EDSGN100 Design Project #2

Final Design Report

Additively Manufacturing a Better Heat Exchanger

Introduction to Engineering Design
EDSGN 100 Section 008

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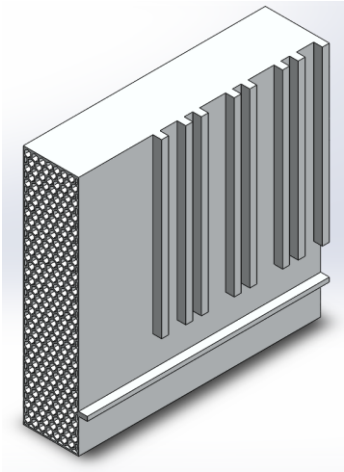

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Executive Summary:
Lockheed Martin presented our group with the task of redesigning their current heat exchanger that they employ on their computer circuit boards for additive manufacturing and to make the exchanger more efficient. To make it more efficient, we had to maximize the airflow, maximize the surface area, and minimize the weight. For our final design, we created a pattern of hexagons in a thin honeycomb shaped interior for the exchanger with 0.02 inch spacing between hexagons. This design increased interior surface area, increased airflow, and decreased the weight of the heat exchanger.

Additively Manufacturing a Better Heat Exchanger

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1.0 Introduction

Each semester, students in EDSGN 100: Introduction to Engineering Design demonstrate their newfound design abilities through a sponsored final project. This project is sponsored by companies that want to impact the engineering design education at Penn State, giving first-year students an opportunity to engage in different interdisciplinary problems and an understanding of what they will be doing as engineers when they graduate.

The official sponsor for the Spring 2016 semester is Lockheed Martin, a global security and aerospace company. It employs approximately 125,000 people worldwide and is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems, products and services.

Led by Marillyn A. Hewson, Lockheed Martin works to advance scientific discovery and deliver innovative solutions to help the U.S. Department of Defense and U.S. federal government agencies keep people safe, provide them essential services and strengthen global security (“About Lockheed Martin”, n.d.).

2.0 Project Background

Our group was presented with the task to redesign an existing heat exchanger. Lockheed martin wanted us to accomplish three goals, make the heat transfer more effective, reduce the weight of the heat exchanger, and find a more efficient way of making their existing heat exchanger. The only way we could accomplish all three of these things is by additive manufacturing. Lockheed Martin gave us this suggestion when they presented the task to us. Lockheed also gave us the dimensions and the weight of their existing heat exchanger. We used these dimensions in our improved model of the heat exchanger and we used the weight as a reference to how much weight we were able to reduce.

The main point in this project is to explore the benefits of additive manufacturing. Additive manufacturing is the future. With additive manufacturing you do not waist material and you are able to make designs that you could not normally make with normal subtractive manufacturing. Lockheed presented this project to find ideas that would take advantage of the benefits of additive manufacturing. With additive manufacturing we were able to succeed in accomplishing all three tasks that Lockheed Martin presented to us.

3.0 Project Objectives

After being given the project by Lockheed Martin, our primary stakeholder in the project, we first had to establish what the problem was and define it. Lockheed had tasked us with creating a new heat exchanger for their computer circuit systems. The purpose of the heat exchanger would be to draw heat away from circuits in their computer systems to prevent overheating and keeping the computers functioning properly.

Lockheed Martin gave us certain design specifications that our final design must meet as their stakeholder requirements. The first of these was that our design must use and take advantage of additive manufacturing techniques. One of the main goals for this project is to create a heat exchanger that uses additive manufacturing because this form of manufacturing, compared to the subtractive techniques that are currently employed, allows much greater flexibility and relatively endless complexity in a design.

With nearly infinite flexibility in design, this allows many other subsequent traits of the product to be changed. The first of these is the weight of the final product. We were specifically assigned to design our project to weigh less than the heat exchanger they already employ, which is manufactured through subtractive means. Reducing the weight of the heat exchanger is important because many of the Lockheed Martin's products, including aircraft, are weight sensitive. That is, the more we can reduce the weight of a heat exchanger, the more weight they can place in an aircraft, either in payload or additional equipment.

