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FinaReport

Team 5: Icy Innovators

Section: E

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0. Executive Summary

Refrigerators are vital to the lifestyle of modern day consumers; however, while keeping and preserving food, the current refrigerator compressor design in use is inefficient and environmentally unfriendly. This project sets out to solve this problem by designing a new mechanism which can more efficiently meet pre-existing performance needs. Cost, use of non-toxic refrigerants, and higher efficiency are the main motivations of this project. The selected design solution to correct this problem is to use a Stirling engine to pump heat out of the refrigerator, while using air as the working fluid.

Patent research as well as research into existing products show that there have been multiple smaller models using Stirling engines made in production; however, each of these products were intended for portable use rather than stationary use in a standard home. Along with this prior art, proof of concept is also important to discuss in producing a viable product. The scarce number of patents previously filed relating to high efficiency Stirling engine coolers as well as the inefficiency of current models led the design team to believe this is a valid proof of concept.

Through analysis and market research, requirements for the project were determined and rated according to their level of importance. Production cost was determined to be the most important engineering requirement due to its direct influence on the customer. The goal is to have the cost of the product below the cost of both current stirling engine coolers as well as standard refrigerators, satisfying the most important customer requirement of low cost.

Key technical challenges of creating the Stirling engine will include the building and assembly of a removable crankshaft and airtight piston cylinders, creating the correct amount of torque and determining the appropriate operating speeds. The evaluation matrices provided demonstrate that an alpha-style Stirling engine in combination with a finned heatsink and cooling fan has the highest potential of meeting project goals.

The dorm-style refrigerator used for the prototype is a representative version, but for the actual fabrication package, a different refrigerator shell will be used, which will better accommodate the altered dimensions of the Stirling engine. Analysis regarding the appropriate sizing of the engine and power consumption was performed in order to construct the prototype. Analysis based on the performance testing of the standard refrigerator has also been completed in order to determine what design specifications must match or exceed the pre-existing compressor's performance levels. Finite element analysis, including thermal, fluid, and stress analysis have been completed and have aided in the material selection, construction, and testing of the Stirling engine.

Future work for this project includes more thorough testing of the Stirling engine to create the most optimal and efficient product. The vibration output and cooling efficiency of the engine can be measured and observed over a longer period of time. For further noise reduction, the engine could be mounted on a platform that absorbs more vibration. Lastly, a patent for the

Stirling engine placed into a refrigerator could be obtained, and contact with manufacturers could result in a distribution and mass production plan.

1. Introduction and Background

Domestic refrigerators have been in use since the early 1900's [1]. While the technology has improved, most of the refrigerators today still use the same vapor compression cycle - compressing a fluid using a compressor then expanding its volume to absorb heat. Although this technology is well proven and developed, there are multiple drawbacks to using this system. A standard refrigerator compressor has a relatively low thermal efficiency. In addition, most compressors use environmentally harmful refrigerants and have a high noise output. The goal for the design team is to replace a refrigerator compressor with a more efficient cooling mechanism by constructing a Stirling engine refrigerator that meets or exceeds current refrigerator standards while keeping it in the affordable range for the consumer. This refrigerator will resemble what will be currently on the market so customers will not notice an aesthetic change. It will be used similar to a standard refrigerator, keeping food cold for preservation. The intended usage environment will be the same as a standard refrigerator in that it will be used for households in order to preserve food. The difference between the Stirling engine refrigerator and a current standard refrigerator is the greater efficiency of the Stirling engine compared to a compressor. The primary design challenge will be to determine how to integrate the Stirling engine into a standard refrigerator casing, and how to remove the heat from the interior of the refrigerator. As a Stirling engine is a closed system, heat sinks will have to be used to externally extract heat from the refrigerator's interior and dissipate it out the back. Another challenge will be to determine the safest and most affordable fluid to use as the refrigerant fluid, making sure that it is still thermodynamically viable. The freezer will not be included in the scope of this design project, therefore the design team will only refer to the refrigerator portion throughout the remainder of the design.

2. Existing Products, Prior Art and Applicable Patents

There are very few Stirling engine refrigerators currently on the market. Coleman and Twinbird have designed Stirling engine electric coolers driven by pistons [2]. The Twinbird model is shown below in Figure 1 [3]. Also in existence are Stirling Engine Cryocoolers, which have relatively strong performance, but cool to temperatures far below a range needed for a standard refrigerator [7]. In addition to these, other Stirling engine refrigerators have been made utilizing thermoacoustics [5]. The thermoacoustic refrigerator utilizes vibrations generated from the engine to help power the the Stirling engine [6]. The recycling of energy could be very useful when designing the refrigerator and knowing that patents out there have been claimed is important background information. These different types of Stirling engine refrigerators provide insight on improvements that can be made and previous ideas that cannot be done with the refrigerator.

Figure 1: Twinbird Stirling Engine Cooler (335mm x 225mm x 340mm and Volume 25 L)

All the products utilize the Stirling engine as a means to extract heat from the container. Pre-existing designs like the one shown above are similar to our concept but they are considerably smaller and are meant to be used as portable coolers instead of permanent refrigerators. The appearances are also largely different. By making our refrigerator look similar to current refrigerators, customers will be more likely to buy them, especially when its performance is shown to be better than what is currently on the market. The main takeaway is that on the market, similar systems exist but none are in use as standard refrigerators or with the high efficiency being aspired to by this project.

3. Customer Requirements and Engineering Design Specifications

The stakeholders, who are involved with the design and implementation of this project include the six team members, Dr. Larson, government agencies, customers, manufacturers, appliance vendors, power companies, standard compressor providers, and maintenance personnel. The first two parties will have the most influence on the project over the course of the semester with the other parties having less immediate influence. The working components of the refrigerator have to pass government inspections for both safety and efficiency and the needs of potential buyers have to be strongly considered and effectively implemented into the design. Furthermore, the ease of manufacturing along with material selection and cost factors need to be addressed. Appliance vendors can influence the success of the product as they can choose whether or not to carry the product in their stores as well as how much to sell them for. Power companies could also be affected by the improvement of refrigeration efficiency. Their goal is to sell as much power as possible to each household, and the replacement of standard appliances with more energy efficient ones may impact their business. However, their influence in the design and implementation of this product is minimal. Another opposing force may be the companies that provide the standard compressors, because their business may be negatively impacted if an improved cooling mechanism design is protected by patents. Finally, it is very important that the product features ease of service for technicians. If the refrigerator is difficult to repair, the customer will end up being dissatisfied as they pay for costly service.

As the project is being designed, each of these stakeholders and their associated interests must be taken into account in order to create a successful product from both an engineering and business perspective. Each of these stakeholders and their influence are shown in the Stakeholder Analysis Matrix, shown in Table 1.

Table 1: Matrix of Stakeholders and Their Respective Interests, Impacts, Importance and Influence

Stakeholder Analysis: Matrix				
Stakeholder	**Interests**	**Impact/Effect**	**Importance**	**Influence**
Team Members	A challenging project to test our skills	Primary Designers	High	High
Dr. Larson	Providing advice and support for the project if needed	Advisor	Medium	High
Government Regulators	Making sure product is safe for the market	Energy consumption regulation and safety	Low	Medium
Customers	A less costly refrigerator	Will determine success of product through purchase	High	Low
Manufacturers	Ease and cost of manufacturing the product	Create the product	High	Medium
Appliance Vendors	Selling price and energy efficiency	Will choose whether to carry the product as well as setting the market price	Medium	Low
Power Companies	Selling electricity to households	Opposition to more efficient household appliances	Medium	Low
Standard Compressor Providers	Selling refrigerator compressors	Opposition to replacement of compressors with alternative device	Low	Low
Maintenance Personnel	Easy-to-fix appliances	Can support or oppose new mechanism depending on ease of repair	High	Low

Table 2 discusses desired specifications and constraints that the cooling mechanism should meet. The overall requirements of the device is to cool 2 cubic feet of volume to a temperature less than 40ºF. Further specifications such as geometry, energy, materials, safety, maintenance, cost, production, and ergonomics are shown, along with their specific numerical constraints can also be seen in Table 2.

The overall geometry of the cooling mechanism in the refrigerator must comply with the allotted space within the refrigerator compartment, which has been estimated as less than 33", 20", and 21" for height, width, and length respectively. The overall weight limit was assigned to be less than 25 lbs in order to minimize the overall weight of the refrigerator and prevent injury when moving.

Constraints involving energy consumption include choosing an electric motor that has a sufficient lifespan that requires minimal amounts of energy while still reducing the refrigerator's interior temperature to operating temperature within 8 hours of being plugged in. The motor must also comply with the standard U.S.Energy Star ratings as well as the outlet specifications of 120 volts supplied by an alternating current.

The chosen materials for the cooling device must withstand temperatures above 100ºF and below 0ºF without exhibiting any deformation that might hinder the performance. The material should also be rust-resistant and must have a yield strength value greater than 20 kpsi. For environmental purposes, the desired minimum percentage of recyclable components within the cooling mechanism is 72%, which would make the design roughly 10% more recyclable than the standard compressors currently in use.

Keeping safety in mind, the demanded working temperature is specified as being no greater than 120ºF to ensure that the components do not overheat and cause harm. The overall percentage of non-toxic materials (including the cooling fluid or gas) must be greater than 94%, making it roughly equivalent in toxicity to the standard compressor system that uses R134a refrigerant.

When considering the customer's expectations with regard to cost and maintenance, the cooling mechanism should be designed to require as little maintenance as possible while keeping cost at a minimum. Specifically, the mechanism should not require maintenance such as oiling and lubricating for a minimum of one year.

In order to make the cooling mechanism affordable, the ease of manufacturing and the ability to assemble must be taken into account. The cooling engine must be compatible for mass production. Taking into account that the cooling mechanism should be designed as a possible product for consumers, the number of components must also be minimized to allow for ease of manufacturing. More specifically, the maximum number of components should be less than 75. For the time constraints of this semester, the assembly time of the engine must be less than 40 days, in order to complete the building and testing process.

Finally, the desired noise output has been specified to be less than 40 dBA, in order to make the product viable for household use.

There are several key customer requirements involved with the re-design of the common household refrigerator's working components. With the use of the House of Quality shown in Figure 2 of the appendix, it was specified that the most important customer requirement is the efficiency of the compressor, specifically thermal efficiency. A high thermal efficiency for the compressor is required by customers due to the corresponding low energy expenditure and cost reduction. If the cooling mechanism is able to cool the refrigerator in a shorter amount of time, it does not have to run as long as the standard refrigerator compressor. Therefore, the more efficient that the compressor is, the less amount of time it needs to cool the refrigerator, resulting in lower costs for the customer. The second most important customer requirement was the energy consumption of the compressor. Standard refrigerators tend to consume a lot of energy when cooling the system, which increases costs for the customer. A low noise output and cost of the compressor were also important customer requirements, which correlates to the thermal efficiency because a more efficient device results in lower cost. Additionally, safety and weight of were assigned high values of importance, and they both correlate with one another. In other words, by minimizing the weight of the refrigerator's working components, neck and back injuries can be minimized when moving and transporting the refrigerator. The House of Quality indicates that the least important customer requirements are the size, ease of assembly and disassembly and lifespan of the compressor. Therefore, it is important to reflect these results during the manufacturing process in order to pay more attention to the requirements that the customer values the most.

The House of Quality also depicts the engineering requirements that are most important for the manufacturer to focus on, allowing for greater customer satisfaction. Production cost in the engineering requirements was determined to be the most important due to its influence on customer requirements such as cost of the product. If the production cost is low, then the cost of the compressor will also be low, which is one of the most important requirements the customer has. Therefore it makes sense that the most important engineering requirement would be production cost, which in turn satisfies the most important customer requirement. The least important engineering requirement was determined to be portability, which correlates to the customer requirement of size. If the customer does not find the size of the cooling mechanism to be important, then the engineering requirements should reflect that. The space for the cooling mechanism in the prototype is a fixed amount of space, but for manufacturing purposes, the refrigerator would be redesigned to incorporate a larger or smaller volume for the cooling mechanism depending on the size of the Stirling engine. This would result in a change in the volume of the refrigerator space, which would need to be maximized, given the results of the customer survey. In other words, the manufactured refrigerator would maximize interior storage space while still allowing for sufficient space to store a cooling mechanism large enough to satisfy minimum performance requirements that must be met above all else.

