Boeing Heat Exchanger

Initial Design Report

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DISCLAIMER

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. J 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 demonstrator 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 and proper 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 J-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 in place that could 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.
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.
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 10 °C.

2. Small System Volume: The entire system must be easily transportable for the purposes of transferring from NAU to the Boeing facility in Mesa, AZ. 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 Head Losses:** 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.

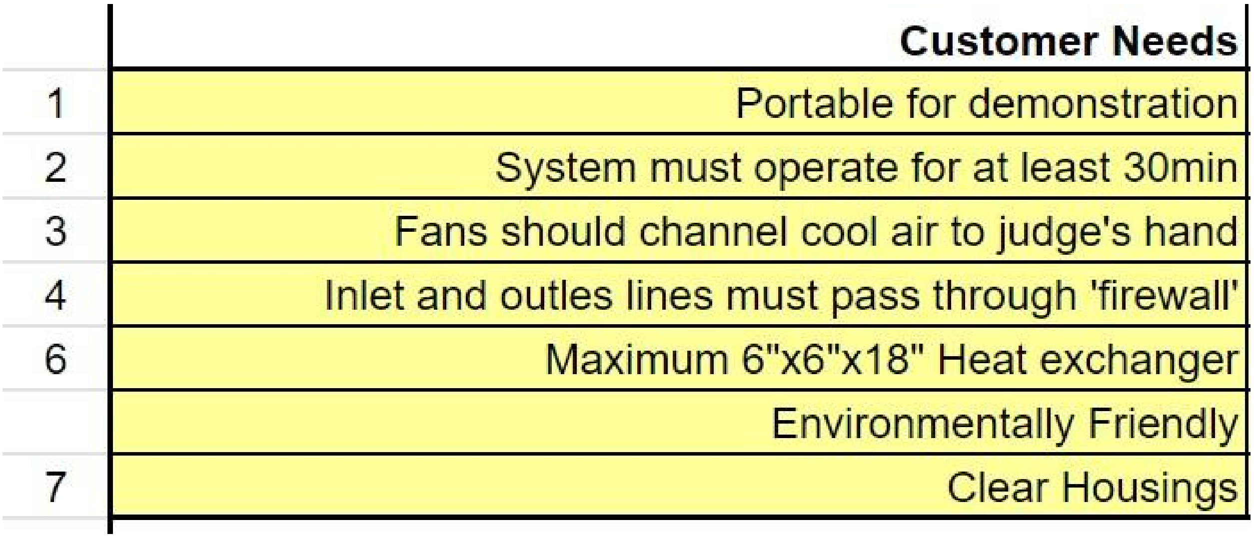
5. **Low Cost:** The team has a budget of $5,000 provided by Boeing with an additional $1,000 in the form of a VA grant. All testing equipment, prototyping, and material costs must collectively be below the $6,000 of funding available. To appropriately allocate the budget, the material cost of the system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

6. **High Heat Transfer:** 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 a minimum effectiveness of 50% with a target of 60%.

7. **Environmental Impact:** Since the premise of this project is to model a more environmentally friendly ECS system, environmental impact is important. Materials such as coolant should be selected with environmental concerns in mind such as toxicity. Since the coolant has the potential to spread to natural bodies of water, environmental impact is measured in the lethal concentration (LC50) for trout. Thus, coolant should have a high LC50 of at least 41,000 mg/L for aquatic life.

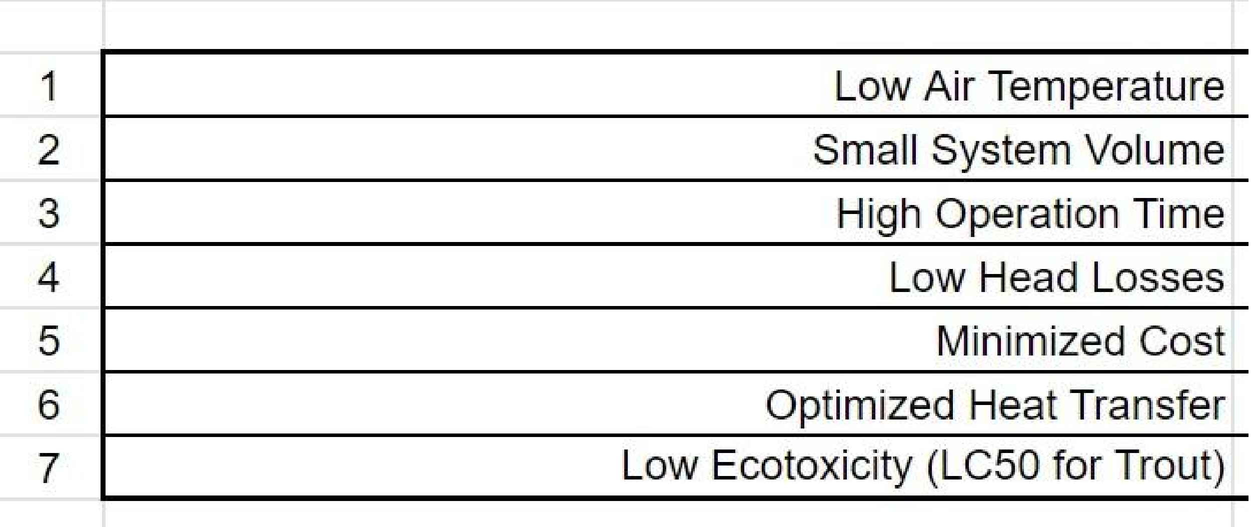
2.3 House of Quality (QFD)

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	Portable for demonstration
2	System must operate for at least 30min
3	Fans should channel cool air to judge's hand
4	Inlet and outles lines must pass through 'firewall'
6	Maximum 6"x6"x18" Heat exchanger
	Environmentally Friendly
7	Clear Housings

