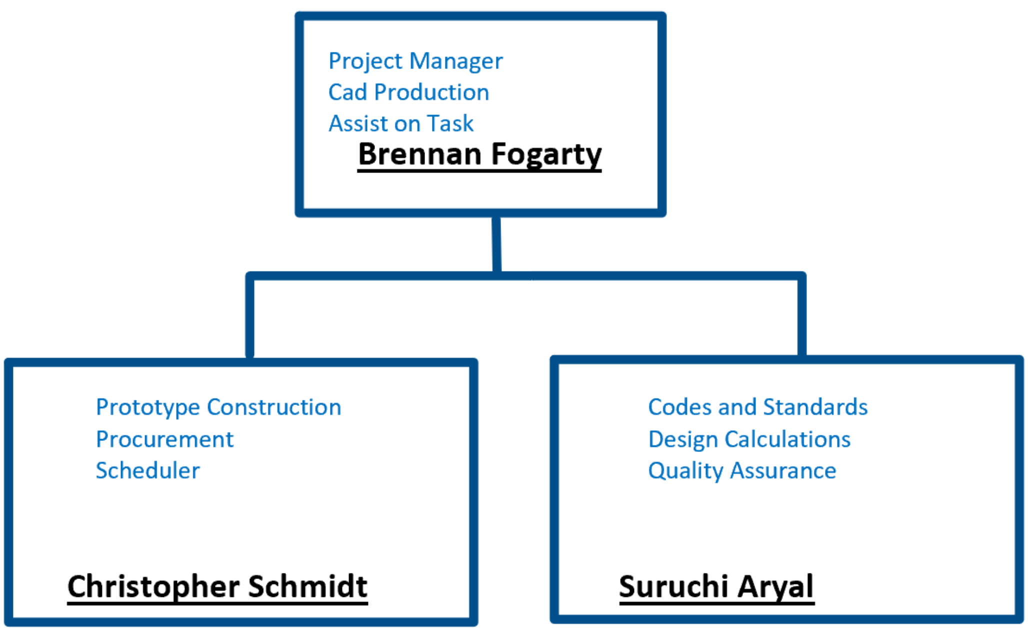
1.1 VALUE PROPOSITION / PROJECT SUGGESTION

A data center submerged into dielectric fluid so that heat can be transported more efficiently than air to air cooling is currently used. This method is theorized to make the data center operate on a third of the power needed to cool a comparable air to air cooled data center.

1.2 LIST OF TEAM MEMBERS

Brennan and Chris ended up on the same team because of similar work styles, in that they like to turn in good work but also have lots of other commitments. For Brennan, it's a blossoming family and for Chris, it's also a family with some civil service. Chris and Brennan also have a few years of history working with one another towards their degrees in the UMSL/WashU Joint Program. Suruchi joined the group when Chris and Brennan indicated they were open to adding a third member. She jumped at the opportunity to join a group that needed another person and has worked alongside her two other members in her past courses.

Chris and Brennan discussed the available projects prior to the first class period. They settled on a top three choices and project 5 - Data Center Cooling was the group's second choice. By the time Suruchi was selected to pick a project on behalf of the group, the first choice was gone. Chris and Brennan confirmed that project 5 was something Suruchi would be willing to work on and she affirmed that it was. The group then selected project 5 – Data center Cooling.



2 BACKGROUND INFORMATION STUDY

2.1 DESIGN BRIEF

The group will design a way to efficiently move heat within a framework of using dielectric fluid as a heat transfer medium. The heat will be removed from a data center or a simulated data center. The group will evaluate the best possible design with the understanding that cooling data centers generate a large amount of heat. The design will also be constructed in such a manner that it can be scaled up to a larger size. Dielectric fluid will be used due to its efficiency compared to that of an air cooled system or a compressed refrigerant system. Account for safety factors to both the equipment and the environment while designing a system that addresses current design faults in data center cooling. Continue to be mindful of faults that may be encountered due to the proposed design as the group will be forced to design around not only engineering constraints but also resource constraints.

2.2 BACKGROUND SUMMARY

Our initial design intent centers on immersion cooling. In immersion cooling, the electronic components are immersed in a dielectric fluid that is readily accessible. The heat from the electronic components is transferred to the fluid. This has a great advantage from an efficiency standpoint when compared to traditional air cooling. It also has the potential to reduce the volume of space required for the data center.

3 CONCEPT DESIGN AND SPECIFICATION

3.1 USER NEEDS AND METRICS

3.1.1 Record of the user needs interview

What is the life expectancy of the system in order to determine quality of materials (Are you mining or using GPUs or servers)?
The system is expected to run daily for at least 5 years based on the warranty.
Is there any opposition to using Deionized water and Glycol mixture as the Dielectric fluid (this is to ensure value added performance and electronic reliability)?
There is opposition to using deionized water due to how corrosive it is to the electronics. The deionized water will damage the equipment so that it degrades sooner.

What is the T-initial and T-final (35 degrees or higher)?
To overclock the system provided it can be cooled , the initial temperature will be circa 120F, and the cooling needs to cool to at least 90 degrees Fahrenheit.

How many servers will you need to cool and what are their dimensions in the Conex (in order to accommodate total cooling load)?
The number of servers for this experiment will be 2 servers. The dimensions are listed as 28” by 16” by 10”. The total amount of cooling will be 3000 watts

Where will the Conex be located (both for construction and environmental considerations)?
The Conex will be stationary and located around accessible power lines.

Will conex be mobile (as it bears on HX placement)?
No. The Conex will be for all intents and purposes of this project stationary.

What will your maintenance schedule look like (weekly, biweekly, monthly or longer)?
The maintenance schedule will be bi-weekly to monthly maintenance on air filters. Need to ensure there are adequate safeties.

3.1.2 List of identified metrics

3.1.2.1 Reduced energy usage.

3.1.2.2 Submerged electronics into dielectric fluids.

3.1.2.3 Fits into a Conex

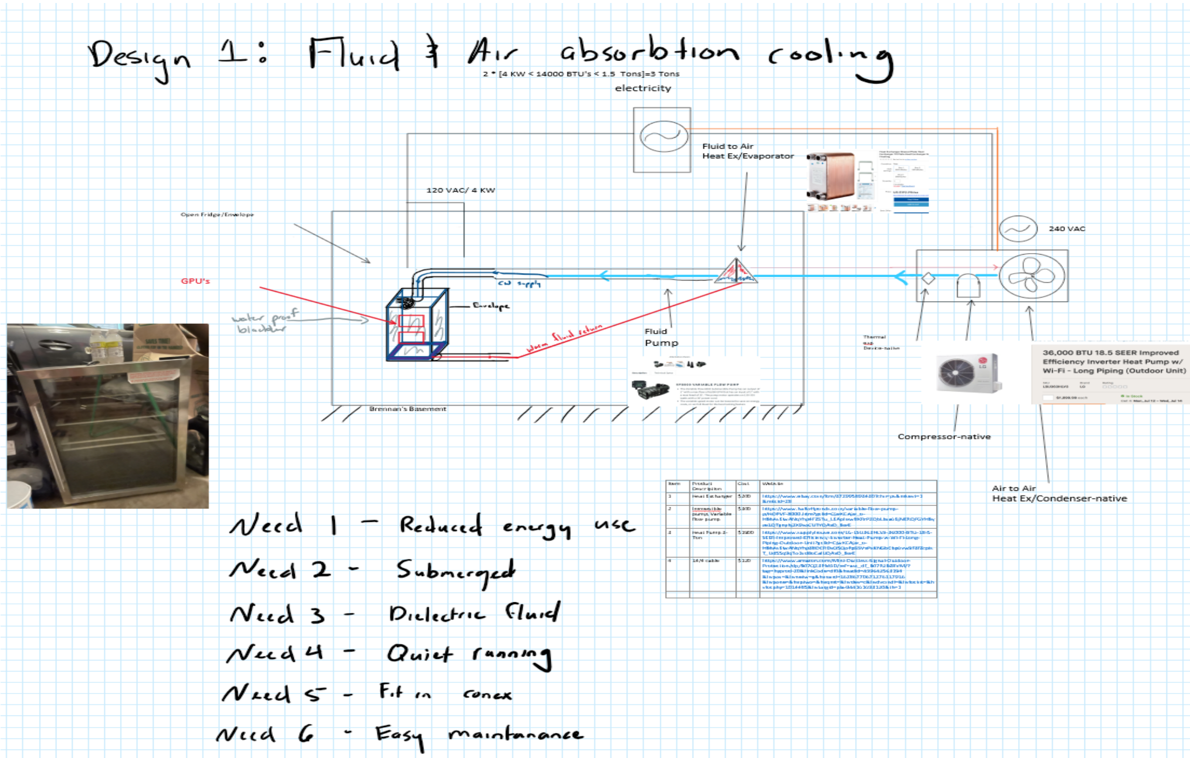
3.1.2.4 Easy to maintain

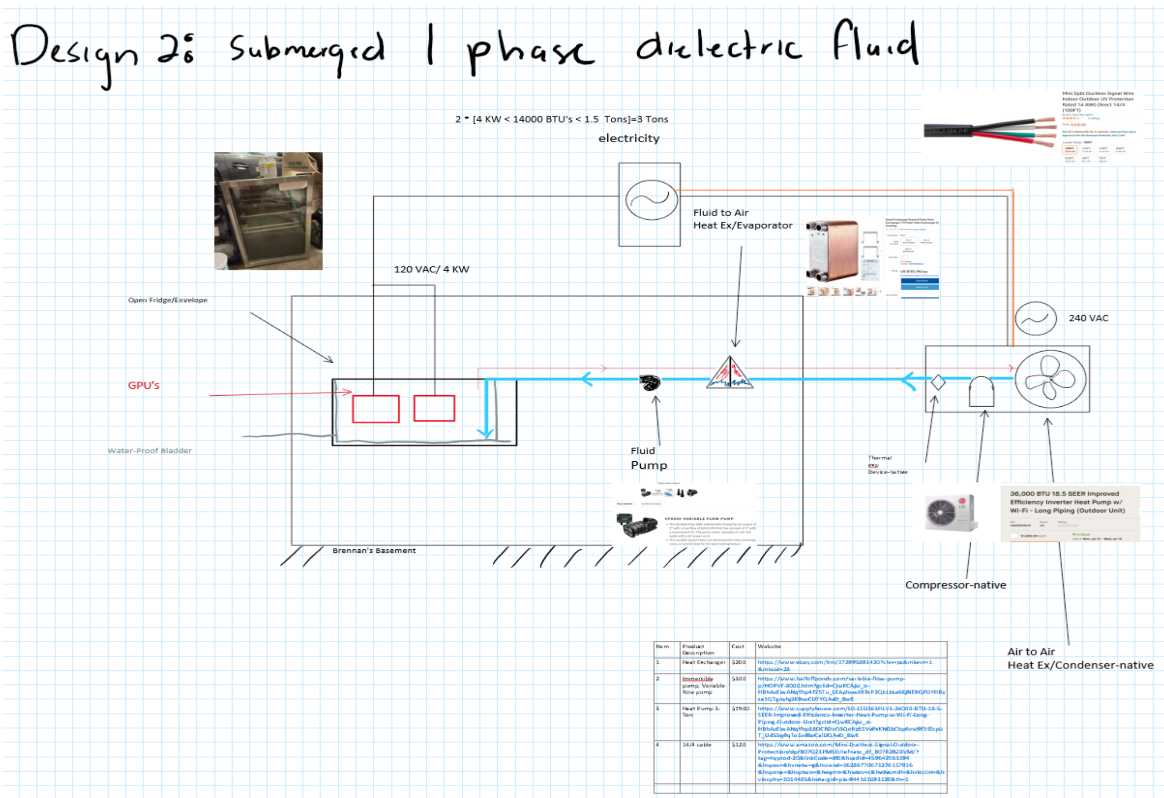
3.1.3 **Table/list of quantified needs equations**

Power Usage
Immersion Cooled
Dielectric Fluid
Noise Level (excluding exterior components)
Length
Width
Height
Standard Maintenance Time
of Major System Components
Cost
Assembly Time

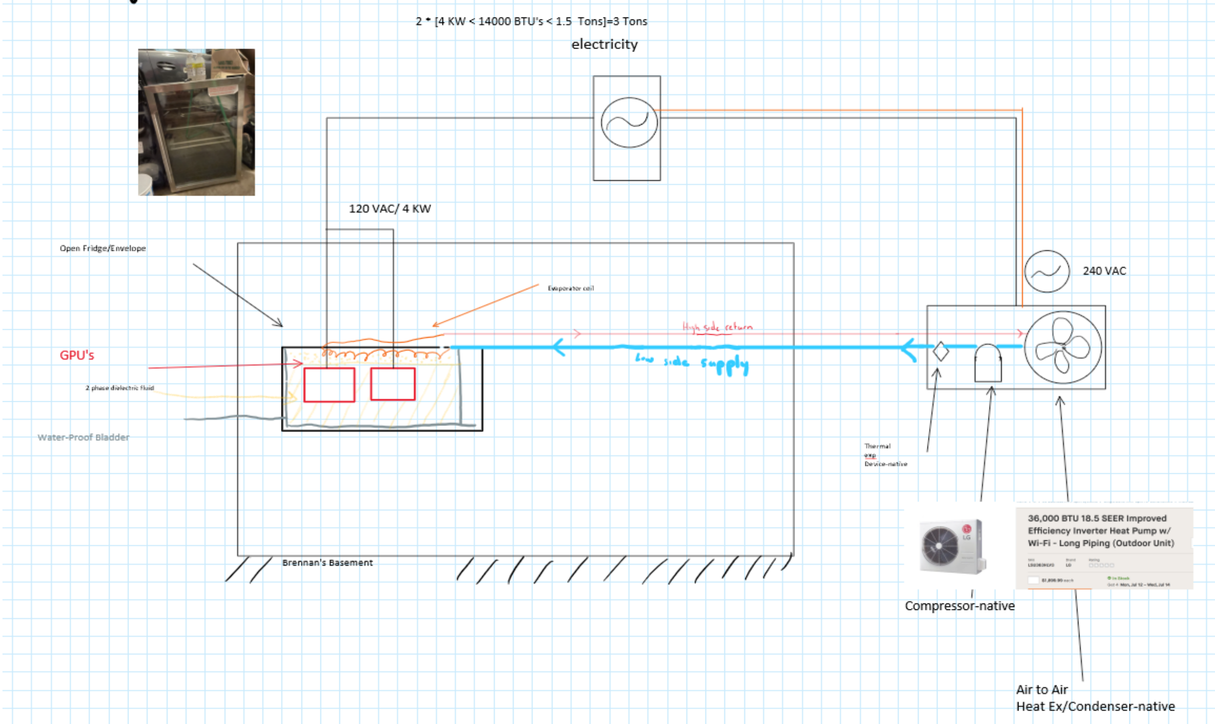
3.1.4

3.2 CONCEPT DRAWINGS

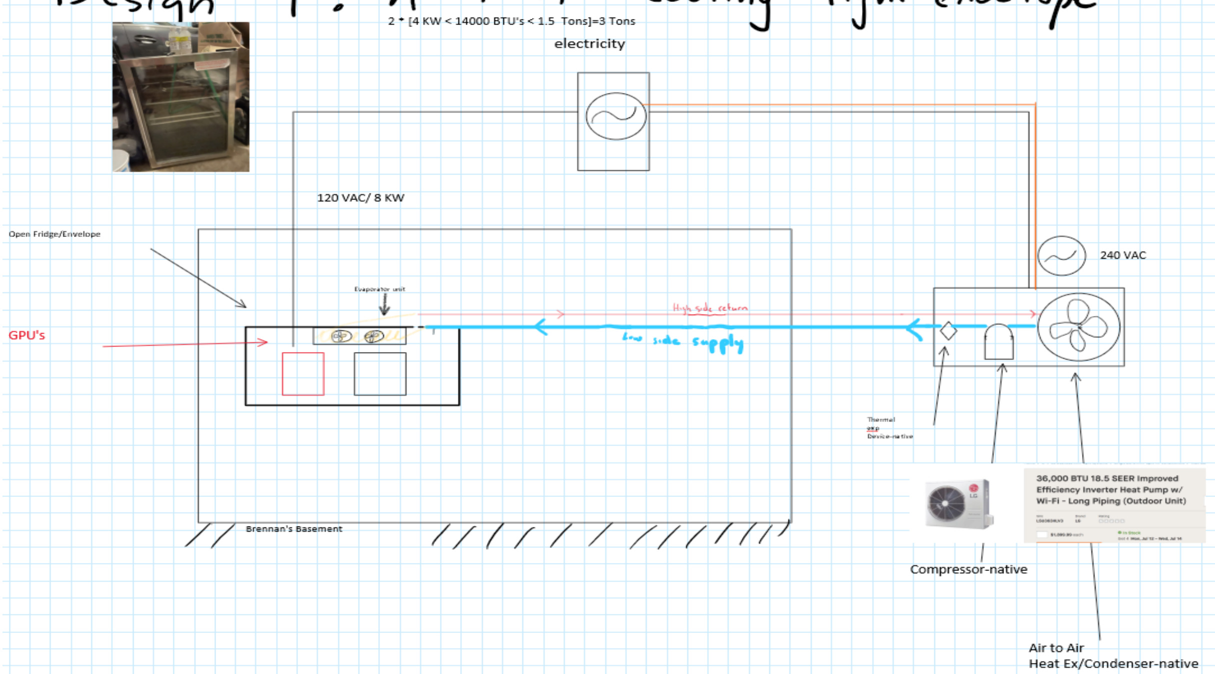




Design 3: Submerged 2 phase dielectric fluid



Design 4: Air to Air cooling tight envelope



3.3 CONCEPT SELECTION PROCESS.

3.3.1 **Concept scoring (not screening)**

#	Need
1	Reduce/Minimize Energy Usage
2	Uses Immersion Cooling
3	Uses Dielectric Fluid
4	Runs Quietly
5	Fits in Connex
6	Ease of Maintenance
7	Limit the parts
8	Cost of entire system components
9	Time to assemble

3.3.2 **Preliminary analysis of each concept's physical feasibility**

During a meeting on 7/8/21, we discussed all five of our designs with the project sponsor, Mr. Molitor, and professor Giesmann. It was determined that the air to air heat exchanger and compressor would be unnecessary components and a radiator and fan combination would suffice. This decision was made following the concept design stage of this assignment but prior to the preliminary physical feasibility review.

As such, our initial designs will be discussed without these components.

i. There were no foreseen issues with this design.
ii. Obtaining standard dielectric fluid was seen as a potential obstacle but is believed possible.
iii. Obtaining two phase dielectric fluid was determined to be too difficult. This design was ruled out by the feasibility review due to timeframe.
iv. There were no foreseen issues with this design.

Data Cooling		Metric										
		Power Usage	Immersion Cooled	Dielectric Fluid	Noise Level (excluding exterior components)	Length	Width	Height	Standard Maintenance Time	# of Major System Components	Cost	Assembly Time
Need#	Need	1	2	3	4	5	6	7	8	9	10	11
1	Reduce/Minimize Energy Usage	1.00										
2	Uses Immersion Cooling		1.00									
3	Uses Dielectric Fluid			1.00								
4	Runs Quietly				1.00							
5	Fits in Connex					0.33	0.33	0.33				
6	Ease of Maintenance								1.00			
7	Limit the parts									1.00		
8	Cost of entire system components										1.00	
9	Time to assemble											1.00
	Units	Integer	Binary	Binary	dB	in.	in.	in.	min	Integer	$	hr

Need#	Need	Need Weight	Design 1			Design 2			Design 3			Design 4			Design 5		
			Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value	Need Happiness	Importance Weight (all entries should add up to 1)	Total Happiness Value
1	Reduce/Minimize Energy Usage	4	0.50	0.13	0.07	0.25	0.13	0.03	0.25	0.13	0.03	0.50	0.13	0.07	0.50	0.13	0.07
2	Uses Immersion Cooling	3	0.00	0.10	0.00	1.00	0.10	0.10	1.00	0.10	0.10	0.00	0.10	0.00	0.00	0.10	0.00
3	Uses Dielectric Fluid	3	0.00	0.10	0.00	1.00	0.10	0.10	1.00	0.10	0.10	0.00	0.10	0.00	0.00	0.10	0.00
4	Runs Quietly	3	0.73	0.10	0.07	0.73	0.10	0.07	0.73	0.10	0.07	0.53	0.10	0.05	0.53	0.10	0.05
5	Fits in Connex	3	1.00	0.10	0.10	1.00	0.10	0.10	0.83	0.10	0.08	0.83	0.10	0.08	0.67	0.10	0.07
6	Ease of Maintenance	3	0.33	0.10	0.03	0.67	0.10	0.07	0.33	0.10	0.03	0.33	0.10	0.03	0.33	0.10	0.03
7	Limit the parts	4	0.80	0.13	0.11	0.80	0.13	0.11	1.00	0.13	0.13	1.00	0.13	0.13	1.00	0.13	0.13
8	Cost of entire system components	4	0.40	0.13	0.05	0.40	0.13	0.05	0.00	0.13	0.00	0.00	0.13	0.00	0.40	0.13	0.05
9	Time to assemble	3	0.67	0.10	0.07	0.67	0.10	0.07	0.50	0.10	0.05	0.33	0.10	0.03	0.00	0.10	0.00
	Units	30	D1 Happiness		0.500	D2 Happiness		0.700	D3 Happiness		0.607	D4 Happiness		0.403	D5 Happiness		0.407

3.3.3 **Final summary statement**

The design with the most needs met, is design 2 and that can be seen under design 2 towards the center of the figure. Towards the lower portion of the figure you can see that design 2 got the most points on a scale of 0-1 with 0.7. Design 3 is the runner up and design 1 comes in 3rd. The second design was chosen to be modified without the air to air heat exchanger and compressor but replace them with a radiator and fan off of the dielectric fluid closed system. This design was discussed during the group's 7/8/21 meeting as the best design to move forward with. The design passed the physical feasibility review and uses immersion cooling which was something both the group and the project sponsor wanted to implement.