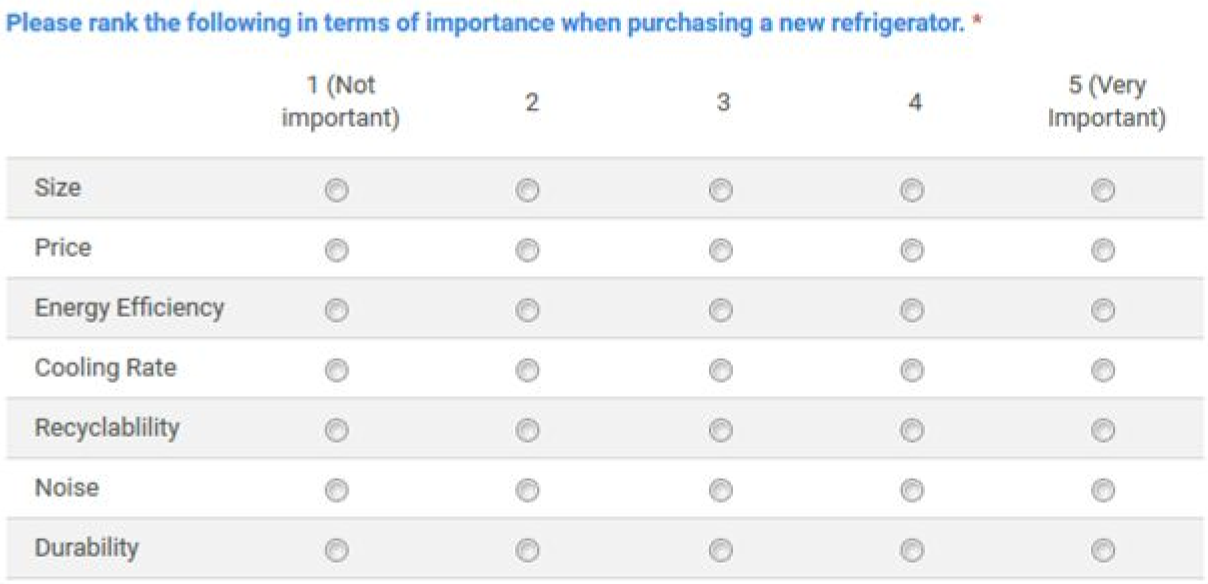
Table 2: List of Specifications

Date	D/W	Requirement	Value	Responsibility	Source
Jan 17th 2015	D	Cool approximately 2 cubic feet of inside air to a temperature	< 40º F	All	Project
Jan 17th 2015		**Geometry (of engine)**			Standard Mini Refrigerator (4.3 cubic ft)
	D	Height	<33”	Josh	
	D	Width	< 20”	Josh	
	D	Length	< 21”	Poulomi	
	W	Weight	< 25 lbs	August	
Jan 17th 2015		**Energy**			energystar.gov U.S. standards
	W	Motor Life	> 8 yrs	Poulomi	
	D	Average Energy Consumption	< 60 W	Duncan	
	W	Cooling Time	< 8 h	Duncan	
	D	Compatible with standard U.S. outlets	120 V; AC current	Josh	
Jan 17th 2015		**Materials**			ASME Standards
	D	Max temperature endurance of engine	> 100ºF	Sam	
	W	Water (rust) resistant	Yes	Yuon	
	W	Min Temperature endurance of engine	< 0.0ºF	August	
	D	Yield Strength	>15Kpsi	Yuon	

	W	Recyclable and maximize number of biodegradable components	> 72%	Duncan	
Jan 17th 2015		**Safety**			Refrigeration Standards
	W	Max working temp	<120º F	Duncan	
	D	Non-toxic materials	> 94%	Poulomi	
Jan 17th 2015		**Maintenance**			Team
	D	Oiling and lubrication lifetime	>1 year	August	
Jan 17th 2015		**Cost**			Class Guidelines
	W	Raw Materials	< $300	Josh	
	W	Manufacturing & Production	< $200	Poulomi	
	W	Replacement Parts	<$120	Yuon	
Jan 17th 2015		**Production**			
	W	Capable of Mass Production	Yes	Sam	Team
	D	Assembly Time	< 40 Day	Duncan	Class time constraint
	W	Maximum Number of Components	< 75	Josh	Basic manufacturing principal
Jan 17th 2015		**Ergonomics/Usability**			noise control. com
		Noise output	<85 dBa	Federal Regulations	

4. Market Research

In order to evaluate customer requirements for refrigerators, an online survey was conducted and 113 responses were received. The survey was distributed to college age students as well other groups of potential consumers including homeowners and people who live in apartments. This wide range of potential consumers covers the market for both a refrigerator used in a college dormitory as well as for standard household refrigerators. These are the main target markets for this refrigerator, but anyone in need of a small refrigerator or wine cooler could also be considered as the target market. As shown in Figure 3**,** the survey covers different customers needs and their relative importance.



Please rank the following in terms of importance when purchasing a new refrigerator. *

	1 (Not important)	2	3	4	5 (Very Important)
Size	○	○	○	○	○
Price	○	○	○	○	○
Energy Efficiency	○	○	○	○	○
Cooling Rate	○	○	○	○	○
Recyclablility	○	○	○	○	○
Noise	○	○	○	○	○
Durability	○	○	○	○	○

Figure 3: Sample Market Research Question

Those who completed the survey were asked to rank the requirements in terms of importance to them with 5 being very important and 1 being not important at all. The total scores for each requirement are added and shown in Figure 4. Of the seven options, price has the highest score of 88, followed by durability at 77, energy efficiency at 76, noise and size each at 74, cooling rate at 66, and recyclability at 59. These results encourage the use of stirling engines in refrigerators as they are known to be more efficient, durable, and quieter than standard compressors if cost can be kept competitive.

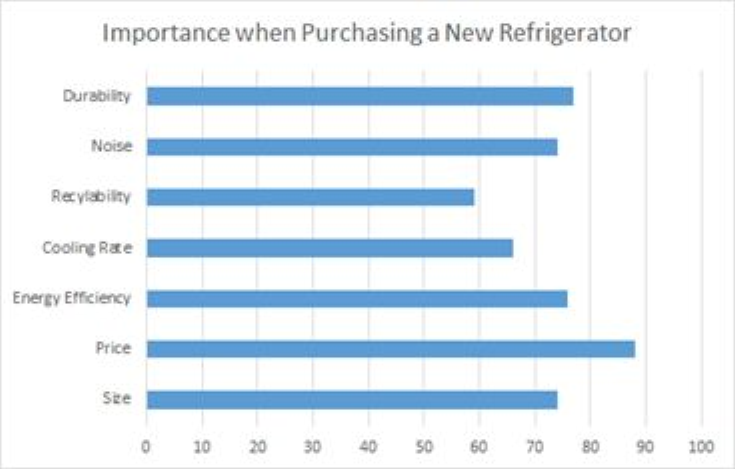


Figure 4: Customer Expectations Versus Total Sums of All Participants' Rankings

When asked whether one would pay a premium for a refrigerator that cools down quickly, 57% of the surveyed responded "No, that seems unnecessary." This is significant because a Stirling engine refrigerator may have a slower cooling rate than a standard compressor. If customers are not very concerned about cooling rate, a Stirling engine will fit the application well. Another question asks customers if they would be opposed to a refrigerator with a different refrigeration system; 100% of the surveyed responded "No, as long as it works". Knowing that customers will not be opposed to a new system further encourages the stirling engine refrigeration system. A copy of the complete survey and its results are shown in the appendix as Figures 5a - 5e.

5. Design Concept Ideation

The mechanism to cool a refrigerator is required to perform many functions that must be addressed in the design process. In order to create the best design to fulfill these functions, a morph chart shown in Figure 6 of the appendix was created. The morph chart exhibits the multiple functions that the cooling mechanism must perform and lists different design ideas for how they can be accomplished. An important function that the product must be able to perform is to compress the working fluid. In order for the system to be cooled, a fluid must first be compressed by a pump. The morph chart shows many ideas for the type of pump that could be used to perform this task. For instance, a piston pump, vane pump, or scroll pump could be used to compress the fluid, but some of these choices may work better with other items on the morph chart. Therefore it is important to have many different combinations of components in order to achieve the most efficient design. The morph chart also contains different ideas to perform the function of dissipating heat from the system. It is important to have a mechanism to dissipate heat because otherwise the system may overheat, causing a malfunction in the product. One method of dissipating heat from the system is to use a heatsink and fan that could be attached to the cooling mechanism. Another method would be to use a high thermal conductivity material that could absorb the heat and lead it outside of the system. Many other functions and ideas for how to complete these tasks are contained on the morph chart. These ideas were combined in various ways to create preliminary designs for the product, shown in the Evaluation Matrices. Note that this Morph Chart has been developed specifically for the manufactured product and not for the initial prototype. In the prototype design, pre-existing features found in the refrigerator frame such as a sloping drainage system and insulation will be used. However, in the final product, each of these functional requirements will be addressed as shown in the Morph Chart.

6. Concept Selection and Justification

In order to design the best type of engine, several types of cooling mechanisms first had to be considered to determine which design offered the best potential at successfully satisfying each of the customer and engineering requirements shown in the House of Quality. Figures 7 through 15 in the appendix show ideation schematics and descriptions for each of the considered cooling mechanisms. Figure 16 in the appendix shows an evaluation matrix for each of these ideation schematics and ranks them according to their ability to satisfy the weighted customer requirements. After considering nine potential designs, the Stirling engine had the highest total score, demonstrating its potential for this project. The importance of each customer requirement is weighted differently in the evaluation matrix from that of the House of Quality due to the results from the customer survey completed during the market research. The House of Quality was completed as a preliminary step in order to gage the most important requirements based upon the importance values that the design team determined. After obtaining the results from the customer survey, the importance values for the customer requirements were adjusted in the evaluation matrices to convey more accurate information.

Three different types of Stirling engines shown in Figures 17, 18, and 19 were compared using a second evaluation matrix shown in Figure 20. Figures 18 and 19 are included in the appendix. These engines include alpha, beta, and gamma-type designs. Again, the customer criteria was ranked, weighted, and summed for each potential design. The alpha-style of engine was proven to best satisfy each of the criteria, especially some of the most important criteria such as cost, energy consumption, size, and efficiency. Another benefit of the alpha engine is the clear physical separation between the hot and the cold pistons, which would allow for an easier design process when installing the attachments to create a temperature differential. The gamma-style engine ranked in second, but one key problem with this design is the lack of clear separation from the hot and cold portions of the piston housing, which would reduce the engine’s overall efficiency. Finally, the beta-style engine ranked third, because of a higher energy consumption, lower ease of assembly, and a higher weight.

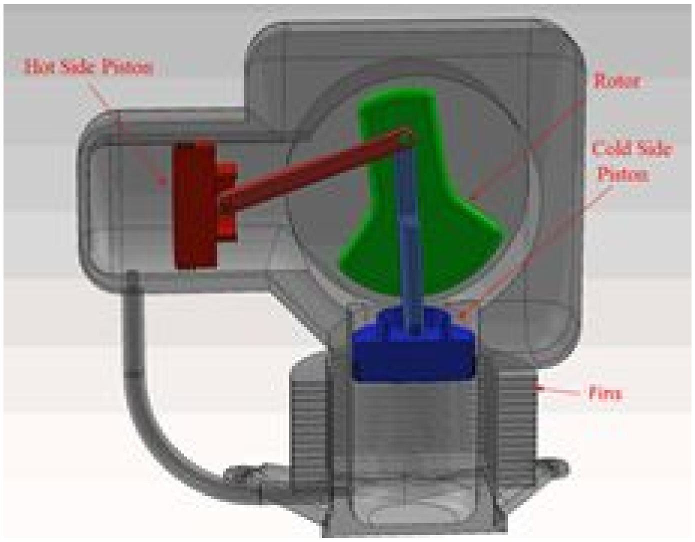


Figure 17: Alpha-Style Stirling Engine

Figure 17 shows an alpha style engine featuring an electrically driven rotor in the center, which is connected to hot-side and cold-side pistons that are separated by 90 degrees and connected by a tube to create a closed-cycle system. One key advantage is that harnessing the thermal gradient is easier when the hot and cold temperatures are generated at separate locations.

Concept	**Multiplier**	**1. Stirling Engine: Alpha Style**	**2. Stirling Engine: Beta Style**	**3. Stirling Engine: Gamma Style**
4 = Very Good 3 = Good 2 = Satisfactory 1 = Just Tolerable 0 = Unacceptable **Criteria**	(1-6)			
Low Noise Output	2	3	3	3
Cost	6	4	3	4
Durability	2	4	4	3
Energy Consumption	5	2	1	2

Size	5	3	3	4
Lifespan	2	4	4	3
Ease of Assembly/Disassembly	2	2	2	3
Weight	1	4	4	4
Safety	2	4	2	3
Low Maintenance	3	4	4	4
Efficiency	3	4	3	3
Weighted Total		111	93	109
Relative Total		1	0.838	0.982

Figure 20: Evaluation Matrix for Type of Stirling Engine

An important aspect of the Stirling engine design is the way that the engine is attached into the refrigerator. Therefore, Figures 21 through 30 show schematics of potential attachments that could be incorporated into the design of the engine. Figures 22 to 30 are shown in the appendix. These attachments are compared on a third evaluation matrix shown in Figure 31 of the appendix. Taking the customer requirements into account, the finned heat sink and fan scored the highest, while the heat exchanger and fan scored the lowest. The fan is being used to move chilled air from the engine across the housing of a heat exchanger, while a standard pump inside of the heat exchanger will then be used to move the fluid through the housing. This then chills the fluid and pumps it throughout the pre-existing piping network to cool the refrigerator. This model did not satisfy the most important customer requirements of cost and low noise output, which resulted in a poor comparison to the other alternative designs. The best attachment design was determined to be the finned heat sink and fan, which is intended to move air across the chilled and heated fins on each side of the engine and then transport the cooled and heated air into the refrigerator’s interior and out the back respectively.

Figure 21: Finned Heat Sink and Fan

Figure 21 depicts a standard heat sink with various fins in addition to a fan. This preliminary engine attachment design is intended to move air across the chilled and heated fins on each side of the engine and then transport the cooled and heated air into the refrigerator's interior and out the back respectively. If this design were to be pursued, a network of various heatsinks and fans could be investigated in order to increase cooling efficiency.

7. Industrial Design

Several factors were considered throughout the design process to address the industrial design component of the Stirling engine, including aesthetics, noise and vibration, usability, and packaging. To appeal to aesthetics, the design team will keep the Stirling engine where it can not be seen, similar to the placement of the compressor. This will not change how the refrigerator will look, making it less likely for a customer to be deterred by the Stirling engine powered refrigerator. To reduce noise and vibration, the design will use a damper that dampens the vibration from the engine, ensuring a quiet operation. Market research indicates that customers prefer a quieter refrigerator, therefore the Stirling engine will be designed to match, or exceed the quietness of a standard compressor. To address usability of the Stirling engine, it was determined that most customers do not interact with the mechanism that cools the refrigerator, therefore the engine will be designed to minimize space inside the refrigerator. The packaging of the Stirling engine will be designed to fit inside the refrigerator without any exposed moving mechanism. With these factors in mind, the design was given constraints in aesthetics, noise, usability, and packaging.