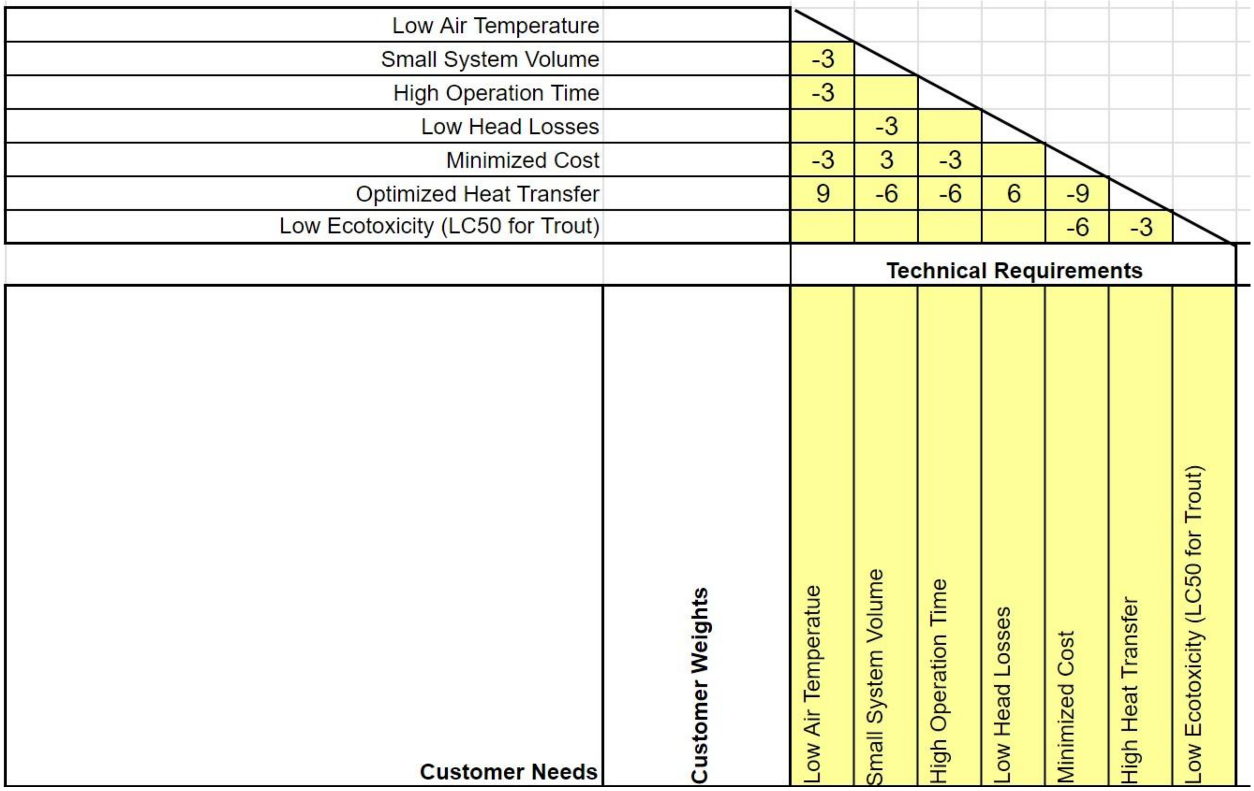
Fig 1. Customer requirements



1	Low Air Temperature
2	Small System Volume
3	High Operation Time
4	Low Head Losses
5	Minimized Cost
6	Optimized Heat Transfer
7	Low Ecotoxicity (LC50 for Trout)

Fig 2. Engineering Requirements

Fig 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



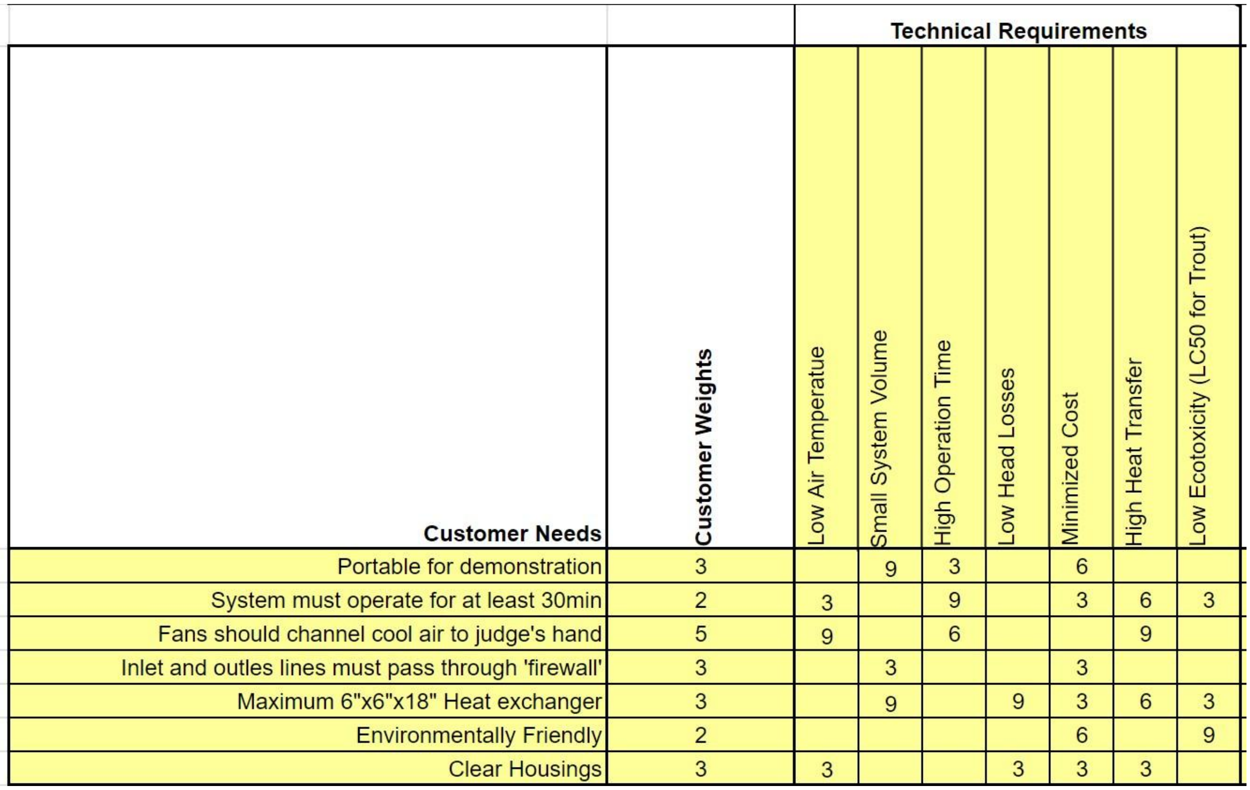
Low Air Temperature							
Small System Volume	-3						
High Operation Time	-3						
Low Head Losses		-3					
Minimized Cost	-3	3	-3				
Optimized Heat Transfer	9	-6	-6	6	-9		
Low Ecotoxicity (LC50 for Trout)					-6	-3	

Technical Requirements

Customer Needs	Customer Weights	Low Air Temperatue	Small System Volume	High Operation Time	Low Head Losses	Minimized Cost	High Heat Transfer	Low Ecotoxicity (LC50 for Trout)