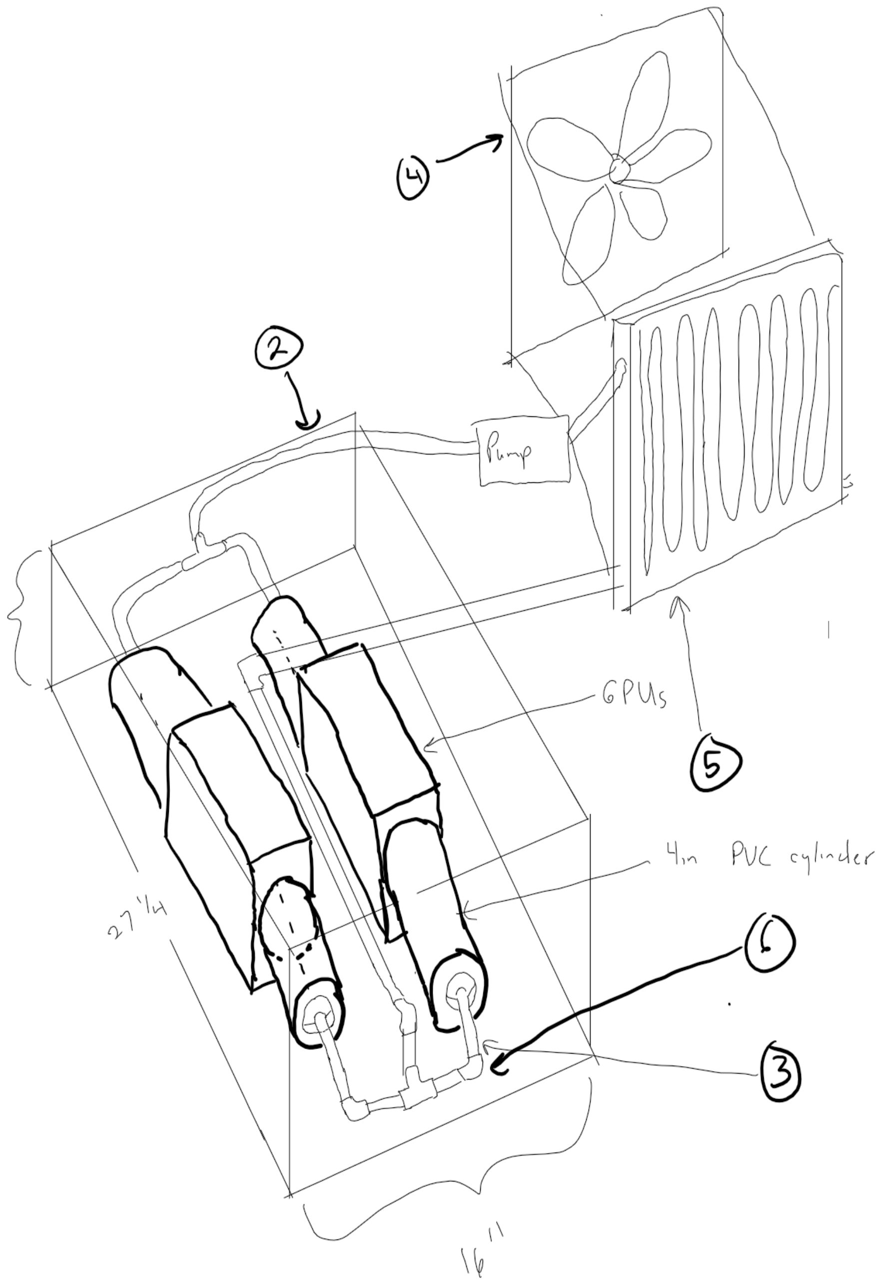
3.4 PROPOSED PERFORMANCE MEASURES FOR THE DESIGN

The main performance measure was initially chosen to be energy usage. However, as the design process progressed the main performance measure was updated to be the change in temperature and the ability of the tank to maintain a temperature within the GPU operating range of 75-85 °C.

4 EMBODIMENT AND FABRICATION PLAN

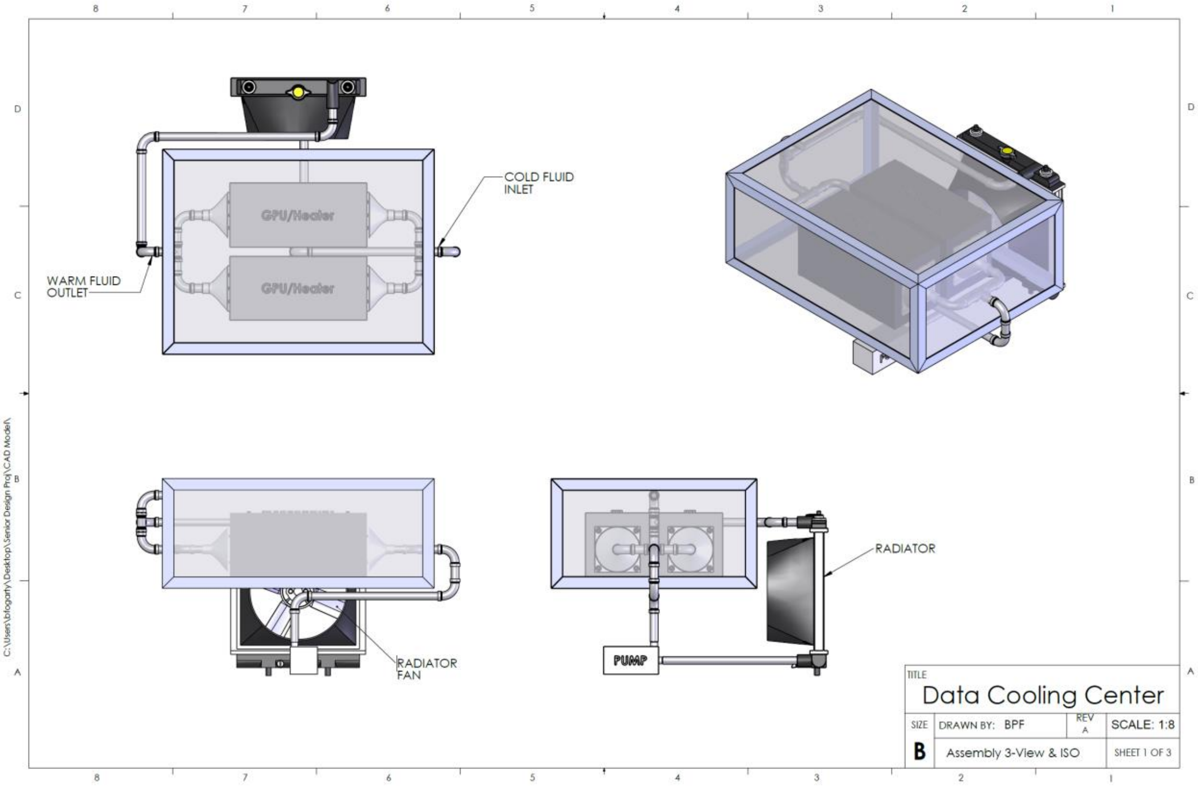
4.1 EMBODIMENT/ASSEMBLY DRAWING

4.1.1 Initial Rough Sketch

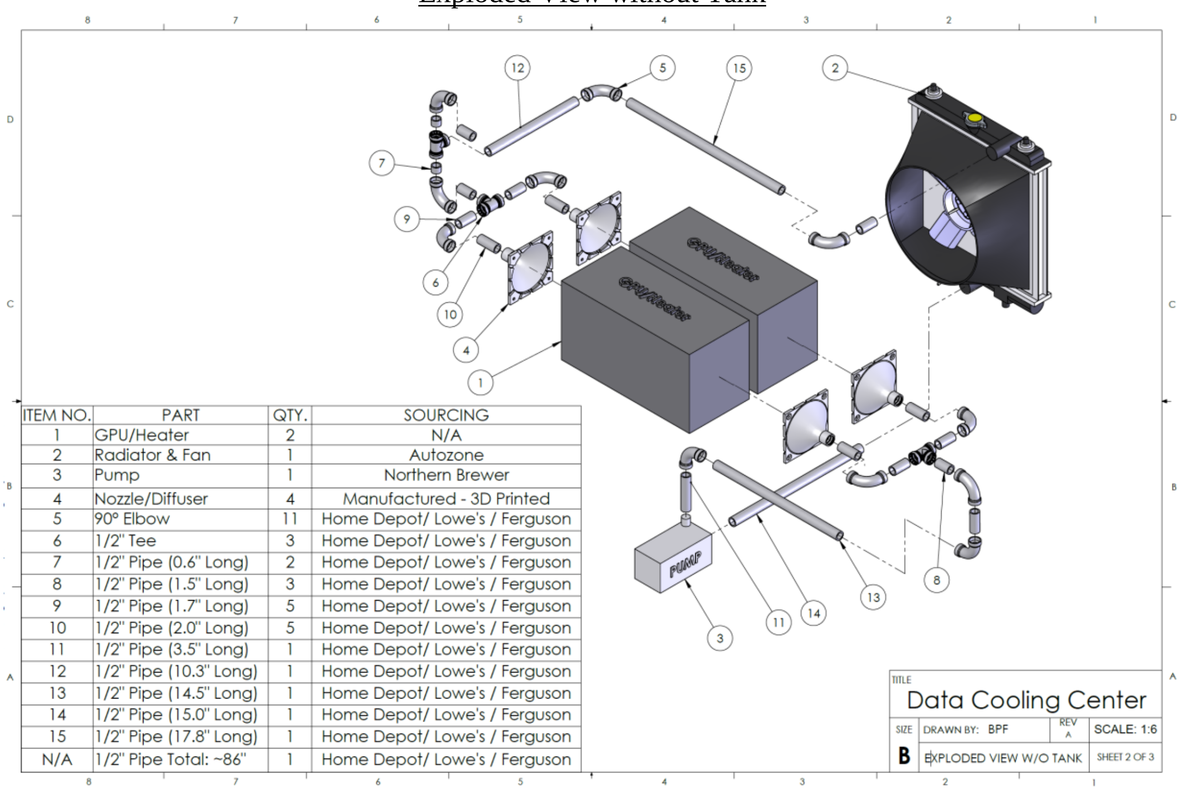


4.1.2 Initial CAD Drawings

Assembly 3-View & Isometric

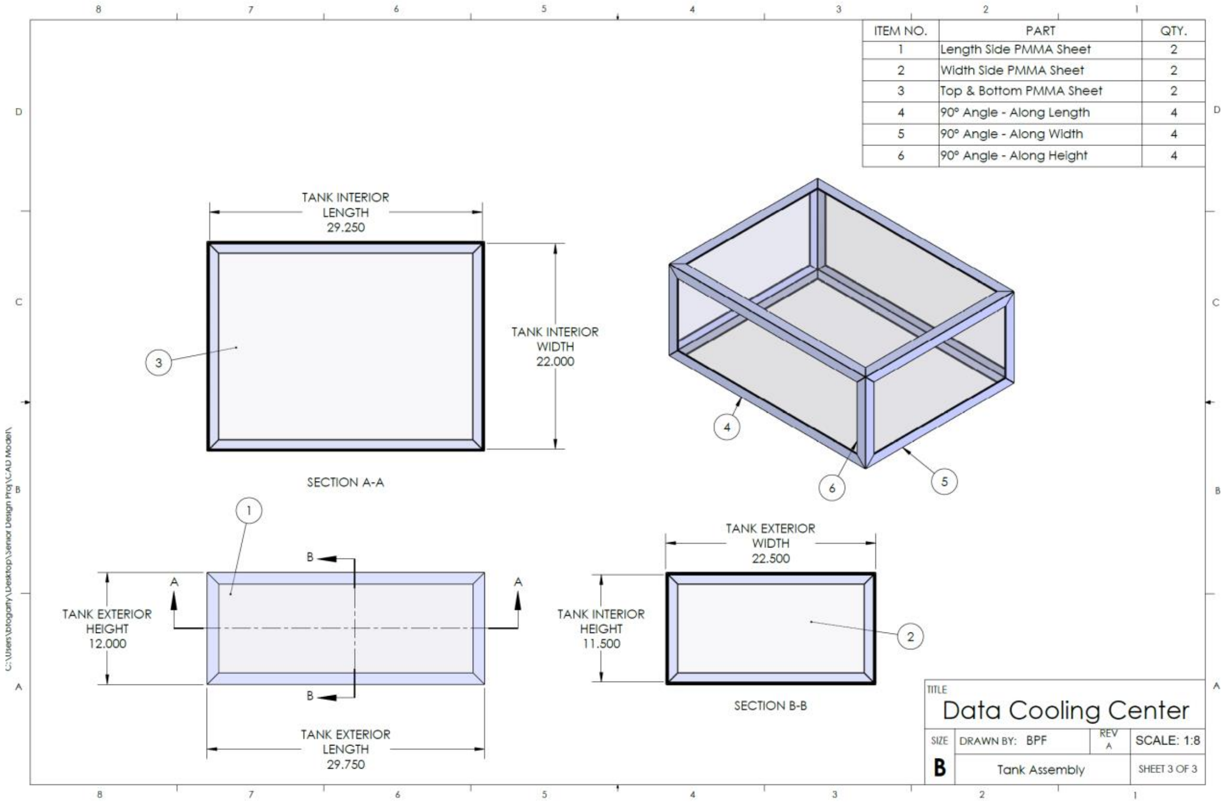


Exploded View without Tank



ITEM NO.	PART	QTY.	SOURCING
1	GPU/Heater	2	N/A
2	Radiator & Fan	1	Autozone
3	Pump	1	Northern Brewer
4	Nozzle/Diffuser	4	Manufactured - 3D Printed
5	90° Elbow	11	Home Depot/ Lowe's / Ferguson
6	1/2" Tee	3	Home Depot/ Lowe's / Ferguson
7	1/2" Pipe (0.6" Long)	2	Home Depot/ Lowe's / Ferguson
8	1/2" Pipe (1.5" Long)	3	Home Depot/ Lowe's / Ferguson
9	1/2" Pipe (1.7" Long)	5	Home Depot/ Lowe's / Ferguson
10	1/2" Pipe (2.0" Long)	5	Home Depot/ Lowe's / Ferguson
11	1/2" Pipe (3.5" Long)	1	Home Depot/ Lowe's / Ferguson
12	1/2" Pipe (10.3" Long)	1	Home Depot/ Lowe's / Ferguson
13	1/2" Pipe (14.5" Long)	1	Home Depot/ Lowe's / Ferguson
14	1/2" Pipe (15.0" Long)	1	Home Depot/ Lowe's / Ferguson
15	1/2" Pipe (17.8" Long)	1	Home Depot/ Lowe's / Ferguson
N/A	1/2" Pipe Total: ~86"	1	Home Depot/ Lowe's / Ferguson

<u>Tank Exploded View</u>



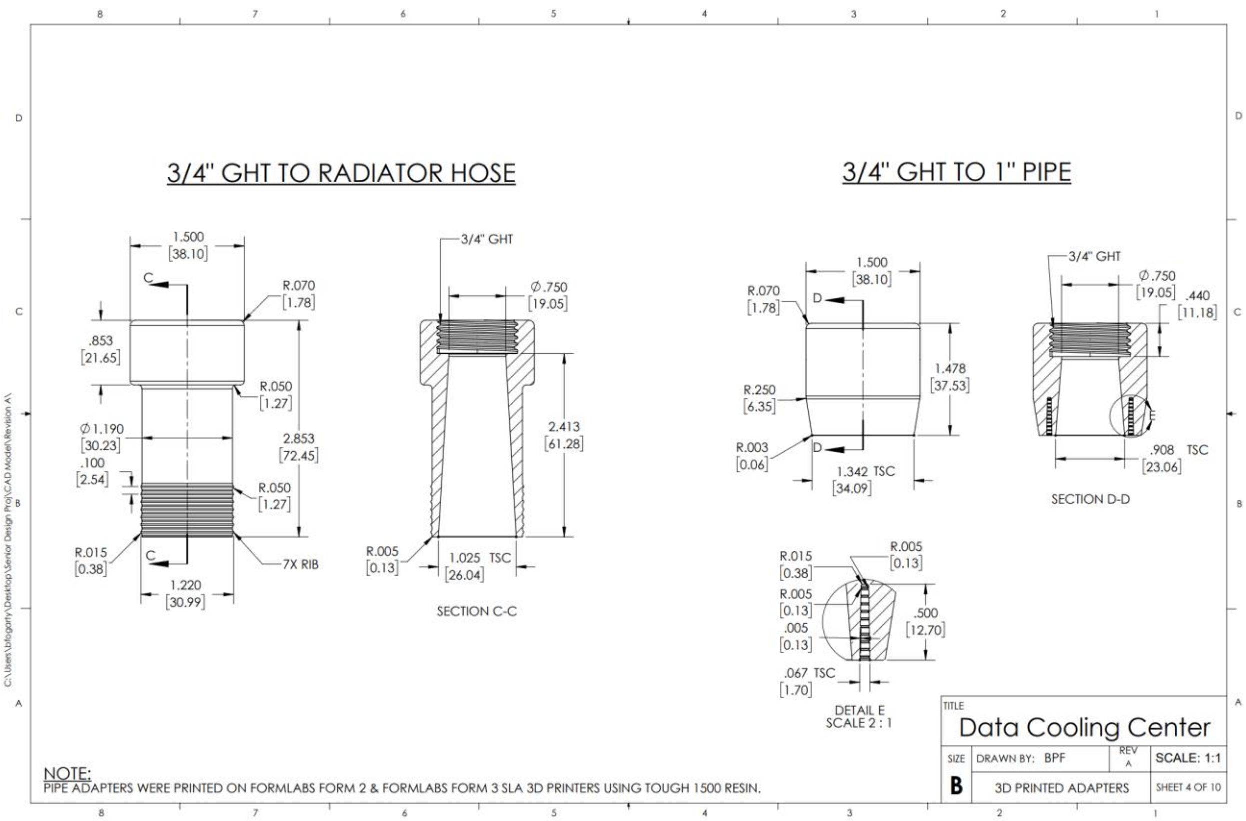
4.2 PARTS LIST

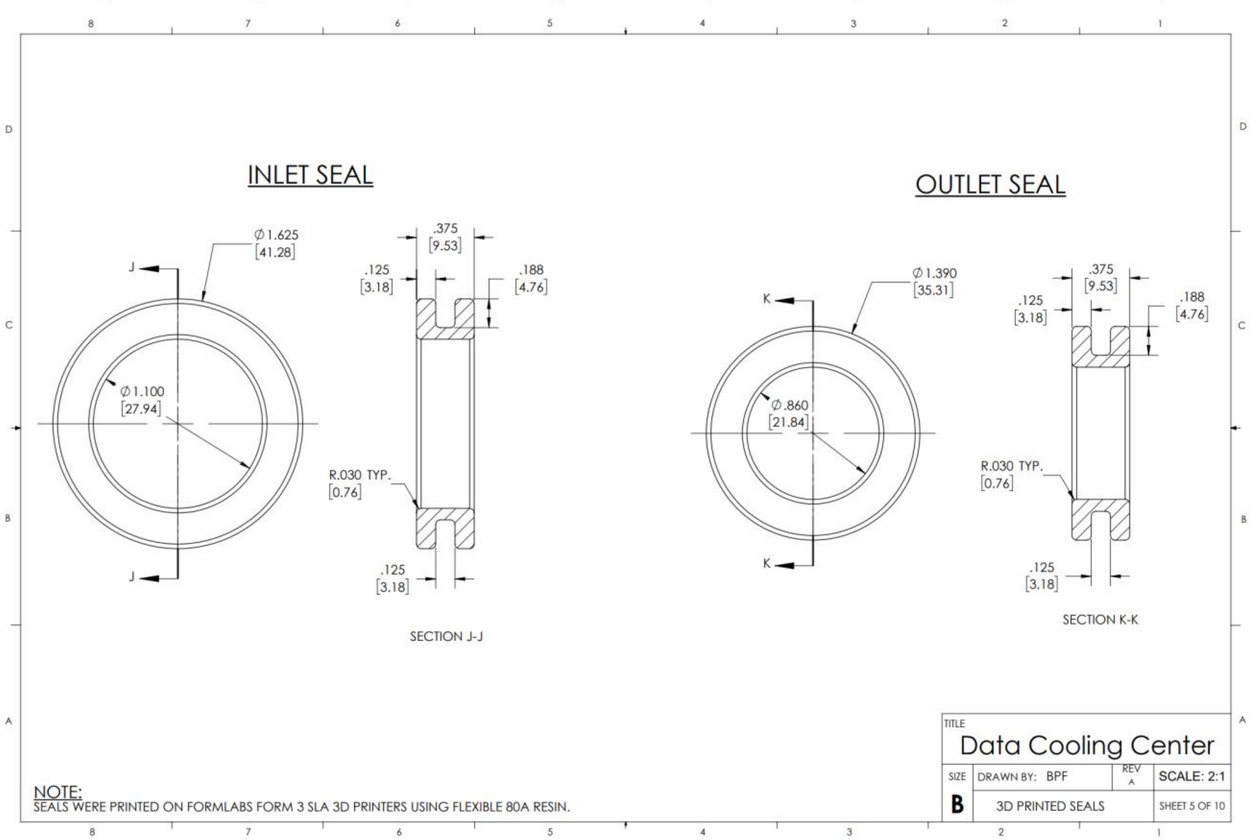
*The initial BOM with sourcing can be found in the above drawings. The final parts list is below and located in Appendix C.