Visual hierarchy is also integrated to the design. The cylinders are designed to draw the attention of the consumer first, therefore its surface is shiny and sleek, giving customers a sense of simplicity and modernness. The crankcase is designed to draw attention next, and it be painted the same color as the refrigerator, showing uniformity. The AC motor corresponds to the design language by its color and sleek profile; they communicate the efficiency and simplicity of the Stirling engine cooling mechanism.

The target demographics are average homeowners who prefer a more energy efficient, quieter, and environmentally friendly refrigerator. The engine will be predominantly made of metal, showing its sturdiness because market research indicates that homeowners want durable appliances.

8. Detailed Technical Analyses, Experimentation, and Design Performance Prediction

To determine the performance of standard refrigerator compressor, an array of sensors was connected to a standard dorm refrigerator. This data was taken in order to examine the components needed for the Stirling engine to be more efficient compared to the compressor. The temperature sensors were able to take temperature measurements over a period of approximately 1600 minutes with various marked events where the system was disturbed, including opening the door of the refrigerator, placing a warm or room temperature object in the refrigerator, and turning off the refrigerator for a small amount of time. The datum obtained from these tests were used to determine the cooling rate of the refrigerator and are shown in Figure 32. Using this, the power consumption of the refrigerator was also calculated and is shown in Table 3. Through this data, the team was able to accurately size the engine using the team developed MATLAB code shown in the Appendix as Figure 33. Through experimentation, the thermal energy transfer rate required to produce the desired temperature difference was determined. The most accurate method used was to put a high current resistor inside of the refrigerator, and pass a current through it, which can be accurately measured along with the voltage drop across the resistor.

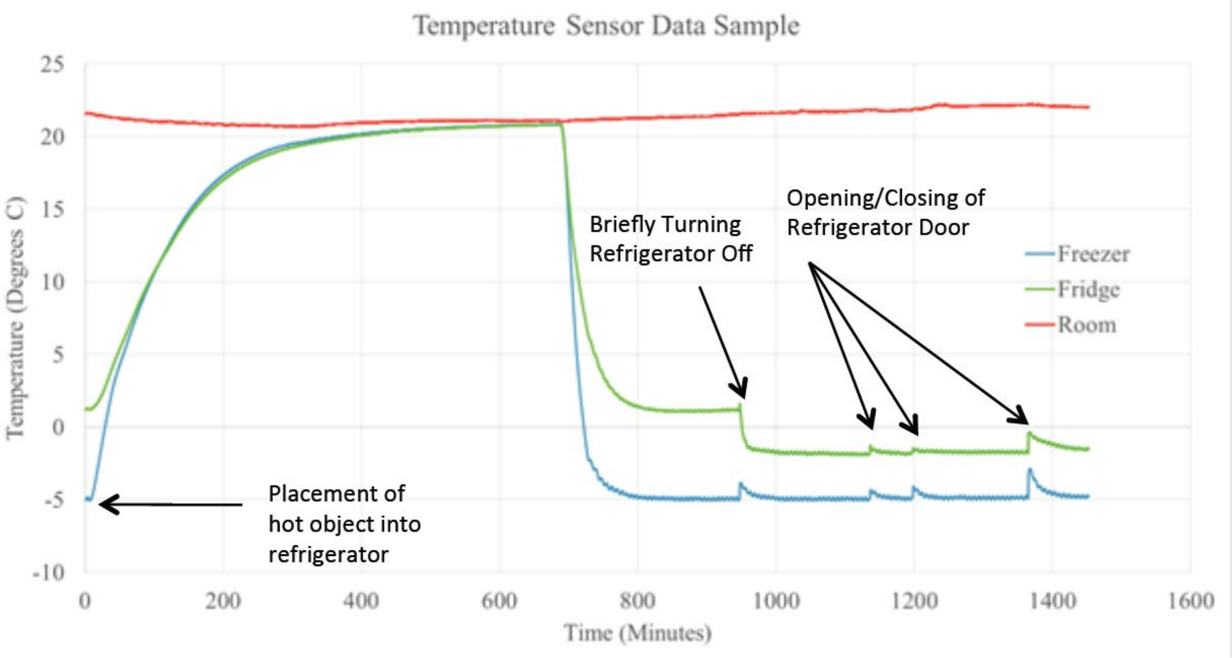


Figure 32: Temperature Sensor Data Sample

Table 3: Measurements taken during testing

Test	Voltage [V]	Current [mA]	Power [W]	ΔT [ºC]
0	0.000	0.000	0.000	0.0
1	12.0	150.56	1.807	2.0
2	31.25	126.82	3.963	4.8
3	31.25	254.37	7.949	9.3
4	31.25	809.60	25.300	28.4

Four different power levels were dissipated by the resistor, and the corresponding temperature differential was measured inside of the refrigerator. A plot of energy vs. temperature was then created shown in Figure 34, where the slope of a regression line would represent the refrigerator's thermal leakage per degree Celsius.

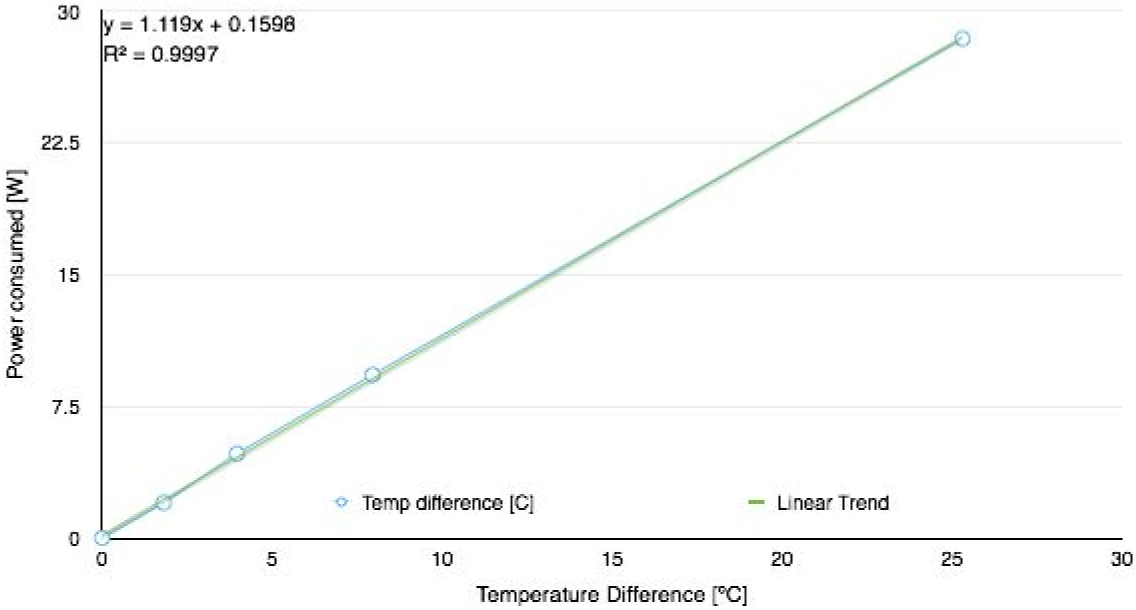


Figure 34: Power Consumption vs. Temperature Difference

A thermal finite element analysis (FEA) was performed on the Stirling engine's hot and cold pistons using Siemens NX software. The results showing the heat flux and temperature gradient for the hot piston are shown in the appendix in Figures 35 and 36. For the hot cylinder, the maximum temperature was set as 40 ℃ and the minimum temperature was set as room temperature, or 23℃. For the cold cylinder, the maximum temperature was set as room temperature and the minimum temperature was set to be 0℃. Using FEA tools in Siemens NX, the average thermal heat flux value at the bottom of the hot piston (where the connecting rod attaches) was found to be 0.039 W/mm^2. Hand calculations, shown in the appendix, were performed on this part as well to confirm the computer-generated results. There was a percent difference of 15.2%, indicating that there is an adequate correlation between the hand calculation and the computational result. These values are not perfectly comparable as the heat flux varies from node to node across the surface of the piston. The hand calculations were designed to find the heat flux value across the piston from top to bottom in a 1D vertical direction. This is why the length that was used in the hand calculations was actually the height of the piston. This distinction is important because knowing the heat flux capacity across this piece of material will indicate how well the Stirling engine can contain the hot and cold temperatures that it generates. If the heat flux capacity was high, this would indicate that the engine might be less efficient, as a significant portion of its resulting temperature gradient cannot be utilized if it is transferring into the crankshaft, rather than through the cylinders and into the attached heat sinks as planned. For the cold-side cylinder, the average thermal heat flux value at the bottom of the cold piston was found to be 0.047 W/mm^2. This value is slightly higher than the average heat flux observed at the top of the piston, which was 0.039 W/mm^2. This is because a larger percentage of the material at the bottom of the piston had been removed for the connecting rod attachment. This loss of material results in a higher average heat flux across the surface. When comparing the hand calculation to the computational value at the top of the cold piston, there is a resulting 6.8% difference in the values, showing an acceptable correlation.

Just like the thermal piston analysis, the hot and cold cylinders were modeled as 1D singular thermal spring elements using Siemens NX FEA shown in Figure 37 of the appendix. The average thermal heat flux value of the top and sides of the hot cylinder was found to be 0.159 W/mm$_2$. This is a percent difference of 11.9% from the hand calculations, indicating that there is an acceptable match between the hand calculation and the computational result. Again, the individual heat flux values vary from node to node, resulting in comparisons that are not exact, but should be evaluated on whether results are within the same range of values. The hand calculations were designed to find the heat flux value across the wall of the cylinder, which is why thickness was taken into account when calculating cross sectional area. The thickness at the top and sides of the cylinder is the same, which is why an average heat flux value could be taken from both the top and sides. This distinction is important because in order for the engine to function properly, heat must be able to travel across the walls of the cylinders and into the radially connecting heat sinks. The average thermal heat flux value of the top and sides of the cold cylinder was found to be 0.267 W/mm^2. The difference between the hand calculations and computational results for the cold cylinder is larger than for the hot cylinder. One reason for this is because the temperature change for the hot cylinder is 17°C (40°C - 23°C) and the temperature change for the cold cylinder is 23°C (23°C - 0°C). A higher temperature difference will inflate the heat flux values, and may make slightly exaggerated differences in results.

Stress analysis was also performed in Siemens NX on the hot-side cylinder. A pressure of 100 N/mm^2 was applied to the inside of the hot cylinder (compression) and -100 N/mm^2 was applied to the inside of the cold cylinder (expansion). Figures 38, and 39 in the appendix show the resulting stress when the cylinder is under internal compression. Figure 40 then shows the resulting deformation.

The connecting rod was modeled as a 1D singular spring element with a hypothetical test load of 100 N. The connecting rod's maximum stress values and resulting deformation is shown in Figures 41 and 42 in the appendix, as well as the supporting verification calculations. The maximum displacement value on the connecting rod was found to be 8.310 X10^{-4} mm. This is a percent difference of 0.014% from the verification calculation, indicating that there is a strong match between the hand calculation and the computational result. The small displacement values are a good sign that choosing standard steel as the material will minimize part deformation.

In order to simplify the wrist pin analysis, symmetry was used to divide the part in half, so that it could be analyzed like a simple beam element with one end fixed and the other end enduring a force of 100 N. The wrist pin's stress response and resulting deformation are shown in Figures 43 and 44 in the appendix, along with the supporting verification calculations. As expected, the maximum displacement occurs at the very center of the wrist pin, exactly where the applied force is acting. Using Siemens NX FEA, the maximum displacement value on the wrist pin was found to be 0.0133 mm. The resulting percent difference between the verification calculations and the computationally derived value is 1.48% indicating a strong match between the two values. Just like the connecting rod, the small displacement values are a good sign that choosing standard steel as the material will minimize part deformation. In all FEA analyses involving loading, constant loading was assumed as opposed to cyclic loading in order to simplify calculations while still effectively analyzing each part's response to a particular magnitude of applied force.

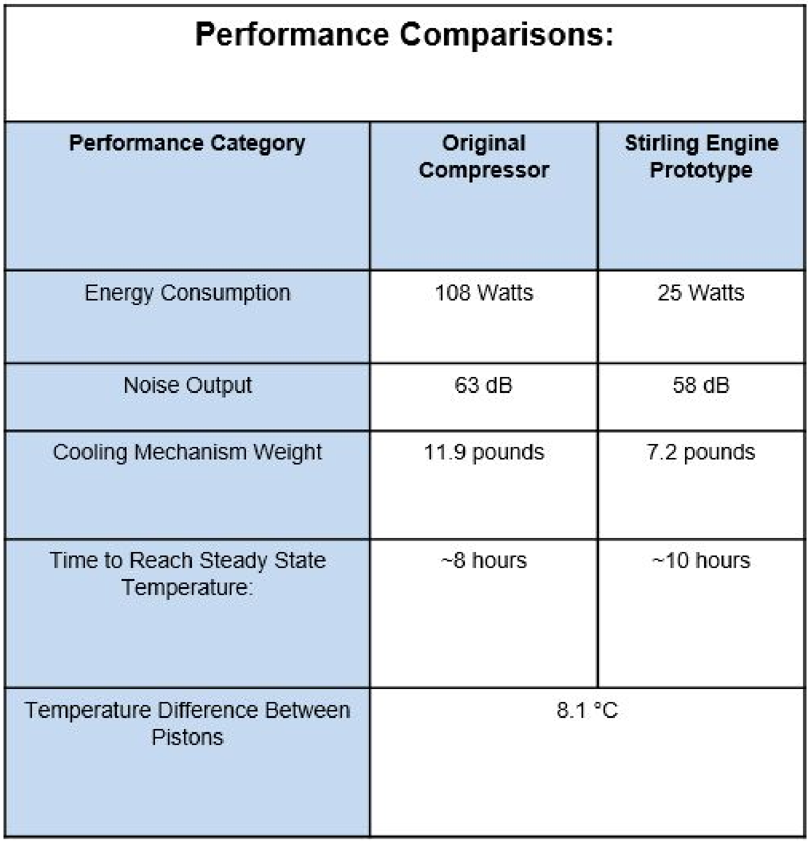
The results from a finite element stress analysis on the Stirling engine's crankshaft is shown in Figure 45 in the appendix. The high stress points can be seen along the welding point at the center of the shaft where the stress response reaches magnitudes of roughly 2.5 MPa seen by the orange and red nodes. These minimal values indicate that choosing steel will prove to be an appropriate choice of material for the engine's crankshaft.