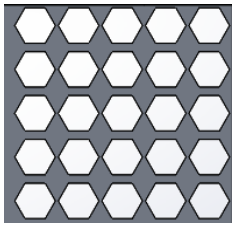
The next trait that we had to improve utilizing additive manufacturing was the thermal efficiency of the heat exchanger; i.e. make one that dissipates more heat more quickly than their current design. As a team, we decided that two things affected the thermal efficiency of the heat exchanger: the internal surface area and the airflow through the exchanger. Thus, our final design had to have more surface area than their current exchanger, and have better airflow through the exchanger than their current one.

Now that we have established what our design objectives and stakeholder requirements are, it is important to define the mission of our project. The mission statement is important because it outlines our goals for the project in one clear, concise sentence. *Our mission is to design a heat exchanger for computer circuits that leverages additive manufacturing technologies to create a more efficient and cost effective product.*

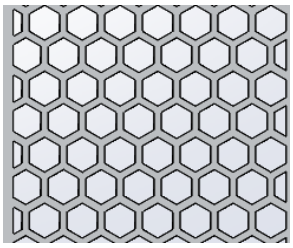
4.0 Conceptual Designs

4.1 Descriptions

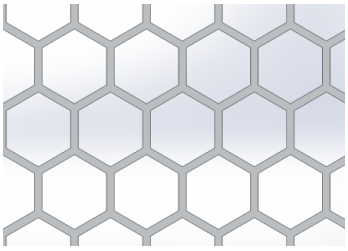
Now that we have fully defined the problem space and specifications for the design, we began to brainstorm possible solutions to the problem. In our designs, we had to remember the constraints placed on us. First, the new exchanger must fit the same footprint as the original design; i.e. it must be the same dimensions and have the same mating features as Lockheed's current design. Also, our solutions must attempt to increase the efficiency of the exchanger by increasing surface area and airflow, and also decrease the overall weight of the device.



Our first idea on how to improve the heat exchanger was to create a linear hexagon pattern, as shown in the figure on the right, on the interior of the heat exchanger. Our initial thought was that a shape with more sides, such as a hexagon, would create more surface area within the heat exchanger to help dissipate heat more efficiently. We proceeded to line up the hexagons in a linear pattern.

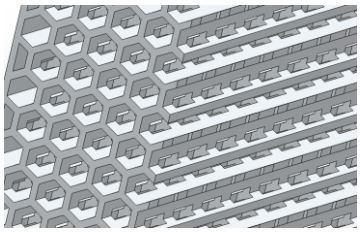


After examining our first brainstormed idea, we realized that we were wasting a lot of space by lining up the hexagons in a linear fashion. We decided that for our next brainstormed idea, we could line up the hexagons in a honeycomb pattern, similar to how honey bees in the wild build their hives to produce honey. We lined up the hexagons in this new honeycomb pattern for our second brainstormed idea, and gave each hexagon a 0.04 inch distance between each.



Building on our second brainstormed idea, we decided that we might be able to reduce the spacing between each hexagon in the honeycomb to try to again reduce weight and maximize surface area. For this idea, we decided to try a 0.02 inch spacing between each hexagon in the honeycomb.

For our fourth and final brainstormed idea, we decided that we had maximized what we could of the pattern running parallel to the body of the heat exchanger. We then came up with the idea of using square, perpendicular cut-outs through the honeycomb in an attempt to create



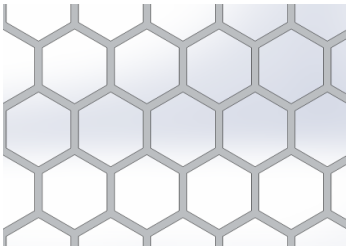
even more surface area and to further reduce the weight of the heat exchanger.

4.2 Research and Analysis

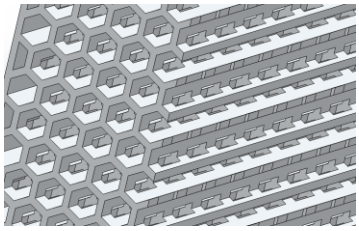
Following the creation of a CAD model for each brainstormed idea, we evaluated the mass and surface area properties of each model. The following table shows the comparison of each model's surface areas and masses. We chose to analyze surface area, because by maximizing surface area we would be able to maximize heat transfer over time according to the equation: Where *Q* is heat transfer, and *A* is Area of surface.