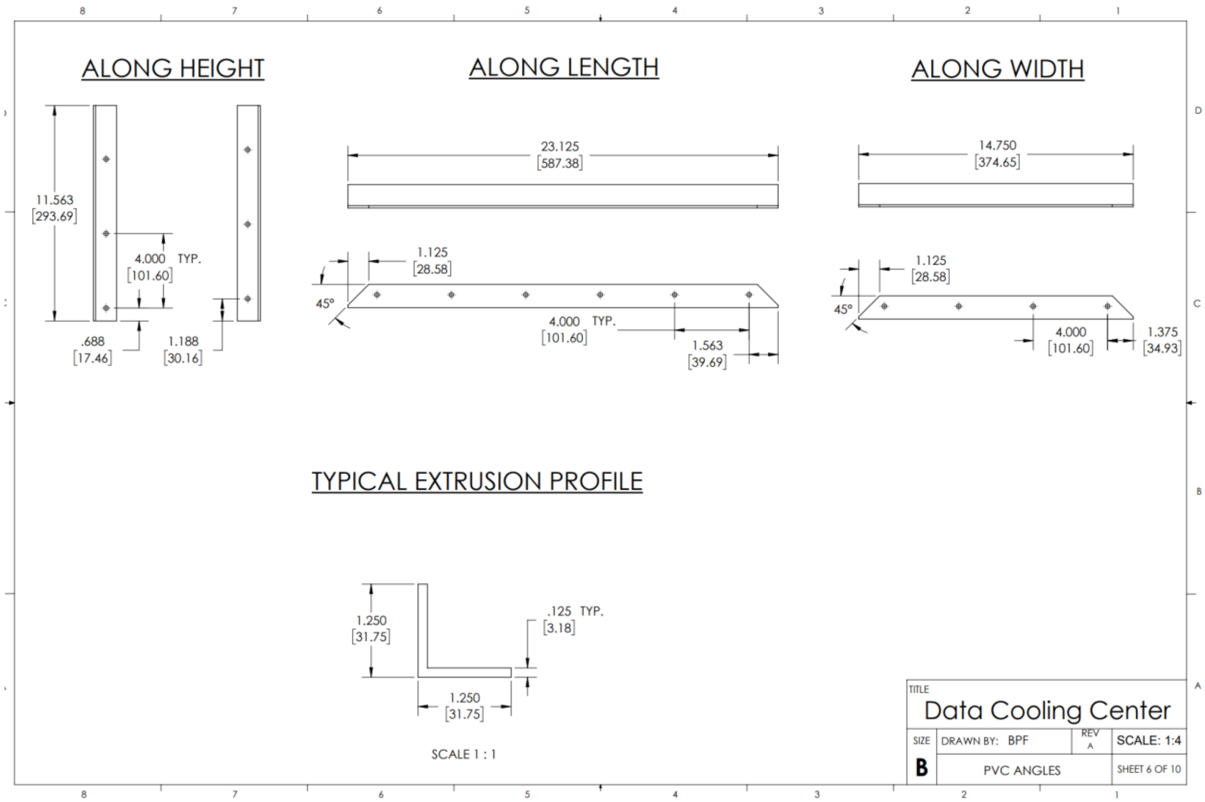
Item	Name	Quantity	Piece Cost	Total Cost	Website/Location & Hyperlink	Scrounged Description	Lead Time
1	Fan/Air Movers	2	$99.00	$198.00	Lowes		Over the counter (OTC)
2	Radiator	1	$125.70	$125.70	Advance Auto Parts		Over the counter (OTC)
3	3/4in | Copper Pipe | 5ft Long	1	$13.96	$13.96	Lowes		Over the counter (OTC)
4	Radiator Hose |Outlet	1	$9.95	$9.95	RockAuto.com		5 days
5	Radiator Hose | Inlet	1	$3.49	$3.49	RockAuto.com		5 days
6	Hose Clamps	4	$1.29	$5.16	Home Depot		Over the counter (OTC)
7	Tank Seal - Inlet	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin	~2 hours print time
8	Tank Seal -Outlet	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin	~2 hours print time
9	3/4" GHT to 1-1/4" Radiator Hose	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin	~5 hours print time
10	3/4" GHT to 1" Pipe	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin	~5 hours print time
11	1in | Copper Pipe | 5ft Long	1	$29.45	$29.45	Lowes		Over the counter (OTC)
12	Pump	1	$98.00	$98.00	Home Depot		Over the counter (OTC)
13	3/4in | 90° Elbow Copper Fitting	2	$10.98	$21.96	Lowes		Over the counter (OTC)
14	1in | 90° Elbow Copper Fitting	2	$17.98	$35.96	Lowes		Over the counter (OTC)
15	Heater | 1500 Watt	2	$43.99	$87.98	Amazon		Over the counter (OTC)

16	Strut Channel | 10 ft	1	$22.58	$22.58	Lowes		Over the counter (OTC)
17	GPUs	2	$-	$-	N/A		N/A
18	Tank Support Plank	1	$-	$-	Scrounged	Any material that can be scrounged to help support the bottom PMMA sheet will suffice.	N/A
19	Strapping	4	$-	$-	Scrounged	Any material that can be scrounged to help support the bottom PMMA sheet will suffice.	N/A
20	PMMA Sheet | 48" x 96" x 1/8"	1	$153.94	$153.94	McMaster-Carr		1 day
21	PVC 90° Angle | 1-1/4" x 1-1/4" x 1/8"	6	$12.62	$75.72	McMaster-Carr		1 day
22	18-8 Stainless Steel Hex Screw | 50 Pack	2	$8.28	$16.56	McMaster-Carr		1 day
23	18-8 Stainless Steel Hex Nut | 100 Pack	1	$3.85	$3.85	McMaster-Carr		1 day
24	Shipping & Sales Tax - McMasterCarr	1	$118.62	$118.62	McMaster-Carr		N/A
Total				**$1,020.88**			

4.3 DRAFT DETAIL DRAWINGS FOR EACH MANUFACTURED PART



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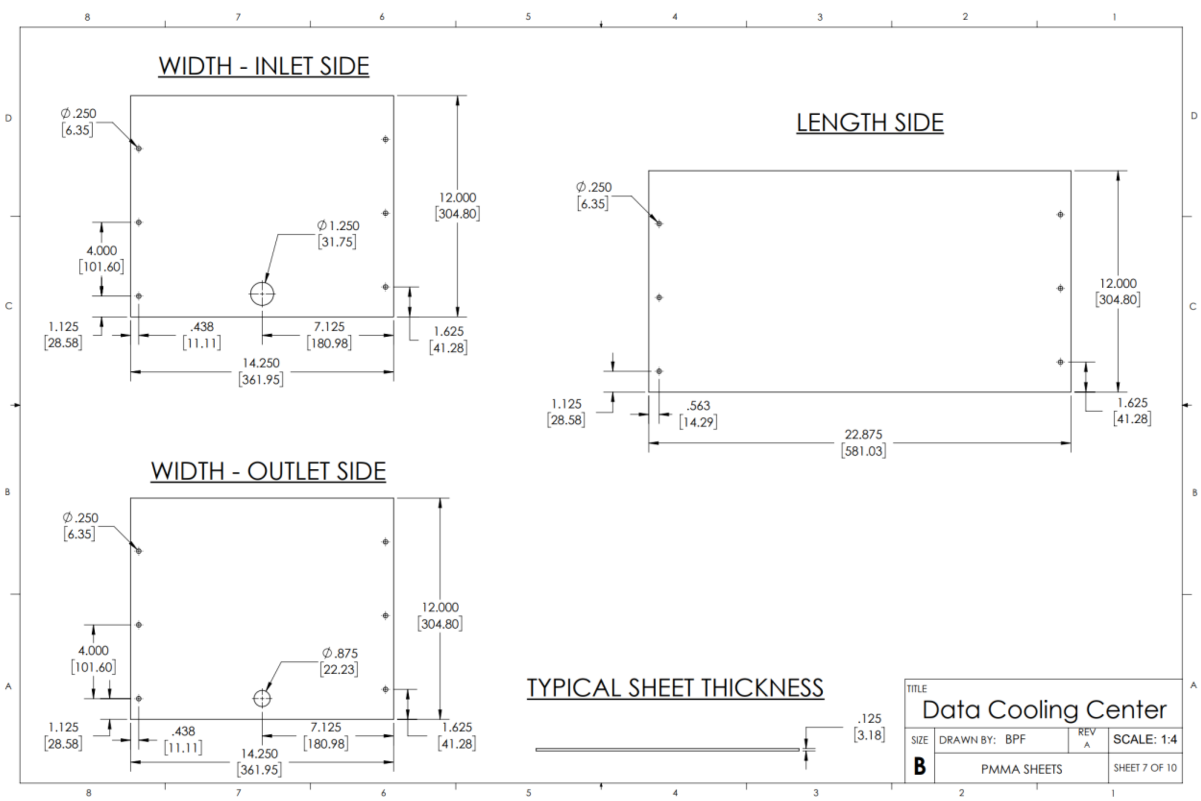
REV A
SCALE: 1:4
B
PVC ANGLES
SHEET 6 OF 10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Data Cooling Center
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REV A
SCALE: 1:4
B
PMMA SHEETS
SHEET 7 OF 10

4.4 DESCRIPTION OF THE DESIGN RATIONALE

The major design changes from initial to final involved the removal of branching of inlet and outlet pipes. This was done to simplify calculations, eliminate some of the possibility of error in calculations, and reduce the cost of additional fittings. Additionally, the 3D printed nozzle/diffuser parts that direct the flow through the GPUs were removed. This was done as the fluid was changed to water and the GPUs were simulated by two 1500W heaters. A more accurate representation of the pump and radiator were also modeled to show the physical parts purchased and more accurately reflect the size of the connecting fittings.

Some pipe dimensional changes were made due to the availability of scrounged fittings and parts for an intermediate build. Final parts were purchased unless explicitly stated.

5 ENGINEERING ANALYSIS

5.1 ENGINEERING ANALYSIS PROPOSAL

ANALYSIS TASKS AGREEMENT

PROJECT: Data Center NAMES: Brennan Fogarty INSTRUCTOR: Prof. Jakiela

Christopher Schmid

Suruchi Aryal

The following engineering analysis tasks will be performed:

1. **Analysis of heat transfer and flow rate**
2. **Pipe flow analysis**

The work will be divided among the group members in the following way:

1. **Christopher | CS**
2. **Christopher, Suruchi, and Brennan | CS, BF, SA**

Instructor signature: Craig J. Giesmann; Print instructor name: Craig Giesmann

Instructor signature: ________________; Print instructor name: Mark Jakiela

(Group members should initial near their name above.)

5.2 ENGINEERING ANALYSIS RESULTS

5.2.1 **Motivation**

We will be looking into the rate of heat transfer within the data center so that we can better calculate the amount of heat that is being moved from the fluid being heated by the working electronics to the surrounding environment. Along the same line of analysis and covered under heat transfer will be flow rate analysis. Both these analyses will carry the project forward as they deal exclusively with how heat will be transferred both within and through the system.

5.2.2 **Summary statement of analysis done**

The heat transfer rate for what the user needed was 3000 watts. So in order to find the heat transfer rates' minimum the experiment included calculations to determine the minimum mass flow rate of both fluid and air. Lastly for engineering analysis of the pipe flow the group will be looking at how the fluid moves through the system via the pipe and how this can contribute to major and minor flow losses.

5.2.3 **Methodology**

The analysis of heat transfer and flow rate was done using thermodynamic formulas for q and mass flow rate. The analysis of pipe flow was done using fluid dynamic formulas such as Darcy-Weisback formula, Reynolds number formula and summing major and minor losses. Please refer to the calculations for reference on formulas and to review calculations.

5.2.4 **Results**

5.2.4.1 The flow rate depends entirely on radiator size/efficiency; our flow needs to be 2 CFM of air and 0.2 GPM fluid thru pipes. *Apply specific heat changes for dielectric fluids*.

5.2.4.2 Head pressure was 14.24 ft of head loss. *Apply viscosity changes to account for the dielectric fluid pump needed.*

5.2.4.3 Conclusion: The radiator determines the bulk of calculations and the engineer should design around the radiator's limitations and strengths.

5.2.5 **Significance**

The results have influenced the final prototype in the materials we need to use. For the heat transfer we will need a motor strong enough to move the fluid more than 2 gallons a minute. And the significance of the pipe will be crucial in finding a pump large enough to overcome the head pressure caused by the small, planned diameter of the pipe, causing the pipe diameter to increase to lower head pressure.

6 RISK ASSESMENT

6.1 RISK IDENTIFICATION

6.1.1 Traveling

6.1.2 Equipment Safety

6.1.3 Environmental

6.1.4 Horse Play

6.1.5 Lifting and Rigging

6.1.6 Weather

6.1.7 Electrical Safety

6.2 RISK ANALYSIS

Risk Management Register

0	Open Red Risks
0	Open Yellow Risks
1	Open Green Risks
0	Risks w/ no Response Strategy
2	Closed risks

Project Name: Data Center cooling
Project Manager: Brennan Fogarty
Start Date: 6/14/2021
Location: St. Louis
Add'l Info:
Updated On:
Overall Project Risk Indicator: 8

Risk Level

Probability					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
Impact	1	2	3	4	5

Legend:
Impact
1 - Negligible
2 - Marginal
3 - Significant
4 - Critical
5 - Catastrophic

Probability
1 - Rare
2 - Unlikely
3 - Possible
4 - Likely
5 - Certain

Item	Project/ Phase	Risk Status	Risk	Potential Impact (Cause and Effect)	Risk Response Strategy	Triggers (indicators that the risk will occur)
0			Short Term Holding			
1		open	Schedule	there will be times when team members couldnot make it to work related to various personal issues	communicate well and work on days that works for everyone and also divide work so that everyone contribute equally	time constraints to finish the project and unavoidable circumstances of the team.
2		closed	Equipment Safety	not properly made cooling device without following proper safety features and also maintaining the standards	only prototype has to be made and team is following safety features.	not properly planned work.
3		accepted	Environmental	conflict within team members , injuries, lack of input from team members	safety measures should be applied, conflict management techniques should be applied, good communication with team members and equaldivision of work load	lack of proper communication and unequal work load.
4		Closed	Horse Play	Students playing at a time where a chain reaction of accididents can lead to injury or death	Students will be educated and trained to not play or wear imporper clothing during lab experiments	not properly discussingand planning the work within team members.
6		Accepted	Lifting and Rigging	Lifting heavy objects could injure a worker through improper form or dropping material	Teach proper lifting techniques and use two people to carry heavy objects	loud banging and people yelling.
5		Accepted	Weather	It could cause slower and less attenative work while also dehydrating workers	Stay hydrated and ensure that proper breaks are added to the work schedule	extreme weather swings to hot or cold as well as layered clothing
7		open	Electrical Safety	some accident due to electrical component or chemical burns or any cuts or injuries	properly following the safety standards and in safe working area	distractions during work and not properly planning the work

									Baseline Risk Scoring							Current Risk Score							
									Impact							Impact							
Item	Estimated Schedule Impact (Days)	Maximum Exposure ($000)	Estimated Exposure (Contingency) ($000) $61	Risk Category	Risk Sub Category	Action Owner	Start Exposure	End Exposure	Tech Perf	Schedule	Cost	Safety	Probability	Risk Ranking		Tech Perf	Schedule	Cost	Safety	Probability	Risk Ranking	$%	
0			$0																	1	0	0%	0.00
1		$52	$1	Schedule						1			5	5			5			1	5	2%	0.11
2		$126	$3	Performance						1			5	5			4	3		1	4	5%	0.21
3		$200	$5	Operational Impact						2			3	6			4	2		1	4	8%	0.33
4		$50	$5	Financial/Regulatory						5			5	25			5	5		2	10	9%	0.86
6		$200	$21	Schedule						1			5	5			3	5		2	10	35%	3.46
5		$500	$13	Schedule								5	5	25			5			1	5	21%	1.03
7		$500	$13	Operational Impact															5	1	5	21%	1.03

6.3 RISK PRIORITIZATION :

As group members, what was discussed was the possible risks that could occur during our project. Also, as future engineers, we thought that safety should be the main risk and should be taken seriously. For that, we were cautious while handling chemicals and using electrical equipment. Also, following the codes and standards needed for the prototype.

7 CODES AND STANDARDS

7.1 IDENTIFICATION

It is a regionally adoptable standard for the safe installation of electrical wiring and equipment in the United States. It is part of the National Fire Code series. As we deal with wirings that is the reason we chose this code. It requires users to apply a permanent label to all service equipment rated 1,200 amps or higher.

7.2 JUSTIFICATION

This is significant to the group as we use these standards and codes because we are dealing with electrical equipment and also it is very necessary to conserve energy and follow precautions with using any form of energy. Though we are just building the prototype all the constraints like the power of the load and building space are hard to apply on our project. However, we tried to limit the maximum power in our prototype to be 3kw which is under 100kw. Moreover, this helps us build a safe device.

7.3 DESIGN CONSTRAINTS:

Location of the prototype was a major constraint when planning for this project. The system the way the user described required a lot of electricity that would need specially trained re-wiring. In addition, we in the group were spread across MO and IL and we were all performing this experiment during another covid outbreak which limited any in person contact. This influenced who had and made modifications to the design. Electrical safety was another main constraint we had to face for this project, as we were dealing with high energy electrical equipment but needed to use power tools to construct our prototype. The final constraint to be discussed in this review is that of resources. We had to buy components of major end items and fabricate them ourselves. An example would be the tank that was made for the prototype or the copper pipes that we used because they belonged to the program where other pipes may have been better to used due to adiabatic responses.

7.3.1 Functional

For the functional design the constraint that we had to work within was to cool through a process that is normally considered a pre-cooling process in HVAC. The best way to cool electronics is using a heat pump but it's not efficient. Resources led to a redesign to only cool using a radiator and a fan.

7.3.2 Safety

For the design constraints as it pertains to safety the constraint that most concerned the group was the use of multiple 220VAC wires for each data center. This constraint made us change our design to simulate the electronics using heaters. Also since we could not get dielectric fluid in time we needed to use water and no electricity in the fluid.

7.3.3 Quality

The constraint when it came to quality is the same constraint that most engineers have in that there are never quite enough resources to do everything you design. Whether it be material or time the quality suffered from lack of resources and time.

7.3.4 **Manufacturing**

The manufacturing design constraint that the group fell under was that of a design that could be scaled up to a larger size and number. That made the design more modular so that it could be moved, enlarged or modified for future use.

7.3.5 **Timing**

The time constraint was the worst one during this experiment due to the fact that we all had other projects that needed our work along with the work for the design. This put a real strain on the project more than most constraints.

7.3.6 **Economic**

The economic constraint was such that we knew any money we spent on this project would likely be used and not reimbursed. This has led to less quality on the prototype.

7.3.7 **Ergonomic**

The ergonomic constraint was that the project would be a tank that was filled with liquid. Making the project a heavy carry when it was time to work on it or move it. This led to the design being plastic and steel reinforced with the option of adding handles to future versions.

7.3.8 **Ecological**

The ecological constraints were that we used items that should not be thrown away in nature. Whether it was waste from the design or the design's product life cycle the group wanted to make the project as recyclable as possible.

7.3.9 **Aesthetic**

The design constraints that the group suffered from was letting people see the design work in real time. In that sense the group member Brennan insisted that we build a tank from scratch out of acrylic that allowed the project to be seen in action.

7.3.10 **Life Cycle**

Pertaining to the life cycle constraint the most important thing was the dielectric fluid. In that the lifecycle of the system relied entirely on fluid moving through the system to cool it. The fluid and the pump are the lifecycle that should be reviewed. If the fluid only lasts 3 months then that's the life cycle before return on investment has reached its conclusion as that is one of the most expensive costs to replace. The pump is cheap and replaceable and holes in the system can be patched.

7.3.11 **Legal**

Legal constraints are what to do with the waste heat and to make it as safe as possible to prevent further engineering disasters that can result in displaced resources.

7.4 SIGNIFIGANCE

7.4.1 **Effects on the Group**

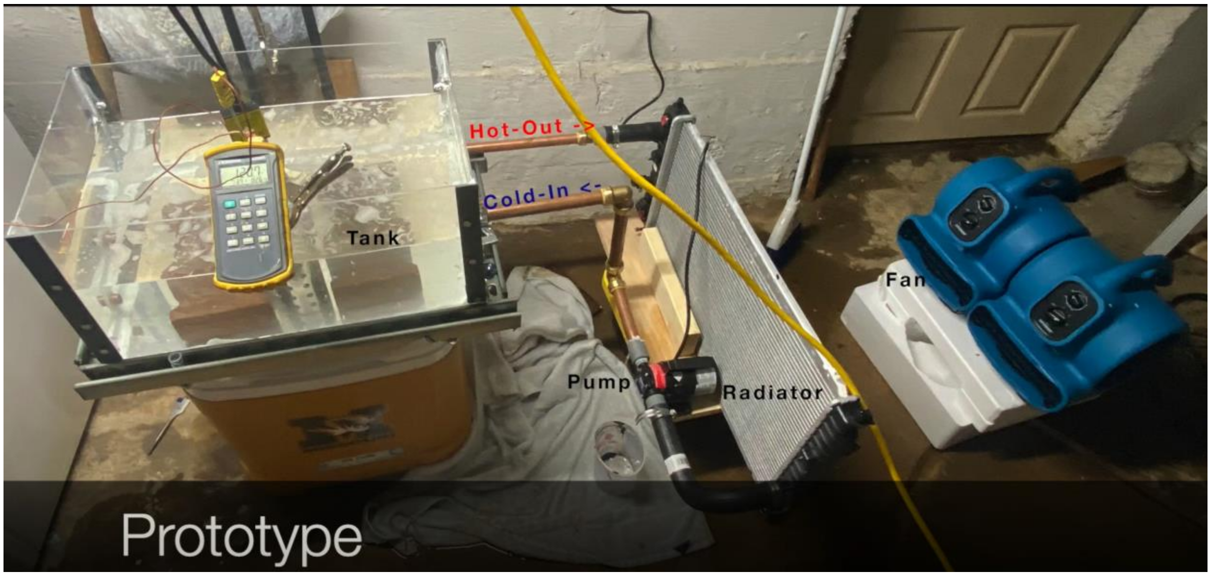
In the future when the prototype begins to serve the heat transfer of the actual data center there will need to be proper labeling of the equipment and it will have to be installed and inspected by a licensed electrician. During that inspection the electrician will respond to all the legal regulations and to assist the protype will have a shut-off breaker that is able to be locked out so as to perform maintenance on the system. It will also be located away from spaces that will need to be conditioned and the exhaust will go by the guidance laid out by ASHARE.

