Boeing Heat Exchanger

Final Report

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EXECUTIVE SUMMARY

Our project is dedicated to the design and development of a liquid-to-liquid heat exchanger, with a primary focus on optimizing heat transfer efficiency. This heat exchanger is to be integrated into a demonstrator that emulates the Environmental Control System of an AH-64 Apache helicopter using HFO-1234yf in place of R134a. Sponsored by Boeing, this project is a step towards environmental sustainability in the aerospace industry.

The team has made significant progress in project planning and design. Project requirements were clearly defined and performance/success targets were established according to client requirements. The team also conducted extensive literature review on critical subsystems of the demonstrator. This included mathematical modeling to guide and validate design choices and analysis of ECS on existing planes and helicopters.

The team created four different design alternatives for the demonstrator and evaluated their performance according to the mathematical modeling of each subsystem. The final design uses a copper U-Tube and shell heat exchanger, a water-propylene mixture as coolant, and polyurethane as insulation. This design has an estimated effectiveness of approximately 60% and it requires approximately 94 lbs of ice to operate for the required time period. K type thermocouples will be used for temperature monitoring on the heat exchanger.

Moving forward, the team will begin prototyping and refinement of the selected design. This will comprise of validating our heat transfer and pressure drop models experimentally and creating CAD models within SolidWorks. Additionally, the specific dimensions and geometry of the heat exchanger will be modified as needed to achieve the target heat transfer effectiveness or head loss requirements.

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1 BACKGROUND

This project was sponsored by the Boeing Company. As our clients, they outlined the overall premise of the project, project deliverables outside of course requirements, and project success criteria.

1.1 Project Description

The primary objective of this project is to design and construct an efficient liquid-to-liquid heat exchanger, with a strong emphasis on optimizing heat transfer efficiency, in collaboration with our esteemed client, Boeing, a global aerospace industry leader.

This project is of paramount importance as it addresses Boeing's transition from the widely used R-134a refrigerant to the more environmentally conscious R-1234yf refrigerant. This shift represents a substantial reduction in the environmental impact, with R-1234yf having a climate change potential over 1,000 times lower than R-134a. The project's primary significance lies in providing a robust and efficient heat exchanger that not only enhances aircraft systems' performance but also safeguards the cockpit and personnel from potential fire hazards due to R-1234yf's flammability.

1.2 Deliverables

The following items are the deliverables expected by the client by the end of the project:

1. **Efficient Liquid-to-Liquid Heat Exchanger:** The primary deliverable of the project is the design and construction of an efficient liquid-to-liquid heat exchanger. The heat exchanger will demonstrate the team's ability to optimize heat transfer, achieving high efficiency in heat exchange.
2. **Demonstrator:** A functional demonstration unit will be developed, showcasing the effectiveness of the heat exchanger. This demonstrator serves as a tangible representation of the team's proficiency in heat exchanger technology.
3. **Knowledge Showcase:** The project will include comprehensive documentation and presentations to effectively communicate the team's understanding of heat exchanger principles, design considerations, and the engineering process. This will serve as an essential component of the project's deliverables.
4. **Budget and Funding:** The project will outline a budget that encompasses costs related to design, construction, and documentation. The team may explore potential sources of funding or sponsorship to support the project.

1.3 Success Metrics

For the Boeing Heat Exchanger demonstrator success can be quantified by three metrics aligned with the customer requirements, successful operation of the system with no leaks, achieving predefined effectiveness goals and meeting all design constraints defined by the customer. Successful operation with no leaks can be defined as the system operating as intended with thermocouple display values displayed with reasonable accuracy, Proper flow through system with pumps operated by one master switch and the liquids in the system being completely contained in their respective flow path with zero leakage into either the outside environment or the other flow path. The heat transfer shall be dependent on ambient air temperature and radiator effectiveness. Proper effectiveness can be quantified simply as coolant exit temperature operating within 5 percent of the calculated exit temperature. This Data will be gathered using a

K-Type thermocouple and will be compared to values found through heat transfer analysis described in Section 3.3.3, with an input of the coolant inlet temperature and cold fluid inlet temperature. As per Boeing project Liaisons the physical dimensions and construction criteria and required components can be found in section 2, meeting all design constraints can be quantified as all dimensional constraints are not exceeded and all specified construction aspects are utilized as well as all customer specified components in their specified quantities are utilized in the final system.

2 REQUIREMENTS

Before the team can begin designing the heat exchanger demonstrator, the design requirements and performance metrics must be defined. The first step was to list out the requirements specified by the client. The team then created several technical requirements and performance targets based on the needs of the client. This information was correlated and summarized in a QFD to see which criteria were the most important for project success.

2.1 Customer Requirements (CRs)

Boeing outlined the following the success criteria for the demonstrator:

1. **Blows cold air onto the judge's hand:** The heat exchanger must have a high enough efficiency that the water cools the coolant far enough so the air through the radiator will feel cold.

2. **Inlets and outlets must pass through a firewall:** This system is to model a system which uses a flammable refrigerant, so there must be a firewall or metal shielding in place that could isolate/protect the pilot from potential combustion.

3. **Heat exchange must fit inside a 6”x6”x18” box:** The liquid-to-liquid heat exchanger must meet this maximum sizing requirement. No weight constraint is specified.

4. **Clear housing for the heat exchanger:** Since the client requires the design of a demonstrator, they have requested a clear housing to make the internal design of the heat exchanger visible.

5. **Portable:** The client would like to see the demonstration of the heat exchanger in person, so the system must be easy to transport and can be set up and operational within 1 hour.

6. **It must work for at least 30 minutes:** The client would like the heat exchanger to operate for a reasonable amount of time.

2.2 Engineering Requirements (ERs)

Taking the requirements defined by Boeing, the team created seven engineering requirements that the final design must meet:

1. Low Air Temperature: The system must channel cold air to an observer’s hand. As such, the design must be able to bring the fan air temperature as low as possible. At minimum, air temperature should be at least 5 °C below room temperature while the target temperature is 15 °C.

2. Small System Volume: The entire system must be easily transportable for transferring between facilities for testing or demonstration purposes. Thus, all components should fit within a compact volume. When packed, the system should fit within a volume of 1 m^3. Additionally, the client defined a maximum area of 6”x6”x18” for the liquid-to-liquid heat exchanger, which represents an additional volume constraint specific to that subsystem.

3. High Operation Time: The client specified that the system must operate for at least 30 minutes without melting all the ice within the system. As such, the design should be fully functional for more than half an hour.

4. **Low Pressure Drop:** An important consideration for heat exchanger design is the amount of head losses in the form of pressure drop. Client listed a specified pump that supplied 45 psi of pressure head. Given this limit, the team set the maximum allowable pressure loss to be 40 psi.

5. **Low Cost:** The team has a budget of $5,000 provided by Boeing with an additional $1,000 in the form of a VA grant. All testing equipment, prototyping, and material costs must collectively be below the $6,000 of funding available. To appropriately allocate the budget, the material cost of the system should be less than $1,000, excluding expenditures for ice.

6. **High Effectiveness:** The liquid-to-liquid heat exchanger is the main component to be designed. Since the team is unable to control the efficiency of the radiator (coolant-air heat exchanger), the liquid-to-liquid heat exchanger should be as efficient as possible. The team has defined an effectiveness target of 50%.

2.3 House of Quality (QFD)

The House of Quality (HoQ) is a fundamental tool used in quality function deployment (QFD), it serves as a method to establish a correlation between customer needs and expectations. In an engineering design project, the HoQ ensures that the design aligns with customer expectations by prioritizing design features/aspects that are often contradicting to make informed decisions to achieve a successful design that meets the customer requirements in their order of importance.

	Customer Needs
1	Fans should channel cool air to judge's hand
2	Inlet and outlet lines must pass through 'firewall'
3	Maximum 6"x6"x18" Heat exchanger
4	Clear Housings
5	Portable for demonstration
6	System must operate for 30 minutes

Fig 1. Customer requirements

1	Low Air Temperature
2	Small System Volume
3	High Operation Time
4	Low Pressure Drop
5	Minimized Cost
6	High HXR Effectiveness

Fig 2. Engineering Requirements

Figures 1 and 2 displays the customer and engineering requirements listed in the QFD for the Boeing Heat exchanger Demonstrator. A more detailed explanation of these can be found above in section 2.1 and 2.2 respectively. The full QFD can be seen in Appendix A

Low Air Temperature						
Small System Volume	-3					
High Operation Time	-3					
Low Pressure Drop		-3				
Minimized Cost	-3	3	-3			
High HXR Effectiveness	9	-6	-6	6	-9	
	Technical Requirements					
Customer Needs / **Customer Weights**	Temperatue Drop	Small System Volume	High Operation Time	Low Pressure Drop	Minimized Cost	High HXR Effectiveness

Fig 3. Engineering Requirements correlation

In Figure 3, we can clearly observe the correlations among engineering requirements (ERs). This relational aspect is a pivotal component of an effective Quality Function Deployment (QFD) for several reasons, including prioritization, resource allocation, trade-off assessment, and system optimization. Prioritization plays a crucial role by aiding in the identification of the most critical ERs during the design and development process. As depicted in Figure 3, there is a strong correlation between ER 1 and 6, highlighting their significance and need for prioritization. Careful allocation of resources is an important part of an engineering project, It serves to prevent excessive investments in less critical or relatively independent facets of the design, thereby ensuring that these aspects receive proportional benefits. When studying the correlations of ERs this allocation can be determined. In the context of the heat exchanger demonstrator project, many ERs conflict with one another requiring compromises. These conflicts are represented with a negative value for correlation.

Customer Needs	Customer Weights	Temperatue Drop	Small System Volume	High Operation Time	Low Pressure Drop	Minimized Cost	High HXR Effectiveness
Fans should channel cool air to judge's hand	5	9		6			9
Inlet and outlet lines must pass through 'firewall'	3		3			3	
Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6
Clear Housings	3	3			3	3	3
Portable for demonstration	3		9	3		6	
System must operate for 30 minutes	2	3		9		3	6

Figure 4. Engineering and Customer requirements correlation

In Figure 4 the correlations between the customer specified requirements and the engineering requirements can be seen as well as the weighting or importance of those customer requirements. The final weighted score can be seen in figure 5. Correlating engineering requirements and customer requirements in Quality Function Deployment is crucial for several reasons including ensuring a Customer-Centric Design, Measuring Success, and efficiency. A customer centric design ensures the product is more likely to satisfy the customer. Success can be more easily defined as relating CR’s and ER’s allows you to set up clear metrics for success. It also aids in avoiding over engineering.

Customer Needs	Customer Weights	Temperatue Drop	Small System Volume	High Operation Time	Low Pressure Drop	Minimized Cost	High HXR Effectiveness
Fans should channel cool air to judge's hand	5	9		6			9
Inlet and outlet lines must pass through 'firewall'	3		3			3	
Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6
Clear Housings	3	3			3	3	3
Portable for demonstration	3		9	3		6	
System must operate for 30 minutes	2	3		9		3	6
Technical Requirement Units		°C	m^3	min	PSI	USD	%
Technical Requirement Targets		>5	1	>30	<40	<6000	>50
Absolute Technical Importance		60	63	57	36	51	84
Relative Technical Importance		3	2	4	6	5	1

Figure 5. Target values and units

Figure 5 shows many crucial pieces to the team's final design including the weighted rankings, the target values and their units. As somewhat expected, high heat transfer and system volume are the two most important criteria for success (seen in the Relative Technical Importance section with rank 1). The team has defined this success metric as having a heat exchanger with a greater than 50 percent effectiveness. The rest of the values can be clearly shown in the figure above.

Benchmarking in a QFD is finding several products in the market to compare your design to. In most cases this will compare performance, learning from top performers, and setting performance targets. The teams selected benchmarking options can be seen in Appendix A. The team's selections for our product are not perfect comparisons as the majority of our benchmarks rank at the top or bottom of the list compared to our CR's. This is due to the team's target design being a demonstrator unit rather than a commercial unit like most products. The specific benchmarking selections are explained further in Section 3.1.

3 Research Within Your Design Space

The team conducted a comprehensive review of existing Environmental Control Systems (ECS) and literature relevant to the subsystems of the demonstrator. Additionally, the team performed a variety of mathematical modeling processes to make informed decisions regarding the final design.

3.1 Benchmarking

In order for the team to gain a better understanding of how to make the project stand out they will need to understand the current market for similar systems. Most heat exchangers in the aeronautica world today focus on the effectiveness and heat transfer per unit volume. The team went through and judged three that would be possible to make and graded them based on how they met the customer requirements as well as how much manufacturing would be needed in order for them to be implemented.