By performing thermal and stress finite element analyses on critical components of the engine, it was concluded that the materials chosen for the piston, cylinders, connecting rod, wrist pin, and crankshaft satisfied minimal strength requirements and thermal flux capabilities. These results are necessary to prevent mechanical failure and meet the thermal performance capabilities as specified.

The constructed prototype has undergone experimentation to find physical evidence to support the proof of concept. The prototype was tested using a Fluke IR thermometer to measure the temperature of the pistons. Three trials were performed with the engine running for three minutes each with the fan, the insulation, and the insulation attachments. The datum with no attachments heated the hot and cold pistons to an average of 48.3 degrees Celsius and 32.2 degrees C respectively. Comparing this result to the fan only trial, the hot piston had an average temperature of 33.1 degrees Celsius and cold piston had an average of 25.2 degrees Celsius with the average room temperature for both being 25 degrees Celsius From this experiment, the fan provided the best results at a 0.2 degree Celsius temperature difference between the room temperature and the cold piston. Even though this is a positive average gain in temperature, two of the three trials were cooled to below room temperature with a third trial that was 2.5 degrees Celsius above room temperature. All attachments improved the efficiency of the engine from the datum and given more time and money, fins would be added and experimented with to enhance heat transfer as well. For further detail, refer to Table 4 in the appendix. Compared to the compressor, the Stirling engine prototype does not reach cooling specifications as needed, but with precise manufacturing of piston-cylinder assembly to ensure sealing and the use of fins, the Stirling engine concept could work as well as the compressor cooling a refrigerator with about 25% of the power usage. The results for the Stirling engine and compressor are compared in Table 5.

To test the thermal conductivity of the engine, the thermal transfer rate equation was used where the thermal conductivity, k, the surface area of the refrigerator, A, and the wall thickness, dx, are all constant. This means that the heat transfer rate, Q, is directly proportional to the temperature difference. The thermal conductivity of the refrigerator materials will vary slightly with temperature, but for the narrow range of temperatures seen here, it can be approximated as a constant. The concluding absolute thermal resistance of the refrigerator is 1.25 ^{O}C per Watt. The desired temperature difference between room temperature and the refrigerator's interior is between 20 and 25 degrees Celsius, and therefore, somewhere between 16 and 20 Watts of heat need to be removed. In order to include a design factor which will incorporate any inefficiencies in the design, the final design of the Stirling engine should be capable of removing 25 Watts of heat.

Table 5 : Performance Comparison of Stirling Engine versus Compressor



Performance Comparisons:

Performance Category	Original Compressor	Stirling Engine Prototype
Energy Consumption	108 Watts	25 Watts
Noise Output	63 dB	58 dB
Cooling Mechanism Weight	11.9 pounds	7.2 pounds
Time to Reach Steady State Temperature:	~8 hours	~10 hours
Temperature Difference Between Pistons	8.1 °C	

9. Final Design, Mockup, and Prototype

Detailed isometric CAD drawings and their dimensioned sketches for the fabrication package are shown in Figures 46 to 60 of the appendix. The final design works as a heat pump removing heat from the refrigerator interior and pumping it out using an electric motor as the initiating force. The cold cylinder is exposed to the inside of the refrigerator while the hot cylinder is exposed to outside air. This is completed by pumping an environmentally friendly working fluid, air, in a closed system Stirling engine. The complete assembly is shown in Figure 60, depicting the Stirling engine.

The AC motor connects to the crankshaft via a pulley and belt system. As electric motor spins the power is transmitted to the crankshaft which moves the pistons within the cylinders. The “cold” piston retracts decreasing the pressure and temperature inside the “cold” cylinder inside the refrigerator. When the interior piston extends, the “hot” piston will retract, cooling the air in the hot piston, while at the same time air from the interior piston will be pushed into the connecting hose into the exterior piston chamber. This air will replace the air in the exterior cylinder with the cooler air going to the interior cylinder. This cycle will then continue depending on the signals from the thermocouple and control system within the refrigerator. If the temperature is below 35-40 degrees Fahrenheit depending on the setting, the motor will not run. If the temperature is above the specified values, the motor will run continuously until the sensor reads the desired temperature. The Stirling engine was designed to have a cooling capacity of 32 degrees Fahrenheit to help offset inefficiencies that may happen in the engine.

A variety of parts and materials are used in the construction of the Stirling engine prototype and are shown in the detailed Bill of Materials (Table 6). The material to construct the pistons was purchased from McMaster Carr and are made of wear-resistant Nylon, 1 inch in diameter and 1 foot in length. This rod was then placed on a lathe and machined into two separate pistons. Other material such as 6061 Aluminum Tubing, Fluoroelastomer, and ABS plastic were purchased and obtained, then machined to create the cylinders, the piston rings, and the pulley. Brass and wood were obtained from Home Depot and the Invention Studio scrap bin to create the nipple, engine mount, and motor mount. The total cost of prototype material is determined to be $46.38.

The mass production of the Stirling engine would require higher quality material and more advanced machining techniques and is shown in the Bill of Materials (Table 6). The mass production material differs from that used in the prototype in the construction of the pistons and cylinders. The prototype used nylon and aluminum while the manufactured product would contain steel for both of these parts. The majority of the manufactured Stirling engine would contain steel apart from the crankcase, wrist pin, motor mount, engine mount, and hose, The manufactured material could be purchased from McMaster Carr, Walmart, or the MetalDepot. The total cost for the mass produced Stirling engine would be approximately $55.67 due to the discounted price of bulk purchasing.

The prototype of the Stirling engine was constructed according to the mockups created in 3D CAD software, and is shown in the appendix as Figure 61. The prototype has been thoroughly tested to ensure that it performs at the highest possible efficiency, with results shown in Table 4 of the appendix.

The prototype was created with budget and time constraints, therefore it differs from the final design intended for manufacturing. The differences include a 3D printed crankcase of ABS plastic used for the prototype instead of an aluminum crankcase. The crankcase is 3D printed due to the lower cost and ease of construction, as compared to the aluminum material. Another difference in the prototype design from the manufactured design is that the cylinders in the prototype have a 1 inch inner diameter instead of the specified 25 mm inner diameter in the mockup. A 1 inch diameter is used in the prototype due to its greater availability and ease of attainment. The crankshaft and connecting rods have been constructed separately and are assembled together for the prototype, while the designs for manufacture indicate the casting and molding of those parts. The separate construction and assembly of the crankshaft and connecting rods are to decrease the amount of time and expenses needed to cast and mold. Time constraints also prevented the prototype from containing fins along the interior of the cylinder.

Other differences in the prototype from the manufactured design include the placement of the nipple on the cylinders, the construction of the connecting rods, cylinder, nipple, and cap, as well as the design of the engine and motor mounts. The prototype has the nipple assembled on the tops of the cylinders, instead of the sides, making the hose a longer length. The hose is shorter on the manufacture design, but is long on the prototype due to the ease of construction for the design team. The connecting rods, cylinders, nipple, and cap are casted then machined down to specification in the manufacture design, but are separately constructed and assembled in the prototype to save time and reduce expenses. Lastly, for the prototype, the engine and motor mounts are constructed from wood, however when manufactured, they are designed using steel brackets.

The Stirling engine's initial performance goals are established in the Specification sheet, found in Table 2. The overall requirement of cooling approximately 2 cubic feet of air inside the refrigerator to a temperature of less than 40º F has not yet been fully satisfied by the prototype. Reasons for this limited performance include an excess of friction between the cylinder and the piston, poor heat transfer between the cylinder and the atmosphere, and air leakage between the piston and the cylinder. This leakage is mostly due to minor differences in diameter of the cylinder and rod that are not fully accounted for by the inclusion of O-rings. The Stirling engine meets all geometric requirements of which height was 10", width was 8", length was 5", where the requirements were to be less than 33", 20", 21" respectively. The final prototype assembly had a net weight of 7.2 pounds which was significantly less than the set weight limit of 25 pounds. The energy requirement of having an average energy consumption of less than 60 W was accomplished as the prototype uses 25 W when in operation. The Stirling engine system succeeds in being compatible with 120 V AC current US standard outlets. This succeeds because the motor installed had the correct implementation to connect to US outlets. A motor lifetime of greater than 8 years was unable to be tested, due to the time scale of this performance requirement. The prototype engine was not able to fully reduce the refrigerator's internal temperature to the desired setpoint within 8 hours, but it was able to properly dissipate temperatures over 100 ºF through the hot piston and fan. A large percentage of the engine's materials include aluminum and brass, helping to achieve a rust-free engine. However, because of its strength, steel had to be used for the connecting rod, counterweight, cylinder cap, and cylinder mount. The cold-side cylinder, which will experience the coldest temperatures within the engine is capable of withstanding temperatures below 0.0 ºF without any performance-limiting deformation, however once the prototype is producing such temperatures, further testing should be performed.

The prototype succeeds in having a greater yield strength than the required 15 kpsi for essential load bearing parts. The aluminum used has a yield strength of 16 kpsi and steel 26 kpsi. The prototype assembly has more than 72% recyclable and biodegradable materials. The majority of the non-recyclable materials comes from the epoxy. Having a maintenance cycle of greater than one year is a performance criteria that can not be tested within the scope of this semester, but is likely to be satisfied because of the low levels of stress exerted on the crankshaft and because of the self-contained lubricant within the cylinders. The raw materials for the engine costs $46.38 which is less than $300 and the manufacturing cost is estimated to be $55.67, which is less than the initial goal of $200. The prototype meets the requirement of low cost replacement parts, due to the fact that relatively inexpensive materials were chosen, thereby meeting the requirement of costing less than $120. The Stirling engine is likely capable of being mass produced because of the ease of machining of the parts and use of widely available materials.The assembly time took approximately 60 hours which is below the requirement of 40 days. The total number of components was 44, which meets the design requirement of having less than 75 parts. The prototype had a noise output of 58 dB, which was an improvement over the 63 dB output from the original compressor, but still wasn't able to meet the initial set goal of less than 40dBA.

10. Manufacturing

In order for any product to be manufactured, preliminary steps and tasks must first be completed. The evaluation process led to a final design of the Stirling engine which was then dimensioned and sized according to specifications that were assigned earlier. This 3D mockup was performed in CAD software, and its multiviews and isometrics are included in the fabrication package located in the appendix. The fabrication package contributed to the construction of the prototype, and is also required for the mass production of the product.

In creating the initial prototype, various types of machinery were used such as a mill, lathe, waterjet, and 3D printer. The wrist pin was turned on the manual lathe from aluminum barstock. The O-ring relief was made on each end with a simple hand file. The pistons were turned to diameter from one inch Nylon barstock on a manual lathe. 2.5 mm seal grooves were cut using a parting tool, and the entire piston was cut off at the appropriate length. The piston was held in a rotary table, and the connecting rod slot was then milled into the bottom using a vertical mill and a 3/16 inch diameter end mill. The piston was then turned on it's side, and the wrist pin hole was drilled with a 4 mm drill bit. The cylinders were turned down from 1.25 inch extruded aluminum tubing. The cylinder caps and mounts were cut out from 0.1 inch steel using an abrasive waterjet and epoxied to the cylinders using JB Weld. Tubing barbs were glued into holes into the top of the cylinders.

The crankshaft was assembled from multiple parts. The counterweights were cut from 0.1 inch thick steel and welded to steel shafts turned down on the lathe. This had the advantage that it did not use one large and expensive piece of barstock. The connecting rods' profiles were cut out on the water-jet, and the holes were drilled to their final size so as to leave a smooth finish. In order to make a crankcase easily and quickly, it was determined that the design team 3D print it. The 3D printed crankcase is not as strong as a machined metal crank case would be, however the ABS plastic is strong enough for a prototype, and is dimensionally accurate.

The main advantage of expanding to mass production from the prototype is the higher quality of the machining tools available. The lower performance of the Stirling engine was due to the extremely tight tolerances that a Stirling engine, or more specifically, the piston and piston cylinders, have to conform to. Hand machining resulted in small, but significant imperfections. This in turn, caused friction within the engine that the design team was unable to completely eliminate. For mass production, many parts can be bought with the desired degree of uniformity and tolerances, and the parts to be machined can achieve higher precision. In addition, some parts can be eliminated in the mass manufacturing model by combination casting. In the prototype, small gaps in between parts allowed for problems in sealing the pistons; by combining, the nipple, piston cylinder, and piston rings would no longer contain leaks. Certain materials can also be utilized in the mass manufactured model that were unable to be utilized due to cost or difficulty of machining. As mentioned in a previous report, brass was originally considered as a material for its thermal properties, but was not chosen because of its price as well as the difficulty involved in welding it.