The design constraints have had the affect on delaying production of the prototype due to all the happiness factors that need to be met.

8 WORKING PROTOYPE

8.1 PROTOTPYE PHOTOS

FRONT VIEW



In this photograph, the tank is shown on the left side of the picture. Inside the tank are two 1500W heaters which simulate the GPUs, or data miners. The pipe exiting the tank on the left side is the hot fluid outlet. It goes around the backside of the tank and then enters the top left side of the radiator, cooling the fluid slightly along the pipe's length. The fluid then flows through the radiator where the two fans blow cool air over the radiator fins. The fluid receives the majority of its cooling while flowing through the radiator. The heat is expelled into the environment surrounding the radiator. The cooled fluid exits the bottom right side of the radiator where it flows through an EPDM hose into the pump. Note the system behaves as a closed system. So, the pump simultaneously pulls the hot fluid through outlet pipe and radiator while pushing the cooled fluid from the radiator through the cooled inlet pipe back into the tank.

SIDE VIEW

In this photograph, the system is shown from the hot water outlet side of the tank. The two heaters can be seen in the center of the tank. Also the temperature monitoring device is shown clamped to the tank (right side of the photo). The radiator is shown in the background along with the two fans assisting in heat transfer through forced convection.

8.2 WORKING PROTOTYPE VIDEO

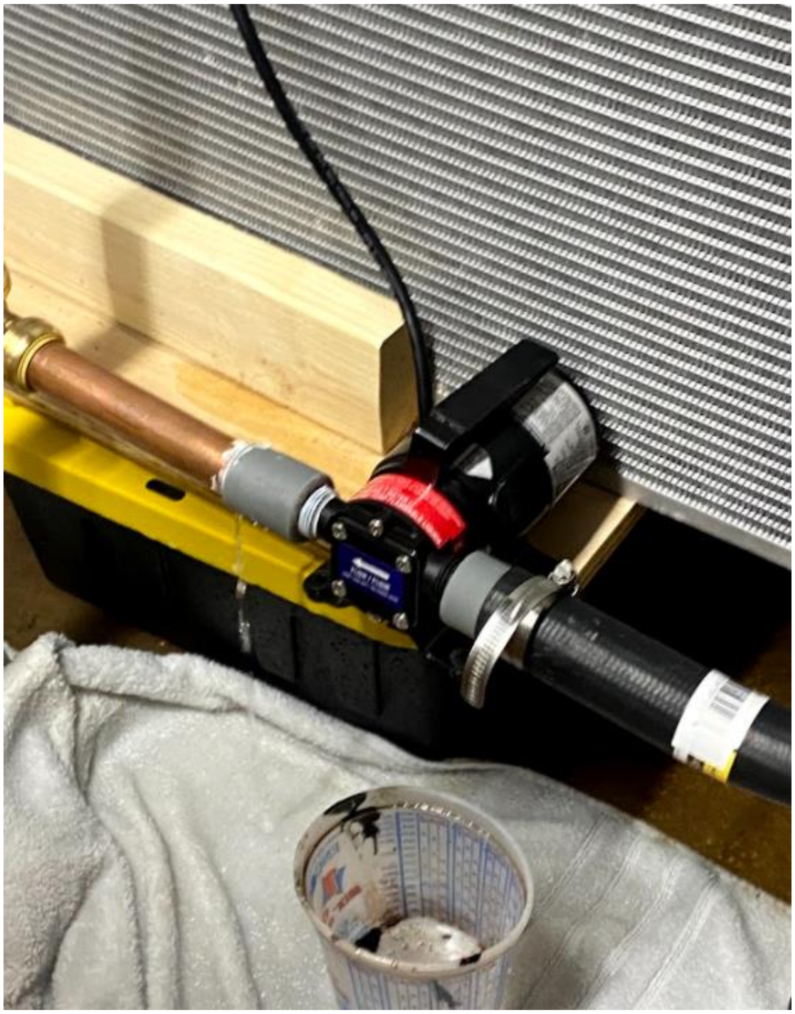
The main performance measure of our system was the change in temperature and the ability to maintain a temperature below 90°C or 194°F. This performance measure was chosen as the maximum safe operating temperature of the data mining equipment considered for our project is 90°C. The two 1500W heaters shown are assumed to be equivalent to the two 1500W GPUs in terms of heat production.

Video Link: https://youtu.be/RBM4eUkn_IY

Note: The video shows some leakage at some pipe unions. This is due to the inability to source fittings in the condensed time frame. As a substitute, 3D printed SLA fittings were created which did not seal completely. The minor leakage resulting from these components did not appear to significantly affect the heat transfer observed or inhibit the group from achieving success on the main performance measure.

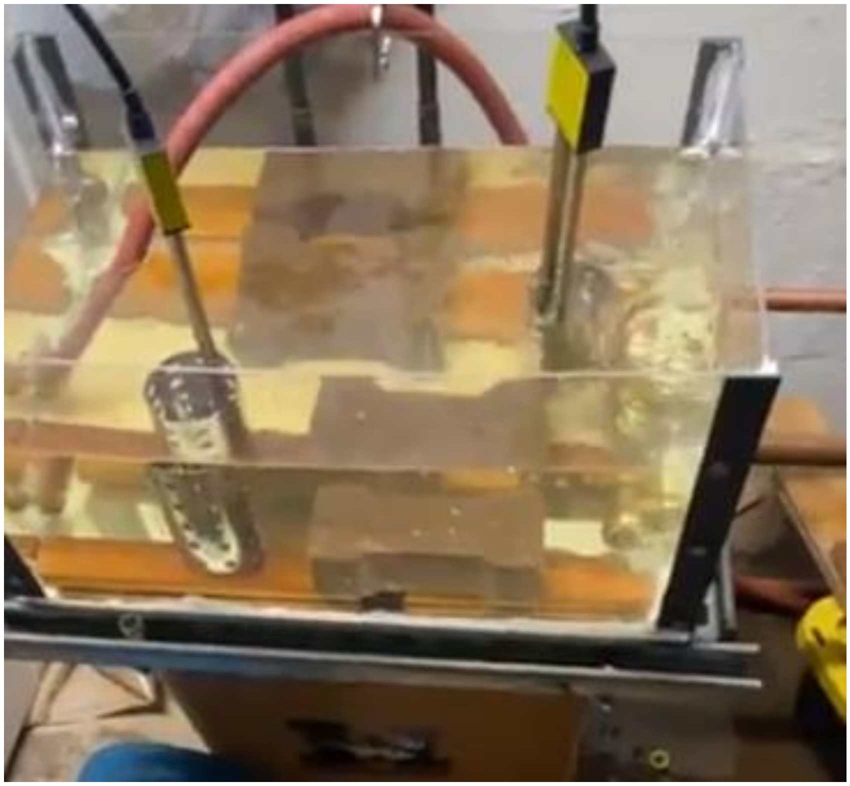
8.3 PROTOTYPE COMPONENTS

PUMP JOINTS



In this photograph, the pump joints are shown. This joint was responsible for most of the leakage in the system. The joint is composed of a 1 ¼” EDPM hose coming from the radiator into a 3D printed SLA 1 ¼” to ¾” GHT adapter with a 3D printed rubber like gasket on the inside. The pump inlet side did not have any leakage at this joint. The pump outlet side, however, did have a moderate amount of leakage. It consisted of a 3D printed SLA ¾” GHT to 1” pipe adapter. On the 1” side the adapter had a slot for which the pipe was meant to slide into then be caulked to seal. Unfortunately this seal did not hold. However, the overall performance of the system was still able to be observed.

TANK



In this photograph, the tank is shown. The tank is responsible for holding the primary heat transfer medium, the fluid. In the prototype demonstration, the fluid used was water. As a result, the GPUs were simulated with the two 1500W heaters that can also be seen in the above photo.

AIR FLOW

Photograph number 3 showcases the two ¼ HP 925 CFM fans used to enable the heat transfer method of forced convection between the cool air and heated radiator fins. It should be noted that during the prototype testing the ambient air temperature of the room was also monitored and seen to have increased by nearly ten degrees. This is a good indication that a secondary application for data cooling could also include the heating of a room or rooms with the expelled heat from the system.

RADIATOR CLOSE-UP

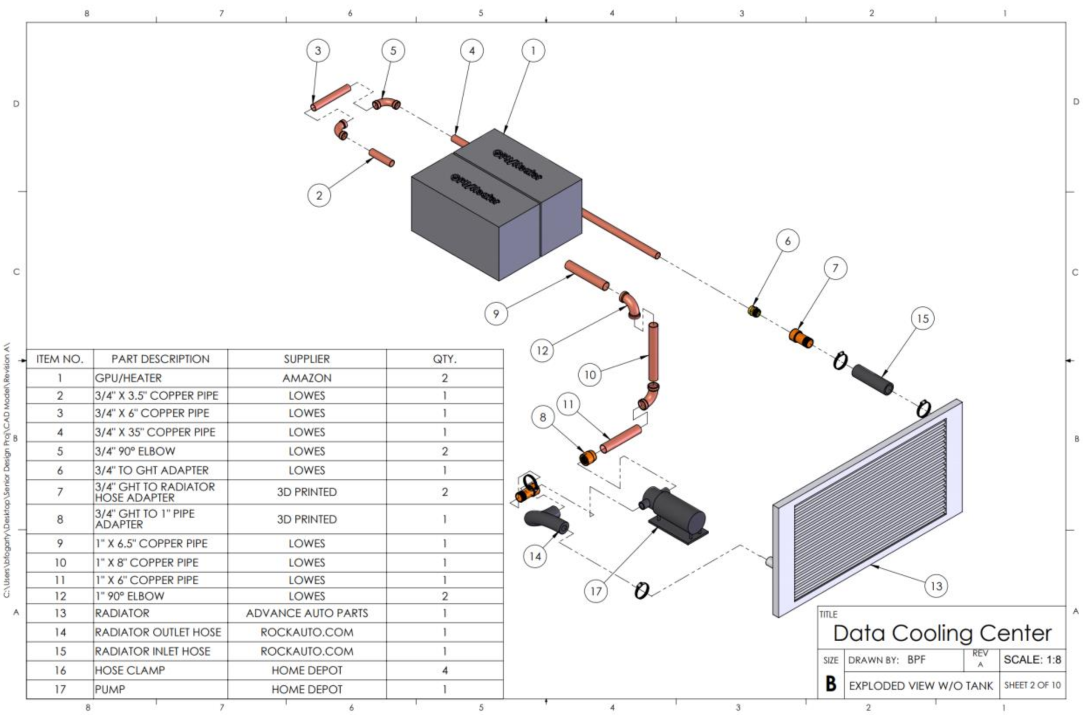
The final photograph shows a closer image of the radiator and the inlet and outlet pipes. The two EPDM hoses entering and leaving it can be seen to have hose locks where necessary. Additionally, a secondary port that could be used for draining or recycling cool water can be seen about halfway up the left side of the radiator. It too has a hose lock ensuring leakage will not occur.

9 DESIGN DOCUMENTATION

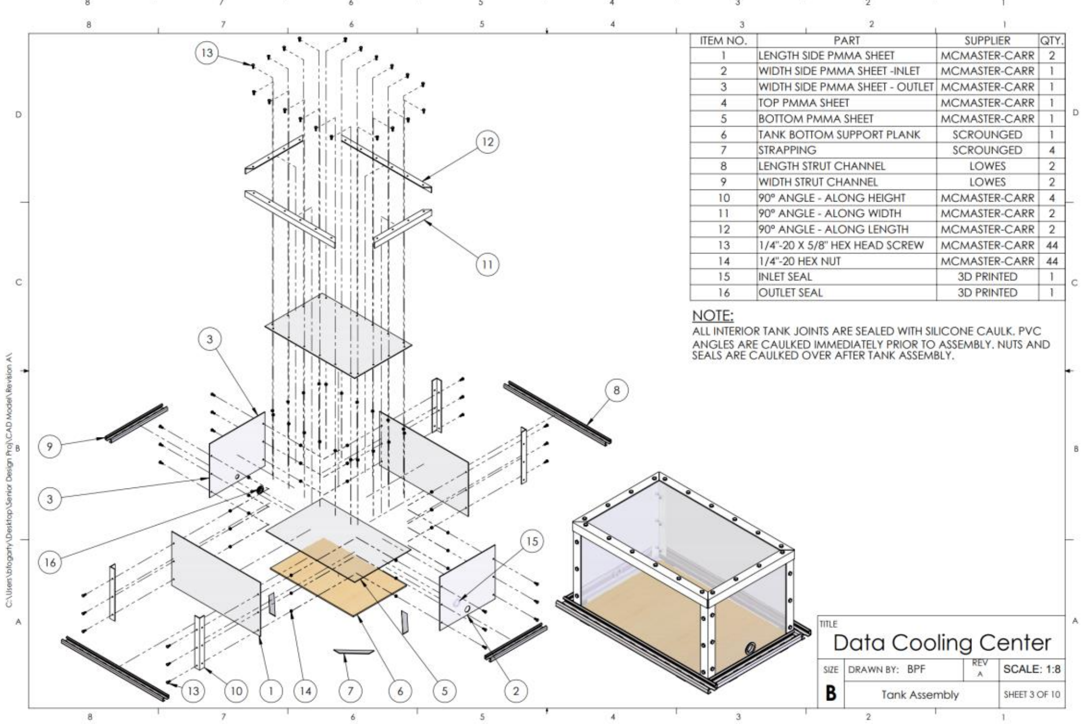
9.1 FINAL DRAWINGS AND DOCUMENTATION

9.1.1 Engineering Drawings

See Appendix A for the complete drawings.



ITEM NO.	PART DESCRIPTION	SUPPLIER	QTY.
1	GPU/HEATER	AMAZON	2
2	3/4" X 3.5" COPPER PIPE	LOWES	1
3	3/4" X 6" COPPER PIPE	LOWES	1
4	3/4" X 35" COPPER PIPE	LOWES	1
5	3/4" 90° ELBOW	LOWES	2
6	3/4" TO GHT ADAPTER	LOWES	1
7	3/4" GHT TO RADIATOR HOSE ADAPTER	3D PRINTED	2
8	3/4" GHT TO 1" PIPE ADAPTER	3D PRINTED	1
9	1" X 6.5" COPPER PIPE	LOWES	1
10	1" X 8" COPPER PIPE	LOWES	1
11	1" X 6" COPPER PIPE	LOWES	1
12	1" 90° ELBOW	LOWES	2
13	RADIATOR	ADVANCE AUTO PARTS	1
14	RADIATOR OUTLET HOSE	ROCKAUTO.COM	1
15	RADIATOR INLET HOSE	ROCKAUTO.COM	1
16	HOSE CLAMP	HOME DEPOT	4
17	PUMP	HOME DEPOT	1



ITEM NO.	PART	SUPPLIER	QTY.
1	LENGTH SIDE PMMA SHEET	MCMASTER-CARR	2
2	WIDTH SIDE PMMA SHEET -INLET	MCMASTER-CARR	1
3	WIDTH SIDE PMMA SHEET - OUTLET	MCMASTER-CARR	1
4	TOP PMMA SHEET	MCMASTER-CARR	1
5	BOTTOM PMMA SHEET	MCMASTER-CARR	1
6	TANK BOTTOM SUPPORT PLANK	SCROUNGED	1
7	STRAPPING	SCROUNGED	4
8	LENGTH STRUT CHANNEL	LOWES	2
9	WIDTH STRUT CHANNEL	LOWES	2
10	90° ANGLE - ALONG HEIGHT	MCMASTER-CARR	4
11	90° ANGLE - ALONG WIDTH	MCMASTER-CARR	2
12	90° ANGLE - ALONG LENGTH	MCMASTER-CARR	2
13	1/4"-20 X 5/8" HEX HEAD SCREW	MCMASTER-CARR	44
14	1/4"-20 HEX NUT	MCMASTER-CARR	44
15	INLET SEAL	3D PRINTED	1
16	OUTLET SEAL	3D PRINTED	1

9.1.2 **Sourcing instructions**

Item	Name	Quantity	Piece Cost	Total Cost	Website/Location & Hyperlink	Scrounged Description
1	Fan/Air Movers	2	$99.00	$198.00	Lowes	
2	Radiator	1	$125.70	$125.70	Advance Auto Parts	
3	3/4in | Copper Pipe | 5ft Long	1	$13.96	$13.96	Lowes	
4	Radiator Hose | Outlet	1	$9.95	$9.95	RockAuto.com	
5	Radiator Hose | Inlet	1	$3.49	$3.49	RockAuto.com	
6	Hose Clamps	4	$1.29	$5.16	Home Depot	
7	Tank Seal - Inlet	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin
8	Tank Seal -Outlet	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin
9	3/4" GHT to 1-1/4" Radiator Hose	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin
10	3/4" GHT to 1" Pipe	1	$-	$-	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin
11	1in | Copper Pipe | 5ft Long	1	$29.45	$29.45	Lowes	
12	Pump	1	$98.00	$98.00	Home Depot	
13	3/4in | 90° Elbow Copper Fitting	2	$10.98	$21.96	Lowes	
14	1in | 90° Elbow Copper Fitting	2	$17.98	$35.96	Lowes	
15	Heater | 1500 Watt	2	$43.99	$87.98	Amazon	
16	Strut Channel | 10 ft	1	$22.58	$22.58	Lowes	
17	GPUs	2	$-	$-	N/A	
18	Tank Support Plank	1	$-	$-	Scrounged	Any material that can be scrounged to help

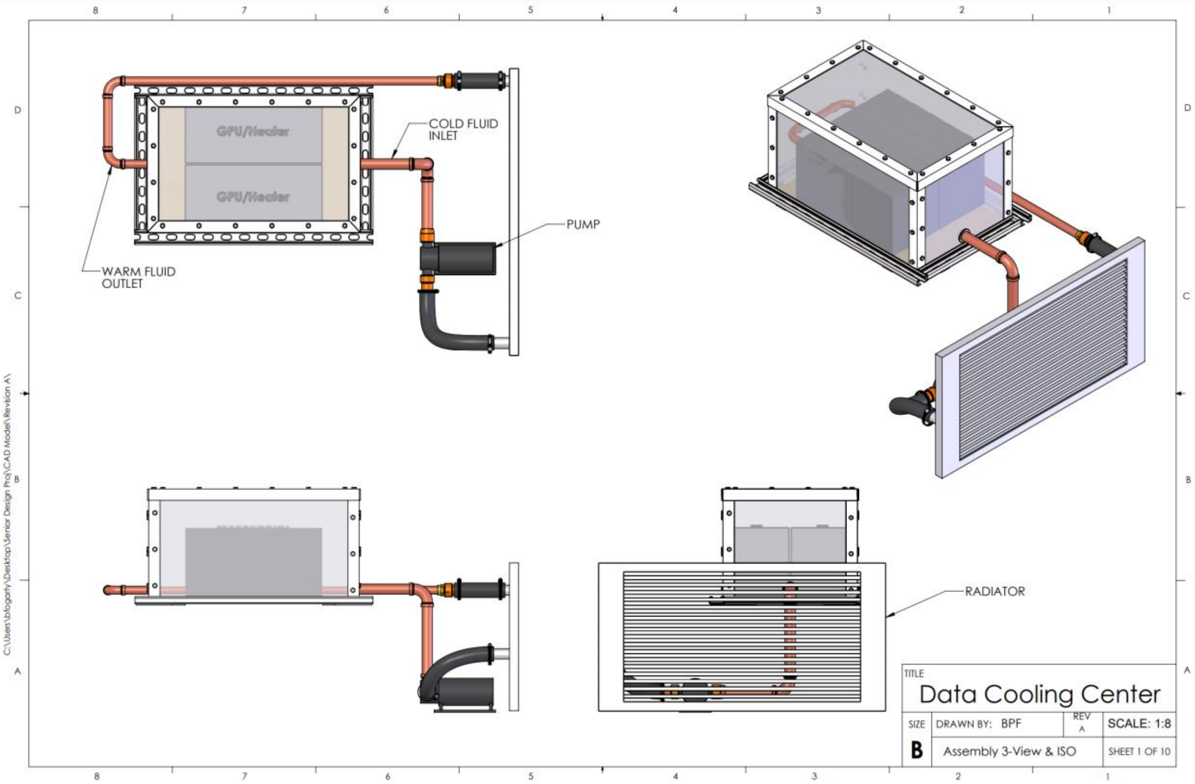
						support the bottom PMMA sheet will suffice.
19	Strapping	4	$-	$-	Scrounged	Any material that can be scrounged to help support the bottom PMMA sheet will suffice.
20	PMMA Sheet | 48" x 96" x 1/8"	1	$153.94	$153.94	McMaster-Carr	
21	PVC 90° Angle | 1-1/4" x 1-1/4" x 1/8"	6	$12.62	$75.72	McMaster-Carr	
22	18-8 Stainless Steel Hex Screw | 50 Pack	2	$8.28	$16.56	McMaster-Carr	
23	18-8 Stainless Steel Hex Nut | 100 Pack	1	$3.85	$3.85	McMaster-Carr	
24	Shipping & Sales Tax - McMasterCarr	1	$118.62	$118.62	McMaster-Carr	
Total				**$1,020.88**		