Plate Heat Exchanger [14]

These heat exchangers provide the best heat transfer per unit volume and are used in most aeronautical applications. They implement the use of plates that funnel the warm fluid through tubes while passing colder fluid over them causing the heat to leave the warm fluid and be transferred into the cold fluid. They are difficult to manufacture and would require a large volume of CNC'd parts. They also require complete surface contact in order for high effectiveness so making them see through is very difficult without compromising effectiveness.

Shell and Coil Heat Exchanger [14]

These heat exchangers implement the use of a shell to hold the cooling fluid to pass over helical tubes that carry the warmer fluid and through the convection of the tubes the heat leaves the warm side and enters the shell side. They generally have an ok effectiveness but their heat transfer per volume is generally pretty low. They are also pretty easily made see through via the shell but the helical tubes would take a lot of manufacturing without compromising the sealing of the tubes.

Shell and Tube Heat Exchanger [14]

These heat exchangers implement a similar design to helical except with the use of straight tubes that then once they pass through the shell once they double back across the shell coming out the same side they started with. They are generally the weakest when it comes to effectiveness but their heat transfer per unit volume is about the same as a shell and coil heat exchange. They are also easily implemented to be seen through and are generally not very difficult to manufacture.

3.2 Literature Review

3.2.1 Chris Mason

3.2.1.1 Papers

Thermal and Acoustic Insulation [4]
This article gives some detailed examples of possible insulations we could use in order to successfully keep thermal energy storage for longer periods of time. In order to make the ice water reservoir more efficient we must add thermal insulation so we can remove the heat gain from the container.

Simon Ostrach's Natural Convection in Enclosures [5]
This article gives the team a better understanding of how convection currents will react within the reservoir as well as lists different experiments the author conducted that the team can relate the design to.

P.B.L Chaurasia's Comparative study of insulating materials in solar water storage systems [6]
This article goes into a detailed comparison of different insulations used in SWS systems which will allow the team to get a good idea of what kind of insulators are used in the corporate world and it may give the team a better idea of what kind of insulators to focus on.

Thermo-economic analysis of old storage systems in full and partial modes with two different scenarios: A case study [7]
This article talks about ice water storage for refrigeration systems used in factories. This will give the team a good example of how to keep the ice water cold for longer periods of time as well as may present different ideas the team may not have thought of.

3.2.1.2 Textbooks

Fundamentals Of Heat and Mass Transfer, Chapter 6 [8]

This chapter goes into a detailed introduction of convection forces and how to simply calculate them within simple geometry. The reservoir will contain both ice cold water and heated water so there will be convection heat transfer between the two and we must calculate how the cold water will be affected if it is to remain ice cold. There will also be convection heat transfer between the surface of the container and the flowing liquid which will involve some heat gain from the container.

Fox and Mcdonald's Introduction to Fluid Mechanics, Chapter 4 [9]

This chapter goes into the basic equations batting on a fluid with a control volume as well as it introduces the energy balance equation that we used to calculate the amount of ice needed to keep the reservoir cool.

Thermal Energy Systems Design and Analysis 2nd Edition [10]

This book contains detailed analysis of both thermal storage systems and heat exchangers. This book will help the team evaluate the heat exchanger and the ice water once they make a physical prototype by demonstrating the expected values from our thermal energy systems as demonstrated in the analysis of thermal energy systems chapter. It also will provide the team with the common economics of some heat exchangers already currently used to help them compare their overall model to those already created.

3.2.1.3 Websites
Final Temperature of mixtures (Richmann's Law) [11]

This formula is just a simple energy balance to find the change in energy in the water and thus what the final temperature will become when mixing hot and cold water. Since there will be two different water temperature mixing together Richmann's law offers a easy way to calculate the final temperature at any point as long as we know the mass and temperature of both temps of water at that point in time.

Ice - Thermal Properties [12]

This table provides the team with what they need in order to account for the specific heat of the ice they will be using in order to completely calculate how much energy the ice will be able to absorb within the ice water reservoir. This also provides the team with the specific properties of ice in case the team wants to find specific times for the ice to melt or other ice properties.

BUTELINE plumbing system - Polyethylene [13]

This website goes into great detail on the applications and costs of polyethylene. The team will be able to use this website in order to find the best polyethylene to use whether it be manufactured or they apply it themselves. This website also provides specific properties of polyethylene which the team will use in calculations for their ice water reservoir.

3.2.2 Dennis Decker

3.2.2.1 Papers

Heat Exchangers : Characteristics, Types and Emerging Applications [14]

This paper breaks down each heat exchanger type and where their strengths lie with numerical values that show compared to traditional shell and tube Heat exchangers. This source was most useful for deciding on the style of heat exchanger the team wanted to go with. Something that I took from this source was that the surface area required for a plate heat exchanger is 30-50% less than shell and tube heat exchanger.

Design and Operation of Heat Exchangers and their Networks-Chapter 3:Steady State characteristics of Heat exchangers [15]

This source was a Chapter of a paper that derives properties of heat exchangers based on flow and heat transfer characteristics at S.S. Condition which was useful for understanding the math at play in the teams designs.

Three-dimensional fin-tube expansion process to achieve high heat transfer efficiency in heat exchangers [16]

This source was a paper that discusses how incorporating grooves on a fin-tube type heat exchanger to greatly improve heat transfer mainly focused around a new 3D ball design that dramatically decreased the need to reduce fin size due to expansion. This source was not especially relevant but it gave some interesting ideas on fin implementation.

3.2.2.2 Textbooks

Heat Exchanger Design Handbook [17]
This book encompasses most heat exchanger designs with good detail into the selection process and Mathematical aspect of them.Some of the chapters include but not limited to thermohydraulics, shell and tube heat exchangers, plate heat exchangers, mechanical design, material selection and fabrication

Fundamentals of Heat and Mass Transfer, Chapter 11 [8]
This chapter of the heat transfer book explains in depth the math involved in analyzing heat exchangers. It was my primary resource for the heat exchange design process as it has a section for all of the math required to properly design a heat exchanger.

Theory and Design for Mechanical Measurements, Fifth Edition [18]
This textbook delves into the uncertainty in systems and the error propagation due to uncertainties. it was the primary resource used in section 6.3.1.

3.2.2.3 Websites

Engineering Toolbox [19]
This was a useful website that provided a large amount of factors that were needed to mathematically model the teams heat exchangers.

GrabCad Solidworks: How to perform a transient Thermal Analysis in Solidworks [20]
This website provided a step by step walkthrough of how to accurately model the heat transfer of an object in solidworks. This will be useful in making sure there isn't heat transfer in places that it shouldn't be.

GD&T and Stack up (Basic to expert level) [21]
This online resource provided an in depth explanation into how GD&T is used and what all of the terminology means as well as design validation. This will be used in the final CAD.

O-Ring Groove Design [22]
This Website goes into great depth into designing the O-ring grooves, tolerances and actual O-ring selection. as our final design needs to be waterproof, O-rings will be utilized in final construction.

3.2.3 Lorenz Vios
3.2.3.1 Papers

Heat Transfer and Flow Characteristics of a Conical Coil Heat Exchanger [23]

This paper provided flow and heat transfer data for a heat exchanger using a coiled tube. The paper details the effects of coiling the tube of the heat exchanger on the overall heat transfer rate. The curved tube induces more mixing in the fluid compared to a straight tube, especially in laminar conditions. The discussion in the paper will be useful for calculating the curvature effects on the heat transfer in coiled heat exchanger tubes.

Heat transfer enhancement for shell and coil heat exchanger [24]

This paper provided an analysis of heat transfer improvement in coiled heat exchangers using a wire to induce turbulence within the coil. The wire improved fluid mixing and increased the reynolds number within the tube, increasing the heat transfer. This also caused a significant increase in pressure drop across the tube side of the heat exchanger. The results of this paper will be useful for determining the performance and potential improvement of coil heat exchangers.

Computational Fluid Dynamics Analysis for Shell and Tube Heat Exchangers [25]

This paper discusses the performance of shell and tube heat exchangers with different tube configurations. Staggered and in-line configurations were analyzed using CFD to determine heat transfer effectiveness. It was found that staggered tube bundles had higher heat transfer than their in-line counterparts. This information will be useful for determining an optimal tube configuration for a shell and tube heat exchanger.

3.2.3.2 Textbooks

Fox and Mcdonald's Fundamentals of Fluid Mechanics, Chapter 8 [9]

This chapter details the analysis of internal incompressible fluid flow. The book provides equations and material properties that are useful for calculating head losses within pipe networks, such as the Colebrook equation, pipe roughness, and Reynolds number formulas.

DOE Fundamentals Handbook: Heat Transfer, Thermodynamics, and Fluid Flow [26]

The chapter on heat exchangers discusses different design considerations regarding fluid flow within heat exchangers. For example, counterflow heat exchangers tend to have higher heat transfer rates and lower thermal stresses compared to designs with parallel flow.

Fundamentals of Heat Exchanger Design [27]

This textbook contains a chapter regarding pressure drop analysis within heat exchangers for some geometries. It also discussed several correction factors to account for inefficiencies due to fouling, leakage, and other operational conditions.

Plant Design and Economics for Chemical Engineers [28]

This textbook details various design considerations for heat exchangers and how to estimate their performance. There is some discussion on the Kern method for evaluating efficiency and pressure drop for shell and tube heat exchangers. The book also lists some operating factors to consider such as fouling and leakage. These factors can lead to higher inefficiencies in some cases, which may be useful for explaining discrepancies between calculated performance and actual performance.

3.2.3.3 Websites

Shell and Tube Heat Exchanger Pressure Drop [29]

This website provides a simple overview on the calculation of pressure drop on both sides of a shell and tube heat exchanger. While not as sophisticated as the equations provided in the previous textbooks, the simple equations and discussions on this site can give a rough estimate of the pressure drop early on in the project. More time consuming calculation methods such as CFD and advanced equations can then be used once the team starts to finalize the design of the liquid-to-liquid heat exchanger.

Solution Setup in Ansys Fluent [30]

This tutorial course walks through the basic steps for setting up solution methods for Ansys Fluent simulations. It was useful for explaining the various options for running simulations and how to monitor convergence. The example solution involved flow simulation through a finned heat exchanger.

Heat Transfer Modeling in Ansys Fluent [31]

This tutorial specifically explains how to conduct heat transfer analysis using Ansys Fluent. It included how to set up thermal boundary conditions and how to model all three modes of heat transfer. CFD software is a powerful tool for modeling our system. The simulation can be used to predict performance parameters with more precision than applying empirically derived formulas, given that the simulation is set up correctly. As such, this tutorial helps the team understand good practices in Fluent which will lead to valid results from the simulation.

3.2.4 Uriah Whitaker
3.2.4.1 Papers
Modeling of thermocouple geometry variations for improved heat transfer monitoring in smart electronic manufacturing environment [32]

To ensure accurate temperature data acquisition and analysis, we delved into existing research studies. One such study, titled "Effect of Thermocouple Constructions on Soldering Profile Acquisition," provided valuable insights into different thermocouple constructions and their implications on temperature measurements during heat transfer processes. This research focused on convection-based reflow and condensation-based vapor phase soldering, processes that share similarities with our heat exchanger application. The key parameters examined in this study included the type of thermocouples (e.g., ASTM-type K, T, J), the length of uninsulated wire, insulation materials (PFA, PVC, PTFE, woven glass-fiber), insulation thickness, and the diameter of the hot-spot. Finite element analysis was used to simulate temperature measurements.

Measurement of local wall temperature and heat flux using the two-thermocouple method for a heat transfer tube [33]

In pursuit of precise temperature measurements within our liquid-to-liquid heat exchanger, I delved into an experimental study that assessed the accuracy of the two-thermocouple method in measuring local wall temperature and heat flux. The study was conducted on a heat transfer tube with an electric heater rod installed in an annulus channel. The key findings of this research unveiled valuable insights into thermocouple placement and their impact on temperature measurement accuracy.

Combination of Local Heat Transfer and Flow Visualization of R245fa Flow Boiling in plate Heat Exchanger[34]

The pursuit of an efficient liquid-to-liquid heat exchanger design has been further enriched by an experimental study that focuses on local heat transfer coefficients in the context of evaporation. This study was conducted using R245fa as the working fluid, which bears substantial significance for our project. The experimental endeavor featured a multifaceted approach, encompassing temperature profile measurement, local heat flux assessment, and the determination of heat transfer coefficients across the plate's surface. To enable this comprehensive data collection, an internally developed heat flux meter was employed. This unique device was assembled from two original plates, each adorned with thermocouples soldered to their surface, and sandwiched with a thermal infill material in between. Through diligent calibration, the heat flux meter's local thermal resistance was established.