When mass producing the Stirling engine, the most critical aspect will be the production of the cylinders and pistons with appropriate tolerances. The finished diameter values must be machined with a tolerance level less than 0.01mm in order to ensure an air-tight fit between the two. It is critical that the manufacturer understand the importance of meeting this quality requirement to ensure that the finished product is performs as intended. There are no specific packing requirements besides noting that the engine must be packaged with styrofoam or any other type of absorptive material to avoid damage during shipping.

The estimated production costs for each of the engine's components can be seen in the Bill of Materials, found in Table 6 in the appendix.

11. Codes and Standards

Relevant engineering standards found do not specifically apply to the Stirling engine, but do apply to the refrigerator and the energy usage of the engine. Federal standards indicate that a refrigerator must use no more than 583 kWh/year of energy consumption. Therefore, the Stirling Engine must not consume more than this amount if it were to be manufactured and processed to be placed inside of a refrigerator. In order for the Stirling Engine to achieve an Energy Star label once it is functioning inside of a refrigerator, it must consume at least 20% less energy than the federal regulations state. The Energy Star guidelines indicate that a refrigerator must consume no more than 486 kWh/year of energy in order to be certified. For a compact refrigerator that is manually defrosted, the Energy Star guidelines state that no more than 6.27 AV + 175.3 based on AV (ft^3) kWh/year of energy can be consumed, with AV equal to the total adjusted volume based in (ft^3).

12. Societal, Environmental, and Sustainability Consideration

The three main materials involved in the construction of the Stirling engine are steel, aluminum, and plastic. The goal for the design team is to create an engine that is greater than 72% recyclable. The percentage of recyclable and biodegradable components in the average refrigerator's cooling mechanism is approximately 60%, therefore the Stirling engine would be more environmentally friendly. The lubricants contained on the engine must be disposed of properly due to their potential harmful effects on the environment and society. The engine itself cannot be disposed of in a regular landfill, but must be specially disposed as not to interfere with environmental processes.

One of the most important factors of the newly designed cooling mechanism is that it requires no additional space than the standard compressor. If anything, the resulting volume consumption of the Stirling engine will be slightly less than the typical refrigerator's cooling mechanism. Therefore, as consumers consider purchasing this refrigerator as opposed to an alternative, they will likely benefit from an improved percentage of food storage space. This assumes that the refrigerator body's external dimensions will be kept constant in the final design, in order to compete with standard refrigerator sizes and maximize marketability. Keeping external dimensions the same as other refrigerator competition is important because many households and apartments spaces are specifically designed to accommodate a particular size refrigerator.

The most significant impact of using a Stirling engine, as opposed to a standard compressor and refrigerant is that Stirling engines can use a non-toxic gas as their working fluid. Even while using air, the typical Stirling engine can still generate an adequate thermal gradient for a household refrigerator. By eliminating refrigerants such as R134a, Forane 134a, Genetron 134a, Florasol 134a, and HFC-134a, the product not only becomes safer for household use, but also safer for the environment. All of these refrigerants pose dangerous side effects when in contact with humans, including blindness, seizures, and suffocation due to potential inhalant abuse.

When a typical refrigerator is thrown out, there is no commonly followed protocol to ensure that all toxic materials are removed before being taken to a landfill. Therefore, the refrigerant remains in-tact and over time, will typically leak out into the soil. This common occurrence can lead to wildlife endangerment, water contamination, and ozone depletion. However, by using a Stirling powered refrigerator, this key health and environmental danger can be completely eliminated.

However, there will most likely be some form of lubricant within a Stirling engine. Its used form may provide a concern during refrigerator disposal or repair. Proper care should be taken during interaction with the interior of the engine in accordance with guidelines available. If improperly disposed, used oil result in the release of dissolved ODS refrigerant and groundwater contamination. In addition, short-term exposure to used oil can cause skin, eye, and respiratory irritation; in the long-term, it can cause cancer and damage to the liver, brain, immune system, and reproductive system. More modern refrigerators have become more conscious of this problem and have taken steps towards solving it, but it is still an issue. Beyond what is currently being used in modern refrigerator, there is most likely not a significantly superior alternative, Research will be done to possibly find superior alternatives. At the very least, the most environmentally friendly lubricant will be used that can be obtained.

13. Risk Assessment, Safety, and Liability

The Risk Assessment Matrix shown in Figure 62 depicts each of the potential risks regarding the cooling mechanism and refrigerator body and provides a visual comparison of the probability of occurrence and impact or severity that each occurrence would entail. The probability of neck and back injury was assigned as the most probable risk imposed by our product. Therefore, in order to address this risk and reduce its potential severity, the mechanism's engineering design and materials selection will take into account the overall weight. The second most likely risk is entanglement in the internal fans. The addition of a simple plastic mesh guard will almost entirely eliminate this potential risk. The internally exposed heat sink fins could be rounded along their edges or a simple plastic guard could be placed over them to still allow for heat flow, but keeping them separated from the user's hands. When servicing the mechanism through the back of the refrigerator, the probability of entanglement to engine parts is fairly low, with a fairly minor severity. However, each of the moving components of the chilling mechanism will be encapsulated in a protective body to prevent contact. A warning message could notify the individual to unplug the device before inspecting any working components. This message could also address the minor probability of burn or frostbite when servicing. By advising maintenance personnel to unplug the refrigerator and wait for a period of time before servicing, this risk can be eliminated. By keeping the rubber skirt component on the perimeter of the refrigerator door, the severity of the user pinching their fingers is minimized, and will most likely not require any additional design improvements. A standard safety measure will include a rubber/plastic insulated electric plug to prevent electric shock when the refrigerator is being plugged and unplugged from the wall outlet.

Although the probability of the refrigerator tipping over and injuring the user is fairly low, the re-designed product will ensure that the stirling engine (which is the heaviest component of the product) is positioned at the bottom of the refrigerator. Doing so will ensure that the refrigerator isn't top heavy and will optimize the overall stability. The probability of exposing the refrigerator's food contents to any type of toxin is very low, but must be considered because the severity of such an occurrence would be high. Therefore, any internal components such as the fans and the finned heat sinks along with their protective coverings must be checked to ensure that they don't contain any toxic materials. Also, if a working fluid other than air is chosen as the engine's cooling element, a toxicity study should first be performed. Finally, if the refrigerator were to cause a fire, the impact would be detrimental. Therefore, the electrical circuitry will include a trip-sensor that will cut power to the refrigerator if any water or power-surge is detected.

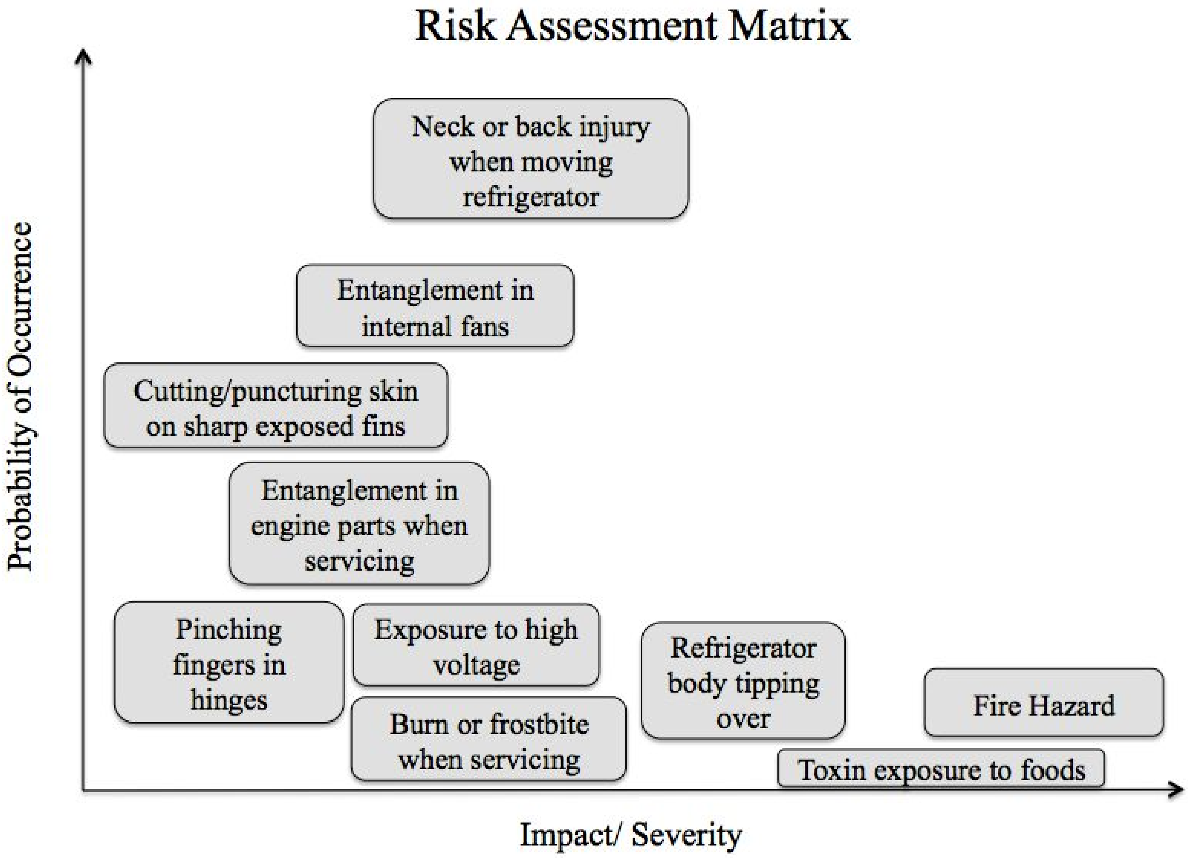


Figure 62: Risk Assessment Matrix

14. Patent Claims and Commercialization

When filing for a patent, several key details regarding the cooling mechanism design should be clearly stated in order to defend the product's originality. Clearly indicating what makes this product different from those found in the prior art analysis will be critical to avoiding patent infringement. Most importantly, if a patent were to be filed for this project, it must clearly emphasize that the group is seeking proprietary rights solely for the Stirling engine, heat sink, and fan cooling system and not the actual refrigerator body. Additionally, the patent will not specify any distinct orientation of the engine within the refrigerator body, as this may vary depending on the refrigerator in which it is used. Design details should be mentioned including that the engine is an alpha-style Stirling engine with two pistons oriented 90 degrees out of phase with one another. Each of the drawings from the production package should be included in the patent application to specify the proportions, dimensions, and overall engine layout including the pistons, crankshaft, cylinders, and positioning of the heat sinks. The actual positioning of the fans with respect to the engine would not be part of the patent application as this may vary depending on the size and geometry of the refrigerator body in which the cooling mechanism will be used. However, it is important to note that the term “cooling mechanism” describes the use of a Stirling engine in combination with heatsinks and fans. Another aspect of the design that will not be considered original is the use of air in a Stirling engine, as well as the use of a hose connecting the hot and cold cylinders to make a closed cycle system, as this aspect is frequently used in a variety of Stirling engine applications on the market today and is not considered proprietary.

If commercialization were to be pursued, the first step would be to consult with a reliable manufacturer and discuss details about the cost of manufacturing each specific element. This would involve deciding when to outsource standard components and when to create specialty parts. After determining how each part of the cooling mechanism would be acquired, a final bid for production price per unit should be obtained. This value would need to be analyzed alongside market research to determine if a reasonable profit could be made after production and sale. Part of evaluating the engine’s selling potential would include presenting performance statistics to pre-existing refrigerator businesses such as GE, Whirlpool, Samsung, Frigidaire, Maytag, LG, and Kenmore. By estimating potential market demand, the product’s economic viability of production can then be assessed.

15. Conclusions/Future Work/etc.

Over the course of the semester, the team worked to design an improved cooling device which has comparable performance properties to the standard refrigerator compressor. Through the use of various concept design evaluation tools, an alpha-style Stirling engine with radial heat sinks and a fan was chosen as the most probable design. A standard dorm room refrigerator was obtained and its electrical consumption, noise output, and cooling efficiency were tested. The new engine’s components were then designed and sized appropriately in order to meet the design performance observed in the pre-existing compressor. Next, the team determined what materials each component would be made of (steel, aluminum, or plastic). Finite element analyses including stress analysis and resulting part deformation, as well as a thermal heat flux and temperature gradient analysis were performed on the engine’s critical parts to estimate it’s ultimate performance capabilities. Next, the team gathered the appropriate materials and built the Stirling engine according to the previously determined design specifications. The refrigerator was then stripped of its compressor and cooling mechanisms, and the new Stirling engine was inserted. Finally, the performance testing that was done initially was repeated for the Stirling engine and the two were compared.

Future work for this project could include more thorough testing of the Stirling engine. This could include testing the engine’s vibrational output and cooling efficiency over a long period of time. By varying aspects of the initial design such as motor speed, number of fans, and number of heat sinks, further optimization could be achieved. Mounting the engine on an absorbing platform with foam of dampers could further reduce noise output and operational vibrations. Finally, if the cooling mechanism were to be mass produced, a patent could be obtained followed by consulting with a manufacturer and refrigerator companies to form a production and distribution plan.