Fig 3. Engineering Requirements correlation

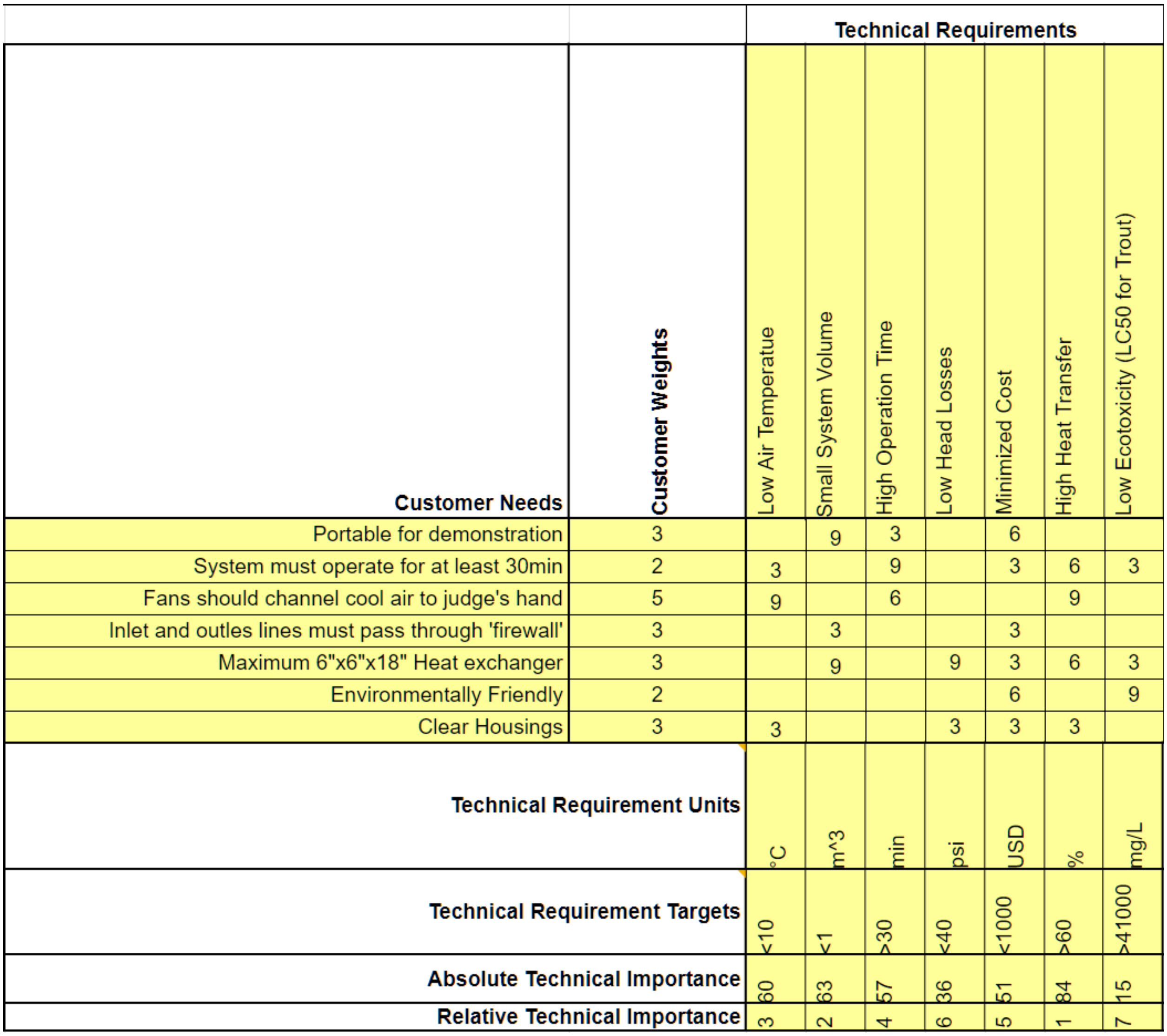
In Figure 3, we can clearly observe the correlations among engineering requirements (ERs). This relational aspect is a pivotal component of an effective Quality Function Deployment (QFD) for several reasons, including prioritization, resource allocation, trade-off assessment, and system optimization. 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.



		Technical Requirements						
Customer Needs	Customer Weights	Low Air Temperatue	Small System Volume	High Operation Time	Low Head Losses	Minimized Cost	High Heat Transfer	Low Ecotoxicity (LC50 for Trout)
Portable for demonstration	3		9	3		6		
System must operate for at least 30min	2	3		9		3	6	3
Fans should channel cool air to judge's hand	5	9		6			9	
Inlet and outles lines must pass through 'firewall'	3		3			3		
Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6	3
Environmentally Friendly	2					6		9
Clear Housings	3	3			3	3	3	

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.



		Technical Requirements						
Customer Needs	**Customer Weights**	Low Air Temperatue	Small System Volume	High Operation Time	Low Head Losses	Minimized Cost	High Heat Transfer	Low Ecotoxicity (LC50 for Trout)
Portable for demonstration	3		9	3		6		
System must operate for at least 30min	2	3		9		3	6	3
Fans should channel cool air to judge's hand	5	9		6			9	
Inlet and outles lines must pass through 'firewall'	3		3			3		
Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6	3
Environmentally Friendly	2					6		9
Clear Housings	3	3			3	3	3	
Technical Requirement Units		°C	m^3	min	psi	USD	%	mg/L
Technical Requirement Targets		<10	<1	>30	<40	<1000	>60	>41000
Absolute Technical Importance		60	63	57	36	51	84	15
Relative Technical Importance		3	2	4	6	5	1	7

Figure 4. Target values and units

Figure 4 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 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 60 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. Although current aerospace companies have not really implemented their current aircraft with HFO-1234yf there are plenty of older aircraft that implement similar systems to the liquid to liquid system the team will be modeling. There has also been extensive research done with refrigerant HFO-1234yf in the automotive industry that the team will use.

Current Boeing Environmental Control System for Apache Helicopter[1]- Implements R-134a which is not very environmentally friendly, and because they use a non combustive refrigerant they do not have a firewall in place so if they were to use HFO-1234yf the pilot would be in harm's way if the refrigerant were to combust.

General Motors Environmental Control System[2]- Implements HFO-1234yf but after many vigorous tests they found that the refrigerant will not combust even in the most extreme circumstances. These are also designed for a car while ours will be designed for a military aircraft that consists of more tech equipment as well as will most likely be shot at.

Boeing 777 Environmental Control System[3]-It has the same situation as the APache helicopter where it uses R-134a and has no firewall in place since the refrigerant is non combustive but it is also made to not only cool a cockpit but also the entire passenger cabin. This requires a much more efficient heat exchanger as well as more coolant than what we are designing for.

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.

3.2.1.3 Websites

Final Temperature of mixtures (Richmann's Law) [10]

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.