$$\frac{Q}{t} = \frac{\kappa A(T_{hot} - T_{cold})}{d}$$

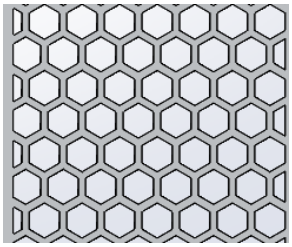
We chose to analyze mass of each model, because by reducing the mass of the exchanger, it would allow Lockheed to put more cargo on the device. Reducing mass saves money and allows for the addition of more sensors, equipment or other cargo. To compare each design's surface area *and* mass, we utilized a surface area to mass factor to easily illustrate how well each design optimized surface area and weight. Because we are trying to *maximize* surface area and *minimize* mass, the factor is □□□□□□ = □□ ÷ □□□□. A small mass and large surface area will produce a large factor, so the higher the factor, the more optimal the design.



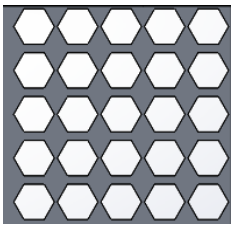
Of our four initial designs, the **.02 wide Honeycomb** had tremendous improvements in both maximizing surface area and minimizing mass, with a factor double the initial design's.



The **Honeycomb with .04 inch spacing and holes** came in second, obviously heavier than the .02 spacing which has thinner walls and therefore less material. The holes reduced mass but sacrificed surface area at the same time. Still, the design had the second highest □□ ÷ □□□□ factor, so numerically it was one of our stronger designs.



The **.04 inch spacing Honeycomb** and **Linear Hexagon** designs both had greater mass' than the initial design, so from that perspective they were not numerically optimal designs. Furthermore, the Linear Hexagon had a smaller surface area to mass factor than the initial design, showing that the design is actually a demotion from the initial design. Looking at the cross-section, there is a lot of wasted space of pure material (which does not contribute to surface area and increases the mass). Numerically, it would be foolish to fully develop each of these ideas, as their mass' alone make them inferior designs to the initial heat exchanger design.



We created a table to easily compare the masses and surface areas of each designs. The masses were determined using the built in SOLIDWORKS mass properties evaluator. We used an Aluminum Alloy – AlSi10Mg – as the material to base the calculations off of.

Material	**Density (kg/m^3)**	**Thermal Conductivity (W/(m*K)**	
Aluminum AlSi10Mg	2670	170	
Design	**Mass (g)**	**Surface Area (sq. cm)**	**Surface Area to Mass (sq. cm / g)**
Initial	1287.719	6708.293	5.20943855
Linear Hexagon	1733.787	5365.476	3.094656956
Honeycomb	967.268	10385.957	10.73741404
Wide Honeycomb	1444.142	8702.279	6.025916427
Wide Honeycomb with Hole	1135.829	7999.107	7.042527528

From the table, it is clear to see that the ranking of the designs (numerically) are as follows: **Honeycomb** (.02), **Wide Honeycomb with Holes** (.04) , **Wide Honeycomb**, **Linear Hexagon.**

Another important characteristic to consider is the thickness of the internal geometries. According to the heat transfer equation, $\frac{Q}{t} = \frac{\kappa A(T_{hot} - T_{cold})}{d}$ a smaller thickness will optimize heat transfer. Therefore, the thinner Honeycomb would transfer heat more effectively than the thicker-walled exchangers.

4.3 Concept Evaluation and Selection

After brainstorming and analyzing all of our conceptual design ideas, we then had to effectively and systematically narrow down our possible solutions and choose the best one. To do this, we came up with five different criteria to grade each of the solutions on: weight optimization, surface area optimization, print as a whole, improved performance, and takes advantage of additive manufacturing. After we had decided that these were the criteria we were going to select best solution based upon, we had to create a means of assigning different weightings to each criteria to see which is most important. To do this, we created a Pairwise Comparison Table, as shown below, that allowed us to grade each criteria compared to other ones.