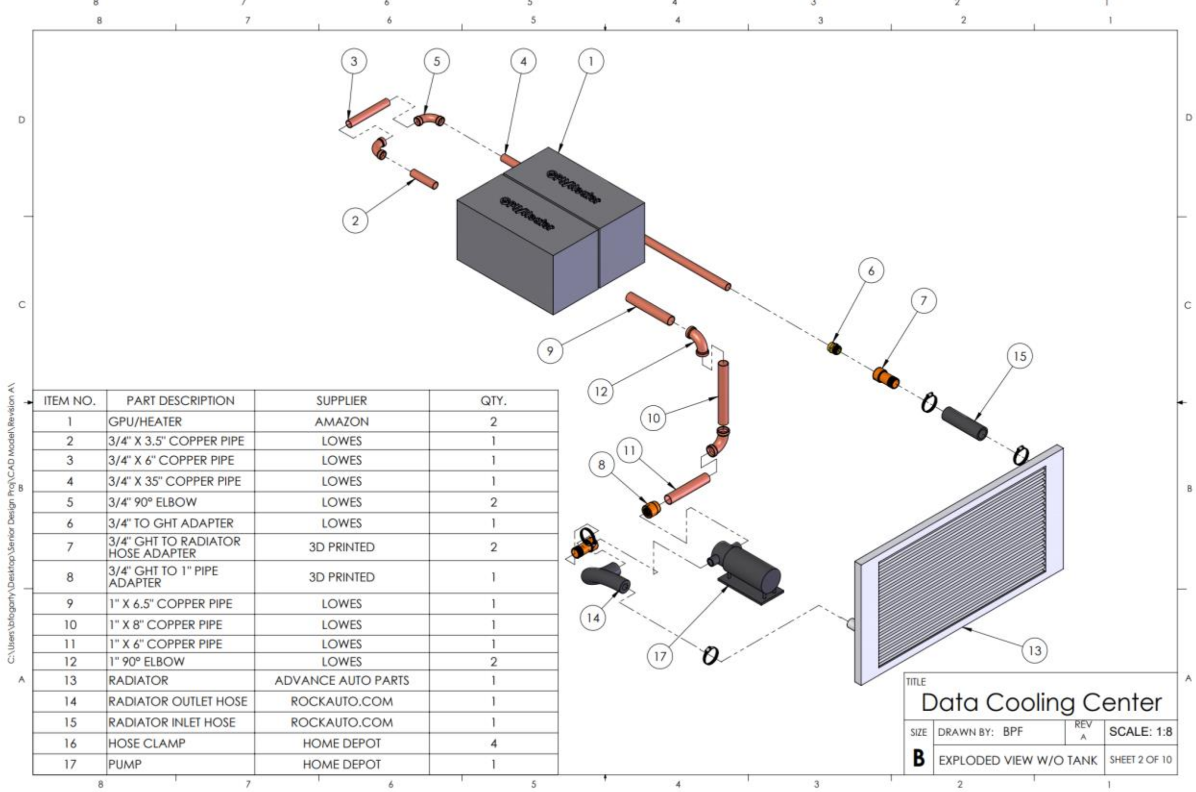
9.2 FINAL PRESENTATION

File Locations of CAD drawings, videos and PPT: https://gowustl-my.sharepoint.com/personal/bpfogarty_wustl_edu/_layouts/15/onedrive.aspx?id=%2Fpersonal%2Fbpfogarty%5Fwustl%5Fedu%2FDocuments%2FSenior%20Design%2FPublic%20Share&ct=1629167812873&or=OWA%2DNT&cid=f01f2cfa%2De685%2D25d6%2D69a3%2Da9a1d72c55d6&originalPath=aHR0cHM6Ly9nb3d1c3RsLW15LnNoYXJlcG9pbnQuY29tLzpmOi9nL3BlcnNvbmFsL2JwZm9nYXJ0eV93dXN0bF9lZHUvRXFacmJuVDEtYzlDb2pUVlVkM1F6SDhaDVLYkxoS2pISG1xVHYwUkRXRXg1Zz9ydGltZT1OdTlaNENkaDJVZw

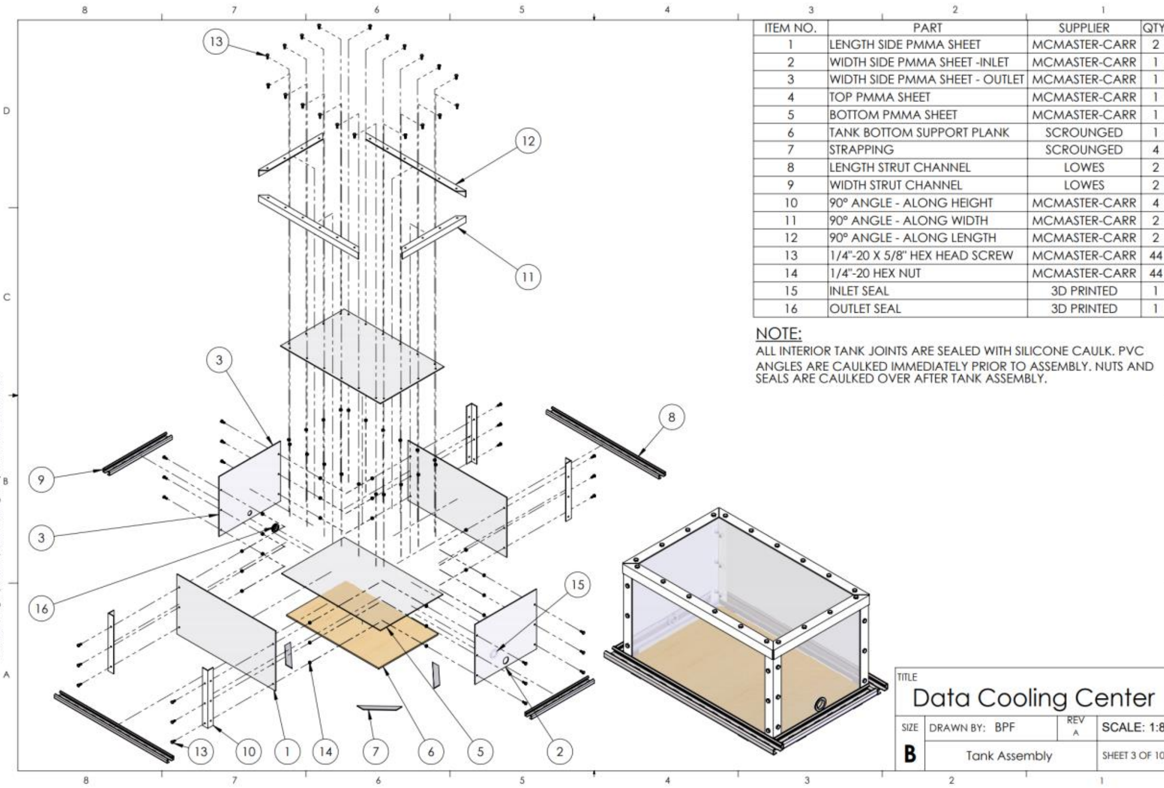
Link to online paper: https://openscholarship.wustl.edu/cgi/preview.cgi?article=1170&context=mems411

10 APPENDIX A - COMPLETE ENGINEERING DRAWINGS



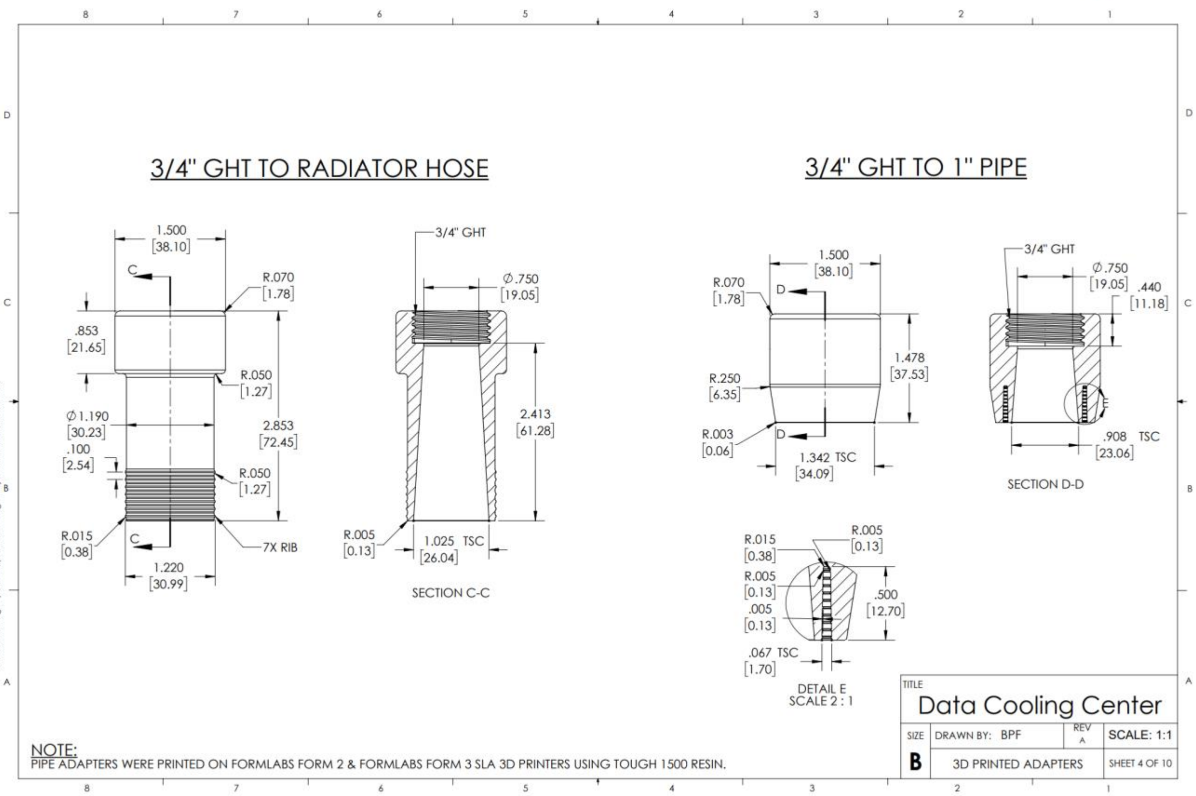


ITEM NO.	PART DESCRIPTION	SUPPLIER	QTY.
1	GPU/HEATER	AMAZON	2
2	3/4" X 3.5" COPPER PIPE	LOWES	1
3	3/4" X 6" COPPER PIPE	LOWES	1
4	3/4" X 35" COPPER PIPE	LOWES	1
5	3/4" 90° ELBOW	LOWES	2
6	3/4" TO GHT ADAPTER	LOWES	1
7	3/4" GHT TO RADIATOR HOSE ADAPTER	3D PRINTED	2
8	3/4" GHT TO 1" PIPE ADAPTER	3D PRINTED	1
9	1" X 6.5" COPPER PIPE	LOWES	1
10	1" X 8" COPPER PIPE	LOWES	1
11	1" X 6" COPPER PIPE	LOWES	1
12	1" 90° ELBOW	LOWES	2
13	RADIATOR	ADVANCE AUTO PARTS	1
14	RADIATOR OUTLET HOSE	ROCKAUTO.COM	1
15	RADIATOR INLET HOSE	ROCKAUTO.COM	1
16	HOSE CLAMP	HOME DEPOT	4
17	PUMP	HOME DEPOT	1

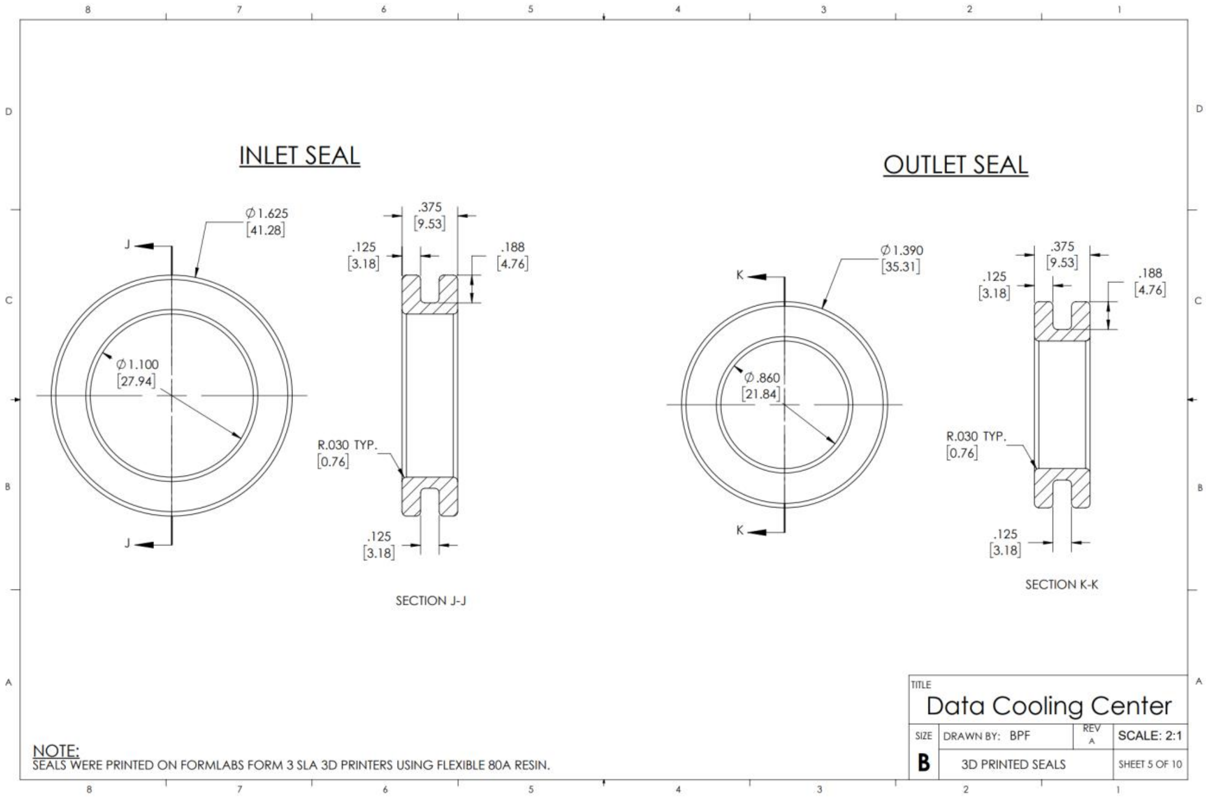


ITEM NO.	PART	SUPPLIER	QTY.
1	LENGTH SIDE PMMA SHEET	MCMASTER-CARR	2
2	WIDTH SIDE PMMA SHEET -INLET	MCMASTER-CARR	1
3	WIDTH SIDE PMMA SHEET - OUTLET	MCMASTER-CARR	1
4	TOP PMMA SHEET	MCMASTER-CARR	1
5	BOTTOM PMMA SHEET	MCMASTER-CARR	1
6	TANK BOTTOM SUPPORT PLANK	SCROUNGED	1
7	STRAPPING	SCROUNGED	4
8	LENGTH STRUT CHANNEL	LOWES	2
9	WIDTH STRUT CHANNEL	LOWES	2
10	90° ANGLE - ALONG HEIGHT	MCMASTER-CARR	4
11	90° ANGLE - ALONG WIDTH	MCMASTER-CARR	2
12	90° ANGLE - ALONG LENGTH	MCMASTER-CARR	2
13	1/4"-20 X 5/8" HEX HEAD SCREW	MCMASTER-CARR	44
14	1/4"-20 HEX NUT	MCMASTER-CARR	44
15	INLET SEAL	3D PRINTED	1
16	OUTLET SEAL	3D PRINTED	1

NOTE:
ALL INTERIOR TANK JOINTS ARE SEALED WITH SILICONE CAULK. PVC ANGLES ARE CAULKED IMMEDIATELY PRIOR TO ASSEMBLY. NUTS AND SEALS ARE CAULKED OVER AFTER TANK ASSEMBLY.



NOTE:
PIPE ADAPTERS WERE PRINTED ON FORMLABS FORM 2 & FORMLABS FORM 3 SLA 3D PRINTERS USING TOUGH 1500 RESIN.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OUTLET SEAL
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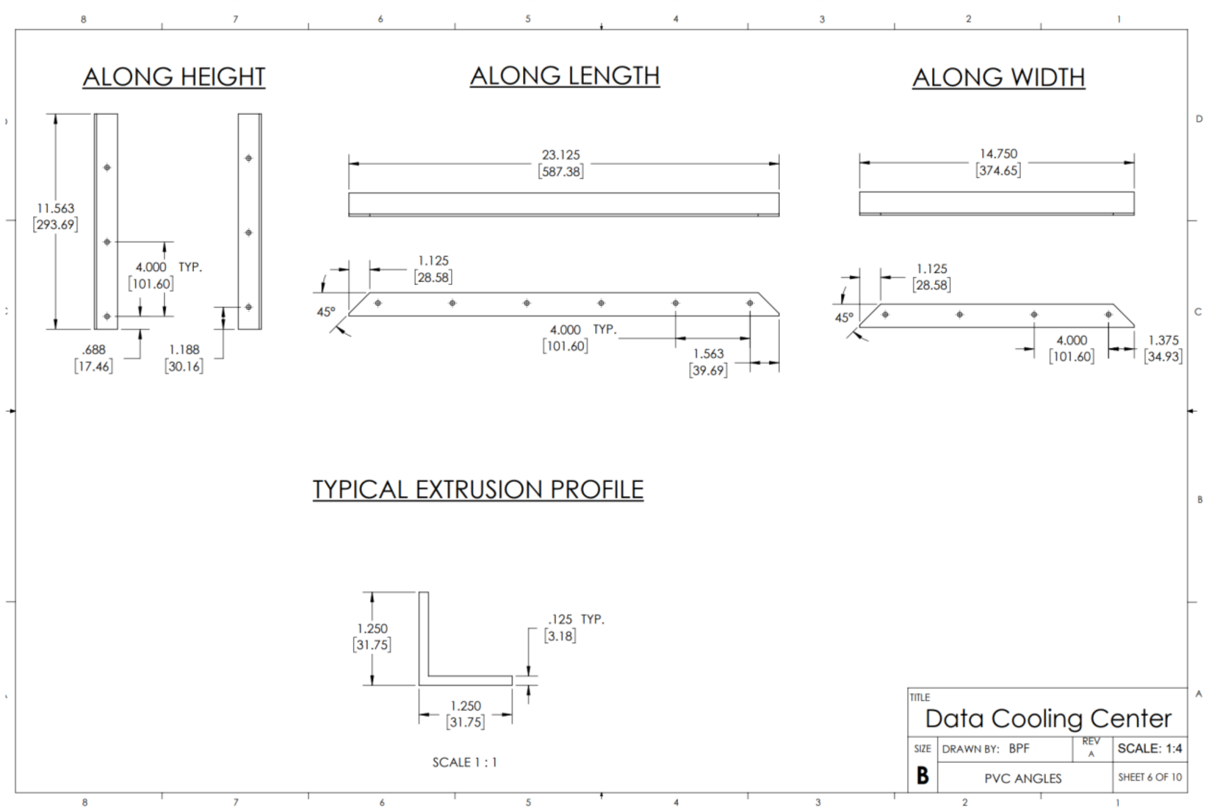
∅1.100 [27.94]
.375 [9.53]
.125 [3.18]
.188 [4.76]
R.030 TYP. [0.76]
SECTION J-J
∅1.390 [35.31]
∅.860 [21.84]
SECTION K-K
NOTE:
SEALS WERE PRINTED ON FORMLABS FORM 3 SLA 3D PRINTERS USING FLEXIBLE 80A RESIN.
TITLE
Data Cooling Center
SIZE B
DRAWN BY: BPF
REV A
SCALE: 2:1
3D PRINTED SEALS
SHEET 5 OF 10