3.2.2 Dennis Decker

3.2.2.1 Papers

Heat Exchangers : Characteristics, Types and Emerging Applications [11]

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 [12]

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 [13]

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 [14]
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.

3.2.2.3 Websites

Engineering Toolbox [15]
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 [16]
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.

3.2.3 Lorenz Vios

3.2.3.1 Papers

Heat Transfer and Flow Characteristics of a Conical Coil Heat Exchanger [17]

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 [18]

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 [19]

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 [20]

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 [21]

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.

3.2.3.3 Websites

Shell and Tube Heat Exchanger Pressure Drop [22]

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.

3.2.4 Uriah Whitaker

3.2.4.1 Papers

Modelling of thermocouple geometry variations for improved heat transfer monitoring in smart electronic manufacturing environment [23]

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 [24]

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[25]

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. [26]

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 [27]

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 [27]

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.

3.2.4.3 Websites

Tinkercad [28]

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.

3.3 Mathematical Modeling

3.3.1 Amount of Ice - 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. The assumptions made were the heat transfer from the ambient air to the water is zero due to us picking a 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 0^0C 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]:

$$E = m \text{ x } h_c \text{ x } \Delta T \qquad (1)$$

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 6.8^0C 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 will get the mass of the water is 454.86 kg. We can then derive using the total amount of mass that the energy needed to be absorbed is, 12947.50 kJ.Next we can then sum up the energies and divide by the 334 $\frac{kj}{kg}$ the ice can absorb and we will get a value of 91.54 lbs of ice that would be required in order to have our heat exchanger run for 30 minutes. These temperature assumptions would be from a low efficiency heat exchanger so as our heat exchanger efficiency increases so will the amount of ice required and so we are currently in discussion as to changing the time allotted in order to keep the amount of ice low.

3.3.2 Reservoir Insulation - Chris Mason

To get a general idea as to what insulation we should acquire for our reservoir I did a very simple insulated wall calculation for different types of cooler installations we might find. This is important because we want to limit as much heat gain from the system in order to get the amount of ice required for our system to a minimum. First I went ahead and took a look at our heat transfer textbook [4] to find the thermal resistances for the insulators polyethylene LD, polyethylene HD, polyurethane, and polystyrene(styrofoam). I found that their thermal resistances were polyethylene LD (k=0.33 $\frac{W}{mK}$), polyethylene HD (k=0.50 $\frac{W}{mK}$), polyurethane (k=0.02 $\frac{W}{mK}$), and polystyrene (k=0.03 $\frac{W}{mK}$). Next, the following assumptions were made: the convection coefficient for the air was 20 $\frac{W}{m^2K}$, the temperature of the ambient air was 20ºC, and the length of the cooler insulation was 102 mm as seen in Figure 5 below.

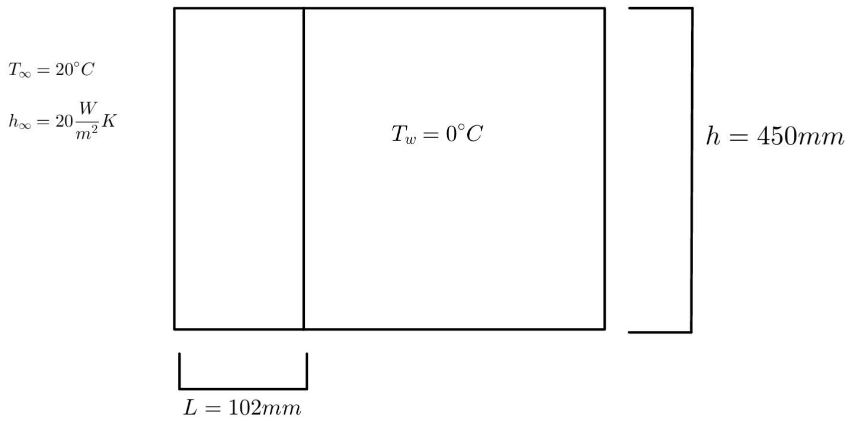


Figure 5. Insulation Diagram

After assuming these dimensions, the heat transfer through the wall was analyzed using the following resistance and heat transfer equations [4]:

$$R_{cond} = \frac{L}{kA} \tag{2}$$

$$R_{conv} = \frac{1}{h_\infty A} \tag{3}$$

$$R_{th} = R_{cond} + R_{conv} \tag{4}$$

$$q = \frac{T_\infty - T_w}{R_{th}} \tag{5}$$

L = length or thickness of the wall
k = thermal conductivity
h_∞ = convection coefficient
T_∞ = Temperature of the ambient air
T_w = Temperature of the water
R_{cond} = Conduction resistance
R_{conv} = Convection resistance
q = heat transfer

Now for the insulator calculations, coolers almost always consists of either polyethylene HD or LD as a base material so for polyurethane and polystyrene I assumed a small insulated wall of length 34 mm and then a polyethylene HD exterior wall with a length of 68mm due to it having a lower thermal resistance in order to capture the worst case scenario for these insulators. Then I went ahead and calculated the convection resistance which is the same for all the materials which gave a value of $0.246\frac{K}{W}$. Then I went ahead and calculate all the resistances due to conduction for the polyethylene insulators and got LD as $1.523\frac{K}{W}$ and HD as $1.005\frac{K}{W}$. Next I calculated the conduction resistances for the other insulators and found the exterior wall polyethylene HD was $0.670\frac{K}{W}$ and the inner walls as polyurethane $8.374\frac{K}{W}$ and polystyrene $5.583\frac{K}{W}$. Then I plugged them into the heat transfer equation and then ,multiplied by the time of 30 minutes to see how much energy would go through the cooler wall and got the following values, for polyethylene LD the energy transferred was 20.36 kJ, for polyethylene HD it was 28.78 kJ, for polyurethane it was 3.87 kJ, and for polystyrene it was 5.54 kJ. As we saw from these results, polyurethane would be the best insulation for us to use because the amount of energy transferred was minimal in the 30 minute time span.

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.

3.3.3.1 U-Tube Shell and Tube analysis [8]

Option A of 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.

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

$$h_t = \frac{Nu_t * k}{d_i} = 8070.54 \text{ W/m}^2{}^\circ\text{C} \tag{11}$$

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.

$$U = \left(\frac{1}{h_s} + \frac{1}{h_t}\right)^{-1} \text{ W/m}^2{}^\circ\text{C} \tag{12}$$

$$C = \dot{m} * C_p \text{ kJ/s} \tag{13}$$

$$NTU = \frac{U*A}{C_{min}} \tag{14}$$

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

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

A 62.1% effectiveness is not especially high but due to our pressure drop constraints this is a reasonable value and the team feels it has been as optimized as possible as in section 3.3.4 the pressure drop is almost at our maximum allowable value assuming a 10 psi drop through the Liquid-Air HXR (Testing required).