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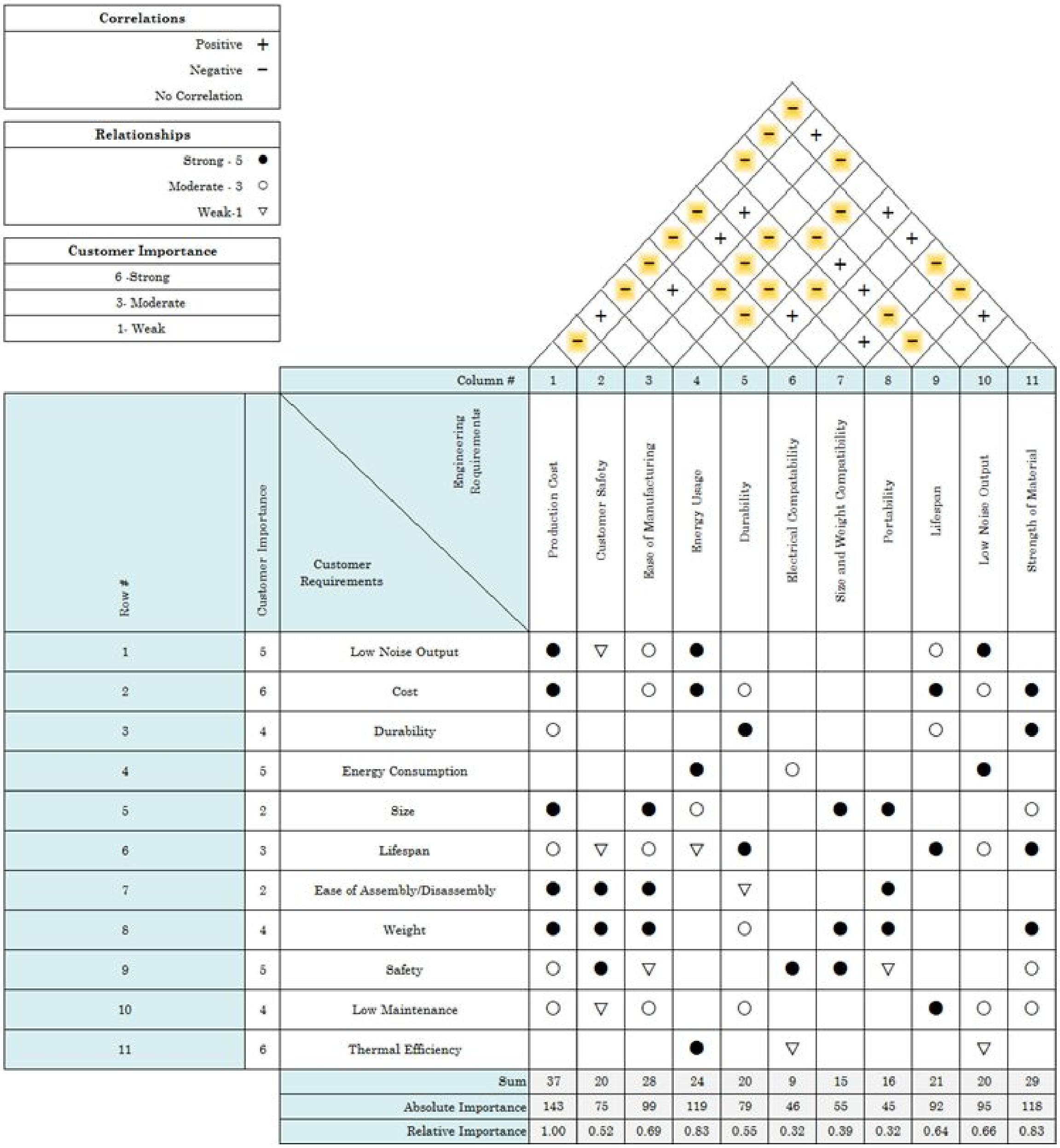
Appendix



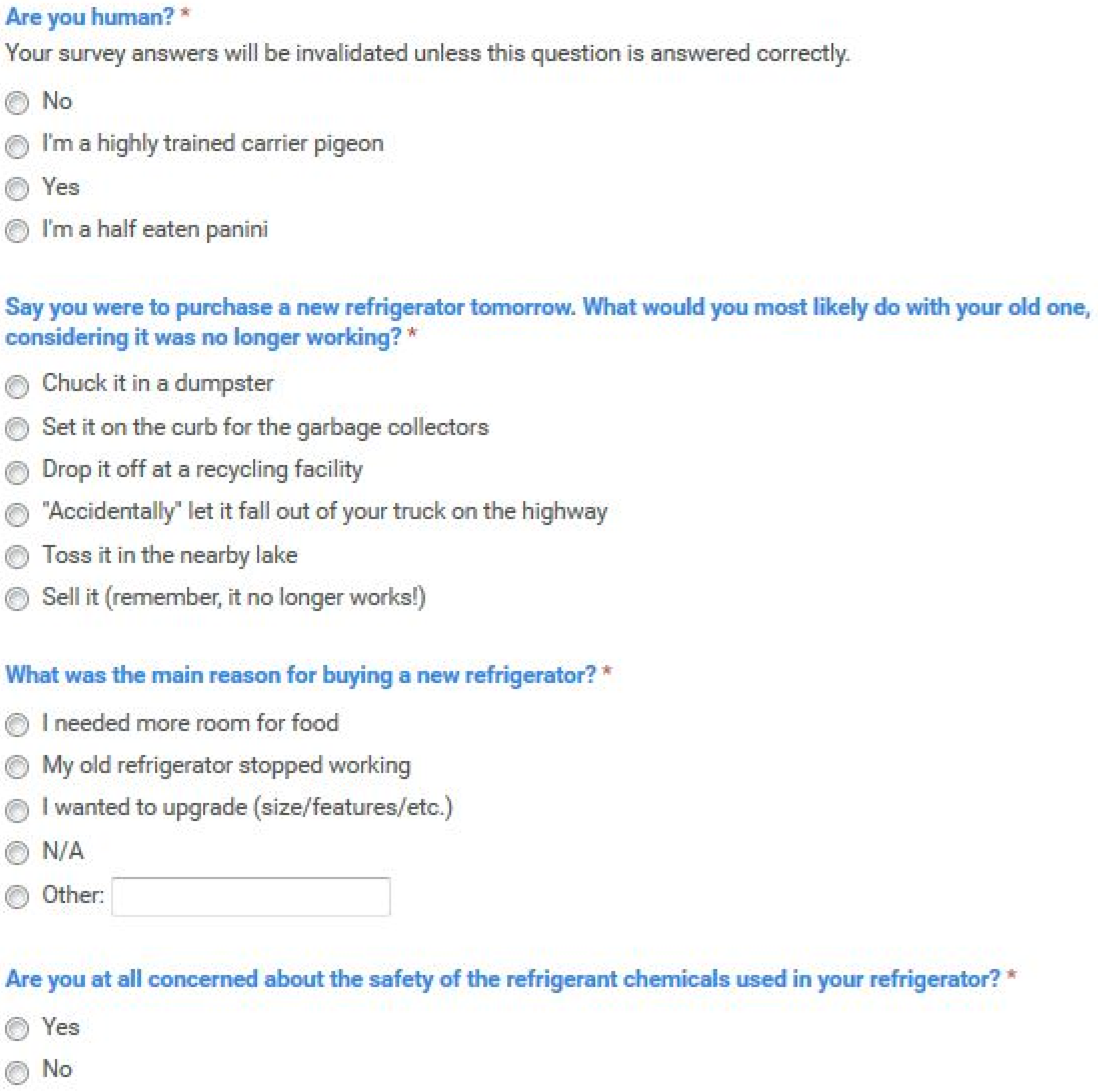
Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong - 5	●
Moderate - 3	○
Weak-1	▽

Customer Importance
6 -Strong
3- Moderate
1- Weak

Row #	Customer Importance	Column #	1	2	3	4	5	6	7	8	9	10	11
		Engineering Requirements Customer Requirements	Production Cost	Customer Safety	Ease of Manufacturing	Energy Usage	Durability	Electrical Compatability	Size and Weight Compatibility	Portability	Lifespan	Low Noise Output	Strength of Material
1	5	Low Noise Output	●	▽	○	●					○	●	
2	6	Cost	●		○	●	○				●	○	●
3	4	Durability	○				●				○		●
4	5	Energy Consumption				●		○				●	
5	2	Size	●		●	○			●	●			○
6	3	Lifespan	○	▽	○	▽	●				●	○	●
7	2	Ease of Assembly/Disassembly	●	●	●		▽			●			
8	4	Weight	●	●	●		○		●	●			●
9	5	Safety	○	●	▽			●	●	▽			○
10	4	Low Maintenance	○	▽	○		○				●	○	○
11	6	Thermal Efficiency				●		▽				▽	
		Sum	37	20	28	24	20	9	15	16	21	20	29
		Absolute Importance	143	75	99	119	79	46	55	45	92	95	118
		Relative Importance	1.00	0.52	0.69	0.83	0.55	0.32	0.39	0.32	0.64	0.66	0.83

Figure 2. House of Quality



Are you human? *

Your survey answers will be invalidated unless this question is answered correctly.

- ○ No
- ○ I'm a highly trained carrier pigeon
- ○ Yes
- ○ I'm a half eaten panini

Say you were to purchase a new refrigerator tomorrow. What would you most likely do with your old one, considering it was no longer working? *

- ○ Chuck it in a dumpster
- ○ Set it on the curb for the garbage collectors
- ○ Drop it off at a recycling facility
- ○ "Accidentally" let it fall out of your truck on the highway
- ○ Toss it in the nearby lake
- ○ Sell it (remember, it no longer works!)

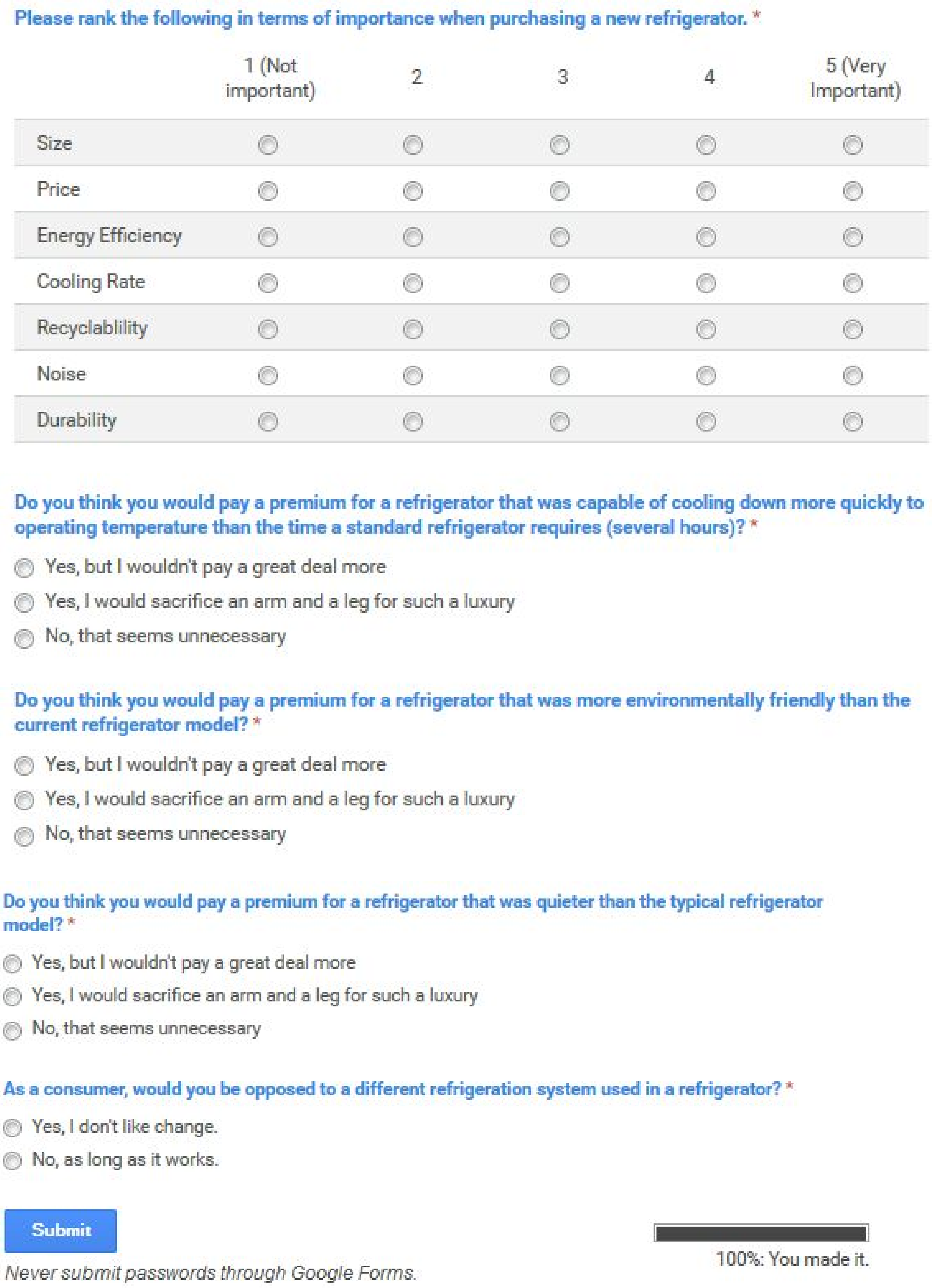
What was the main reason for buying a new refrigerator? *

- ○ I needed more room for food
- ○ My old refrigerator stopped working
- ○ I wanted to upgrade (size/features/etc.)
- ○ N/A
- ○ Other:

Are you at all concerned about the safety of the refrigerant chemicals used in your refrigerator? *

- ○ Yes
- ○ No

Figure 5a: Market Research Survey



Please rank the following in terms of importance when purchasing a new refrigerator. *

	1 (Not important)	2	3	4	5 (Very Important)
Size	○	○	○	○	○
Price	○	○	○	○	○
Energy Efficiency	○	○	○	○	○
Cooling Rate	○	○	○	○	○
Recyclablility	○	○	○	○	○
Noise	○	○	○	○	○
Durability	○	○	○	○	○