3.2.4.2 Books

***Operator's Manual for Army AH-64A Helicopter*. 1989. [35]**

For optimizing heat exchanger technology, it is crucial to consider the unique operational requirements of aviation, particularly in military applications such as the AH-64A Apache attack helicopter. The "TM 1-1520-238-10 Operator's Manual Helicopter, Attack, AH-64A Apache" serves as a valuable resource, shedding light on the specific challenges and requirements related to avionics and comfort cooling within the Apache helicopter. One significant insight derived from this manual is the critical role of avionics cooling in maintaining optimal performance and safety during combat missions. The manual outlines the importance of ensuring that avionics systems are kept within their operational temperature limits, highlighting the relevance of effective cooling mechanisms. This emphasizes the need for a reliable and efficient heat exchanger system that not only maintains cockpit comfort but also safeguards sensitive avionics equipment.

Fundamentals of Engineering Thermodynamics, 8th ed Chapter 2 [36]

Chapter 2 of the textbook "Fundamentals of Engineering Thermodynamics" covers fundamental concepts related to operating conditions for heat transfer systems. This information can help the team understand how to consider and analyze the specific conditions under which the heat exchanger will operate.

Fundamentals of Engineering Thermodynamics, 8th ed Chapter 8 [36]

Delves into fluid properties, including Fourier's Law, which is fundamental to heat transfer analysis. Understanding fluid properties is crucial for optimizing our heat exchanger's performance. Provides information on heat transfer analysis. This chapter covers the principles and methods of analyzing heat transfer, which is central to your project's goals.

Arduino development cookbook [37]

"In 'Arduino Development Cookbook' by Cornel Amariei, published by Packt Publishing in 2015, readers explore a comprehensive guide featuring over 50 hands-on recipes. This 1st edition caters to both Arduino novices and experienced users, offering diverse projects from basic to advanced. Structured in a recipe format, the book enables quick comprehension and implementation of Arduino applications, covering topics such as sensor interfacing, display utilization, and communication protocols. This resource proves beneficial for programming thermocouples with Arduino."

3.2.4.3 Websites

Tinkercad [38]

The integration of Arduinos into the heat exchanger project offers a practical approach to temperature measurement, control, and data acquisition. To better understand the implementation of Arduinos with thermocouples, the team utilized Tinkercad, a popular online platform for simulating and prototyping Arduino-based systems.

“PDE 101: Separation of Variables! ...or how I learned to stop worrying and solve Laplace’s equation [39]

In the tutorial "PDE 101: Separation of Variables," the intricate process of solving Laplace's equation for heat transfer is demystified. The breakdown of Laplace's equation is a key focus, particularly in its application to understanding the heat transfer dynamics within a given system. The tutorial emphasizes the utilization of the Separation of Variables technique, shedding light on how this method simplifies the solution process.

Arduino Thermocouple and LCD Tutorial [40]

In the tutorial titled "Arduino Thermocouple and LCD Tutorial," the intricacies of interfacing a thermocouple with an Arduino and displaying the results on an LCD screen are explored. The tutorial delves into the step-by-step process of setting up the Arduino, connecting the thermocouple, and programming the system to read and display temperature data on the LCD.

3.3 Mathematical Modeling

3.3.1 Amount of Ice With Sensible and Latent Heats - Chris Mason

In order to get our system to run for 30 minutes we will need to know how much ice we will need to keep the ice water cold and in turn the coolant as well. First I implemented the energy balance equation knowing that ice can absorb 334$\frac{kj}{kg}$ before it goes from a solid to liquid state and found that the ice we will be choosing has a specific heat of 2 $\frac{kj}{kg^{o}C}$ when it is kept at -20^{0}C. The assumptions made were the heat transfer from the ambient air to the water is zero due to us picking a well insulated cooler, the volumetric flow rate of the water is equal to the rate of the pumps which is 4 $\frac{gal}{min}$, and that our ice for the time being is at freezing temperature of 0^{0}C to create a nice factor of safety and to neglect the freezing of the water. First we will start with the following energy equation [5]:

$$E = m \times h_c \times \Delta T \tag{1}$$

E = Energy
m = mass
h_c = specific heat capacity
ΔT = difference in temperature

Next we will use this equation to find how much ice we will need to get the initial room temperature water (20ºC) in the reservoir to our starting temp of 0ºC.Using the equation above we get the energy we need to remove is, 922.45 kJ.We can then find the amount of energy needed to be absorbed by the ice in the heated water as it passes from the heat exchanger into the reservoir. Using the specific heat capacity of water and the final temperature being the same as the ice which is 0ºC we will then say the inflowing temperature of the water is 15^{0}C and then we get the mass flow rate from the volumetric flow rate as 0.2567 $\frac{kg}{s}$ and then multiply it by the amount of water that will be flowing in over a 30 minute period. We then get that the total mass of the water flowing in a 30 minute period is 454.86 kg which we can use the mass to derive that the total amount of energy that is needed to be absorbed is, 29,483 kJ.Next we can then sum up the energies and divide by the 334$\frac{kj}{kg}$ the ice can absorb plus the amount of heat required to get the ice to the phase change state which is the specific heat 2 [12] multiplied by the temperature change which is 20ºC which gives us another 40 $\frac{kj}{kg}$ the ice can absorb which gives a total of 374 $\frac{kj}{kg}$ and we will get a value of 173.8 lbs of ice that would be required in order to have our heat exchanger run for 30 minutes. With our increase in our heat transfer efficiency it causes us to have a higher inlet temperature going into the ice reservoir and in doing so requires more ice in order to absorb the amount of energy that is being introduced. The team has also decided on getting a better pump in order to increase our efficiency and in doing so will also increase the mass flow rate going into the reservoir which in turn requires more ice in order for the system to run for 30 minutes.

3.3.2 Reservoir Heat Transfer Analysis - Chris Mason

Once the team found that any insulation for the cooler would work they then needed to find how much heat transfer was truly being lost over the 30 minute period. The team began by choosing a cooler online and although the team know the size and type of insulation they would like for the cooler the team in beginning talks with canyon coolers to see if they could possibly answer a few questions or perhaps donate a cooler if willing. The cooler this analysis will be on is a simple 100 qt polyethylene cooler found on amazon. From the dimensions provided by amazon the team can begin to use shape factors in order to calculate how much heat transfer will be through the cooler walls and into the reservoir. To begin first the team had to calculate the total shape factor of the cooler using the dimensions 90cm x 45cm x 43cm and a thickness of 0.5cm.

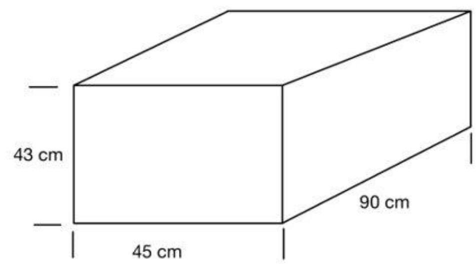


Figure 6. Cooler Dimensions

The following equations were used to calculate the individual components of the shape factor [8].

Sides = $\frac{A}{L}$ Edges = 0.54w Corners = 0.15L

Since the cooler is not completely symmetrical in order to correctly calculate the shape factor there had to be implemented the correct values for all the different sides and edges that were the cooler. The team also assumed the cooler was a perfect rectangular prism as that is what the dimensions on amazon were given as. From the dimensions it was found that this cooler had 3 types of sides, 3 types of edges, and only one type of cooler. Once the team found the individual shape factors for each of the different dimensions the team summed up all the shape factors and got a total shape factor of about 3.86m. The following equation involving the shape factor was used to calculate the heat transfer [8].

$$q_{cond} = k \times S \times \Delta T$$

k = Thermal Conductivity

S = Shape Factor

ΔT = Temperature Difference

Using this equation and plugging in that the thermal conductivity of polyethylene is k = 0.5 $\frac{W}{mK}$ [13] and assuming the ambient air temperature is 20ºC and the internal temperature is 0ºC the team found a heat transfer value of only 69.48 kJ. If you compare this value to the amount of energy that is being added to the reservoir from the inflowing water you will notice that this value is substantially smaller and therefore only removes about 0.2 kg of ice and therefore can be neglected as long as the team puts in a factor of safety for the ice. This whole calculation was used in order for the team to prove that they can neglect the heat transfer from the air through the cooler as long as they choose a well insulated cooler and from these calculations it is safe to assume so.

3.3.3 Heat transfer Analysis - Dennis Decker

To properly design a heat exchanger that reaches our design goals, heat transfer analysis is essential to answer design questions. A proper heat exchanger analysis for the purposes of this project should look at maximizing the efficiency of heat transfer while also determining the ideal size and geometry such as components like tube length, diameter, and shape. It is also important to have a good estimate for performance to determine if a redesign is necessary. The team has decided on two main design options, a Shell and tube and shell and coil. For these two designs the assumptions will be the same and are as follows. The ambient air temperature will be 24 ℃ and the radiator (liquid-air) will have η=100% (i.e. $T_{h,in}=T_{amb}$). Additionallyfully developed steady state flow will be assumed as well as an insulated Shell. Finally since the heat transfer through conduction can be ignored as highly conductive materials will be used.

The team's final design is a shell and tube design due to the simplicity and ease of manufacturing. The aim of this analysis is to determine a preliminary heat transfer and effectiveness value. To start the Reynolds number (Re) the shell and tube side will be needed and can be solved using the equation below with v_c = velocity at the centerline of the tube bank, d_o = OD of the tube, ρ= density of the fluid, and μ = dynamic viscosity

$$Re_s = \frac{\rho * v_c * d_0}{\mu} = 3459.13 \tag{6}$$

and the Reynolds number of the the internal flow can be found with v=velocity of internal fluid, and d_i= internal tube diameter

$$Re_t = \frac{\rho * v * d_i}{\mu} = 178.28 \tag{7}$$

Next, the Nusselt number can be solved using the following equations With the Reynolds number solved for and the Prandtl number (Pr), assumed to be a constant at our desired temperature range. C and m are given as constants within our operation parameters and are C=.51 and m=.5 and *f* is the friction factor for inside the pipe

$$Nu_s = C * Re_s^m * Pr^{(1/3)} = 18.09 \tag{8}$$

$$Nu_t = \frac{(f/8)(Re_s - 1000)Pr}{1 + 12.7(f/8)^{(1/2)}(Pr^{(2/3)} - 1)} = 65.20 \tag{9}$$

These Nusselt numbers can then be used to solve for h the convective heat transfer coefficient using the following equations with k= the conductive heat transfer coefficient of the fluid and d_i=outer diameter of tube and d_o=the OD of the tube.

$$h_s = \frac{Nu_s * k}{d_o} = 1472.02 \text{ W/m}^2\text{℃} \tag{10}$$

$$h_t = \frac{Nu_t * k}{d_i} = 8070.54 \text{ W/m}^2\text{℃} \quad (11)$$

due to half the length of the pipes experiencing counter flow and half experiencing parallel flow using the experimentally verified NTU method is required. To find the NTU number the following equation is used with C_{min}= min(C_h,C_c) and A =the area of the heat transfer surface.

$$U = \left(\frac{A_o}{A_i h_t} + \frac{A_o ln(d_o/d_i)}{2\pi Lk} + \frac{1}{h_s}\right)^{-1} \text{ W/m}^2\text{ K} \quad (12)$$

$$C = \dot{m} * C_p \text{ kJ/s} \quad (13)$$

$$NTU = \frac{U*A}{C_{min}} \quad (14)$$

With the NTU the overall effectiveness of the heat exchanger can now be found using the following equation and Cr=Cmin/Cmax

$$\varepsilon = 2\{1 + C_r + (1 + C_r^2)[\frac{1+exp[-(NTU)(1+C_r^2)^{(1/2)}}{1-exp[-(NTU)(1+C_r^2)^{(1/2)}}]\}^{(-1)} = .621 = 62.1\% \quad (15)$$

A 62.1% effectiveness is not especially high but due to the selected pumps and specific heat capacity of the selected fluids this is approximately the maximum achievable effectiveness.