3.3.3.2 Shell and Coil Heat Exchanger [8]

Option B of the team's heat exchanger is a shell and coil heat exchanger. It was selected due to the turbulence effect caused by the rotation of the cooling element which the team hoped might help optimize heat transfer. The Steps of the analysis are similar but require different equations and a different method for effectiveness. If an equation is not listed it is equivalent to the equation in section 3.3.3.1. Next the internal Nusselt number can be found with the following equation with C equal to the outer diameter of the coil and D equal to the inner diameter of the coil and mu=dynamic viscosity of fluid and mus equal to the dynamic viscosity of the shell side fluid.

$$a = [1 + \frac{927(C/D)}{Re_t^2}] = 1.00 \tag{16}$$

$$b = 1 + \frac{.477}{Pr} = 1.02 \quad (17)$$

$$Nu_t = [(3.66 + \frac{4.343}{a})^3 + 1.158(\frac{Re_t(D/C)}{b})^{(1/3)}(\frac{\mu}{\mu_s})^{.14} = 72.44 \quad (18)$$

These Nusselt numbers can then be used to solve for h the convective heat transfer coefficient using equation 11 and to find heat transfer the following relationship can be used with Delta T equal to (T_{amb}-T_C).

$$R_{eq} = (\frac{1}{h_s*A} + \frac{1}{h_t*A})^{-1} = .0043\ ℃/\mathrm{W} \quad (19)$$

$$q = \frac{\Delta T}{R_{eq}} = 5500.54\ \mathrm{W} \quad (20)$$

The maximum heat transfer can then be found and then with that the overall effectiveness:

$$q_{max} = \dot{m} * C_c(\Delta T)\ \mathrm{W} \quad (21)$$

$$\varepsilon = \frac{q}{q_{max}} = .261 = 26.1\% \quad (22)$$

Compared to design A an effectiveness of 26.1 percent is very inadequate. The team's limiting factor was space as the maximum number of coils in the length allowed was already used so increasing heat transfer would require additional elements.

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]:

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

(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, and the diameters of the U-Tube and Helical tube ($D_{U\text{-}Tube}$ = .125 in. and $D_{Helical}$ = .25 in.), the Colebrook equation can be solved iteratively using MATLAB. The friction factor was found to be:

f = .0654 (U-Tube)
f = .0568 (Helical)

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

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

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

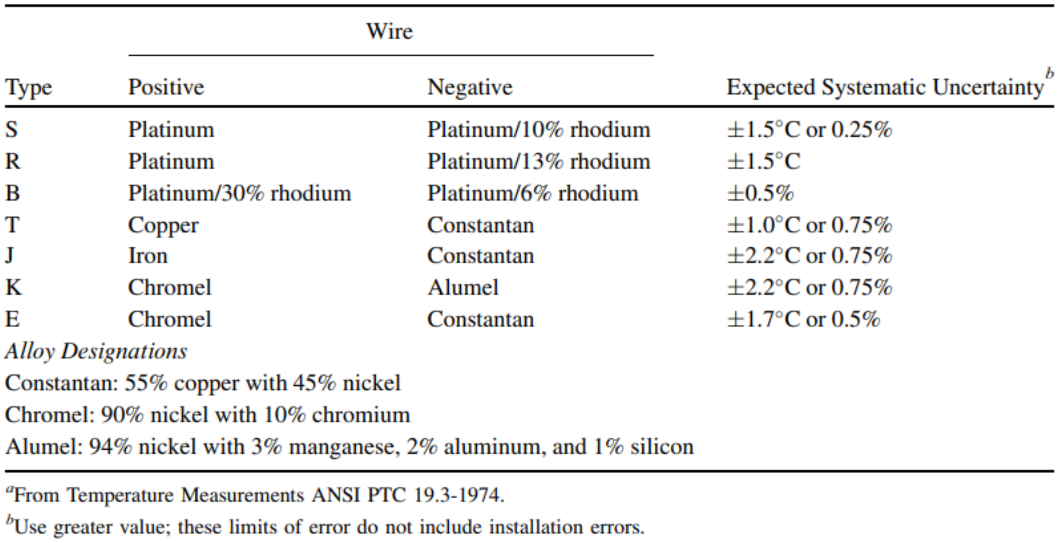
The helical tube is coiled 14 times and the U-Tube does two passes through the shell, so $L_{Helical}$ = 6.7m and $L_{U\text{-}Tube}$ = .812m. Therefore, the total pressure drop of the tube side is:

Δp = 31.122 psi (U-Tube)
Δp = 8.956 psi (Helical)

Due to the smaller tube diameter on the U-Tube geometry, there is more head loss across the heat exchanger. However, both geometries are within the 40 psi head loss limit for the given parameters and are still in the turbulent flow regime. Thus, either design is viable in terms of fluid flow.

3.3.5 Choosing the Thermocouple

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

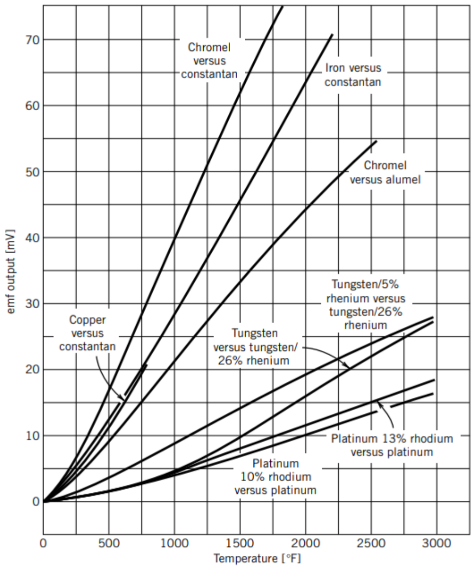


Figure 6: Thermocouple Voltage Output

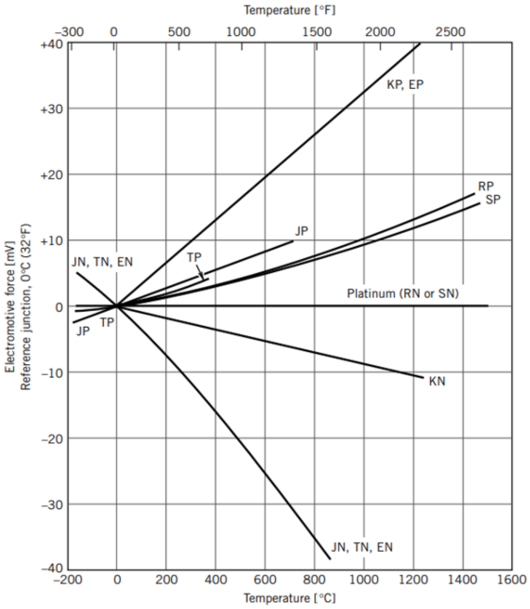


Figure 7: Thermal emf of Thermocouple Materials

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 J 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.