ALONG HEIGHT
ALONG LENGTH
ALONG WIDTH
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4.000 TYP. [101.60]
.688 [17.46]
1.188 [30.16]
23.125 [587.38]
1.125 [28.58]
45°
4.000 TYP. [101.60]
1.563 [39.69]
14.750 [374.65]
4.000 [101.60]
1.375 [34.93]
TYPICAL EXTRUSION PROFILE
1.250 [31.75]
.125 TYP. [3.18]
SCALE 1 : 1
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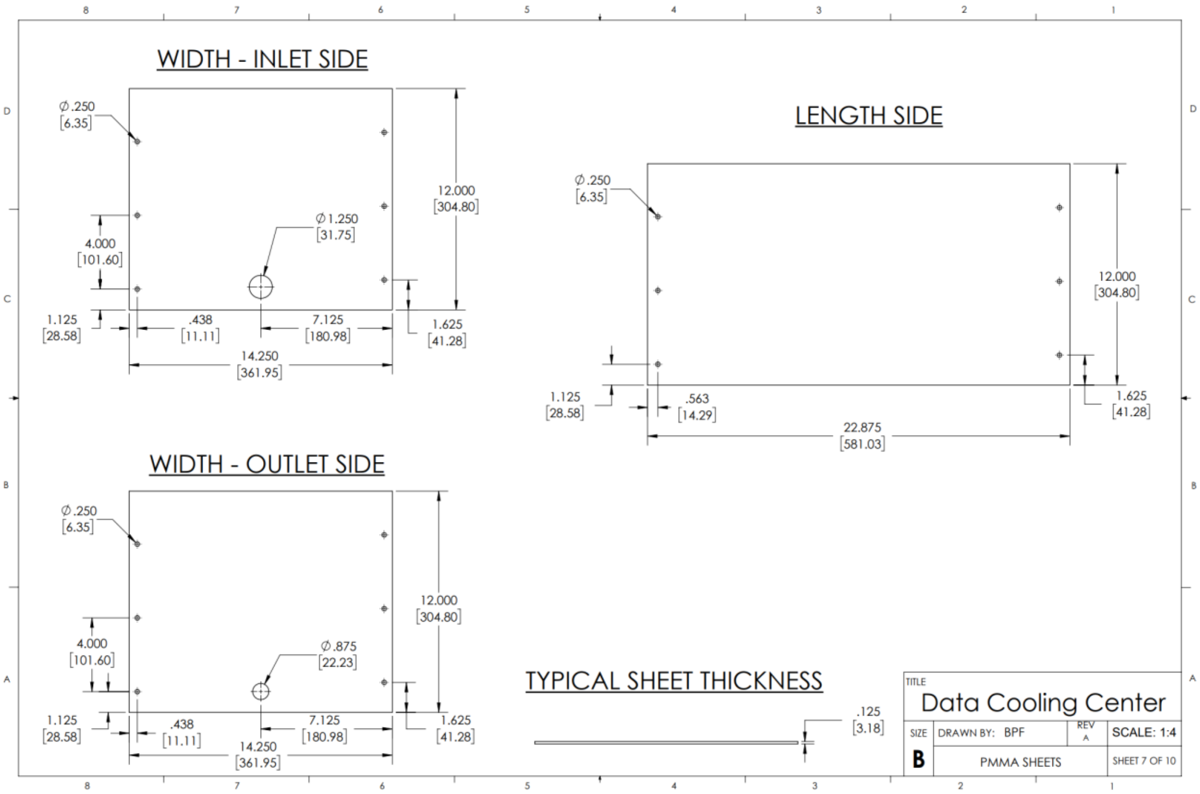
Data Cooling Center
SIZE B
DRAWN BY: BPF
REV A
SCALE: 1:4
PVC ANGLES
SHEET 6 OF 10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LENGTH SIDE
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12.000
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1.125
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[14.29]
1.625
[41.28]
22.875
[581.03]
WIDTH - OUTLET SIDE
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[6.35]
12.000
[304.80]
4.000
[101.60]
Ø.875
[22.23]
1.125
[28.58]
.438
[11.11]
7.125
[180.98]
1.625
[41.28]
14.250
[361.95]
TYPICAL SHEET THICKNESS
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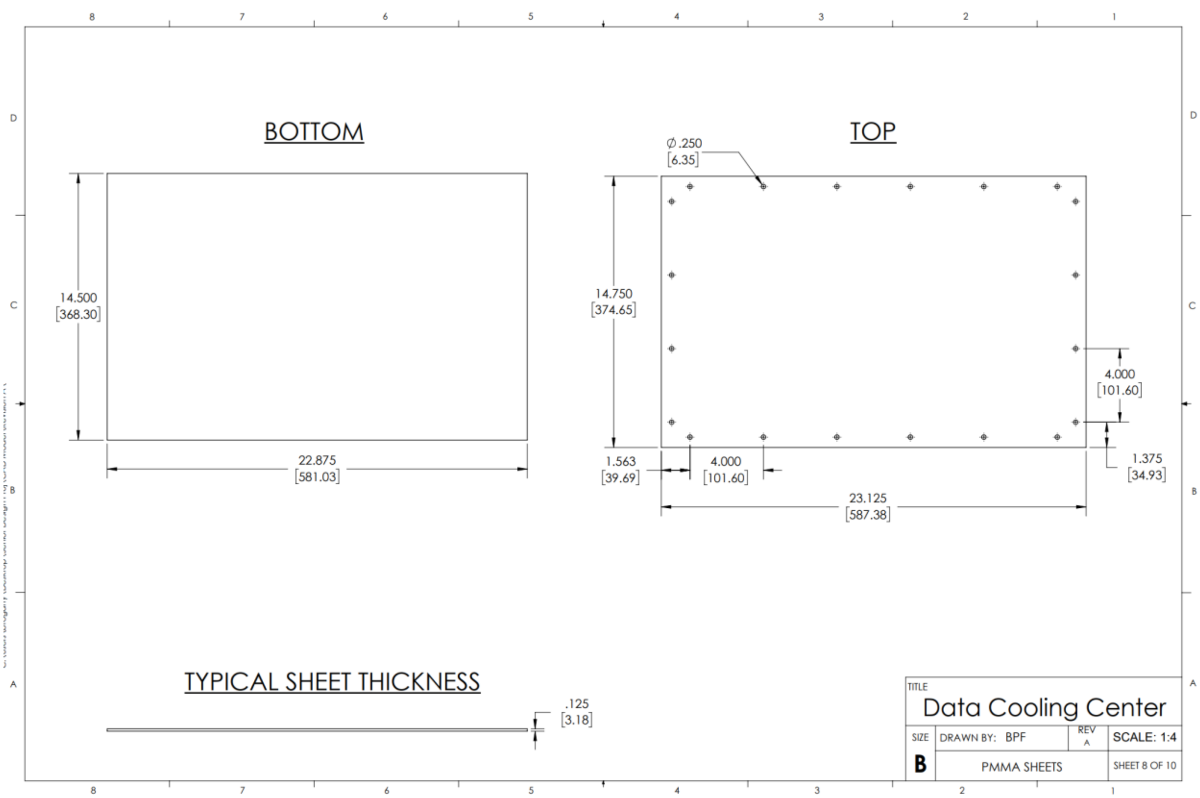
[3.18]
TITLE
Data Cooling Center
SIZE
DRAWN BY: BPF
REV
A
SCALE: 1:4
B
PMMA SHEETS
SHEET 7 OF 10


BOTTOM
14.500
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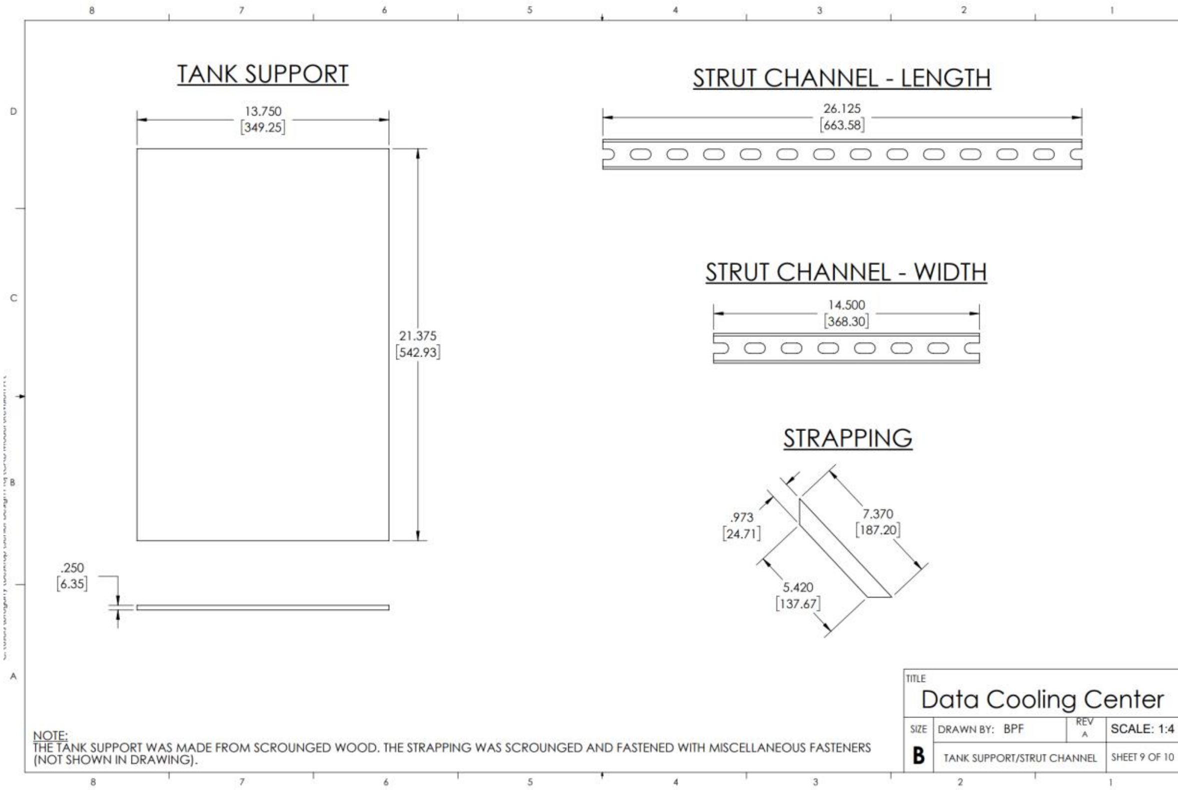
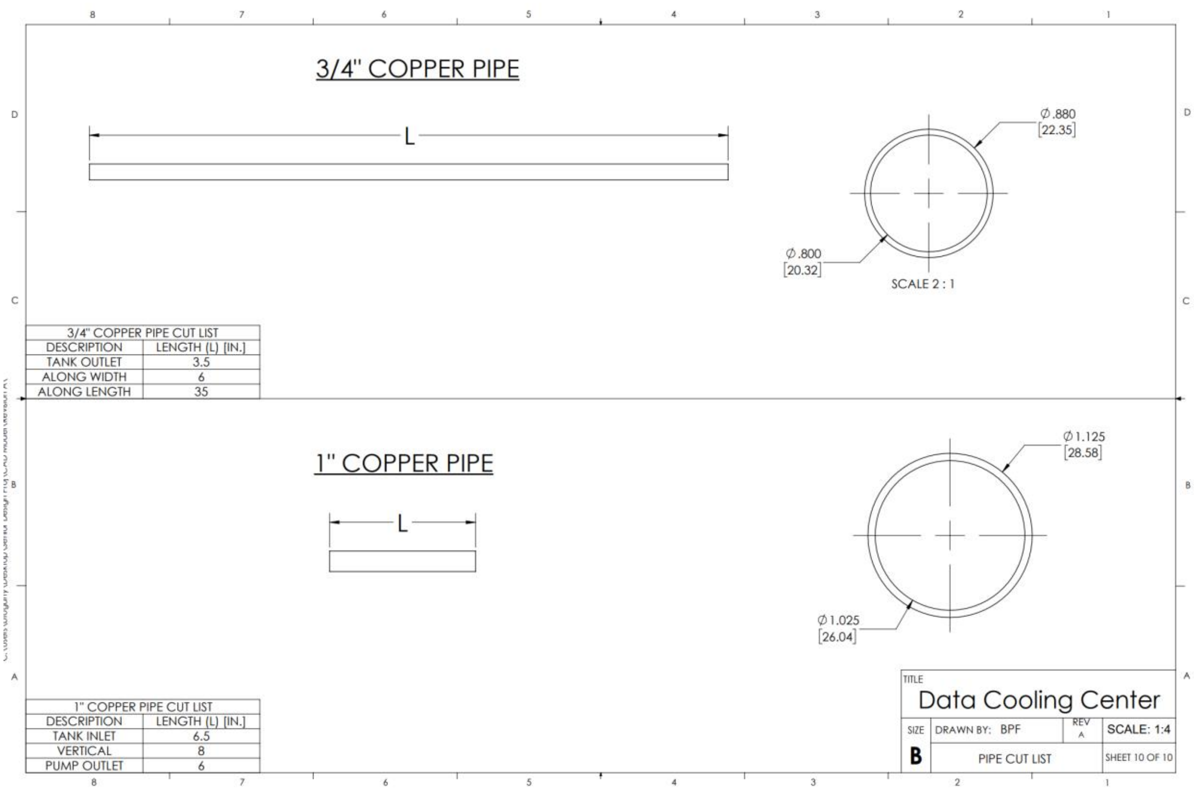
4.000
[101.60]
1.375
[34.93]
23.125
[587.38]
TYPICAL SHEET THICKNESS
.125
[3.18]
TITLE
Data Cooling Center
SIZE
DRAWN BY: BPF
REV
A
SCALE: 1:4
B
PMMA SHEETS
SHEET 8 OF 10





3/4" COPPER PIPE CUT LIST

DESCRIPTION	LENGTH (L) [IN.]
TANK OUTLET	3.5
ALONG WIDTH	6
ALONG LENGTH	35

1" COPPER PIPE CUT LIST

DESCRIPTION	LENGTH (L) [IN.]
TANK INLET	6.5
VERTICAL	8
PUMP OUTLET	6

11 APPENDIX B – CALCULATIONS (FINAL DESIGN)

Assumptions and Constants:

The system is to be treated as a closed system. The system will be evaluated at the worst case scenario temperatures for the following calculations.

Flow rate: $Q = 5\ \frac{gal}{min} * \frac{0.133681\ ft^3}{1\ gal} * \frac{1\ min}{60\ s} = 0.01114\ \frac{ft^3}{s}$

Pipe Inner Diameter Section 1: $D_{1i} = 0.800\ in * \frac{1\ ft}{12\ in} = 0.06667\ ft$

Pipe Outer Diameter Section 1: $D_{1o} = 0.880\ in * \frac{1\ ft}{12\ in} = 0.07333\ ft$

Pipe Inner Diameter Section 2: $D_{2i} = 1.025\ in * \frac{1\ ft}{12\ in} = 0.08542\ ft$

Pipe Outer Diameter Section 2: $D_{2o} = 1.125\ in * \frac{1\ ft}{12\ in} = 0.09375\ ft$

Radiator Hose Inside Diameter: $D_{hose,i} = 1.1875\ in * \frac{1\ ft}{12\ in} = 0.09896\ ft$

Radiator Hose Outside Diameter: $D_{hose,o} = 1.600\ in * \frac{1\ ft}{12\ in} = 0.13333\ ft$

Maximum Tank Temperature: $T_{max,t} = 90°\ C * \frac{9}{5} + 32 = 194\ °F$

Maximum Ambient Temperature: $T_{max,A} = 115\ °F$

Equivalent Roughness, new Copper pipe: $\varepsilon \approx\ 4.92 * 10^{-6}\ ft$

Total Pipe Length Section 1: $l_1 = 48\ in * \frac{1\ ft}{12\ in} = 4\ ft$

Total Pipe Length Section 2: $l_2 = 30\ in * \frac{1\ ft}{12\ in} = 2.5\ ft$

<u>Cross-Sectional Area</u>

Pipe Section 1: $A_{p1} = \frac{\pi}{4}(0.06667)^2 = 3.491 * 10^{-3}\ ft^2$

Pipe Section 2: $A_{p2} = \frac{\pi}{4}(0.08542)^2 = 5.731 * 10^{-3}\ ft^2$

Radiator Hose: $A_{hose} = \frac{\pi}{4}(0.09896)^2 = 7.691 * 10^{-3}\ ft^2$

<u>Flow Rate & Velocity Equations</u>

$Q_1 = Q_2 = Q_{hose}$

$V_1 A_1 = V_2 A_2$

$V_1 * A_{p1} = V_2 A_{p2} \rightarrow V_2 = \frac{V_1 A_{p1}}{A_{p2}}$

$V_1 A_1 = V_{hose} A_{hose} \rightarrow V_{hose} = \frac{V_1 A_{p1}}{A_{hose}}$

Velocity:

$$V_1 = \frac{Q}{A} = \frac{0.01114\, ft^3}{3.491 * 10^{-3}\, ft^2 * s} = 3.191 \frac{ft}{s}$$

$$V_2 = \frac{V_1 A_{p1}}{A_{p2}} = \frac{3.191 \frac{ft}{s} * 3.491 * \ 10^{-3}\, ft^2}{5.731 * \ 10^{-3}\, ft^2} = 1.944 \ \frac{ft}{s}$$

$$V_{hose} = \frac{V_1 A_{p1}}{A_{hose}} = \frac{3.191 \frac{ft}{s} * 3.491 * \ 10^{-3}\, ft^2}{7.691 * \ 10^{-3}\, ft^2} = 1.448 \ \frac{ft}{s}$$

Section 1

Water Properties @ 14.7 psia & $T_{max,t}$:

Density: $\rho = 1.8732 \ \frac{slugs}{ft^3}$

Dynamic Viscosity: $\mu = 6.6015 * \ 10^{-6} \ \frac{lbf * s}{ft^2}$

Specific Heat Ratio: $k = 1.3983$

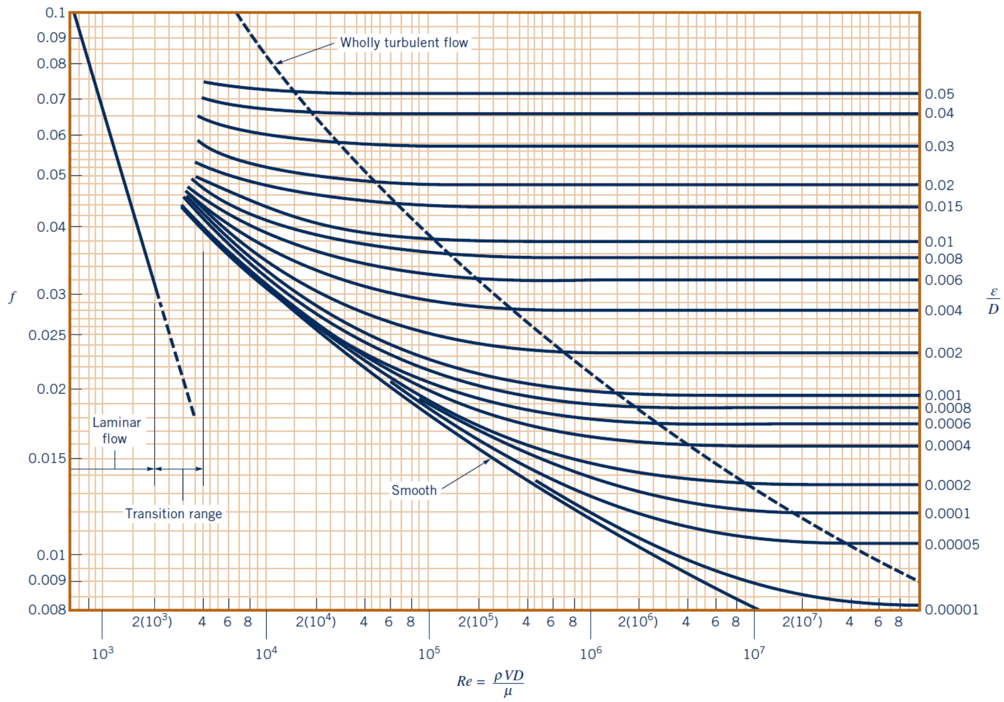
Reynolds Number: $Re = \frac{\rho V D}{\mu}$

$$Re_1 = \frac{\rho V_1 D_{1i}}{\mu} = \frac{1.8732 \ \frac{slugs}{ft^3} \ * 3.191 \frac{ft}{s} \ * \ 0.06667\, ft}{6.6015\, x\, 10^{-6} \ \frac{lb_f * s}{ft^2}} = 60{,}366.89$$

Equivalent roughness:

$$\frac{\varepsilon}{D_{1i}} = \frac{4.92 * \ 10^{-6}}{0.06667} = 7.380 * 10^{-5}$$

Moody Diagram



Friction factor from Moody Diagram:

$f_1 = 0.021$

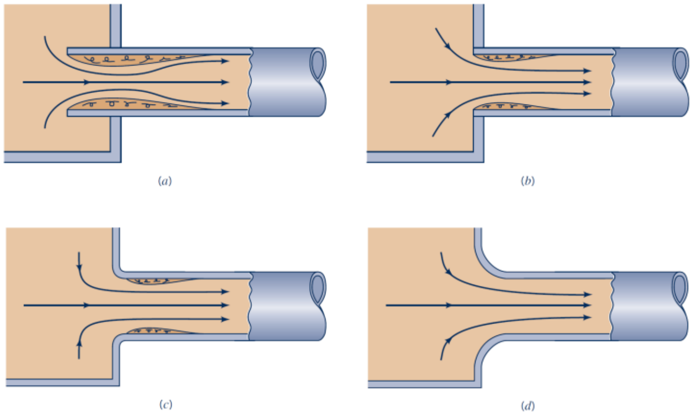
Head Loss:

Head loss is approximated using the Darcy-Weisbach equation. It consists of both major and minor losses. Major losses stem primarily from friction and minor losses from valves, bends, and tees.

The equation accounting for both frictional and minor losses is as follows:

$$\Delta h_f = \left(f\frac{l}{D} + \sum K\right)\frac{V^2}{2g}$$

Where *f* is the friction factor, *l* is the pipe length, *D* is the pipe diameter, *V* is the fluid velocity, *g* is the gravitational constant, and *K* is the loss coefficient. The loss coefficients are known values which are summed to find the total loss coefficient for the system or section being evaluated. The figure and table below show these losses.

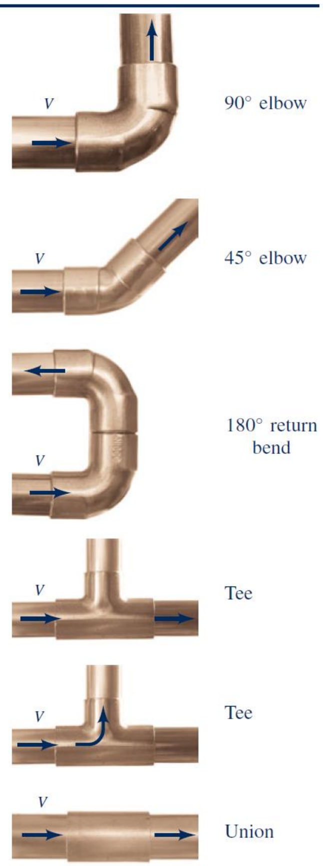


■ **Figure 8.22** Entrance flow conditions and loss coefficient (Data from Refs. 28, 29).
(*a*) Reentrant, $K_L = 0.8$, (*b*) sharp-edged, $K_L = 0.5$, (*c*) slightly rounded, $K_L = 0.2$ (see Fig. 8.24),
(*d*) well-rounded, $K_L = 0.04$ (see Fig. 8.24).