3.3.4 Pressure Drop Analysis - Lorenz Vios

While it is important to select a heat exchanger geometry with a high effectiveness, it is also important to ensure that the pumps are able to provide enough head to drive the flow. The heat exchanger represents the vast majority of the head loss that will occur in the fluid flow. Thus, analysis of the pressure drop across the heat exchanger is critical for the feasibility of the heat exchanger design.
To calculate the major head loss for the tube side of the heat exchanger, the friction factor must be found using the Colebrook equation [5]:

$$\frac{1}{\sqrt{f}} = -2.0 * log(\frac{e/D}{3.7} + \frac{2.51}{Re*\sqrt{f}}) \quad (23)$$

f = friction factor
e = pipe roughness
D = inner diameter of tube
Re = tube Reynold’s number

Assuming a propylene glycol mixture, a commercially smooth metal tube (e = 5E-6 ft.), a flow rate of 4 gpm, 2 tubes, and the diameters of the tube (D = .375 in.), the Colebrook equation can be solved iteratively using MATLAB. The friction factor was found to be:

f = .0654

The friction factor can then be used in the following equation to find the pressure drop (Δp) in the system:

$$\Delta p = \rho(f * \frac{L}{D} * \frac{V^2}{2}) \quad (24)$$

ρ = fluid density
L = tube length
V = average fluid velocity

The tube has two 12 in. tubes doing two passes, so the total length, L_{Total} = .6092 m. Therefore, the total pressure drop of the tube side is:

Δp = **6811 Pa** or **0.988 psi**

With a maximum pressure drop of 40 psi across the entire coolant loop, the pressure drop across the heat exchanger is minimal. The selected pump can safely drive the coolant flow through both the heat exchanger and the radiator.

3.3.5 Choosing the Thermocouple - Uriah Whitaker

Table 1. Thermocouples

	Wire		
Type	Positive	Negative	Expected Systematic Uncertainty[b]
S	Platinum	Platinum/10% rhodium	±1.5°C or 0.25%
R	Platinum	Platinum/13% rhodium	±1.5°C
B	Platinum/30% rhodium	Platinum/6% rhodium	±0.5%
T	Copper	Constantan	±1.0°C or 0.75%
J	Iron	Constantan	±2.2°C or 0.75%
K	Chromel	Alumel	±2.2°C or 0.75%
E	Chromel	Constantan	±1.7°C or 0.5%

Alloy Designations
Constantan: 55% copper with 45% nickel
Chromel: 90% nickel with 10% chromium
Alumel: 94% nickel with 3% manganese, 2% aluminum, and 1% silicon

[a]From Temperature Measurements ANSI PTC 19.3-1974.
[b]Use greater value; these limits of error do not include installation errors.

By carefully considering the temperature range, environment, and specific application requirements of the heat exchanger project, our team can make informed decisions regarding thermocouple type selection. This ensures that the chosen thermocouples are best suited for accurate and reliable temperature measurement within the heat exchanger system.

3.3.6 Accuracy of thermocouples

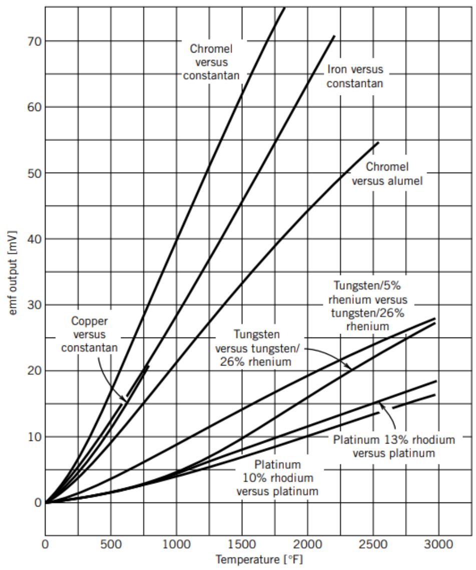


Figure 7: Thermocouple Voltage Output

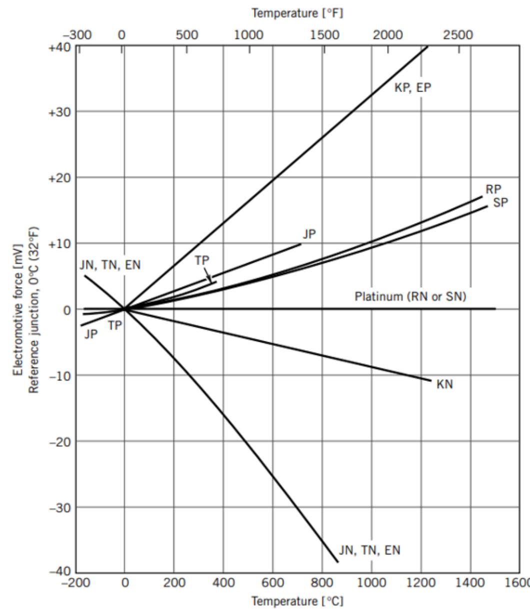


Figure 8: Thermal emf of Thermocouple Materials

The selection of the most suitable thermocouple for our heat exchanger project involved a thorough evaluation of the temperature range, environment, and cost-effectiveness. In this process, reference was made to Theory and Design for Mechanical Measurements to assess the accuracy of available thermocouples within the operating temperature range of our heat exchanger.

Upon analysis, it was determined that multiple thermocouple types were suitable for the intended temperature range of our project. This versatility allowed us to consider factors beyond accuracy, such as cost-effectiveness. In the context of our heat exchanger, where precision and budget constraints play crucial roles, this decision-making process was pivotal. The outcome of this evaluation was the identification of a thermocouple type that not only met the accuracy requirements but also aligned with the cost constraints of our project. This pragmatic approach ensures that we are not only measuring temperature effectively but also doing so in a manner that is financially sustainable. By leveraging Theory and Design for Mechanical Measurements and the balance between accuracy and cost-effectiveness, the team selected K type thermocouples for the heat exchanger, contributing to the overall efficiency of the project.

4 Design Concepts

After extensive research, the team moved forward to system design. A functional model of the system was created to identify key functions and input-output flows. This aided in the identification of key subsystems within the design. The team created several designs based on the generated concept variants for each subsystem then analyzed their expected performance using a Pugh chart and decision matrix according to the engineering requirements previously discussed.

4.1 Functional Decomposition

In order to keep track of the functions of each component and the flow of inputs and outputs, the team created a functional model. The model shown in Figure 8 shows each material, energy, and signal input as they move through the processes in the demonstrator.

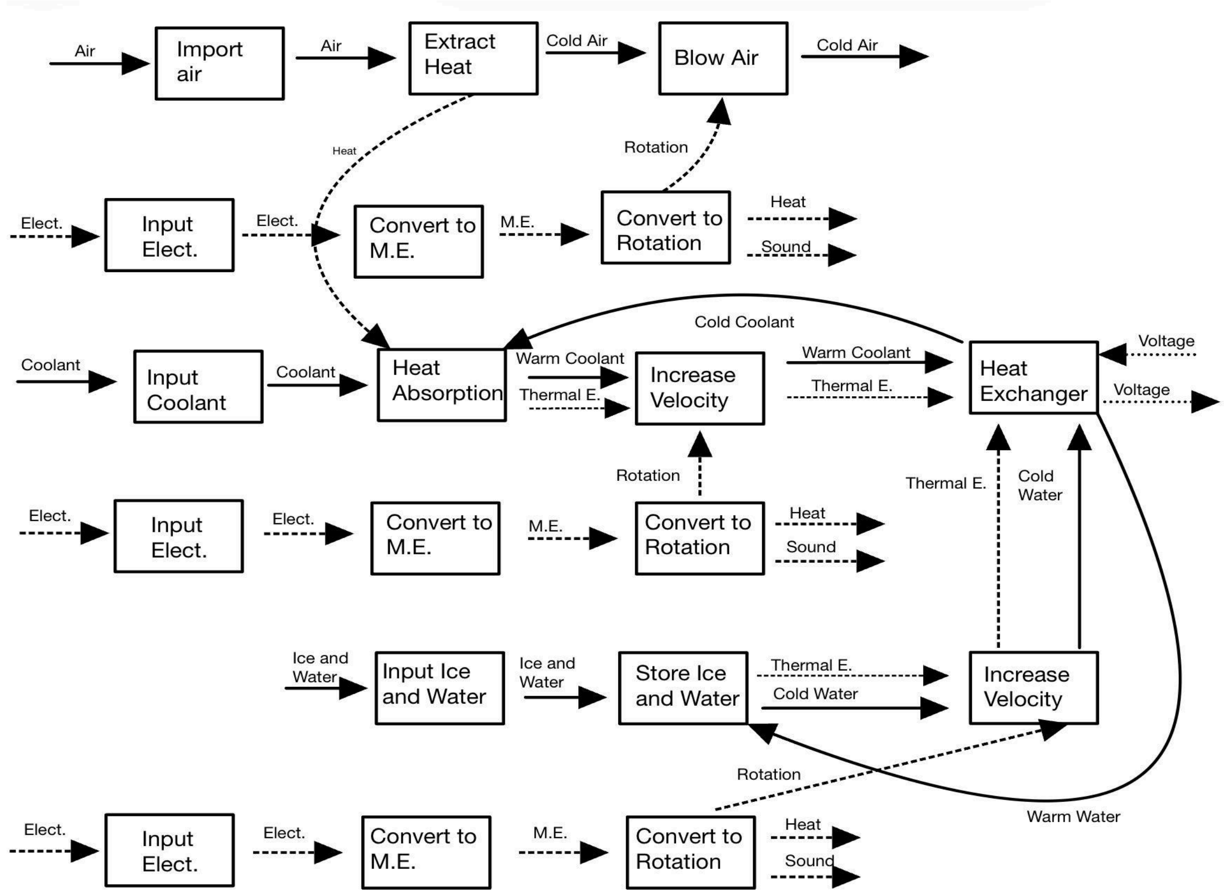


Figure 9: Functional Decomposition Model of Heat Exchanger Demonstrator

With so many inputs and outputs, it is important to understand how each input is used to create the desired output. For example, the water and coolant are shown to be part of a loop as they enter the heat exchanger then flow back to earlier steps in the functional model. Meanwhile electrical energy is being used to power the fans and pumps. The most important output is the cold air but the two liquid loops are heavily involved in cooling down the air. Additionally, the voltage entering and leaving the heat exchanger represent the thermocouples which will be used to monitor the effectiveness of the heat exchanger.

4.2 Concept Generation

In the concept generation phase, our team explored several top-level concepts, each with unique configurations and materials. These concepts aimed to optimize the heat exchanger's efficiency while adhering to the project's specific requirements. Below, we present an overview of each concept and an initial assessment of their pros and cons. An overview of each concept along with initial pro and con assessment is provided below:

4.2.1 Concept A

Tube Material: Copper
Coolant: Propylene Glycol
HXR Geometry: Shell and Tube
Insulation: Polyurethane
- **Pros:** Tubes have high thermal conductivity; geometry is easy to manufacture.
- **Cons:** High relative cost of insulation; high head losses in tubing

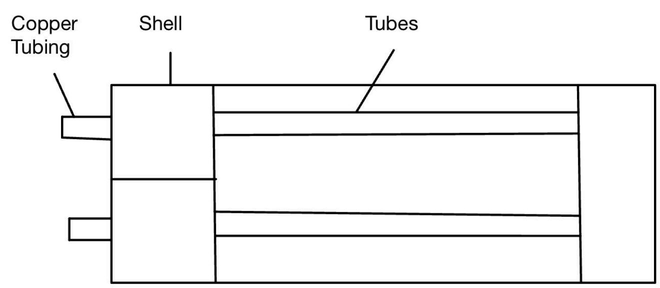


Figure 10. Concept A

4.2.2 Concept B

Tube Material: Aluminum
Coolant: Ethylene Glycol
HXR Geometry: Shell and Helical Tube
Insulation: Polyethylene HD
- **Pros:** Aluminum is cheap and easy to work with; helical tubing reduces heat exchanger volume
- **Cons:** Helical geometry not as effective; helical tube poses manufacturing challenges; coolant is toxic

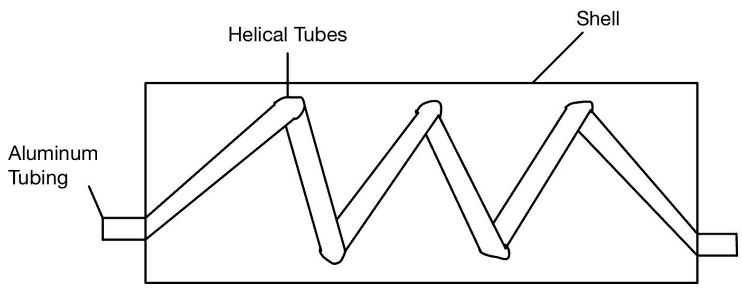


Figure 11. Concept B

4.2.3 **Concept C**

Tube Material: Copper
Coolant: Ethylene Glycol
HXR Geometry: Shell and Tube
Insulation: Polyethylene LD