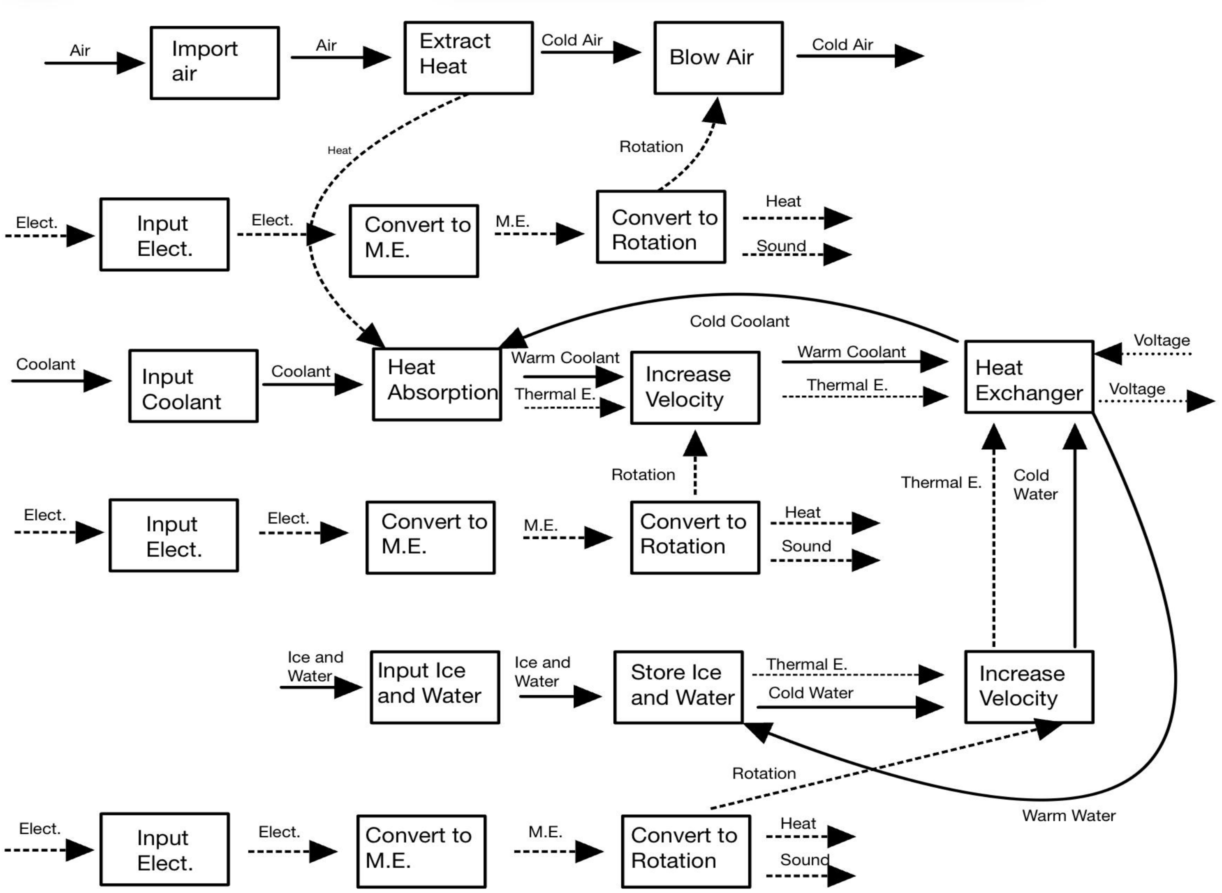


Figure 8: Functional Decomposition Model of Heat Exchanger Demonstrator

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 U-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

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

4.2.3 Concept C

Tube Material: Copper
Coolant: Ethylene Glycol
HXR Geometry: Shell and U-Tube
Insulation: Polyethylene LD
Pros: LD Polyethylene is cheap; helical tubing reduces heat exchanger volume;
Cons: High head losses in tubing; coolant is toxic

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

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)

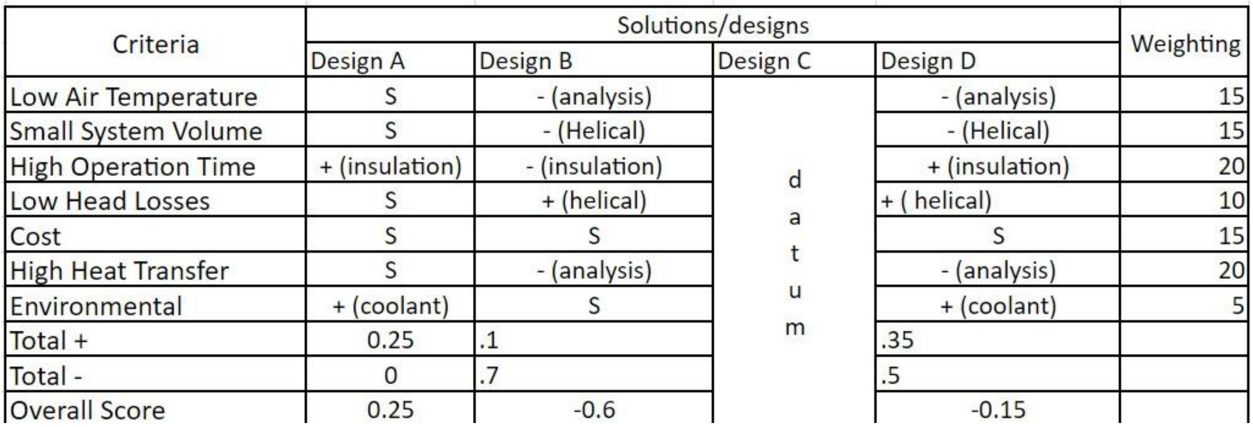
These criteria are rooted in the engineering requirements and will ensure the team selects the most successful design alternative from a technical standpoint.

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.