Do you think you would pay a premium for a refrigerator that was capable of cooling down more quickly to operating temperature than the time a standard refrigerator requires (several hours)? *

○ Yes, but I wouldn't pay a great deal more
○ Yes, I would sacrifice an arm and a leg for such a luxury
○ No, that seems unnecessary

Do you think you would pay a premium for a refrigerator that was more environmentally friendly than the current refrigerator model? *

○ Yes, but I wouldn't pay a great deal more
○ Yes, I would sacrifice an arm and a leg for such a luxury
○ No, that seems unnecessary

Do you think you would pay a premium for a refrigerator that was quieter than the typical refrigerator model? *

○ Yes, but I wouldn't pay a great deal more
○ Yes, I would sacrifice an arm and a leg for such a luxury
○ No, that seems unnecessary

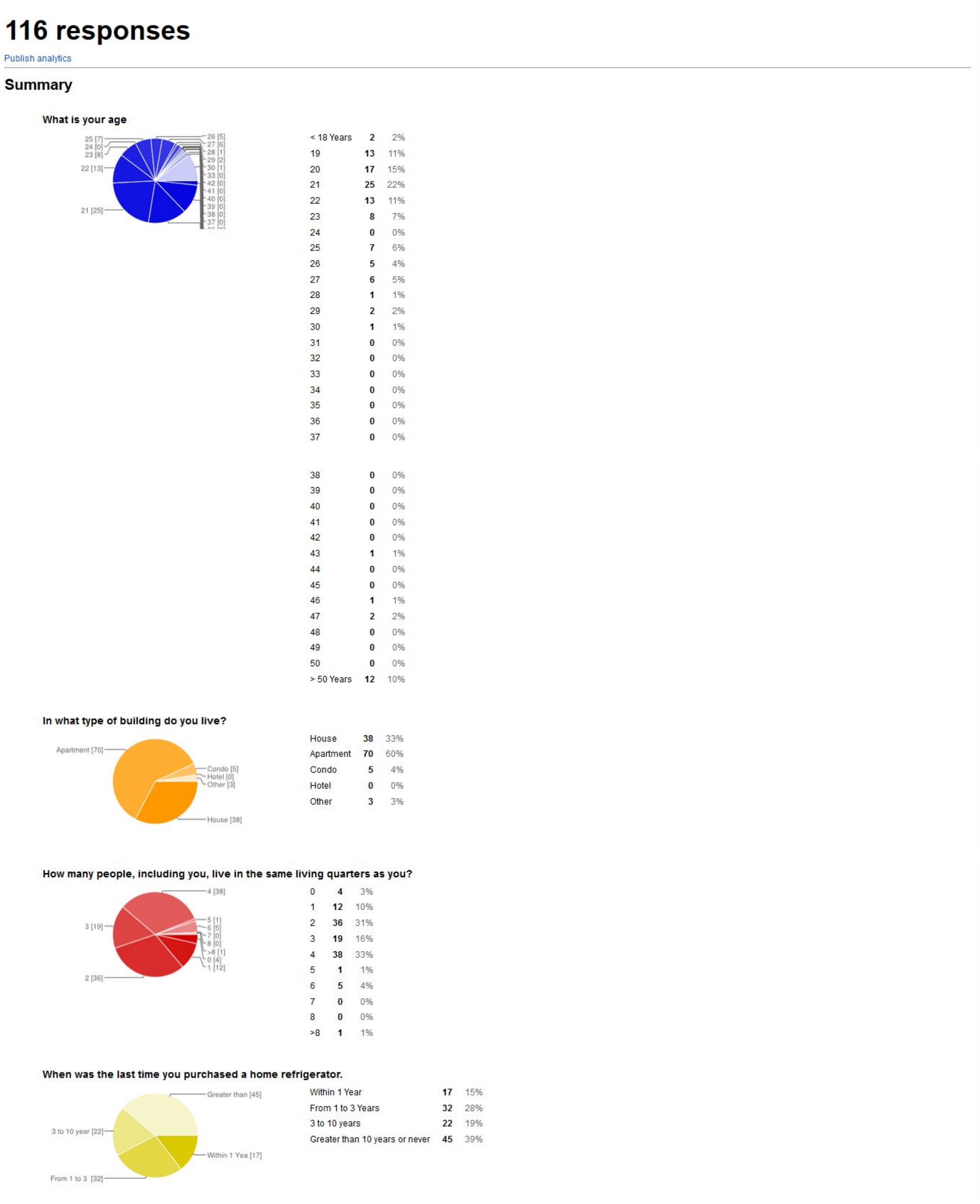
As a consumer, would you be opposed to a different refrigeration system used in a refrigerator? *

○ Yes, I don't like change.
○ No, as long as it works.

Never submit passwords through Google Forms.

100%: You made it.

Figure 5b: Market Research Survey



116 responses

Publish analytics

Summary

What is your age

< 18 Years	**2**	2%
19	**13**	11%
20	**17**	15%
21	**25**	22%
22	**13**	11%
23	**8**	7%
24	**0**	0%
25	**7**	6%
26	**5**	4%
27	**6**	5%
28	**1**	1%
29	**2**	2%
30	**1**	1%
31	**0**	0%
32	**0**	0%
33	**0**	0%
34	**0**	0%
35	**0**	0%
36	**0**	0%
37	**0**	0%
38	**0**	0%
39	**0**	0%
40	**0**	0%
41	**0**	0%
42	**0**	0%
43	**1**	1%
44	**0**	0%
45	**0**	0%
46	**1**	1%
47	**2**	2%
48	**0**	0%
49	**0**	0%
50	**0**	0%
> 50 Years	**12**	10%

In what type of building do you live?

House	**38**	33%
Apartment	**70**	60%
Condo	**5**	4%
Hotel	**0**	0%
Other	**3**	3%

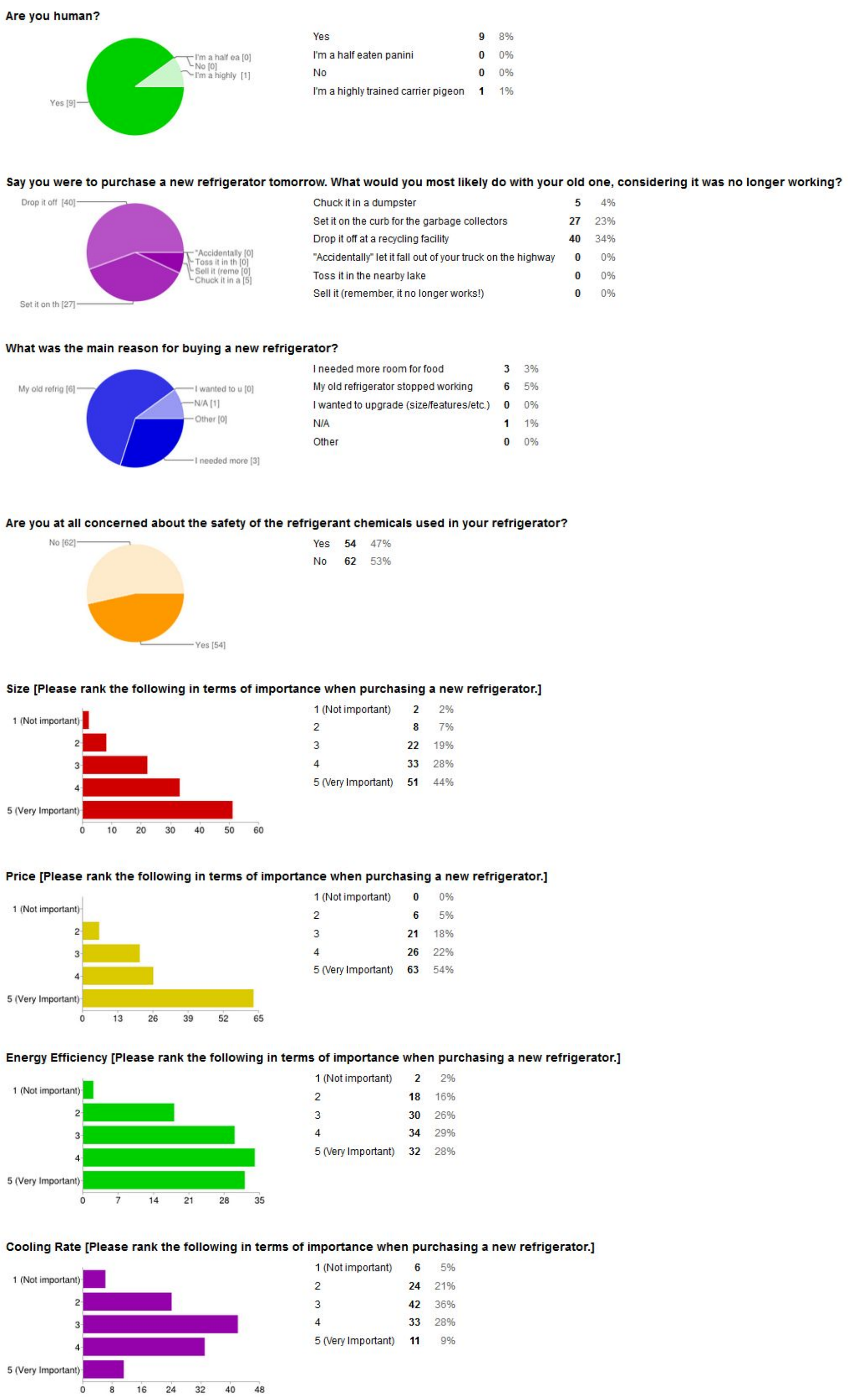
How many people, including you, live in the same living quarters as you?

0	**4**	3%
1	**12**	10%
2	**36**	31%
3	**19**	16%
4	**38**	33%
5	**1**	1%
6	**5**	4%
7	**0**	0%
8	**0**	0%
>8	**1**	1%

When was the last time you purchased a home refrigerator.

Within 1 Year	**17**	15%
From 1 to 3 Years	**32**	28%
3 to 10 years	**22**	19%
Greater than 10 years or never	**45**	39%

Figure 5c: Market Research Survey Results



Are you human?

Yes	9	8%
I'm a half eaten panini	0	0%
No	0	0%
I'm a highly trained carrier pigeon	1	1%

Say you were to purchase a new refrigerator tomorrow. What would you most likely do with your old one, considering it was no longer working?

Chuck it in a dumpster	5	4%
Set it on the curb for the garbage collectors	27	23%
Drop it off at a recycling facility	40	34%
"Accidentally" let it fall out of your truck on the highway	0	0%
Toss it in the nearby lake	0	0%
Sell it (remember, it no longer works!)	0	0%

What was the main reason for buying a new refrigerator?

I needed more room for food	3	3%
My old refrigerator stopped working	6	5%
I wanted to upgrade (size/features/etc.)	0	0%
N/A	1	1%
Other	0	0%

Are you at all concerned about the safety of the refrigerant chemicals used in your refrigerator?

Yes	54	47%
No	62	53%

Size [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	2	2%
2	8	7%
3	22	19%
4	33	28%
5 (Very Important)	51	44%

Price [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	0	0%
2	6	5%
3	21	18%
4	26	22%
5 (Very Important)	63	54%

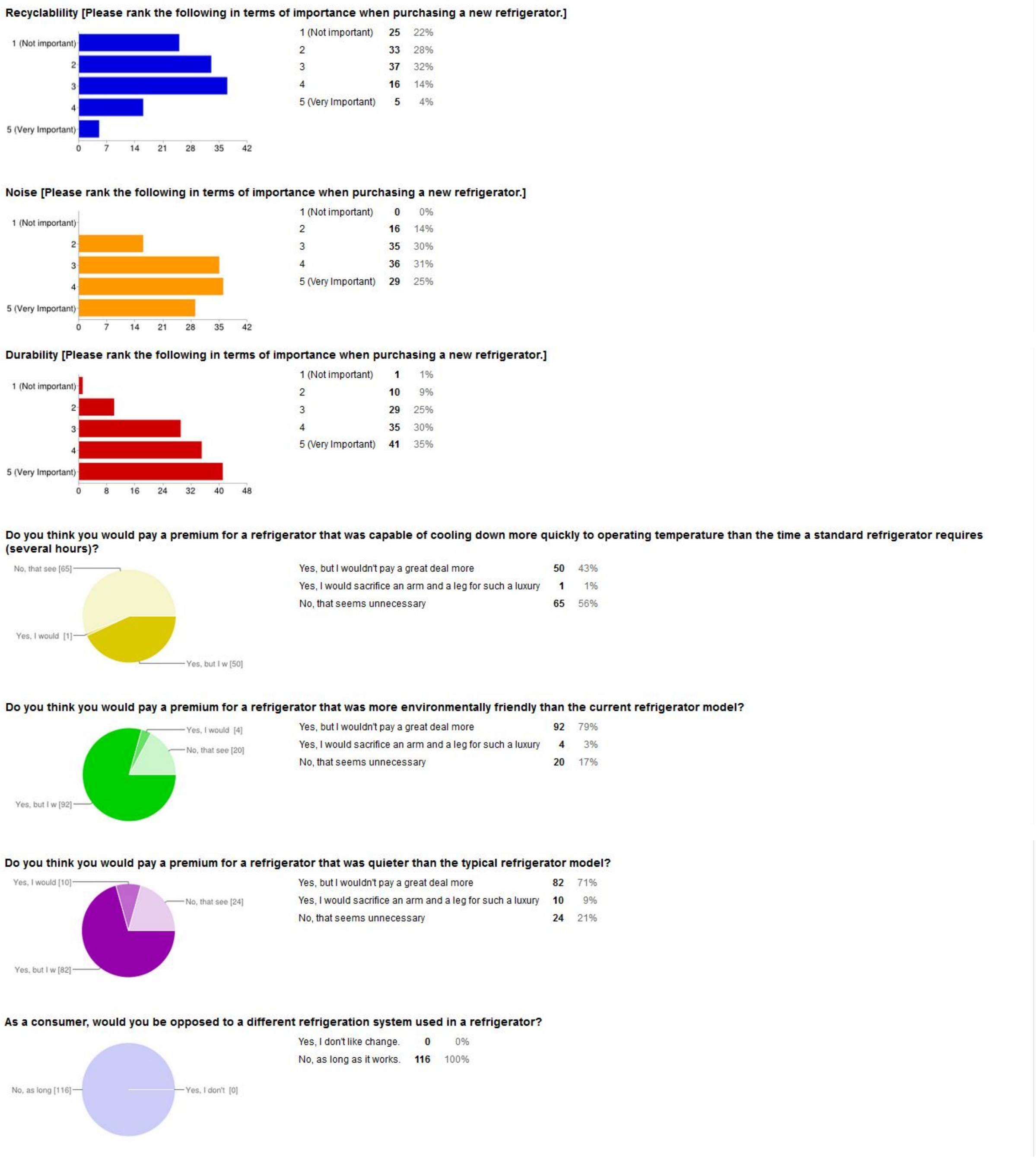
Energy Efficiency [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	2	2%
2	18	16%
3	30	26%
4	34	29%
5 (Very Important)	32	28%

Cooling Rate [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	6	5%
2	24	21%
3	42	36%
4	33	28%
5 (Very Important)	11	9%

Figure 5d: Market Research Survey Results



Recyclablility [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	25	22%
2	33	28%
3	37	32%
4	16	14%
5 (Very Important)	5	4%

Noise [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	0	0%
2	16	14%
3	35	30%
4	36	31%
5 (Very Important)	29	25%

Durability [Please rank the following in terms of importance when purchasing a new refrigerator.]