Pros: LD Polyethylene is cheap; helical tubing reduces heat exchanger volume;
Cons: High head losses in tubing; coolant is toxic

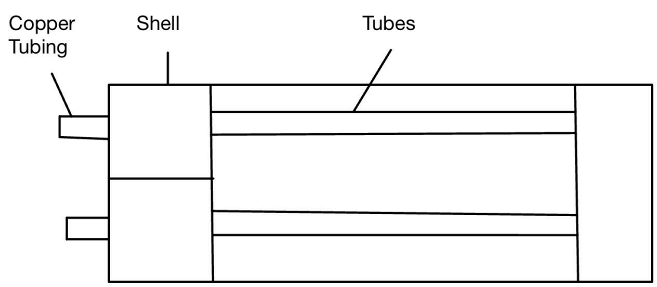


Figure 12. Concept C

4.2.4 **Concept D**

Tube Material: Aluminum
Coolant: Propylene Glycol
HXR Geometry: Shell and Helical Tube
Insulation: Polystyrene (styrofoam)

Pros: Aluminum is cheap and easy to work with; polystyrene provides cost-effective insulation.
Cons: Helical geometry not as effective; helical tube poses manufacturing challenges

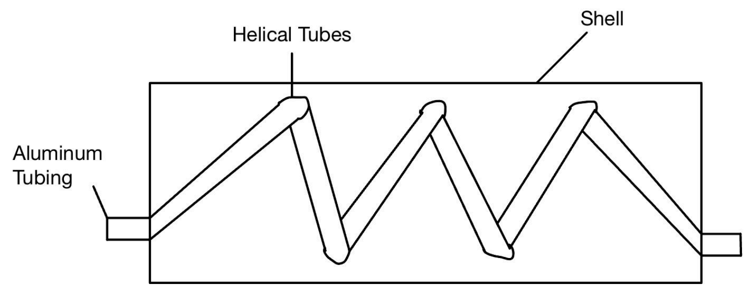


Figure 13. Concept D

The selection of the most suitable concept will be based on a set of defined criteria and evaluation measures. These criteria are rooted in our engineering requirements and are quantifiable, ensuring that the chosen concept aligns with the project's goals.

4.3 Selection Criteria

The selection criteria for design evaluation is based on the engineering requirements discussed in Section 2.2 and given weights according to the technical importance shown in Figure 4:

1. **Low Air Temperature:** The design should achieve the lowest possible air temperature output to maximize cooling efficiency. (Weight: 15)
2. **Small System Volume:** A compact design is preferred for transport and storage. (Weight: 15)
3. **High Operation Time:** The heat exchanger should operate continuously for an extended duration, meeting the requirement of at least 30 minutes. (Weight: 20)
4. **Low Head Losses:** The system should have lower pressure losses to ensure required coolant flow. (Weight: 10)
5. **Cost:** The design should be cost-effective, taking into account materials and components in relation to the total budget available. (Weight: 15)
6. **High Heat Transfer:** The heat exchanger must provide efficient heat transfer, maintaining a low temperature differential between the coolant and the water outlets. (Weight: 20)
7. **Environmental Considerations:** Environmental impact of materials should be relatively minor. (Weight: 5)

These criteria are rooted in the engineering requirements and will ensure the team selects the most successful design alternative from a technical standpoint.

4.4 Concept Selection

In the process of selecting the most suitable design concept for the liquid-to-liquid heat exchanger, our team used the CR's found in section 2.1 to ensure our final selection would meet design requirements and be a customer-centric design. In the selection process the team made use of a pugh chart and decision matrix for the selection process.

Now that the team has adequately determined a method to decide on a final design through various methods such as the QFD and the mathematical modeling the final selection can be made. The first step in this process is creating a Pugh chart with 4 different designs defined in section 4.2.

Table 2: Pugh Chart

Criteria	Solutions/designs				Weighting
	Design A	Design B	Design C	Design D	
Low Air Temperature	S	- (analysis)	d a t u m	- (analysis)	15
Small System Volume	S	- (Helical)		- (Helical)	15
High Operation Time	+ (insulation)	- (insulation)		+ (insulation)	20
Low Head Losses	S	+ (helical)		+ (helical)	10
Cost	S	S		S	15
High Heat Transfer	S	- (analysis)		- (analysis)	20
Environmental	+ (coolant)	S		+ (coolant)	5
Total +	0.25	.1		.35	
Total -	0	.7		.5	
Overall Score	0.25	-0.6		-0.15	

In Table 2 the Pugh chart for the preliminary designs are weighted against a Datum or a design that is middle of the road. The weightings can be seen on the right side of the figure and in alignment with the customers desires the high heat transfer and high operations are weighted the highest with a ranking of 20 percent. With the scores weighted against the Datum the top two designs would be Design A with a score of .25 and the datum, Design C, with an overall score of 0. However due to design A and C being very similar the team decided to select design B to enter into the decision matrix as it may be a better option overall through the manufacturing process.

Table 3: Decision Matrix

Criteria	Weight	Design A		Design D	
		Score	Weighted Score	Score	Weighted Score
Low Air Temperature	15	8	1.2	3	0.45
Small System Volume	15	5	0.75	9	1.35
High Operation Time	20	9	1.8	7	1.4
Low Head Losses	10	2	0.2	6	0.6
Cost	15	4	0.6	2	0.3
High Heat Transfer	20	8	1.6	3	0.6
Environmental	5	7	0.35	5	0.25
Total	100		6.5		4.95

After a thorough evaluation, we have chosen Design A as the most promising concept for the liquid-to-liquid heat exchanger. Design A scored the highest in the decision matrix, with a total weighted score of 6.5, reflecting its exceptional performance across several key criteria.

The selection of Design A aligns seamlessly with Boeing's commitment to innovation, cost-efficiency, and environmental responsibility. The design team is currently in the process of creating a CAD model for Design A, with the aim of further improving and refining this concept.

5 Schedule and Budget

5.1 Schedule

Table 4: Gantt Chart for ME476

Task 1 - Team Charter	Team	100%	9/4/23	9/8/23	5
Task 2 - Heat Exchanger	Dennis	100%	9/12/23	9/17/23	6
Task 3 - Fluid selection	Uriah	100%	9/12/23	9/17/23	6
Task 4 - Fluid Flow	Lorenz	100%	9/12/23	9/17/23	6
Task 5 - Cold Water Reservoir	Christopher	100%	9/12/23	9/17/23	6
Task 6 - Presentation 1	Team	100%	9/12/23	9/18/23	7
Concept Generation and Calculations					27
Task 1 - Functional models	Team	100%	9/20/23	9/22/23	3
Task 2 - Concept Generation	Team	100%	9/22/23	9/29/23	8
Task 3 - Engineering Calculations	Team	100%	9/29/23	10/6/23	8
Task 4 - Concept Evaluation	Team	100%	9/29/23	10/6/23	8
Task 5 - Presentation 2	Team	100%	10/1/23	10/8/23	8
Task 6 - Report 1	Team	100%	10/8/23	10/16/23	9
1st Prototype					26
Task 1 - CAD Models	Lorenz, Uriah	100%	10/11/23	10/20/23	10
Task 2 - Website Development	Christopher	100%	10/11/23	10/23/23	13
Task 3 - 1st Prototype Manufacturing	Dennis, Lorenz	100%	10/11/23	10/27/23	17
Task 4 - Analysis Memo	Team	100%	10/18/23	10/30/23	13
Task 5 - 1st Prototype Testing	Christopher, Uriah	100%	10/27/23	11/3/23	8
Task 6 - Presentation 3	Team	100%	10/31/23	11/5/23	6
Task 7- 1st Prototype	Team	100%	10/31/23	11/13/23	14
2nd Prototype					29
Task 1 - Report 2	Team	100%	11/6/23	11/20/23	15
Task 2 - 2nd Prototype Manufacturing	Dennis, Lorenz	100%	11/8/23	11/22/23	15
Task 3 - Final CAD and BoM	Lorenz	100%	11/15/23	11/27/23	13
Task 4 - 2nd Prototype Testing	Christopher, Uriah	100%	11/26/23	12/2/23	7
Task 5 - 2nd Prototype Demo	Team	100%	11/20/23	12/3/23	14
Task 6 - 486C Project Management	Uriah	100%	11/27/23	12/4/23	8
Task 7 - Website Check 2	Chris	100%	11/20/23	12/10/23	21

Table 4 above shows the team's Gantt chart for the first semester. The schedule was broken up into four phases based on major course deliverables.

The first phase consisted mostly of research tasks along with team organization in the form of the team charter. Each member conducted a literature review of topics relevant to the project and performed basic mathematical modeling based on their selected topic. This information was collated and presented to the client and in-class.

The second phase of the project built upon the previous literature review to create a final design for the system. Functional models were created to identify the processes the design must include, and concepts were generated for critical subsystems. These concept variants were evaluated according to their calculated performance and the project's engineering requirements in order to select a final design. This process was documented in a presentation and a report detailing all progress made so far.

The third phase was the creation of the team's initial prototypes. Initial CAD models for the selected design were created and modified as the team refined the design. Prototypes consisted of a mathematical model and a lab experiment to validate the design before manufacturing. Again, the results of this phase were reported through a presentation. Additionally, the structure of the team's capstone website was developed to showcase the project and store documentation.

The final phase of the semester dealt with manufacturing a final prototype of the heat exchanger and a report listing all progress made throughout the semester. A final CAD model and accompanying Bill of Materials was completed, along with physical manufacturing of the newest prototype. This prototype was developed to answer questions regarding manufacturing and assembly, particularly sealing of components. Miscellaneous tasks included further website development and planning for next semester.

Table 5: Gantt Chart for ME486C

Build 33%					21
Task 1 - Project Management	Team	100%	1/16/2024	1/19/2024	4
Task 2 - Engineering Models	Team	100%	1/22/2024	1/26/2024	5
Task 3 - Initial Build	Team	100%	1/22/2024	2/1/2024	11
Task 4 - Hardware Update 33%	Team	100%	1/29/2024	2/5/2024	8
Build 67%					16
Task 1 - Website Check 1	Christopher	100%	2/12/2024	2/19/2024	8
Task 2 - Build Modifications	Dennis, Lorenz	100%	2/12/2024	2/22/2024	11
Task 3 - Hardware Update 67%	Team	100%	2/25/2024	2/27/2024	3
Task 4 - UGRAD Registrations	Uriah	100%	3/1/2024	3/8/2024	8
Final Build					31
Task 1 - Initial Testing Procedure	Christopher, Lorenz	100%	3/1/2024	3/11/2024	11
Task 2 - Final Testing Procedure	Christopher, Lorenz	100%	3/18/2024	3/22/2024	5
Task 3 - Draft UGRAD Poster	Team	100%	3/18/2024	3/30/2024	13
Task 4 - Complete Build	Team	100%	3/11/2024	3/25/2024	15
Task 5 - Hardware Status Update 100%	Team	100%	3/18/2024	3/26/2024	9
Task 6 - Final CAD Packet	Dennis, Uriah	100%	3/18/2024	3/31/2024	14
Symposium and Project Completion					33
Task 1 - Initial Testing	Team	100%	4/1/2024	4/6/2024	6
Task 2 - Design Modification	Dennis, Uriah	100%	4/6/2024	4/12/2024	7
Task 3 - Final Poster and PPT	Team	100%	4/4/2024	4/15/2024	12
Task 4 - Final Testing	Team	100%	4/13/2024	4/15/2024	3
Task 5 - Final Report	Team	100%	4/13/2024	4/19/2024	7
Task 6 - Final Website Check	Chris	100%	4/13/2024	4/19/2024	7
Task 7 - Design Demonstration	Team	100%	4/13/2024	4/15/2024	3
Task 8 - Final UGRAD Revisions	Lorenz, Uriah	100%	4/17/2024	4/19/2024	3
Task 9 - UGRAD Presentation	Team	0%	4/26/2024	4/26/2024	1
Task 10 - Spec Sheet/Operation Manual	Team	50%	4/27/2024	5/3/2024	7

Table 5 shows the schedule for the second semester of the project. Similarly to the first semester, the project was broken up into four phases based on major course deliverables. The 33% build phase consisted mainly of changes to project management and engineering calculations. The initial build milestone made sure that 2/3rds of all parts were purchased and 1/3rd of the system was assembled/manufactured.