■ **Table 8.2**

Loss Coefficients for Pipe Components $\left(h_L = K_L \frac{V^2}{2g}\right)$ **(Data from Refs. 5, 10, 27)**

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
b. 180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
c. Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
d. Union, threaded	0.08
***e. Valves**	
Globe, fully open	10
Angle, fully open	2
Gate, fully open	0.15
Gate, $\frac{1}{4}$ closed	0.26
Gate, $\frac{1}{2}$ closed	2.1
Gate, $\frac{3}{4}$ closed	17
Swing check, forward flow	2
Swing check, backward flow	∞
Ball valve, fully open	0.05
Ball valve, $\frac{1}{3}$ closed	5.5
Ball valve, $\frac{2}{3}$ closed	210



*See Fig. 8.32 for typical valve geometry.

Examining section one, there is one re-entrant pipe and two elbows.

$\sum K_1 = K_{re-entrant} + 2 * K_{elbow} = 0.8 + 2 * 0.3 = 1.4$

$$\Delta h_1 = \left(f_1 \frac{l_1}{D_{1i}} + \sum K_1\right)\frac{V_1^2}{2g} = \left(0.021 \frac{4}{0.06667} + 1.4\right) \frac{3.191^2}{2 * 32.174} = 0.421\, ft$$

Mass Flow Rate

Mass flow rate, section 1: $\dot{m}_1 = \rho_{H2O} A_1 V_1$

$$\dot{m}_{1,b1} = \left(1.8732 \frac{slugs}{ft^3}\right)(3.491 * 10^{-3}\, ft^2)\left(3.191 \frac{ft}{s}\right) = 20.867 * 10^{-3} \frac{slug}{s}$$

$$\dot{m}_{1,b1} = 20.867 * 10^{-3} \frac{slug}{s} * 32.174 \frac{lbm}{slug} = 0.671 \frac{lbm}{s}$$

Heat Transfer

Pipe Inner Diameter Section 1: $D_{1i} = 0.800\, in * \frac{1\, ft}{12\, in} = 0.06667\, ft$

Pipe Outer Diameter Section 1: $D_{1o} = 0.880\, in * \frac{1\, ft}{12\, in} = 0.07333\, ft$

$$Re_1 = \frac{\rho V_1 D_{1i}}{\mu} = \frac{1.8732\, \frac{slugs}{ft^3} * 3.191 \frac{ft}{s} * 0.06667\, ft}{6.6015\, x\, 10^{-6}\, \frac{lb_f * s}{ft^2}} = 60{,}366.89$$

Convective Heat Transfer Coefficient, Air – Free Convection: $h_A \approx 3 \frac{Btu}{h * ft^2 * °F}$

Maximum Tank Temperature: $T_{max,t} = 90°\, C * \frac{9}{5} + 32 = 194\, °F$

Prandtl number of tank water at $T_{max,t}$: $Pr_{H2O} = 1.95$

Thermal conductivity of water at $T_{max,t}$: $k_{H2O,maxT} = .67589\, \frac{W}{m*K}$

$$k_{H2O,maxT} = 0.67589\, \frac{J}{s * m * K} * \frac{1\, Btu}{1055.06\, J} * \frac{3600\, s}{1\, h} * \frac{1\, m}{3.281\, ft} * \frac{1\, K}{1.8\, °F}$$

$$k_{H2O,maxT} = 0.390501 \frac{Btu}{h * ft * °F}$$

Nusselt Number: For cooling, $Nu = 0.023 Re^{0.8} Pr^{0.3}$

Section 1 (Pre-radiator): $Nu_1 = 0.023 Re_1^{0.8} Pr^{0.3} = 0.023 * 60{,}366.89^{0.8} * 1.95^{0.3} = 187.66$

Convective Heat Transfer Coefficient, Water – Forced Convection: $h_{1,H2O} = \frac{k_{H2O}}{D_{pipe,i}} * Nu_{4A}$

$$h_{1,H2O} = \frac{0.390501}{0.06667} * 187.66 = 1.099 * 10^3 \frac{Btu}{h * ft^2 * °F}$$

Thermal conductivity of copper: $k_{Cu} = 231.84 \frac{Btu}{h*ft*°F}$

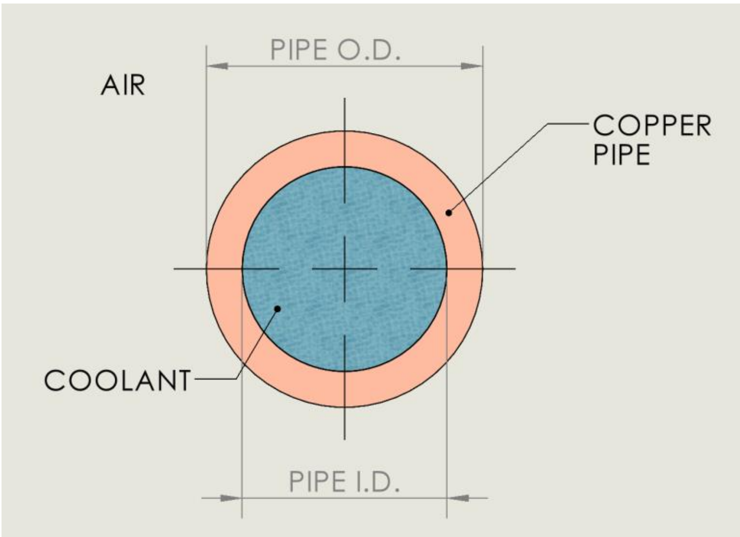
Equivalent Resistance

Maximum Tank Temperature: $T_{max,t} = 90°\ C * \frac{9}{5} + 32 = 194\ °F$

Maximum Ambient Temperature: $T_{max,A} = 115\ °F$

Heat Transfer, Section 4A: $\dot{Q} = \frac{T_{max,t} - T_{max,A}}{R_{total}}$ where R_{total} is the total resistance to heat transfer

Specific Heat of Water at $T_{max,tank}$: $c_{p,H2O,\max t} = 1.005 \frac{Btu}{lbm*°F}$



$$R_{tot} = R_{H2O,conv.} + R_{Cu,cond.} + R_{Air,conv.}$$

$$R_{H2O,conv.} = \frac{1}{h_{H2O} * A_{surf}} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}}$$

$$R_{Cu,cond.} = \frac{ln\left(D_{pipe,o} - D_{pipe,i}\right)}{2\pi * k_{Cu} * l_{section}}$$

$$R_{Air,conv.} = \frac{1}{h_{Air} * A_{surf}} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}}$$

For section 1:

Length: $l_1 = 48\ in = 4\ ft$

$$R_{tot,1} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}} + \frac{ln\left(D_{pipe,o} - D_{pipe,i}\right)}{2\pi * k_{Cu} * l_{section}} + \frac{1}{h_{Air} * \pi * D_{pipe,i} * l_{section}}$$

$$R_{tot,1} = \frac{1}{1.099 * 10^3 * \pi * 0.06667 * 4} + \frac{ln(0.08542 - 0.06667)}{2\pi * 231.84 * 4} + \frac{1}{3 * \pi * 0.06667 * 4}$$

$R_{tot,1} = 0.398 \frac{°\text{F} * h}{Btu}$

$\dot{Q} = \frac{194 - 115}{.398} = 198.36 \frac{Btu}{h}$

Surface Temperature of Pipe Section 1: $\dot{Q} = \frac{T_{surf,4} - T_{Air}}{R_{Air,conv.}}$

$T_{surf,1} = T_{Air} + \dot{Q} * R_{Air,conv.} = 115°\text{F} + 198.36 \frac{Btu}{h} * \frac{1}{3*\pi*0.06667*4} \frac{°\text{F}*h}{Btu} = 193.92\ °\text{F}$

Outlet Temperature of Fluid through Pipe:

$\dot{Q} = \dot{m}c_{p,H2O}(T_i - T_o) = hA_s\Delta T_{lm}$, where ΔT_{lm} is a log-mean temperature defined by:

$$\Delta T_{lm} = \frac{\Delta T_o - \Delta T_i}{\ln \frac{\Delta T_o}{\Delta T_i}}$$

Simplifying and solving for T_o:

$$T_o = T_s - (T_s - T_i)e^{\frac{-hA_s}{\dot{m}c_p}}$$

For section 1:

$$T_{o,1} = 193.92 - (193.92 - 194)e^{\frac{-\left(1.099*10^3 \frac{Btu}{h*ft^2*°\text{F}}\right)(\pi*0.06667\ ft*4\ ft)\left(\frac{1\ h}{3600\ s}\right)}{\left(0.671\frac{lbm}{s}\right)\left(1.005\frac{Btu}{lbm*°\text{F}}\right)}}$$

$$T_{o,1} = 193.92 - (-0.08)e^{-.379} = 193.97\ °\text{F} = T_{i,rad}$$

Radiator Hose (Section 1 to Radiator Transition):

The small section of radiator hose between pipe section 1 and the radiator entrance produces negligible heat transfer. As such, it is ignored in the heat transfer calculations. Only head loss calculations are considered.

Velocity of fluid in hose: $V_{hose} = 1.448 \frac{ft}{s}$

Length of section 1 to radiator transition hose: $L_{hose,1-R} = .25\ ft$

$$Re_{hose,1-R} = \frac{\rho V_{hose} D_{hose,i}}{\mu} = \frac{1.8732 \frac{slugs}{ft^3} * 1.448 \frac{ft}{s} * 0.09896\ ft}{6.6015\ x\ 10^{-6} \frac{lb_f * s}{ft^2}} = 40{,}660.22$$

Absolute Roughness, EPDM hose: $\varepsilon_{EPDM} \approx 1.969 * 10^{-11}$

Equivalent Roughness: $\frac{\varepsilon_{EPDM}}{D_{hose,i}} = \frac{1.969 * 10^{-11}}{0.09896} = 1.989 * 10^{-10}$

From Moody Diagram, Friction Factor: $f_{hose,1-R} = 0.022$

Examining the radiator hose connecting section one to the radiator, there are two unions. There is an additional union between the adapter and section 1. This is included in this calculation for simplicity.

$$\sum K_{hose,1-R} = 3 * K_{union} = 3 * 0.08 = 0.24$$

$$\Delta h_{hose,1-R} = \left(f_{hose,1-R}\frac{l_{hose,1-R}}{D_{hose,1-R}} + \sum K_{hose,1-R}\right)\frac{V_{hose}^2}{2g} = \left(0.022\frac{.25}{0.09896} + 0.24\right)\frac{1.448^2}{2 * 32.174} = 9.631 * 10^{-3}\ ft$$

Radiator:

Number of tubes: $N_{tubes} = 35$

Radiator Width/Tube Length: $W_{rad} = l_{tube} = 26\ in = 2.1667\ ft$

Radiator Height: $H_{rad} = 14.25\ in = 1.1875\ ft$

Radiator Depth: $d_{rad} = 0.640\ in = 0.0533\ ft$

Tube Interior Width: $W_{tube,int} = 0.625\ in$ = 0.0521 ft

Tube Interior Height: $H_{tube,int} = 0.065\ in = 5.4167 * 10^{-3} ft$

Cross-Sectional Area- Tube: $A_{CS,tube} = H_{tube}W_{tube} = (0.0533) * (5.4167 * 10^{-3}) = 2.821 * 10^{-4}\ ft^2$

Perimeter of Tube: $P_{tube} = 2H_{tube} + 2W_{tube} = 2(0.0533) + 2(5.4167 * 10^{-3}) = 0.115\ ft$

Hydraulic Diameter of Tube: $D_{h,tube} = \frac{4A_{C.S.,tube}}{P_{tube}} = \frac{4*2.821*10^{-4}}{0.115} = 9.812 * 10^{-3} ft$

Total Tube Area / Radiator: $A_{rad,i} = N_{tube}A_{C.S.,tube} = 35\ (2.821 * 10^{-4}) = 9.874 * 10^{-3}\ ft^2$

$Q_1 = Q_{rad} \rightarrow V_1A_1 = V_{rad}A_{rad}$

Radiator Velocity: $V_{rad} = \frac{V_1A_{p1}}{A_{rad}} = \frac{3.191\frac{ft}{s}*3.491* 10^{-3}\ ft^2}{9.874* 10^{-3}\ ft^2} = 1.128\ \frac{ft}{s}$

Equivalent Roughness, new Aluminum pipe: $\varepsilon \approx 6 * 10^{-5}$ in

$$Re = \frac{\rho VD}{\mu}$$

Density: $\rho = 1.8732\ \frac{slugs}{ft^3}$

Dynamic Viscosity: $\mu = 6.6015\ x\ 10^{-6}\ \frac{lbf*s}{ft^2}$

$$Re_{rad} = \frac{1.8732\ \frac{slugs}{ft^3} * 1.128\frac{ft}{s} * 9.812 * 10^{-3}\ ft * \frac{lb_f * s^2}{slugs * ft}}{6.6015 * 10^{-6}\ \frac{lb_f * s}{ft^2}} = 3{,}140.23$$

The flow is turbulent as *Re* > 2300

Friction factor: $f = \frac{1}{(1.58 * \ln(Re_{rad}) - 3.28)^2} = \frac{1}{(1.58 * \ln(3140.23) - 3.28)^2} = 0.0112$

From Moody Diagram, Radiator friction factor: $f \approx 0.044$

Head Loss radiator: The radiator tubes run in parallel. As such, it is only necessary to calculate the head loss of a single tube as the total head loss will be equivalent to the head loss of a single tube. Accounted for are a sharp edge entrance, the entrance, and the exit. The entrance and exit are treated as elbows.

$$\sum K_{rad} = K_{re-entrant} + 2 * K_{elbow} = 0.8 + 2 * 0.3 = 1.4$$

$$\Delta h_{rad} = \left(0.0112 \frac{2.1667}{9.874*10^{-3}} + 1.4\right) \frac{(1.128)^2}{2*32.174} = 76.279 * 10^{-3}\ ft$$

Radiator- Heat Transfer (ε-NTU Method):

Coolant Side (Fluid)

Hydraulic Diameter Coolant: $D_{h,c} = D_{h,tube} = 9.812 * 10^{-3} ft$

Reynolds Number: $Re_c = Re_{rad} = 3{,}140.23$

Fluid velocity: $V_c = V_{rad} = 1.128 \frac{ft}{s}$

Because $T_{max} \approx T_{i,rad}$ the properties at $T_{i,rad}$ are assumed equal.

$$\mu_c = 6.6015\ x\ 10^{-6}\ \frac{lbf * s}{ft^2} * 32.174 \frac{lbm * ft}{lbf * s^2} = 2.124 * 10^{-4} \frac{lbm}{ft * s}$$

$$c_{p,H2O,\text{ti,rad}} = 1.005 \frac{Btu}{lbm * °\text{F}}$$

$$k_{H2O,\text{ti,rad}} = .390501 \frac{Btu}{h * ft * °\text{F}} * \frac{1\ h}{3600\ s} = 1.085 * 10^{-4} \frac{Btu}{s * ft * °\text{F}}$$

Prandtl Number: $P_c = \frac{C_{p,c} * \mu_c}{K_c} = \frac{1.005 \frac{Btu}{lbm*°\text{F}} * 2.124\ x\ 10^{-4} \frac{lbm}{ft*s}}{1.085*10^{-4} \frac{Btu}{s*ft*°\text{F}}} = 1.967$

Nusselt Number:

Laminar Flow: $Nu_c = \frac{h_c * D_{h,c}}{k_c} = 1.86(Re * \text{Pr})^{\frac{1}{3}} \left(\frac{L}{D}\right)^{\frac{1}{3}} (\frac{\mu}{\mu_s})^{0.14}$

Turbulent Flow: $Nu_c = \frac{h_c * D_{h,c}}{k_c} = \frac{\left(\frac{f}{2}\right)(Re_c - 1000)Pr}{1 + 12.7(f/2)^{1/2}\left(Pr^{2/3} - 1\right)}$ where Friction Factor: $f = \frac{1}{(1.58 * \ln(Re_c) - 3.28)^2}$

Because *Re* > 2300, the flow in the tube is turbulent. The Nusselt calculation follows:

Friction factor: $f = \frac{1}{(1.58 * \ln(Re_{rad}) - 3.28)^2} = \frac{1}{(1.58 * \ln 3140.23) - 3.28)^2} = 0.0112$

$$Nu_c = \frac{\left(\frac{.0112}{2}\right) * (3{,}140.23 - 1000) * 1.967}{1 + 12.7\left(\frac{.0112}{2}\right)^{\frac{1}{2}}\left(1.967^{\frac{2}{3}} - 1\right)} = 15.310$$

Heat Transfer Coefficient: $h_c = \frac{Nu_c * K_c}{D_{h.c}} = \frac{15.310*1.085*10^{-5}}{9.812*10^{-3}} = 0.0169\ \frac{Btu}{s*ft^2*°F}$

<u>Air</u>

Hydraulic Diameter: $D_{h,A} = \frac{4*d_{core}*A_r}{A_A}$ where d_{core} is the core depth, A_r is the free flow area, and A_A is the total heat transfer area of the air

Number of tubes: $N_{tubes} = 35$

Core Depth: $d_{core} = 0.640\ in = 0.0533\ ft$

Tube Exterior Width: $W_{tube,ext} = 0.635\ in = 0.0529\ ft$

Tube Exterior Height: $H_{tube,ext} = 0.075\ in = 0.00625\ ft$

Tube Length: L_{rad} = 26 in. = 2.1667 ft

Free Flow Area: $A_r \approx 434\ in^2 = 3.014\ ft^2$

Heat Transfer Area of Air: $A_A = N_{tubes} * (2W_{tube,ext} + 2H_{tube,ext}) * L_{rad}$

$A_A = 35 * (2 * 0.635 + 2 * 0.075) * 26 = 1292.2\ in^2 = 8.97\ ft^2$

$$D_{h,A} = \frac{4 * 0.0533 * 3.014}{8.97} = 0.07\ ft$$

Density of Air at Max Ambient Temperature: $\rho_A = 2.147 * 10^{-3}\ \frac{slugs}{ft^3}$

Dynamic Viscosity of Air at Max Ambient Temperature: $\mu_A = 4.00 * 10^{-7}\ \frac{lbm*s}{ft^2}$

$\mu_A = 4.00 * 10^{-7}\ \frac{lbm*s}{ft^2} * 32.174 \frac{lbm*ft}{lbf*s^2} = 1.287 * 10^{-5} \frac{lbm}{ft*s}$

Flow Rate: $Q_A \approx 2 * 925\ \frac{ft^3}{min} = 1{,}850\ \frac{ft^3}{min}$

Velocity: $V_A = \frac{Q_A}{A_r} = \frac{1850}{3.014}\ \frac{ft^3}{ft*min} * \frac{60\ min}{1\ h} = 10.23 \frac{ft}{s}$

Reynolds Number: $Re_A = \frac{\rho_A * V_A * D_{h,A}}{\mu_A} = \frac{2.147*10^{-3}*10.23*0.07}{4.00*10^{-7}} = 3{,}843.67$

Specific Heat of Air at $T_{Ambient,max}$: $c_{p,air} = 0.2407 \frac{Btu}{lbm*°F}$

$$k_{air} = 0.016030 \frac{Btu}{h * ft * °F} * \frac{1\ h}{3600\ s} = 4.453 * 10^{-6} \frac{Btu}{s * ft * °F}$$

Prandtl Number: $P_A = \frac{C_{p,A}*\mu_A}{K_A} = \frac{0.2407*1.287*10^{-5}}{4.453*10^{-6}} = 0.696$

Colburn Factor: $J = \frac{0.174}{Re_A^{0.383}} = \frac{0.174}{3843.67^{0.383}} = 7.372 * 10^{-3}$

Heat transfer Coefficient: $h_A = \frac{J*\rho_A*V_A*C_{p.a}}{Pr_A^{2/3}}$

$$h_A = \frac{J * \rho_A * V_a * C_{p.a}}{Pr_A^{\frac{2}{3}}}$$

$$h_A = \frac{7.372 * 10^{-3} * 2.147 * 10^{-3} \frac{slugs}{ft^3} * 10.23 \frac{ft}{s} * 0.2407 \frac{Btu}{lbm * °F}}{0.696^{\frac{2}{3}}} * \frac{3600\ s}{1\ h} * \frac{32.174\ lbm}{1\ slug}$$

$$h_A = 5.748 \frac{Btu}{h * ft^2 * °F}$$

<u>Heat Rejection</u>

Thermal conductivity of aluminum: $k_{Al} = k_f = 136 \frac{Btu}{h*ft*°F}$

Fin thickness: $t_f = 0.001\ in = 8.333 * 10^{-5}\ ft$

Fin height: $H_f = 0.310\ in = 0.03\ ft$

$$h_A = 5.748 \frac{Btu}{h * ft^2 * °F}$$

$$h_c = 0.0169 \frac{Btu}{s * ft^2 * °F} * \frac{3600\ s}{1\ h} = 60.84 \frac{Btu}{h * ft^2 * °F}$$