		A	B	C	D	E	Row Total	Row Total / Total	Percentages
Weight Optimization	A	1	0.5	5	0.5	4	12	0.2649	26%
Surface Area Optimization	B	2	1	5	0.5	5	13.5	0.298	30%
Print as a Whole	C	0.2	0.2	1	0.2	0.5	2.1	0.0464	5.00%
Improved Performance	D	2	2	5	1	4	14	0.3091	31%
Takes Advantage of AM	E	0.25	0.2	2	0.25	1	3.7	0.0817	8%
						Total	**45.3**		

Once we had assigned percentages to each criteria, we saw that improved performance, weight optimization, and surface area optimization were the highest priority criteria, while must be printed as a whole and takes advantage of additive manufacturing were of medium importance. Now that we had these weightings, we created another table to screen our various solutions to see if there were any that we could eliminate from contention immediately so that we would not waste time scoring bad ideas.

Concept Variants				
Selection Criteria	Wide Honeycomb	Wide Honeycomb w/ Square Cutouts	Thin Honeycomb	Linear Hexagon
Weight Optimization	-	+	+	-
Surface Area Optimization	+	+	+	-
Print as a Whole	+	+	+	+
Improved Performance	+	+	+	0
Take advantage of AM	0	+	+	0
Pluses	2	5	5	1
Sames	2	0	0	2
Minuses	1	0	0	2
Net	+2	+5	+5	-1
Rank	3rd	T-1st	T-1st	4th
Continue?	No	Yes	Yes	No

Once we had completed the concept screening, we saw that clearly the linear hexagon and the wide honeycomb patterns were far behind the thin honeycomb pattern and the honeycomb with square cut-outs. Once we established that these two were our best ideas, we had to systematically score them to see which one was actually better. We used the percentages from the Pairwise Comparison Table, and assigned scores to each category based on the scores we had already given the solutions in the concept screening.

		Concepts				Rating:	Conversion:
		Wide Honeycomb w/ Square Cutouts		Thin Honeycomb		+	4,5
Selection Criteria	**Weighting**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	0	3
Weight Optimization	30%	4	1.20	5	1.50	-	1,2
Print as a Whole	5%	5	0.25	5	0.25		
Surface Area Optimization	20%	4	.80	5	1.00		
Improved Performance	30%	4	1.2	4	1.20		
Take advantage of AM	15%	5	.75	4	.60		
	Total score:	4.2		4.55			
	Ranking:	2nd		1st			
	Continue	Develop!		No			

Why?

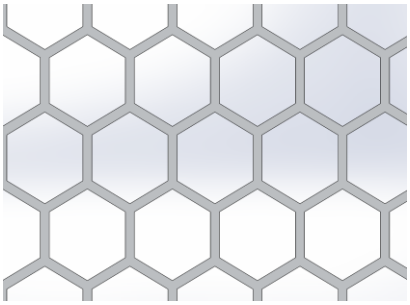
After we completed the concept scoring, we saw that the thin honeycomb pattern had scored the best out of all of the other possible solutions. This makes sense, considering it was able to make performance increases in surface area, airflow, and weight. Since the thin

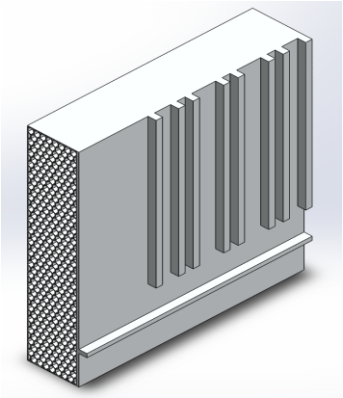
honeycomb had won the concept scoring, we discussed as a group whether or not this was the logical choice to us as well. After discussing the thin honeycomb further, we decided that we agreed with the concept scoring and that the thin honeycomb pattern for the interior of the heat exchanger was the best design solution.

5.0 Detailed Design

5.1 Final Design Graphics and Calculations

Referencing the table above, notice that we decided to develop also the second place design. This was due to the fact that there was a printing error when we printed the .02 Thickness Honeycomb, so we decided to print the .04 Thickness Honeycomb with Holes as well. However, after receiving the print of the thicker honeycomb we realized that the design was not printable due to its internal holed skeleton. Therefore, hands down, our .02 Thickness Design is our best, and final design. This Thin Honeycomb is a huge improvement from the original design, in it's mass, surface area, thickness and also heat transfer properties.





The following table shows how our design improves upon the initial design in various ways.