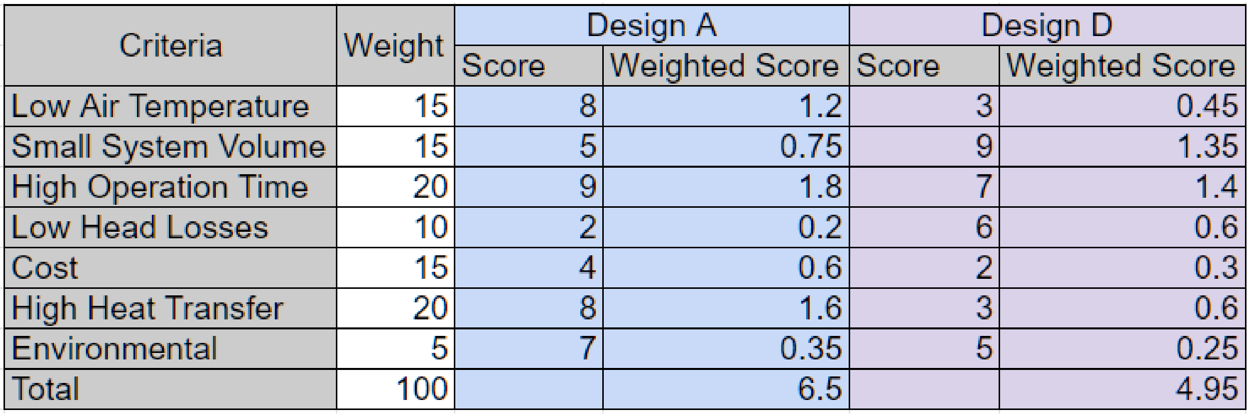
Table 2: Pugh Chart



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 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 polyurethane for the insulation in the reservoir. Now that the team has their final design selected, they will now begin finalizing a solidworks model and have begun prototyping. Prototyping will include computer model validation and heat exchanger experimentation. This design will be changed and optimized as the team learns more from the prototyping stage.

6 REFERENCES

[1] Boeing AH-64A APache Helicopter Operating Manual. Boeing, 06/28/1984. (can provide if needed)
[2]“0723_refrigerant,” *news.gm.com*. https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2010/July/0723_refrigerant.html
[3] Boeing-777-FCOM. Boeing, 01/11/02. http://www.ameacademy.com/pdf/boeing/Boeing-777-FCOM.pdf
[4]R M E Diamant, *Thermal and acoustic insulation*. London: Butterworths, 1986.
[5]S. Ostrach, “Natural Convection in Enclosures,” *Journal of Heat Transfer*, vol. 110, no. 4b, pp. 1175–1190, Nov. 1988, doi: https://doi.org/10.1115/1.3250619.
[6]P. B. L. Chaurasia, “Comparative study of insulating materials in solar water storage systems,” *Energy Conversion and Management*, vol. 33, no. 1, pp. 7–12, Jan. 1992, doi: https://doi.org/10.1016/0196-8904(92)90141-i.
[7]A. R. Shaibani, M. M. Keshtkar, and P. Talebizadeh Sardari, “Thermo-economic analysis of a cold storage system in full and partial modes with two different scenarios: A case study,” *Journal of Energy Storage*, vol. 24, p. 100783, Aug. 2019, doi: https://doi.org/10.1016/j.est.2019.100783.
[8] T. L. BERGMAN, *Fundamentals of heat and mass transfer*, S.l.: WILEY, 2020
[9] R. W. Fox, *Fox And Mcdonald's Introduction To Fluid Mechanics.* S.L.: John Wiley, 2020.
[10] tec-science, “Final temperature of mixtures (Richmann’s law),” *tec-science*, Jan. 20, 2021. https://www.tec-science.com/thermodynamics/temperature/richmanns-law-of-final-temperature-of-mixtures-mixing-fluids/
[11] J. K. Cooper, Ed., Heat exchangers : characteristics, types and emerging applications. New York: Novinka, 2016.
[12] “Design and Operation of Heat Exchangers and their Networks, https://www-sciencedirect-com.libproxy.nau.edu/science/article/pii/B9780128178942000030 (accessed Sep. 14, 2023).
[13] “Three-dimensional fin-tube expansion process to achieve high heat transfer efficiency in heat exchangers,” Springer Link, https://link-springer-com.libproxy.nau.edu/article/10.1007/s12206-019-0836-6 (accessed Sep. 19, 2023).
[14] M. Pennington, “Heat Exchanger Design Handbook,” Academia.edu, https://www.academia.edu/4715789/Heat_Exchanger_Design_Handbook (accessed Sep. 14, 2023).
[15] “The engineering toolbox,” Engineering ToolBox, https://www.engineeringtoolbox.com/index.html (accessed Sep. 17, 2023).
[16] D. L. 8 Jun, D. Lane, and 8 Jun, “Tutorial: How to perform a transient thermal analysis in SolidWorks,” Tutorial: How to perform a transient thermal analysis in SolidWorks | GrabCAD Tutorials,

https://grabcad.com/tutorials/tutorial-how-to-perform-a-transient-thermal-analysis-in-solidworks (accessed Sep. 18, 2023).

[17] A. Sheeba, R. Akhil, and M. J. Prakash, “Heat transfer and flow characteristics of a conical coil heat exchanger,” *International Journal of Refrigeration*, vol. 110, pp. 268–276, 2020. doi:10.1016/j.ijrefrig.2019.10.006

[18] R. Kumar, P. Chandra, and Prabhansu, “Innovative method for heat transfer enhancement through shell and coil side fluid flow in shell and helical coil heat exchanger,” *Archives of Thermodynamics*, vol. 41, no. 2, pp. 239–256, 2020. doi:10.24425/ather.2020.133631

[19] S. Sharma et al., “Computational fluid dynamics analysis of flow patterns, pressure drop, and heat transfer coefficient in staggered and inline shell-tube heat exchangers,” Mathematical Problems in Engineering, vol. 2021, pp. 1–10, Jun. 2021. doi:10.1155/2021/6645128

[20] DOE Fundamentals Handbook: Thermodynamics, Heat Transfer, and Fluid Flow, vol. 2, United States. Dept. of Energy, Oak Ridge, TN, USA, 1992.

[21] D. P. Sekulić and R. K. Shah, *Fundamentals of Heat Exchanger Design*. Hoboken, NJ: Wiley, 2003.

[22] “Shell & Tube Heat exchanger pressure drop,” EnggCyclopedia, https://enggcyclopedia.com/2019/05/shell-tube-heat-exchanger-pressure-drop/ (accessed Sep. 13, 2023).

[23]D. Straubinger, B. Illés, D. Busek, N. Codreanu, and A. Géczy, “Modelling of thermocouple geometry variations for improved heat transfer monitoring in smart electronic manufacturing environment,” *Case Studies in Thermal Engineering*, vol. 33, p. 102001, May 2022, doi: https://doi.org/10.1016/j.csite.2022.102001.