The 66% build phase focused mostly on ensuring that all parts were purchased and 2/3rds of the system has been assembled/manufactured. Minor tasks included updates to the website and registration for undergraduate symposium presentations at the end of the semester.

The final build phase consisted of fully assembling the system and finalizing CAD files. The team also created a draft for symposium deliverables as well as finalizing testing plans to evaluate the performance of the heat exchanger.

The last phase consisted primarily of testing of the design. The team performed several experiments to measure the durability and performance of the liquid-to-liquid heat exchanger. Other tasks included the final report, presentations, and website updates.

5.2 Budget

The team received $5,000 from Boeing to fund the entire project. An additional $1,000 was secured through a VA grant to satisfy capstone fundraising requirements, giving a total project budget of $6,000. Most expenses will come from the original client funding and the grant funding will act as an emergency fund for unforeseen expenses and circumstances.

Prototyping expenses amounted to $665.81 for materials and parts that cannot be reused in the final design. Many parts were purchased with the intention of use in the final product, however, design changes rendered most prototyping parts obsolete. This figure also includes the purchase of spare parts in case of failures in the final product. These spare components included a pump, fittings/adapters, and plastic tubing.

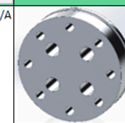
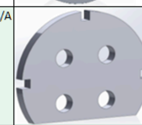
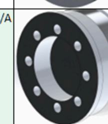
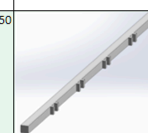
The total testing equipment cost totaled to $777.96. The majority of this cost went to a Pico TC-08 Data Logger for temperature data acquisition. Other testing equipment included K-type thermocouples, digital flow meters, and digital pressure gauges. Fittings to attach these instruments to the flow tubes.

The total cost per unit of the heat exchanger demonstrator was $805.10. This included all off-the-shelf components, all custom made parts, and all raw materials used in manufacturing. This brought total project expenditures to $2,248.87 out of the $6,000 budget. Given that the entire project cost about 1/3rd of the total budget, it is clear that the team successfully and significantly reduced project costs.

5.3 Bill of Materials

A partial view of the Bill of Materials for the final product is shown in Table 6. Most parts were purchased from other manufacturers, however the end caps were machined out of aluminum by the team. Lead times show that most parts can be ordered and delivered within a week. Three parts have a lead time over two weeks, with the fans taking almost a month to arrive. The full Bill of Materials is available in Appendix B.

Table 6: Partial Bill of Materials

Part #	Part Description	QTY	Testing Equipment	Source	Manufacturer	Lead Time (Days)	Material	Part Status	Cost	Image
N/A	End cap coolant inner	2	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	Baffle	4	No	Manufactured	Uriah Whitaker	1	PLA	Completed	N/A	
N/A	End cap coolant in/out Outer	1	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	End cap coolant reservoir Outer	1	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	Baffle Spine Top/Bottom	2	No	Purchased	NAU Idea Lab	6	PLA	Received	$17.50	
N/A	Baffle Side Spine	2	No	Purchased	NAU Idea Lab	6	PLA	Received	$17.50	
Custom	Acrylic PMMA Clear Tube	1	No	Purchased	Queen City Polymers	5	Acrylic	Received	$106.00	
H-6604	Black Wire Utility Cart - 36 x 24 x 40"	1	No	Purchased	Uline	9	N/A	Received	$165.00	

6 Design Validation and Initial Prototyping

6.1 *Failure Modes and Effects Analysis (FMEA)*

Moving into the manufacturing stage understanding the potential failures and their effect on the system is a crucial step in designing a successful product. When looking at failure modes there are three key factors that should be assessed. First the severity of the failure or how detrimental it is to the system's operation. Second, How likely is this failure to occur and third, how easily can it be detected. Additionally by rating these on a scale of 1-10 and multiplying these ratings the most crucial failure modes will become apparent this is also called the risk priority number or RPN.

The heat exchanger demonstrator can be divided into six sub assemblies. The heat exchanger itself, the piping connecting all parts,the pumps, the ice water reservoir, the radiator, and all of the sensors for data collection and validation. In each of these sub assemblies several instances where a critical failure could possibly occur but the severity is not the only measurement that matters, to determine the problem areas the RPN should be mainly considered except in the cases where bodily harm is a factor. For our predicted temperature operation range that is not a consideration.

The system's most worrisome areas come in heat exchanger and ice water reservoir sub assemblies. In the HXR sub-assembly and the ice water reservoir tied the highest RPN comes from the internal sealant failures with a score of 150 and identical scores. The severity of this was ranked at six as if it occurred, hot and cold fluid mixing and or external leakage could result which will either cause significant performance decreases or leak harmful coolant indoors. Next they were ranked 5 for occurrence as it is very possible to occur but not guaranteed. The detection was also ranked 5 as in one case the detection will be very easy to detect but in the case of internal leakage detection may be much harder. The recommended action is to make sure all of the manufactured parts are within the specified tolerances to avoid large gaps increasing the occurrence number. The next highest RPN comes from the incorrect calibration of sensors with a score of 84. The severity scored a 3 as it is not crucial to operation but the data is the main goal of the system. The occurrence was scored a 4 as due to inexperience an incorrect calibration curve is a possible mistake. and lastly it scored 7 on detection due to the fact that if data is slightly off then it may not be caught.The recommended action is to collect a large sample size when creating a calibration curve. All other potential failure modes ranked similarly outside of the top 3. All rankings, scores and recommended actions can be seen in Appendix C.

6.2 Initial Prototyping

6.2.1 Virtual Prototype

For this prototype the team created an excel spreadsheet where they mathematically modeled the heat exchanger they believe would be best fit. This prototype was used to help find the overall efficiency and heat transfer of the selected heat exchanger and ultimately would tell if they needed to change any of the specifications in order to get a better efficiency. From this mathematical model they found that the heat exchanger's overall efficiency was about 62% due to the specified pump they were recommended on using by Boeing. Since this efficiency was nowhere near what the team was aiming for they decided that they would need to upgrade the pump they were using in the ice water loop in order to generate the velocity they needed for a much higher efficiency within the heat exchanger.

6.2.2 Physical Prototype

For this prototype the team set out to test the heat exchanger in the thermal labs in order to experimentally verify the team's mathematical model which was explained in the previous prototype. When the team went into the thermal fluids lab they set up the heat exchange and evaluated it in two different methods. First they fluctuated the volumetric rate of the shell flow but kept the tube flow constant and took the readings from 6 different flow rates and took the readings that came from the thermal couples from the inlet and outlets of the heat exchanger which gave them the temperatures at the inlets and outlets. Next the team then changed the tube flow rate and left the shell flow rate constant and took readings from 6 data points. From this the team was able to calculate the effectiveness from the Reynolds number at each of the data points and then mathematically model the heat exchanger to compare the effectiveness of the theoretical to the actual effectiveness. The team found that the mathematical model and the experimented values were very similar and thus were able to conclude their equations are correct and therefore their own mathematical modeling would be correct which they can also compare experimentally once they create a physical prototype.**e**

6.3 *Other Engineering Calculation*

6.3.1 *Error propagation due to sensors*

As the team moves further into the manufacturing stage selecting sensors to measure the outputs of the heat exchangers is a critical component of the final product. Said sensors will be primarily responsible for design validation. All sensors come with a resolution uncertainty, accuracy and other uncertainties that can contribute to incorrect data. This section will deal with the heat transfer and actual effectiveness seen below.

$$q = \rho \dot{V} C_p (T_2 - T_1) \quad (1)$$

$$\varepsilon = q/q_{max} \quad (2)$$

All components in equation 1 will have some design stage uncertainty. The design stage uncertainty equation can be seen below with u_o being the uncertainty due to accuracy and u_c being the resolution uncertainty

$$u_d = \sqrt{u_o^2 + u_c^2} \quad (3)$$

With the design stage uncertainty now the error propagation can be found below. The d in the subscript changed to denote the design stage uncertainty of that particular variable.

$$u_t = [(\frac{\partial q}{\partial \rho} u_\rho)^2 + (\frac{\partial q}{\partial V} u_V)^2 + (\frac{\partial q}{\partial C} u_C)^2 + (\frac{\partial q}{\partial T_2} u_{T_2})^2 + (\frac{\partial q}{\partial T_1} u_{T_1})^2]^{1/2} \quad (4)$$

Solving the partial derivatives in equation 4 results in the following uncertainty in q (i.e ∓ the resultant value).

$$u_t = [(\dot{V} C_p (T_2 - T_1) * u_\rho)^2 + (\rho C_p (T_2 - T_1) * u_V)^2 + (\rho C_p (T_2 - T_1) * u_C)^2 + (\rho \dot{V} C_p * u_{T_2})^2 + (-\rho \dot{V} C_p * u_{T_1})^2]^{1/2} (5)$$

since q_{max} is theoretical and no error propagation will be seen the effectiveness uncertainty can be simple found with

$$\varepsilon_{uncertainty} = u_t/q_{max} = .0895 = \pm\ 8.95\% \quad (7)$$

and finally the deviation can be found with ½ of the range and the resultant is $\pm\ 8.95\%$ which is relatively high and is not in line with the team's goals of 5 percent accuracy. The next steps are to look into more accurate thermocouples as the selected k type with arduino's has an uncertainty of 1.5 degrees C which contributes the most to the uncertainty.

6.3.2 Clamping force and Gasket Compression

One of the primary seals in the system is the gaskets used in the heat exchanger end caps. The compression percent is a necessary value to make a preliminary determination on the sealing of various materials and the clamping force provided by the bolts. Traditionally the allowable torque calculation is made with a P equal to 75% of the materials modulus of elasticity. The subsequent torque was found using the following equation with a K for aluminum and steel.

$$T = K * D * P$$

T = Target Tighten Torque K = Coefficient of friction D = Bolts Nominal Diameter

P = Bolts desired tensile load

As an added Factor of Safety, use 75% of the calculated torque. The following equation calculates the clamping force.

$$F = \frac{T}{K} * D$$

F = clamping force

The total clamping force was determined using the sum of the individual clamping forces. Since the equations are general approximations it is best to use the worst-case scenario of 25% of the calculated force.With this, the compression percentage can be found with the following 2 equations, treating the gasket as a beam with uniform cross section and uniform material properties.

$$\delta = \frac{F*L_i}{A*E}$$

$$Percent\ Compression = \frac{L_i - L_n}{L_i} * 100\%$$

F=total clamping force L_i =Length Initial L_n=compressed gasket length

A=Cross Sectional Area E=Young's modulus

The expected compression from these equations is 10-60% due to the range of young's modulus for the rubber which falls within the ideal static sealing range for rubber gaskets of 10-50%. These calculations are approximations as many factors can influence the actual clamping force, hence the necessity of testing.

7 Final Hardware

7.1 Final Physical Design

The final liquid to liquid heat exchanger is a 2 pass 2 tube heat exchanger that utilizes 3D printed baffles to direct flow. As per the customer requirements the outer shell is acrylic and will be ¼ inches thick and have an outer diameter of 4.25 inches. All aluminum components, the outer and inner end caps, are machined T-6061 aluminum manufactured in house on the 3-axis vertical mill and lathe. The heat transfer material was selected to be 99% pure ⅜ inch ID copper tubing selected for its high thermal conductivity and availability. The acrylic shell with the ice water flow will be sealed by 3/16 inch O-rings and the end caps containing the coolant flow will be sealed with a rubber gasket. Eight 5/16-24 Cap head Allens per side are used to provide the required clamping force for sealing. The final design CAD and Physical model can be seen below in figures 14-16.