	Initial Design	Our Final Design	Improvement	% Improvement
Mass (g)	1287.719	967.268	320.451	24.89% decrease
Surface Area (cm^2)	6708.293	10385.957	3677.664	54.82% increase
Surface Area to Mass (cm^2/g)	5.20943855	10.73741404	5.52797549	106.11% increase
Thickness (cm)	0.127	0.0508	0.0762	60% decrease
Heat Transfer Coefficient * (m) http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/heatcond.html	52.82	204.45	151.63	287.07% increase

*We determined Heat Transfer using the following equation:

$$\frac{Q}{t} = \frac{\kappa A(T_{hot} - T_{cold})}{d}$$

Then manipulated it to show two variables we calculated for: *Surface Area – A* and *Thickness – d*

$$\frac{Q}{t * k * (T_{hot} - T_{cold})} = \frac{A}{d}$$

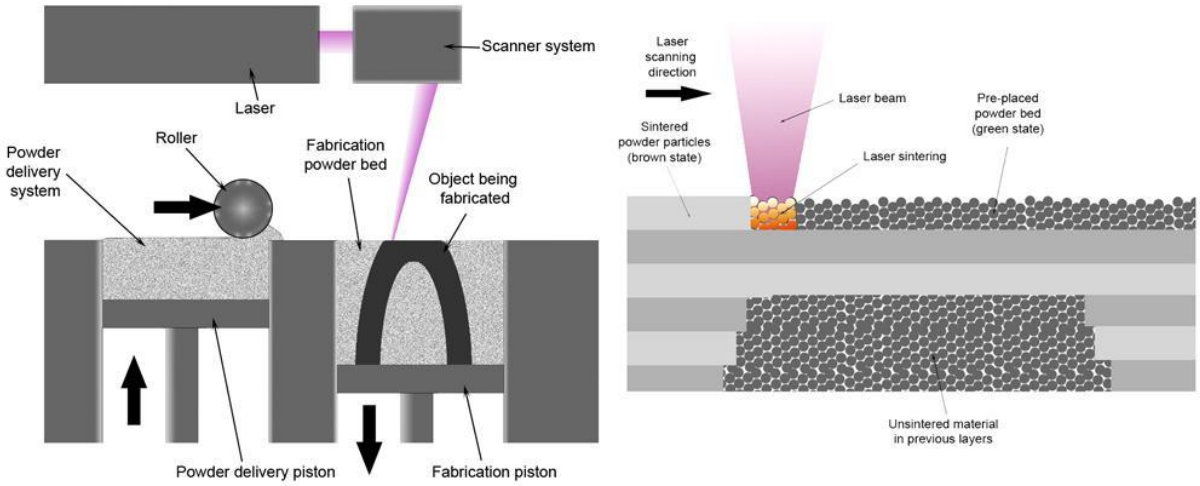
K, the thermal conductivity constant remains constant, as we are assuming that each design is made out of the same material.

We used the surface areas of the entire model, and the thickness of the internal geometries to calculate the Heat Transfer coefficient. This is not the exact Heat Transfer coefficient, as the surface area takes into account the *entire model*. However, the comparison between the two designs is accurate, as it keeps all variables consistent.

5.2 Powder Bed Fusion Process

To produce the heat exchanger we designed, the additive manufacturing technique of powdered bed fusion would be used. This method would be the most efficient and the most effective for our design. There are many different types of powder bed fusion techniques. Some examples of powder bed fusion are Electron Beam Melting, Selective Heat Sintering, Selective laser Melting, and Selective Laser Sintering. All these techniques use the same basic process to additive manufacture. They all use some sort of heat to fuse powder together to make a solid. Many different powdered materials can be used in powder bed fusion. These materials range from ceramic to steel. This is a good quality for our design because aluminum powder will be used when making our project.

After analyzing the different powder bed fusion techniques, we found that the Selective Laser Sintering (SLS) manufacturing technique would produce the most effective model of our heat exchanger. During the SLS process, a bed of powder is laid out and a laser goes over the powdered material and fuses it together. After the lasers makes the outline of the 3D rendering, a roller rolls out more of the powdered material over top of the lasered material and then a laser goes over it again following the 3D rendering. This process happens over and over again until the laser completely fused together the whole product. The final structure is very durable and it is made exactly how you would want. This process would work the best for us because you are able to use metal powder and you also do not need support structures put into your product. Our heat exchanger is made up of intricate shapes that would need support if we were not using this powder bed fusion technique. Powder bed fusion is the most efficient and effective type of additive manufacturing technique that you would produce or heat exchanger.