[24]T. Ahn, J. Kang, J. J. Jeong, and B. Yun, “Measurement of local wall temperature and heat flux using the two-thermocouple method for a heat transfer tube,” *Nuclear Engineering and Technology*, vol. 51, no. 7, pp. 1853–1859, Oct. 2019, doi: https://doi.org/10.1016/j.net.2019.05.007.

[25]A.-R. Farraj and P. Hrnjak, “Combination of Local Heat Transfer and Flow Visualization of Combination of Local Heat Transfer and Flow Visualization of R245fa Flow Boiling in plate Heat Exchanger R245fa Flow Boiling in plate Heat Exchanger Combination of Local Heat Transfer and Flow Visualization of R245fa Flow Boiling in Plate Heat Exchanger.” Accessed: Oct. 29, 2023. [Online]. Available: https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3186&context=iracc

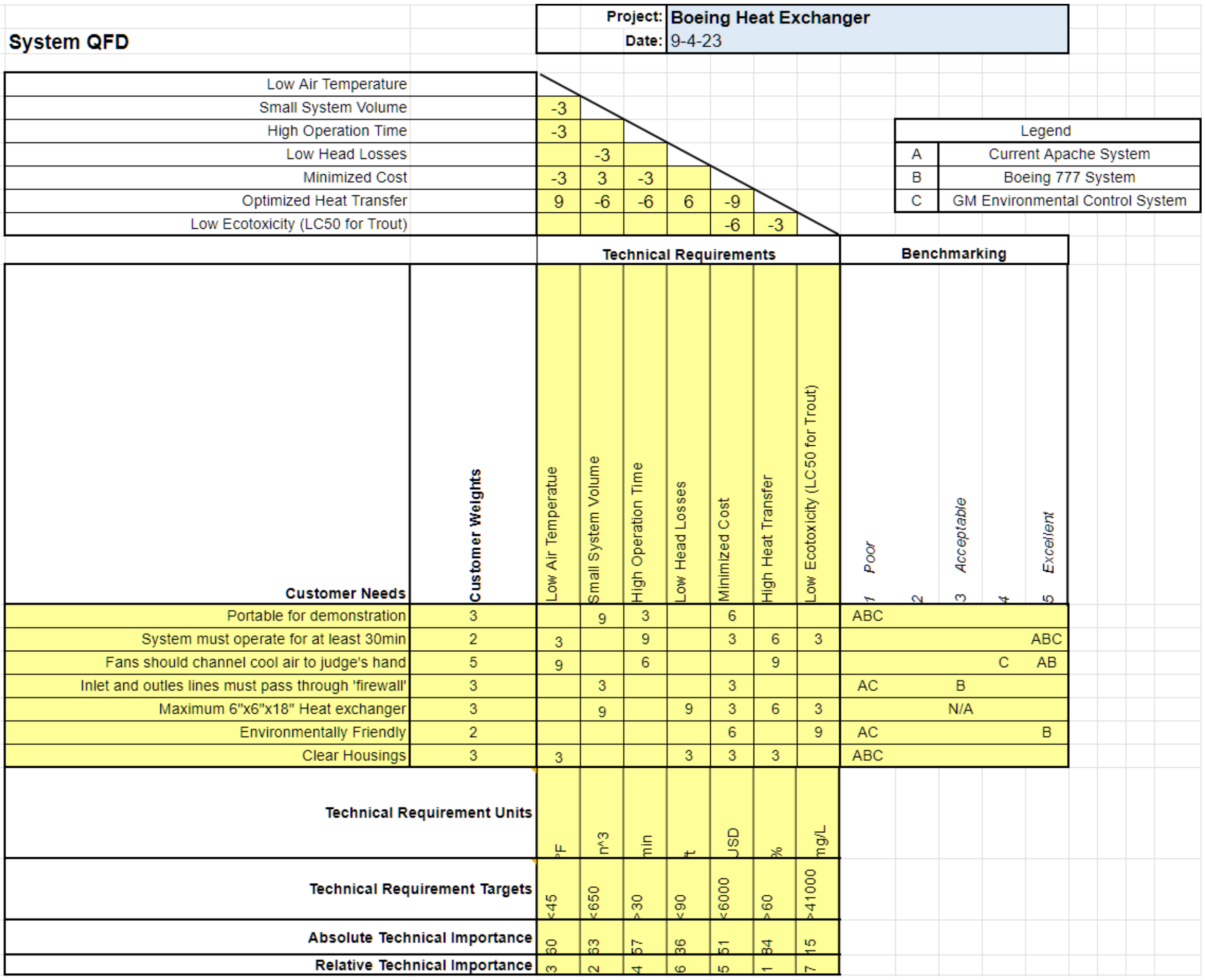
[26]Operator’s Manual for Army AH-64A Helicopter. 1989.

[1] M. J. MORAN, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, *Fundamentals of Engineering Thermodynamics*. WILEY, 2014.

[28]Tinkercad, “Tinkercad | From mind to design in minutes,” *Tinkercad*, 2019. https://www.tinkercad.com/

7 APPENDICES

7.1 Appendix A: QFD



System QFD

Project: Boeing Heat Exchanger
Date: 9-4-23

	Low Air Temperature	Small System Volume	High Operation Time	Low Head Losses	Minimized Cost	Optimized Heat Transfer
Low Air Temperature						
Small System Volume	-3					
High Operation Time	-3					
Low Head Losses		-3				
Minimized Cost	-3	3	-3			
Optimized Heat Transfer	9	-6	-6	6	-9	
Low Ecotoxicity (LC50 for Trout)					-6	-3

Legend	
A	Current Apache System
B	Boeing 777 System
C	GM Environmental Control System

Customer Needs	**Customer Weights**	Low Air Temperatue	Small System Volume	High Operation Time	Low Head Losses	Minimized Cost	High Heat Transfer	Low Ecotoxicity (LC50 for Trout)	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
Portable for demonstration	3		9	3		6			ABC				
System must operate for at least 30min	2	3		9		3	6	3					ABC
Fans should channel cool air to judge's hand	5	9		6			9					C	AB
Inlet and outles lines must pass through 'firewall'	3		3			3			AC		B		
Maximum 6"x6"x18" Heat exchanger	3		9		9	3	6	3			N/A		
Environmentally Friendly	2					6		9	AC				B
Clear Housings	3	3			3	3	3		ABC				
Technical Requirement Units		°F	n^3	min	t	USD	%	mg/L					
Technical Requirement Targets		<45	<650	>30	<90	<6000	>60	>41000					
Absolute Technical Importance		60	63	57	36	51	84	15					
Relative Technical Importance		3	2	4	6	5	1	7					