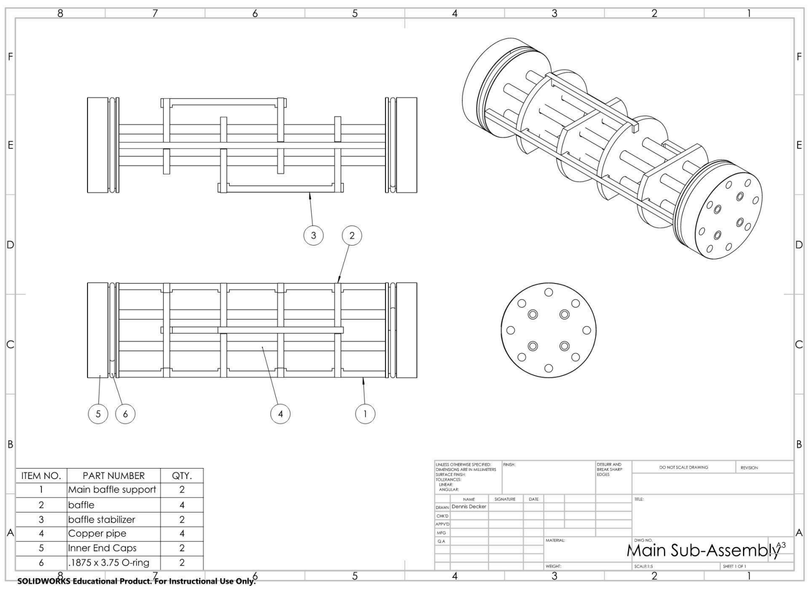


Figure 14. CAD Sub-Assembly

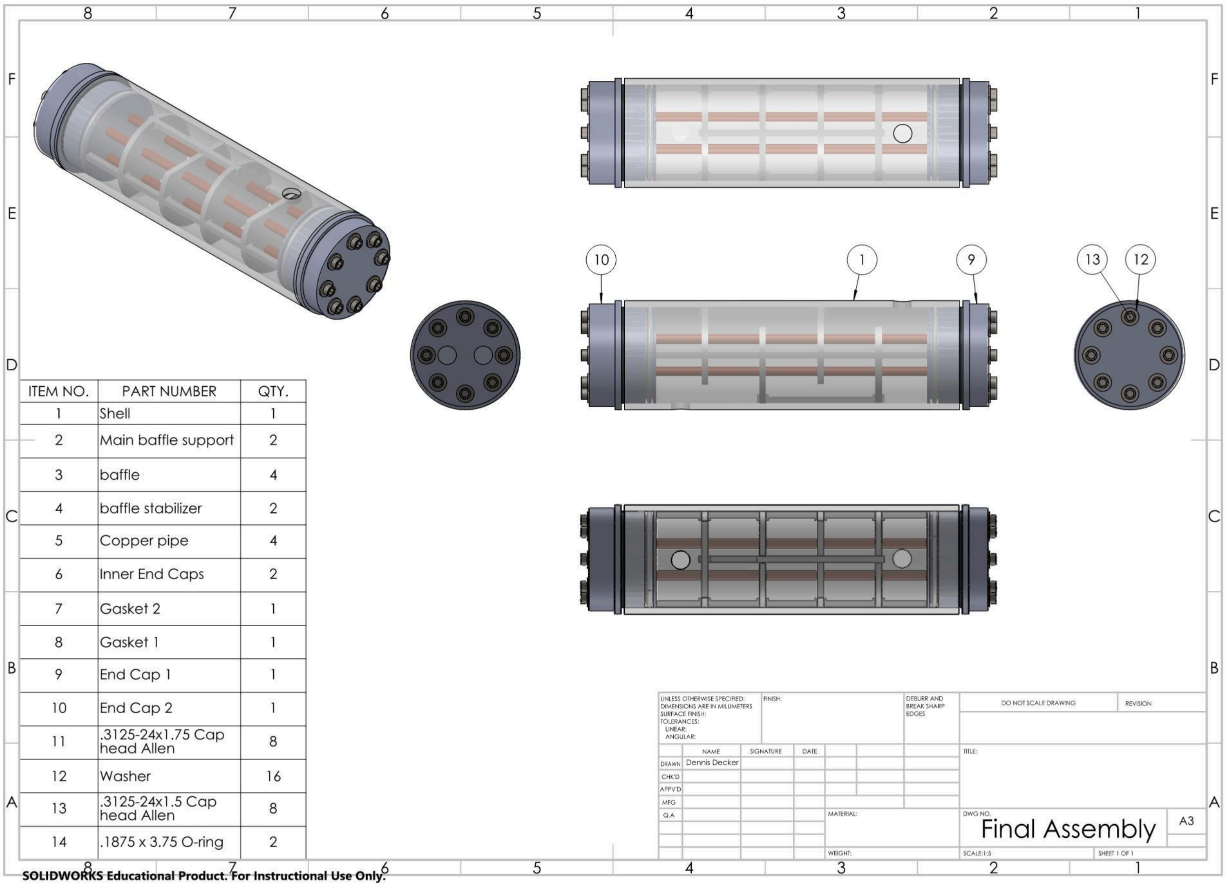


Figure 15. CAD Final Assembly

Figure 16. Physical model

7.1.1 Shell flow - Ice water

The shell flow will be contained in the acrylic tube and will thus be the 'Visible" fluid. This flow will enter the shell through a ½ inch bung on the acrylic tube. The flow will be routed in a S shaped pattern via 4 baffles spaced 2 inches apart exiting on the opposite side as the inlet. This can be more easily visualized below in the CAD drawing above in figure 14 and the physical model 16.

7.1.2 Tube Flow - Coolant

The Tube flow will be contained in the aluminum end caps and the copper tubes. This flow will enter one end cap through a ½ inch bung and will be forced through two ⅜ inch copper tubes where it will be forced into a mixing chamber at the opposite end ultimately being forced back through another pair of copper tubes. Exiting on the same end as the entrance for easy firewall mounting.

8 Final Testing

8.1 Top level testing summary table

Table 7. Summary Table

Experiment/Test	*Relevant DRs*
Exp 1 – Inlet/Outlet Temperature Test	***CR1, ER1, ER3, ER6***
Exp 2 – Pressure Drop	***ER4***
Exp 3 – Sealing Tests	***CR6, ER3***

8.2 Detailed testing plan

Each of the experiments will be conducted under normal operating conditions. This gives the team information regarding how the design will perform compared to the expected performance from calculations.

8.2.1 Inlet/Outlet Temperature Test

8.2.1.1 Summary

The temperature test will check the effectiveness of the liquid-to-liquid heat exchanger and the overall system. CR1 will be tested by measuring the coolant temperature at the inlet and outlet of the radiator. Temperature measurements of the radiator inlet and outlet will be taken to ensure the air flow is colder than the ambient environment (ER1). The temperatures of the liquid-to-liquid heat exchanger inlets and outlets will be used to calculate the heat exchanger's effectiveness (ER6). The temperature of the water expelled into the ice water tank will be used to determine the time it takes to melt the ice in the tank (ER3). This test will use eight NPT threaded thermocouples inserted near the inlets and outlets of all major components (holding tanks, heat exchanger, radiator). These thermocouples will be connected to a Pico TC-08 data logger and PicoLog DAQ software to collect temperature data. These temperatures will be used to calculate effectiveness for the system and the temperature of the airflow.

8.2.1.2 Procedure

1. Connect thermocouples to TC-08.
2. Start PicoLog and enable all channels, setting sample interval to 100ms.
3. Power on pumps and fans to start the system.
4. Wait for temperatures to reach steady state operation.
5. Calculate the effectiveness of the heat exchanger.
6. Calculate the temperature of the outlet air.

8.2.1.3 Results

The target effectiveness for the heat exchanger is 60%. The following fundamental equations are how the team calculated the theoretical efficiency.

$$\varepsilon = \frac{q}{q_{max}}$$

$$\varepsilon = efficiency \qquad q = heat\ transfer \quad q_{max} = max\ heat\ transfer$$

The following equation gives the theoretical heat transfer:

$$q = \frac{(T_{hi} - T_{co})}{R_{eq}}$$

$$T_{hi} = High\ Temperature \quad T_{co} = Cold\ Temperature \quad R_{eq} = Thermal\ Resistance$$

To get the cold side heat transfer, the team will assume the temperatures of the inlets and outlets to be 0 °C and 20 °C respectively for the ice water side and the thermal resistance will be for water. The following equation was used to find the maximum heat transfer via the coolant.

$$q_{max} = C_m \left(T_{hi} - T_{co} \right)$$

$$C_m = Specific\ Heat\ Capacity$$

The team used similar assumptions knowing the temperatures of the inlets and outlets from the previously used NTU method and found the heat transfer via the hot side. These calculations resulted in an effectiveness of about 0.62, or 62%. The full math and values can be found in the team's past presentations as well as in the mathematical model. This expected value is within the teams' expectations, so if the assumptions hold true, the design should reach the target effectiveness. The team also needed to find the temperature from the outlet of the radiator to blow onto a judge's hand. Using the fundamental equations for the efficiency of the heat exchanger, the following equation was devised.

$$T_{air,out} = T_{air,in} - \varepsilon * \left(T_{air,in} - T_{coolant,in} \right)$$

Since air has a lower heat capacity than the coolant, air outlet temperature was dependent solely on efficiency and inlet temperatures. The air coming out of the radiator was calculated to be about 13.77 °C which is below the 15 °C target temperature.

This experiment also determines the amount of ice that is needed to meet DRs CR1, ER1, and ER3. This was achieved by calculating the total energy the ice needed to absorb to last for 30 minutes. The following equation was used to find the amount of energy needed for the ice to bring the initial water down to 0 °C.

$$m = V * 3.79 = 22.7\ \text{kg}$$

$$V = Volume\ mass\ of\ water$$

$$E_i = m * h_c * \left(T_i - T_f \right) = 1903.8\ kJ$$

$$E_i = Initial\ Energy\ h_c = Specific\ Heat\ \ T_i = Initial\ Temperature$$
$$T_f = final\ Temperature$$

Then, the amount of energy that was being brought into the system from the heat exchanger was calculated.

$$m = 0.257 * (1800) = 454.9\ kg$$
$$E_m = m * h_c * \left(T_i - T_f\right) = 25130\ kJ$$

The total of these two energies is the amount of energy absorbed by the ice.

$$E_f = E_i - E_m = 27034\ kJ$$

The following equation gives the total number of energies the ice can absorb based on sensible and latent heat.

$$Q_{total} = Latent\ + Sensible\ = 374\ \frac{kJ}{kg}$$
$$m_{ice} = \frac{E_f}{Q_{total}} = 72.3\ kg\ or\ 159.6\ lb\ of\ ice$$

To operate for 30 minutes, 160 lbs. of ice is needed to keep the ice bath at constant temperature. The experiment will give a better approximation of this amount, but this gives a good estimate for the required amount of ice.

8.2.2 Pressure Drop Test

8.2.2.1 Summary

This test will measure the pressure drop across the liquid-to-liquid heat exchanger. The pressure at the inlets and outlets of the heat exchanger will be compared to ensure the head loss is below 40 psi (ER4). Four digital pressure gauges will be connected to the system to measure the inlet and outlet pressures of each fluid moving through the heat exchanger. Pressure loss will be calculated by taking the difference between the inlet and outlet pressures.

8.2.2.2 Procedure

1. Turn on digital pressure gauges and pumps.
2. Wait until all four pressure gauges have stabilized their readings.
3. Calculate the difference between inlet and outlet pressures for each fluid.

8.2.2.3 Results

To calculate the theoretical pressure difference across the heat exchanger the friction factor had to be calculated using the following equation.

$$\frac{1}{\sqrt{f}} =- 2.0\ *\ log\left(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re*\sqrt{f}}\right)$$

$f\ = Friction\ factor e\ = pipe\ roughness$ $\quad D\ = inner\ diameter\ of\ tube$ $\quad$ Re = Reynold's number

The team got a friction factor of about 0.0654 with the team's current diameter assumed Reynolds number to make the flow turbulent and the pipe roughness. The team then calculated the pressure difference using the following equation.

$$\Delta p = \rho\left(f * \frac{L}{D} + \frac{V^2}{2}\right)$$

$$\Delta p = pressure\ difference \quad \rho = fluid\ density \quad L = tube\ length$$
$$V = average\ fluid\ velocity$$

The team found the expected head loss should be around 1.2 psi, the allowable head loss for the system would be about 40 psi so the team does not expect any issues with the pressure loss across the heat exchanger but will perform the experiment to validate the equations and solutions.

8.2.3 Sealant Test

8.2.3.1 Summary

This test determines where seals have failed. The system will operate continuously for half an hour to ensure that all external seals prevent leaks and that both fluid loops are isolated from each other. Any leaks necessitate system shutdown, so this test will ensure the system can reach the desired operation time (CR6, ER3). There are no variables associated with this test.

8.2.3.2 Procedure

1. Turn on both pumps to start fluid flows and start a 30-minute timer.
2. Check for external leaks in fittings and connections in between plastic tubing and the pumps, testing equipment, heat exchanger, and radiator.
3. Check for external leaks in both heat exchanger end caps (gaskets and O-rings).
4. Check for internal leaks in the heat exchanger. Coolant will be a distinct color from ice water, so leaks will be apparent.
5. Repeat leak checks until 30 minutes have elapsed.