Fin Efficiency Factor: $F_f = \left[\frac{2*h_A}{k_f*t_f}\right]^{0.5} \left(\frac{H_f}{2}\right)$

$$F_f = \left[\frac{2 * 5.748 \frac{Btu}{h * ft^2 * °F}}{136 \frac{Btu}{h * ft * °F} * 8.333 * 10^{-5}\ ft}\right]^{0.5} \left(\frac{0.03\ ft}{2}\right) = 0.466$$

Fin Efficiency: $n_f = \frac{\tanh F_f}{F_f} = 0.9334$

Fin Area: $A_f = 16.12\ ft^2$

$A_A = 8.97\ ft^2$

Effectiveness of Fins: $\varepsilon_f = 1 - (1 - n_f)\left(\frac{A_f}{A_A}\right) = 1 - (1 - 0.9334)\left(\frac{16.12}{8.97}\right) = 0.8803$

Radiator Width/Tube Length: $W_{rad} = L_{tube} = 26\ in = 2.1667\ ft$

Radiator Height: $H_{rad} = 14.25\ in = 1.1875\ ft$

Radiator Depth: $d_{rad} = 0.640\ in = 0.0533\ ft$

Radiator Core Volume: $V_c = 2.1667 * 1.1875 * 0.0533 = 0.137\ ft^3$

$A_{rad,i} = A_c = 35\ (2.821 * 10^{-4}) = 9.874 * 10^{-3}\ ft^2$

Tube Thickness: $t_{Tube} = 0.010\ in. = 8.333 * 10^{-4}\ ft$

Overall Thermal Resistance: $R = \frac{1}{\varepsilon_f h_A} + \frac{1}{\left[\frac{A_{c,A}/C_v}{A_A/C_v}\right] * h_c} + \frac{t_{Tube}}{k_{Tube}}$

$$R = \frac{1}{0.8803 * 5.748\ \frac{Btu}{h * ft^2 * °F}} + \frac{1}{\left[\frac{7.078\ ft^2/0.137\ ft^3}{8.97\ ft^2/0.137\ ft^3}\right] * 60.84 \frac{Btu}{h * ft^2 * °F}} + \frac{8.333 * 10^{-4}\ ft}{136 \frac{Btu}{h * ft * °F}} = 0.2184\ \frac{h * ft^2 * °F}{Btu}$$

Overall Heat transfer Coefficient: $U = \frac{1}{R} = \frac{1}{15.13 \frac{h*ft^2*°F}{Btu}} = 4.58\ \frac{Btu}{h*ft^2*°F}$

$$\dot{m}_A = \rho_A A_R V_A = 2.147 * 10^{-3}\ \frac{slugs}{ft^3} * 3.014\ ft^2 * 10.23 \frac{ft}{s} = 6.620 * 10^{-2} \frac{slugs}{s}$$

$$\dot{m}_A = 6.620 * 10^{-2} \frac{slugs}{s} * 32.174 \frac{lbm}{slug} = 2.130\ \frac{lbm}{s}$$

$$\dot{m}_c = \rho_c A_{c.s.\ tube} V_c = 1.8732\ \frac{slugs}{ft^3} * 2.821 * 10^{-4}\ ft^2 * 1.128 \frac{ft}{s} = 5.961 * 10^{-4} \frac{slugs}{s}$$

$$\dot{m}_c = 5.961 * 10^{-4} \frac{slugs}{s} * 32.174 \frac{lbm}{slug} = 1.918 * 10^{-2}\ \frac{lbm}{s}$$

$$c_{p,air} = 0.2407 \frac{Btu}{lbm * °F}$$

$$c_{p,H2O,\text{ti,rad}} = c_{p,c} = 1.005 \frac{Btu}{lbm * °F}$$

Stream heat capacity rate for air: $C_A = \dot{m}_A * c_{p,A} = 2.130\ \frac{lbm}{s} * 0.2407 \frac{Btu}{lbm*°F} = 0.513\ \frac{Btu}{s*°F}$

$$C_A = 0.513\ \frac{Btu}{s * °F} * \frac{3600\ s}{1\ h} = 1845.69\ \frac{Btu}{h * °F}$$

Stream heat capacity rate for coolant: $C_c = \dot{m}_c * c_{p,c} = 1.918 * 10^{-2}\ \frac{lbm}{s} * 1.005 \frac{Btu}{lbm*°F}$

$$C_c = 1.913 * 10^{-2}\ \frac{Btu}{s * °F} * \frac{3600\ s}{1\ h} = 69.39\ \frac{Btu}{h * °F}$$

Stream heat capacity ratio: $C_r = \frac{\min\ (C_A\ or\ C_c)}{\max\ (C_A\ or\ C_c)} = \frac{C_c}{C_A} = \frac{69.39}{1845.69} = 3.759 * 10^{-2}$

Number of transfer units: $NTU_{max} = \frac{U * \frac{A_A}{2}}{\min\ (C_A\ or\ C_c)} = \frac{4.577\ \frac{Btu}{h*ft^2*°F} * \frac{8.97\ ft^2}{2}}{69.39 \frac{Btu}{h*°F}} = 0.296$

Effectiveness of Heat Exchanger: $\varepsilon_{HE} = 1 - e^{\frac{\left[e^{\left(-C_r * NTU_{max}^{0.78}\right)} - 1\right]}{C_r * NTU_{max}^{-0.22}}} = 1 - e^{\frac{\left[e^{\left(-3.759*10^{-2}*(0.296)^{0.78}\right)} - 1\right]}{3.759*10^{-2}*0.296^{-0,22}}} = 0.255$

Radiator Inlet Temperature: $T_{i,rad} = 193.97\ °\text{F} = T_c$

Maximum Ambient Temperature: $T_{max,A} = 115\ °\text{F} = T_A$

Total Heat Transfer Rate: $Q_{tot} = \varepsilon_{HE} * \min(C_A\ or\ C_c) * (T_c - T_A)$

$$Q_{tot} = 0.255 * 69.39\ \frac{Btu}{h * °\text{F}} * (193.81°\text{F} - 115°\text{F}) = 1394.50 \frac{Btu}{h}$$

Coolant Outlet Temperature: $T_{o,c} = T_{i,c} - \frac{Q_{tot}}{C_c} = 193.97°\text{F} - \frac{1394.50\frac{Btu}{h}}{69.39\frac{Btu}{h*°\text{F}}} = 173.87\ °\text{F}$

Air Outlet Temperature: $T_{o,a} = T_{i,A} + \frac{Q_{tot}}{C_A} = 115°\text{F} + \frac{1394.50\frac{Btu}{h}}{1845.69\frac{Btu}{h*°\text{F}}} = 115.76\ °\text{F}$

Radiator Hose (Radiator to Section 2 Transition):

The small section of radiator hose between pipe the radiator exit and section 2 produces negligible heat transfer. As such, it is ignored in the heat transfer calculations. Only head loss calculations are considered.

Temperature of fluid in hose: $T_{H2O,2-R} = 173.87\ °\text{F}$

Water Properties @ 14.7 psia & $T_{H20,2-R}$:

Density: $\rho = 1.887\ \frac{slugs}{ft^3}$

Dynamic Viscosity: $\mu = 7.546 *\ 10^{-6}\ \frac{lbf*s}{ft^2}$

Velocity of fluid in hose: $V_{hose} = 1.448\ \frac{ft}{s}$

Length of radiator to section 2 transition hose: $L_{hose,R-2} = 1\ ft$

$$Re_{hose,R-2} = \frac{\rho V_{hose} D_{hose,i}}{\mu} = \frac{1.887\ \frac{slugs}{ft^3} * 1.448\frac{ft}{s} *\ 0.09896\ ft}{7.546\ x\ 10^{-6}\ \frac{lb_f * s}{ft^2}} = 35{,}883.01$$

Absolute Roughness, EPDM hose: $\varepsilon_{EPDM} \approx\ 1.969 * 10^{-11}$

Equivalent Roughness: $\frac{\varepsilon_{EPDM}}{D_{hose,i}} = \frac{1.969 * 10^{-11}}{0.09896} = 1.989 * 10^{-10}$

From Moody Diagram, Friction Factor: $f_{hose,R-2} =\ 0.023$

Examining the radiator hose connecting the radiator to the pump, there are two unions and a curve that is the shape of two elbows. There is an additional union between the adapter and the pump. This is included in this calculation for simplicity.

$$\sum K_{hose,R-2} = 3 * K_{union} + 2 * K_{elbow} = 3 * 0.08 + 2 * 0.3 = 0.84$$

$$\Delta h_{hose,R-2} = \left(f_{hose,R-2}\frac{l_{hose,R-2}}{D_{hose,R-2}} + \sum K_{hose,R-2}\right)\frac{V_{hose}^2}{2g} = \left(0.023\frac{1}{0.09896} + 0.84\right)\frac{1.448^2}{2*32.174}$$
$$= 34.943 * 10^{-3}\ ft$$

Section 2

Convective Heat Transfer Coefficient, Air – Free Convection: $h_A \approx 3\frac{Btu}{h*ft^2*°F}$

$T_{o,rad} = 173.87\ °F$

Pipe Inner Diameter Section 2: $D_{2i} = 1.025\ in * \frac{1\ ft}{12\ in} = 0.08542\ ft$

Pipe Outer Diameter Section 2: $D_{2o} = 1.125\ in * \frac{1\ ft}{12\ in} = 0.09375\ ft$

Total Pipe Length Section 2: $l_2 = 30\ in * \frac{1\ ft}{12\ in} = 2.5\ ft$

Area, Pipe Section 2: $A_{p2} = \frac{\pi}{4}(0.08542)^2 = 5.731 * 10^{-3}\ ft^2$

$$V_2 = \frac{V_1 A_{p1}}{A_{p2}} = \frac{3.191\frac{ft}{s} * 3.491 * 10^{-3}\ ft^2}{5.731 * 10^{-3}\ ft^2} = 1.944\ \frac{ft}{s}$$

$$Re_2 = \frac{\rho V_2 D_{2i}}{\mu} = \frac{1.887\ \frac{slugs}{ft^3} * 1.944\frac{ft}{s} * 0.08542\ ft}{7.546\ x\ 10^{-6}\ \frac{lb_f * s}{ft^2}} = 41{,}525.12$$

Prandtl number of tank water at $T_{o,rad}$: $Pr_{H2O,o,rad} = 2.23$

Thermal conductivity of water at $T_{o,rad}$: $k_{H2O,o,rad} = .669\ \frac{W}{m*K}$

$$k_{H2O,o,rad} = 0.669\ \frac{J}{s*m*K} * \frac{1\ Btu}{1055.06\ J} * \frac{3600\ s}{1\ h} * \frac{1\ m}{3.281\ ft} * \frac{1\ K}{1.8\ °F}$$

$$k_{H2O,o,rad} = 0.38652\frac{Btu}{h*ft*°F}$$

Nusselt Number: For cooling, $Nu = 0.023Re^{0.8}Pr^{0.3}$

Section 2 (Post-radiator): $Nu_2 = 0.023Re_2^{0.8}Pr^{0.3} = 0.023 * 41{,}525.12^{0.8} * 2.23^{0.3} = 144.83$

Convective Heat Transfer Coefficient, Water – Forced Convection: $h_{2,H2O} = \frac{k_{H2O}}{D_{pipe,i}} * Nu_2$

$$h_{2,H2O} = \frac{0.38652}{0.08542} * 144.83 = 655.35\frac{Btu}{h*ft^2*°F}$$

Thermal conductivity of copper: $k_{Cu} = 231.84\frac{Btu}{h*ft*°F}$

Head Loss

$$\frac{\varepsilon}{D_{2i}} = \frac{4.92 * 10^{-6}}{0.08542} = 5.760 * 10^{-5}$$

From Moody Diagram, Friction Factor: $f_2 = 0.023$

Examining section two, there is one union and two elbows.

$$\sum K_2 = K_{union} + 2 * K_{elbow} = 0.08 + 2 * 0.3 = 0.68$$

$$\Delta h_2 = \left(f_2 \frac{l_2}{D_{2i}} + \sum K_2\right)\frac{V_2^2}{2g} = \left(0.023\frac{2.5}{0.08542} + 0.68\right)\frac{1.944^2}{2 * 32.174} = 0.0829\, ft$$

Equivalent Resistance

Maximum Ambient Temperature: $T_{max,A} = 115\ °\mathrm{F}$

Heat Transfer, Section 2: $\dot{Q} = \frac{T_{o,rad} - T_{max,A}}{R_{total}}$ where R_{total} is the total resistance to heat transfer

Specific Heat of Water at $T_{o,rad}$: $c_{p,H2O,o,rad} = 1.002 \frac{Btu}{lbm * °\mathrm{F}}$

$$R_{tot} = R_{H2O,conv.} + R_{Cu,cond.} + R_{Air,conv.}$$

$$R_{H2O,conv.} = \frac{1}{h_{H2O} * A_{surf}} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}}$$

$$R_{Cu,cond.} = \frac{ln(D_{pipe,o} - D_{pipe,i})}{2\pi * k_{Cu} * l_{section}}$$

$$R_{Air,conv.} = \frac{1}{h_{Air} * A_{surf}} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}}$$

$$R_{tot} = \frac{1}{h_{H2O} * \pi * D_{pipe,i} * l_{section}} + \frac{ln(D_{pipe,o} - D_{pipe,i})}{2\pi * k_{Cu} * l_{section}} + \frac{1}{h_{Air} * \pi * D_{pipe,i} * l_{section}}$$

$$R_{tot,2} = \frac{1}{655.35 * \pi * 0.08542 * 2.5} + \frac{ln(0.09375 - 0.08542)}{2\pi * 231.84 * 2.5} + \frac{1}{3 * \pi * 0.08542 * 2.5}$$

$$R_{tot,4B} = 0.498\ \frac{°\mathrm{F} * h}{Btu}$$

$$\dot{Q} = \frac{173.87 - 115}{.498} = 118.26\ \frac{Btu}{h}$$

Surface Temperature of Pipe Section 4: $\dot{Q} = \frac{T_{surf,4} - T_{Air}}{R_{Air,conv.}}$

$$T_{surf,4} = T_{Air} + \dot{Q} * R_{Air,conv.} = 115°\mathrm{F} + 118.26\ \frac{Btu}{h} * \frac{1}{3 * \pi * 0.08542 * 2.5}\frac{°\mathrm{F} * h}{Btu} = 173.76\ °\mathrm{F}$$

Mass Flow Rate

Mass flow rate, section 2: $\dot{m}_2 = \rho_{H2O} A_2 V_2$

$$\dot{m}_{1,b1} = \left(1.887\frac{slugs}{ft^3}\right)(5.731 * 10^{-3}\ ft^2)\left(1.944\frac{ft}{s}\right) = 21.023 * 10^{-3}\frac{slug}{s}$$

$$\dot{m}_{1,b1} = 21.023 * 10^{-3}\frac{slug}{s} * 32.174\frac{lbm}{slug} = 0.676\frac{lbm}{s}$$

Outlet Temperature of Fluid through Pipe:

$\dot{Q} = \dot{m}c_{p,H2O}(T_i - T_o) = hA_s\Delta T_{lm}$, where ΔT_{lm} is a log-mean temperature defined by:

$$\Delta T_{lm} = \frac{\Delta T_o - \Delta T_i}{\ln\frac{\Delta T_o}{\Delta T_i}}$$

Simplifying and solving for T_o:

$$T_o = T_s - (T_s - T_i)e^{\frac{-hA_s}{\dot{m}c_p}}$$

For section 2:

$$T_{o,2} = 173.76 - (173.76 - 173.87)e^{\frac{-\left(655.35\frac{Btu}{h*ft^2*°F}\right)(\pi*0.08542\ ft*2.5\ ft)\left(\frac{1\ h}{3600\ s}\right)}{\left(0.676\frac{lbm}{s}\right)\left(1.002\frac{Btu}{lbm*°F}\right)}}$$

$$T_{o,2} = 173.67 - (-0.11)e^{-0.180} = 173.76\ °F = 78.76\ ℃ = T_{i,tank}$$

The tank inlet temperature of 78.76 ℃ is within the recommended maximum operating range of the GPUS of 75 ℃ $- 85$ ℃. This is under the conditions that the tank reached the maximum temperature before automatic shutoff of the GPUs of 90 ℃ $(194$ °F$)$ and the maximum recorded temperature of the St. Louis, Missouri area in history, 115 °F.

Total Head Loss

$$\Delta h_{total} = \Delta h_1 + \Delta h_{hose,1-R} + \Delta h_{rad} + \Delta h_{hose,R-2} + \Delta h_2$$

$$\Delta h_{total} = 0.421 + 9.631 * 10^{-3} + 76.279 * 10^{-3} + 34.943 * 10^{-3} + 0.0829$$

$$\Delta h_{total} = 0.625\ ft$$

Design Requirement: A pump is needed that can overcome 0.625 ft of head loss. The pump from the final design is rated for maximum of 48 ft of head.

12 APPENDIX C – BILL OF MATERIALS

Item	Name	Quantity	Piece Cost	Total Cost	Website/Location & Hyperlink	Scrounged Description	Lead Time
1	Fan/Air Movers	2	$ 99.00	$ 198.00	Lowes		Over the counter (OTC)
2	Radiator	1	$ 125.70	$ 125.70	Advance Auto Parts		Over the counter (OTC)
3	3/4in | Copper Pipe | 5ft Long	1	$ 13.96	$ 13.96	Lowes		Over the counter (OTC)
4	Radiator Hose | Outlet	1	$ 9.95	$ 9.95	RockAuto.com		5 days
5	Radiator Hose | Inlet	1	$ 3.49	$ 3.49	RockAuto.com		5 days
6	Hose Clamps	4	$ 1.29	$ 5.16	Home Depot		Over the counter (OTC)
7	Tank Seal - Inlet	1	$ -	$ -	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin	~2 hours print time
8	Tank Seal -Outlet	1	$ -	$ -	3D Printed	3D printed on Formlabs Form 3 SLA printer with Flexible 80A resin	~2 hours print time
9	3/4" GHT to 1-1/4" Radiator Hose	1	$ -	$ -	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin	~5 hours print time
10	3/4" GHT to 1" Pipe	1	$ -	$ -	3D Printed	3D printed on Formlabs Form 3 SLA printer with Tough 1500 resin	~5 hours print time
11	1in | Copper Pipe | 5ft Long	1	$ 29.45	$ 29.45	Lowes		Over the counter (OTC)
12	Pump	1	$ 98.00	$ 98.00	Home Depot		Over the counter (OTC)
13	3/4in | 90° Elbow Copper Fitting	2	$ 10.98	$ 21.96	Lowes		Over the counter (OTC)
14	1in | 90° Elbow Copper Fitting	2	$ 17.98	$ 35.96	Lowes		Over the counter (OTC)
15	Heater | 1500 Watt	2	$ 43.99	$ 87.98	Amazon		Over the counter (OTC)
16	Strut Channel | 10 ft	1	$ 22.58	$ 22.58	Lowes		Over the counter (OTC)
17	GPUs	2	$ -	$ -	N/A		N/A
18	Tank Support Plank	1	$ -	$ -	Scrounged	Any material that can be scrounged to help support the bottom PMMA sheet will suffice.	N/A
19	Strapping	4	$ -	$ -	Scrounged	Any material that can be scrounged to help support the bottom PMMA sheet will suffice.	N/A
20	PMMA Sheet | 48" x 96" x 1/8"	1	$ 153.94	$ 153.94	McMaster-Carr		1 day
21	PVC 90° Angle | 1-1/4" x 1-1/4" x 1/8"	6	$ 12.62	$ 75.72	McMaster-Carr		1 day
22	18-8 Stainless Steel Hex Screw | 50 Pack	2	$ 8.28	$ 16.56	McMaster-Carr		1 day
23	18-8 Stainless Steel Hex Nut | 100 Pack	1	$ 3.85	$ 3.85	McMaster-Carr		1 day
24	Shipping & Sales Tax - McMasterCarr	1	$ 118.62	$ 118.62	McMaster-Carr		N/A
Total				$ 1,020.88			

13 APPENDIX D - ANNOTATED BIBLIOGRAPHY

Lipika. (2018, April 17). *Why immersion cooling is imminent to power the next generation datacenters?* Web Hosting | Cloud Computing | Datacenter | Domain News. https://www.dailyhostnews.com/why-immersion-cooling-is-imminent-to-power-the-next-generation-datacenters.

Boushra, John; Duncan, Kyle; Koan Aleksandr; Pham, Giang. Sustainability: *Reusing Data Center Waste Heat.* Alexandria, Virginia: Capstone Design Expo Posters, 2016. Online Publication.

Kruse, Jason; Sesay, Osman; Goggin-Burns, Stephanie. *Optimizing Data Center Operations with Virtualization*. Alexandria, Virginia: Capstone Design Expo Posters, 2015. Online Publication.

Weidenbaum, Murray L. "The New Wave of Environmental Regulation: The Impact on Business and Consumers." Center for the Study of American Business. Paper 93 (1991): Published online.

Losio, Renato. "Cloud Computing in a SHipping Container: Microsoft Introduces the Azure Modular Datacenter." InfoQ.com (2020): Online Publication.

Munson, B. R., Okiishi, T. H., Huebsch, W. W., and Rothmayer, A. R., 2013,Fundamentals of Fluid Mechanics, JohnWiley and Sons, Inc., Hoboken, NJ.

Bergman, T. L. and Lavine, A. S., 2017,Fundamentals of Heat and Mass Transfer, John Wiley Sons, Inc., Hoboken,NJ.

Losses in Pipes," Queen's Universoty, CKingston, Ontario, Canada, accessed November 5, 2020, https://me.queensu.ca/People/Sellens/LossesinPipes.html

https://www.energycodes.gov/performance_based_compliance

http://www.ashrae.ottawa.on.ca/ashrae-ovc_history/2012-2013/Newsletter/201302-COM.pdf

https://www.c3controls.com/white-paper/nfpa-70-an-overview/

https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70E