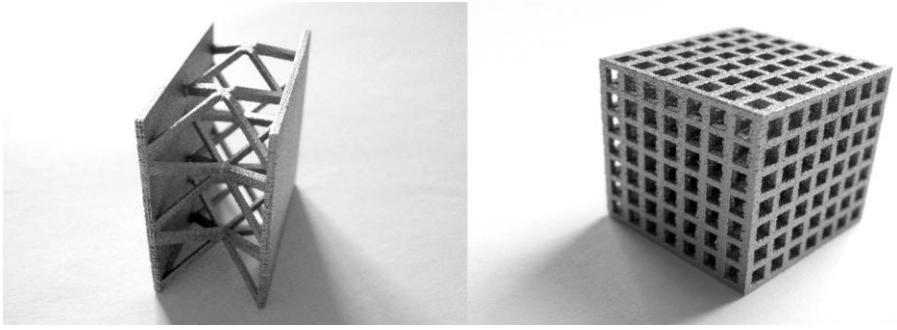


5.3 Aluminum AlSi10Mg

The material we decided to proceed with is the AlSi10Mg, which is an aluminum alloy in fine powder that has all the characteristics we wanted in our design. Some of the properties of this material are low weight, good thermal properties, strength and hardness. It also has excellent malleability and machinability, which makes fast building possible and reduces the time needed for the manufacturing process.

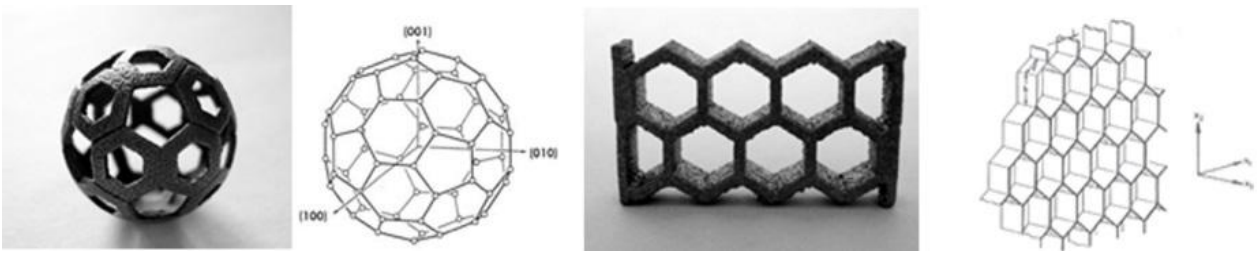
The AlSi10Mg is used in direct metal laser sintering with a lot of different applications such as thin walls, complex geometries and lower cost prototypes, as well as aerospace and automotive applications.

Furthermore, it was demonstrated that it is possible to manufacture aluminum lattice structures by powder bed fusion process as the ones reported in the above figure, with desired shape and internal features in a single fabrication step.



These complex geometry structures have very good base metal properties thanks to the very fine microstructure typical of this process. This means that a wide variety of different

architectures can be made with fine control, allowing the production of cellular structures like the honeycomb pattern (Manfredi et al., 2014).



5.4 Bill of Materials

The average market price for the Aluminum alloy AlSi10Mg is about $123 per kilogram. Knowing the total mass of our final design we were able to calculate an small bill of materials for the estimated cost of our heat exchanger.

Bill of materials			
Material	Quantity in g	Cost per kg	Cost
AlSi10Mg	967.268	$123	$119
		Total Cost:	$119

6.0 Conclusions

We went step by step through the design process to design and create a model of our new and improved heat exchanger. Lockheed Martin gave us the task to redesign and improve a heat exchanger that they have been using. They told us to do this by using additive manufacturing. We successfully did this. We made their heat exchanger more efficient by utilizing the benefits of additive manufacturing.To come up with our final design, we went through many obstacles. We had to find a way to maximize surface area within our heat exchanger, while reducing the weight. This was made possible by additive manufacturing. Our first print of our final design did

not turn out the way we wanted it because the hexagonal shapes were too thin for the 3D printer to print nicely. To fix this, we made the hexagonal shapes thicker but smaller which actually helped us more because it reduced the weight. Through trial and error, we were able to come up with a design that greatly improves upon Lockheed Martin's original design not only in performance, but by also making the manufacturing process more cost effective and less wasteful.

7.0 References

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