8.2.3.3 Results

The most important seal in the system is the gaskets used in the heat exchanger end caps. The compression percent needed to be calculated to figure out how much gasketing material to use. The allowable torque of 75% material modulus was found using the following equation.

$$T = K * D * P$$

$$T = Target\ Tighten\ Torque \quad K = Coefficient\ of\ friction \quad D = Bolts\ Nominal\ Diameter$$
$$P = Bolts\ desired\ tensile\ load$$

Next, the following equation calculated the clamping force using the worst-case scenario of 25% of the calculated force.

$$F = \frac{T}{K} * D$$

$$F = clamping\ force$$

The total clamping force was determined using the sum of the individual clamping forces. With this, the compression percentage can be found with the following 2 equations, treating the gasket as a beam with uniform cross section and uniform material properties.

$$\delta = \frac{F*L_i}{A*E}$$

$$Percent\ compression = \frac{L_i - L_n}{L_i} * 100\%$$

$\delta = displacement$ $\quad F = total\ clamping\ force$ $\quad L_i = original\ gasket\ height$

$L_n = new\ gasket\ height$ $\quad A = Cross\ sectional\ area$ $\quad E = Young's\ modulus$

The expected compression from these equations is 10-60% which falls within the ideal static sealing range for rubber gaskets of 10-50%. These calculations are approximations as many factors can influence the actual clamping force, hence the necessity of testing.

8.3 Final Testing Summary Tables

Using the above experiments, the team was able to see if the current design meets the specified design requirements. The following tables communicate which design requirements are currently met by the design. Table 8 shows the customer requirements, whether the design satisfies them, and whether the client finds the design acceptable.

Table 8: Summary of Customer Requirements

Customer Requirement	CR met? (✓ or X)	Client Acceptable? (✓ or X)
CR1 – Air Temperature	✓	✓
CR2 – Firewall Installed	✓	✓
CR3 – HXR Volume Limit	✓	✓
CR4 – Clear HXR	✓	✓
CR5 – Portable System	✓	✓
CR6 – 30 min Operation	✓	✓

The design satisfies all requirements. The system is segmented by an acrylic sheet representing the firewall. The heat exchanger is smaller than the 6”x6”x18” maximum size specified by the client. The tube of the heat exchanger is made of transparent acrylic, satisfying the requirement for a clear housing. All components collectively fit within a 1 cubic meter volume, which means that the system is easy to transport. Requirements of the air temperature and operation time are also sufficient to meet the client requirements.

Table 3 shows the engineering requirements, the ER target, the actual value, and whether values meet ER targets or client targets.

Table 9: Summary of Engineering Requirements

Engineering Requirement	Target	Measured/ Calculated Value	ER met? (✓ or X)	Client Acceptable? (✓ or X)
ER1 – Low Air Temp	>5 °C Drop	5.4 °C	✓	✓
ER2 – Small System Volume	< 1 m^3	0.16 m^3	✓	✓
ER3 – High Operation Time	> 30 min	> 30 min	✓	✓
ER4 – Low Pressure Drop	< 40 psi	2.2 psi	✓	✓
ER5 – Minimized Cost	< $1000	$772.33	✓	✓
ER6 – High HXR Effectiveness	> 50%	29%	X	✓

Currently, the design meets most engineering requirements. The temperature of the airflow is below the set target of 5 °C lower than room temperature. The actual volume of the system when packed is below the target volume. Pressure drop across the tube side of the heat exchanger is well below the allowable pressure drop determined by the pump performance. Current material costs for the system, excluding testing equipment, is less than the $1,000 allocation set by the team. Effectiveness failed to meet the engineering requirement reaching only 29% but after a client consultation it has been deemed acceptable.

9 *Future Work*

If this product were to undergo further development, the team would introduce several improvements. Firstly, they would enhance the design by incorporating better-fitted baffles, welding the tubes to the end caps, utilizing a greater number of smaller tubes, and overall optimizing the heat exchanger for increased efficiency. Additionally, efforts would be made to reduce weight by using less material for the end caps while maintaining structural integrity. Subsequently, the team would conduct rigorous testing of the heat exchanger using precise equipment and adjusting the flow rate to minimize uncertainty in effectiveness calculations, resulting in significantly improved performance. With improved effectiveness established, the team would transition to using the actual refrigerant HFO-1234yf instead of the ice water loop, alongside implementing a vapor compression system, thereby transforming the system into a demonstrator for the AH-64 Apache.

10 CONCLUSIONS

For our project the team is tasked to create an effective liquid to liquid heat exchanger that shows the team's understanding of heat exchanger technologies and systems. The requirements for the project are that it successfully blows cool air on a person's hand, that it lasts for 30 minutes, and it must fit within a certain specified size as well as a few other minor requirements listed previously. From this the team was able to create the customer requirements and use them to create a basic idea of how the system will work and created a black box and functional model dictating all the functions that will go into the system. From there the team was able to create 4 different initial designs that would meet the different customer requirements mentioned. Then the team went and individually created mathematical models for different critical calculations for the system which were then implemented in the decision matrix to determine which design was the best. The team found design A to be the overall best which included copper tubing, propylene for the coolant, U-tubes within the heat exchanger, and an insulated cooler for the reservoir. Once they had the final design selected the team began prototyping by creating a virtual mathematical model and then testing their method with an already developed heat exchanger. The team was then able to verify their methods and continued to update their mathematical models in order to begin creating an actual physical prototype of the heat exchanger. Going forward the team will finish off the semester by creating the two physical prototypes mentioned above to help answer some final manufacturing questions before they begin working next semester.

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12 APPENDICES

12.1 Appendix A: QFD

System QFD

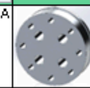
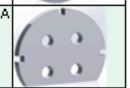
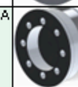
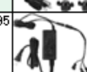
Project: Boeing Heat Exchanger
Date: 4-9-24

		1	2	3	4	5
1	Low Air Temperature					
2	Small System Volume	-3				
3	High Operation Time	-3				
4	Low Pressure Drop		-3			
5	Minimized Cost	-3	3	-3		
6	High HXR Effectiveness	9	-6	-6	6	-9

Legend	
A	Plate Heat Exchanger
B	Shell and Coil Heat Exchanger
C	Shell and Tube Heat Exchanger

			Technical Requirements						Benchmarking				
	Customer Needs	Customer Weights	Temperatue Drop	Small System Volume	High Operation Time	Low Pressure Drop	Minimized Cost	High HXR Effectiveness	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
1	Fans should channel cool air to judge's hand	5	9		6			9			BC		A
2	Inlet and outlet lines must pass through 'firewall'	3		3			3				N/A		
3	Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6			BC		A
4	Clear Housings	3	3			3	3	3	A				BC
5	Portable for demonstration	3		9	3		6						ABC
6	System must operate for 30 minutes	2	3		9		3	6					ABC
	Technical Requirement Units		°C	m^3	min	PSI	USD	%					
	Technical Requirement Targets		>5	1	>30	<40	<6000	>50					
	Absolute Technical Importance		60	63	57	36	51	84					
	Relative Technical Importance		3	2	4	6	5	1					

12.2 Appendix B: Bill of Materials

Part #	Part Description	QTY	Testing Eq en	Source	Manufacturer	Lead Tim (Da	Material	Part Stat	Cost	Image
N/A	End cap coolant inner	2	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	Baffle	4	No	Manufactured	Uriah Whitaker	1	PLA	Completed	N/A	
N/A	End cap coolant in/out Outer	1	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	End cap coolant reservoir Outer	1	No	Manufactured	Uriah Whitaker	3	Aluminum 6061	Completed	N/A	
N/A	Baffle Spine Top/Bottom	2	No	Purchased	NAU Idea Lab	6	PLA	Received	$17.50	
N/A	Baffle Side Spine	2	No	Purchased	NAU Idea Lab	6	PLA	Received	$17.50	
Custom	Acrylic PMMA Clear Tube	1	No	Purchased	Queen City Polymers	5	Acrylic	Received	$106.00	
H-6604	Black Wire Utility Cart - 36 x 24 x 40"	1	No	Purchased	Uline	9	N/A	Received	$165.00	
N/A	4.5 in 6061-T6511 Aluminum Round	1	No	Purchased	Uriah Whitaker	18	Aluminum 6061	Received	$131.42	
B095ST97PZ	Water Pressure Diaphragm Pump Industrial 115V, Self Priming Pump 4 Gpm 45 Psi	2	No	Purchased	Dreyoo	6	N/A	Received	$137.98	
B099M8KZ87	Coolerguys 3A 100-240v AC to 12v DC Three (3) Fan Power Supply	1	No	Purchased	Coolerguys	6	N/A	Received	$15.95	
B08FJFJ53Y	Water Cooling Radiator, 12 Pipe Aluminum Heat Exchanger Radiator	1	No	Purchased	Clyxgs	6	N/A	Received	$22.99	
B08SNXDMJ5	1/2 Inch ID PVC Clear Vinyl Tubing, 10 Foot Length	4	No	Purchased	EZ-FLO	6	N/A	Received	$27.52	
B07F7Z2YCM	Delta 120mm High CFM Fan AFB1212SHE High Speed 12V DC 120mm 3Pin PC Computer Fan with Metal Finger Guard Grill	1	No	Purchased	Delta	27	N/A	Received	$45.12	
31231302	3/8in. ID Copper Coil - 5 ft.	1	No	Purchased	Streamline	4	N/A	Received	$17.02	
3E+09	Coleman 316 Series Insulated Portable Cooler with Heavy Duty Handles, Leak-Proof Outdoor Hard Cooler	1	No	Purchased	Coleman	4	N/A	Received	$58.97	
3BA608A14C12F17	American Biltrite AB-563 Black EPDM Rubber Sheet 1/8 in thick 12x12 in rubber	1	No	Purchased	Gasket Supply	7	EPDM	Received	$22.77	
46807	Black O-Ring 3 3/4in	4	No	Purchased	Parker	6	N/A	Received	$19.36	
								Total	$805.10	
								Purchased	100.00%	
								Percent on Hand	100.00%	

12.3 Appendix C: FMEA

Product Name: Heat Exhanger Demonstrator		Development Team					Page No of			
System Name							FMEA Number			
Subsystem Name							Date			
Component Name										
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action	
HXR-SA										
	Pressure induced failure	Fluid Leakage	8	Overstressing/Inadequate manufacturing	2	Pressure Transducer	3	48	Select quality material	
	Sealant Failure	Fluid Leakage	6	Incorrect Tolerances	5	Visual Inspection	5	150	Take measurments before assembly	
	Copper Corrosion	Lower effectivness	2	Liquid Contaminates	2	Thermocouple	2	8	Ensure Distilled water is used	
Piping-SA										
	Pressure induced failure	Fluid Leakage	6	Overstressing	2	Pressure Transducer	2	24	Use thicher walled copper tubing	
Pump	High Cycle Fatigue	No Flow	10	High Usage	1	Flow Meter	2	20	Minimize pump usage when not operating	
	Seizure	No Flow	10	Running Dry	2	Flow Meter	2	40	Cage with mesh to keep ice from impeding inlet	
	Cavitation	Damages Blades; Unsteady Flow	4	Insufficient net positive suction head	2	Pressure Transducer	6	48	Perform calculations before testing	
	Electrical	No Flow	10	Power surge	1	Flow Meter	2	20	Low probability, No Action needed	
Ice Reservoir-SA										
	Sealant Failure	Fluid Leakage	6	Incorrect Tolerances	5	Measurments	5	150	Take measurments prior to construction	
Radiator-SA										
	Fans-High Cycle Fatigue	No Airflow	7	High Usage	1	Visual Inspection	2	14	Minimize fan usage when not operating	
	Pressure induced failure	Fluid Leakage	8	Overstressing/Inadequate manufacturing	2	Pressure Transducer	3	48	Calculations prior to testing	
	Fans-Electrical	No Flow	10	Power surge	1	Flow Meter	2	20	Low probability, No Action needed	
	Pipe Connections	Leakage	8	High Pressure	2	Visual Inspection	2	32	Calculations prior to testing	
Sensors-SA										
	Incorrect Calibration	Incorrect Data	3	User Error	4	N/A	7	84	multiple data points for calibration for high accuarcy	
	Poor Connections	No Data	4	Improper installation	3	Data Collection	2	24	Test mounting positions	
	Sensor Failure	Incorect Data	4	Manufacturer error	1	N/A	6	24	Compare data to theoretical for large discrepencies	
	FM- Too high of flow	Incorrect Data	3	Incorrect Sensor Selection	1	Data Comparison	6	18	Ensure Correct Specs	