1 (Not important)	1	1%
2	10	9%
3	29	25%
4	35	30%
5 (Very Important)	41	35%

Do you think you would pay a premium for a refrigerator that was capable of cooling down more quickly to operating temperature than the time a standard refrigerator requires (several hours)?

Yes, but I wouldn't pay a great deal more	50	43%
Yes, I would sacrifice an arm and a leg for such a luxury	1	1%
No, that seems unnecessary	65	56%

Do you think you would pay a premium for a refrigerator that was more environmentally friendly than the current refrigerator model?

Yes, but I wouldn't pay a great deal more	92	79%
Yes, I would sacrifice an arm and a leg for such a luxury	4	3%
No, that seems unnecessary	20	17%

Do you think you would pay a premium for a refrigerator that was quieter than the typical refrigerator model?

Yes, but I wouldn't pay a great deal more	82	71%
Yes, I would sacrifice an arm and a leg for such a luxury	10	9%
No, that seems unnecessary	24	21%

As a consumer, would you be opposed to a different refrigeration system used in a refrigerator?

Yes, I don't like change.	0	0%
No, as long as it works.	116	100%

Figure 5e: Market Research Survey Results

*****Insert Morph Chart as Figure 6**

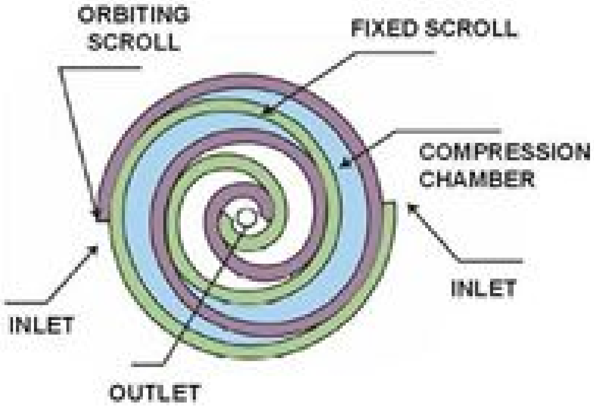


Figure 7: Scroll Pump [7]

Scroll compressors use two sets of helical vanes moving in circular paths eccentric from each other. This motions a volume of gas along a spiral path towards the center as it slowly reduces in volume. Scroll compressors have the capability to be very efficient, however they require very precise machining of a complicated shape. This also causes small amounts of wear to have a very significant impact on the performance and lifespan. For this reason, scroll compressors are a poor choice for the specified requirements.

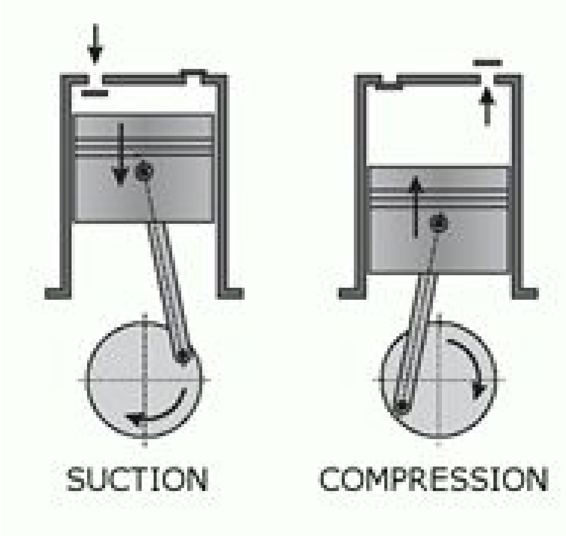


Figure 8: Piston Pump [5]

Piston compressors are the most common type of compressor due to their reliability and mechanical simplicity. They operate by drawing in and compressing a discrete mass of air with each stroke. However, because of the piston rings, seals, and valves required, they have significantly higher losses than other types of compressors.

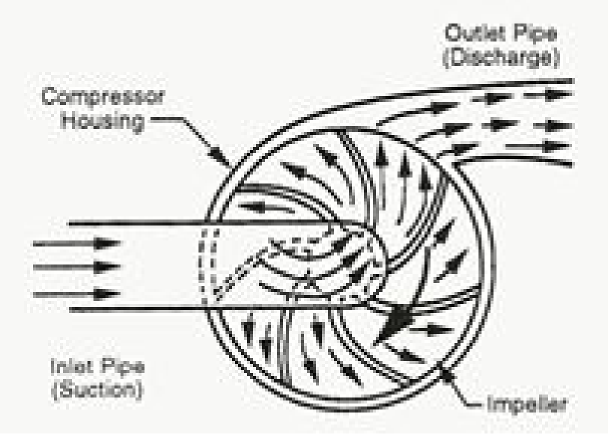


Figure 9: Centrifugal Pump [3]

Centrifugal pumps operate on the principle of reactionary centrifugal force. By spinning a ring air at high speed a pressure difference is created between the center and outside of the ring. Centrifugal pumps are useful in high flow rate applications, however due to the high speed required, high frictional and acoustic losses occur. This results in high noise output as well as lower compression compared to other types of compressors

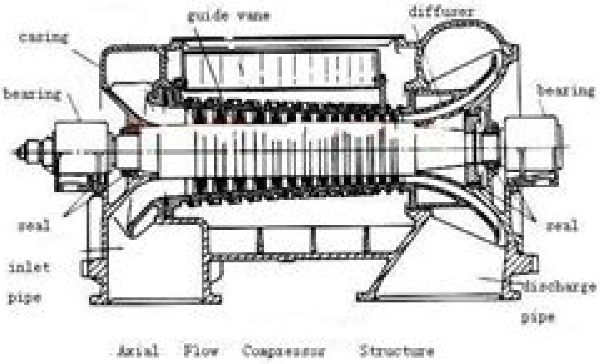


Figure 10: Axial Flow Pump [7]

Axial Compressors, like centrifugal, can only achieve high compression under very extreme circumstances. They operate by forcing the gas through a pipe of narrowing cross sectional area. Because they are not positive displacement compressors, they require high speed fans and are often extremely noisy. They often only achieve competitive efficiencies when they become very large, making them unsuitable for use in a refrigerator.

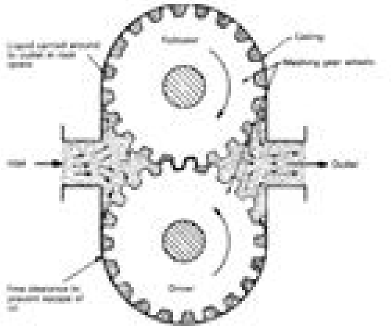


Figure 11: Gear Pump [5]

Gear compressors work by transporting fluid between the teeth of two gears around the outside of an enclosed case. The mating teeth of the two gears displaces the fluid that might travel in the wrong direction. This causes the fluid to be pumped in one direction only. Due to the of the complicated shape of the gears involved, complex and precision machining is required for gear pumps to operate without leaks and losses. Gear pumps also require a larger size for the volume of fluid compressed, but can achieve extremely high pressures; much higher than is required for refrigeration.

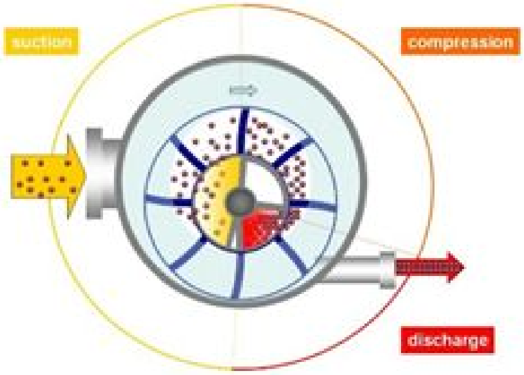


Figure 12: Liquid Ring Pump [3]

Liquid ring pumps operate similarly to rotary vane pumps, in that they use a eccentrically located set of vanes, however they achieve compression not through mechanical vanes, but through variable displacement caused by a ring of liquid spinning with the rotor. Liquid ring pumps can have a very long lifespan because they use very few contacting parts, however the working liquid can become mixed into the compressed gas and requires either separators or recyclers which add to the cost and size of the pump.

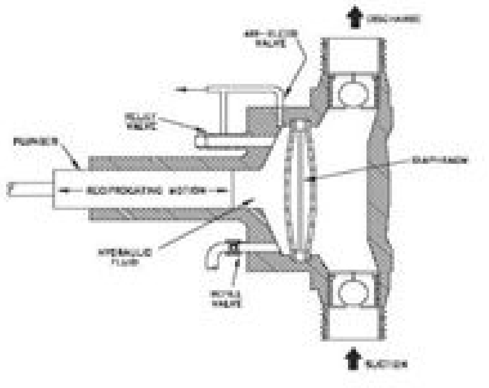


Figure 13: Diaphragm Compressor [7]

Diaphragm pumps operate similarly to piston pumps except that the piston is replaced by a flexible diaphragm. This can be useful when the fluid to be pumped is unknown or harmful to metal pistons. The diaphragm can not move as far as a piston often can, therefore they either have lower volumetric flow rates or operate at high speed, leading to energy waste in the form of noise and heat output.

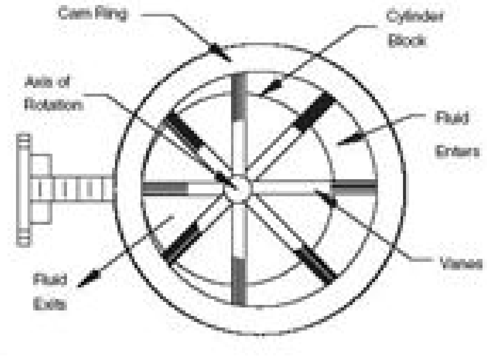


Figure 14: Rotary Vane Pump [9]

Rotary vane pumps are positive displacement pumps that can efficiently achieve very high pressures. They operate through the use of a rotating set of vanes mounted eccentrically from its enclosing cylinder. As the the rotor turns, the vanes retract, keeping uniform pressure and seal against the outside wall. This causes a varying volume between consecutive vanes that can draw in and then expel fluid. Due to the inability to employ tradition seals, high precision parts must be used. This means that any wear or damage can cause severe or complete loss of operation. Also, they rarely achieve long a long lifespan without proper and regular maintenance.

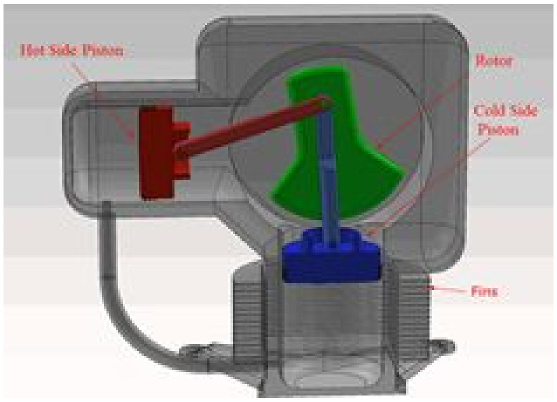


Figure 15: Stirling Engine Heat Pump [9]

Stirling engines operate similarly to piston pumps, except that they reuse a self contained working fluid rather than drawing in from, and venting to the atmosphere. They operate by compressing a working gas in one location, causing it to give up heat. Then gas is moved to a different location within the engine (usually a second cylinder), and decompressed, allowing the gas to cool and absorb thermal energy. Stirling engines are often larger than other types of compressors for the same volume and pressure, but they have much higher theoretical efficiencies than other types of compressors.The stirling engine features an electric motor which drives a centrally positioned rotor that drives 2 different pistons. Compression and expansion of a gas within a closed-cycle system results in hot and cold temperatures respectively. One key advantage of the stirling engine would be its operating efficiency.

***Next Page is Evaluation Matrix table for cooling mechanisms→ Figure 16**

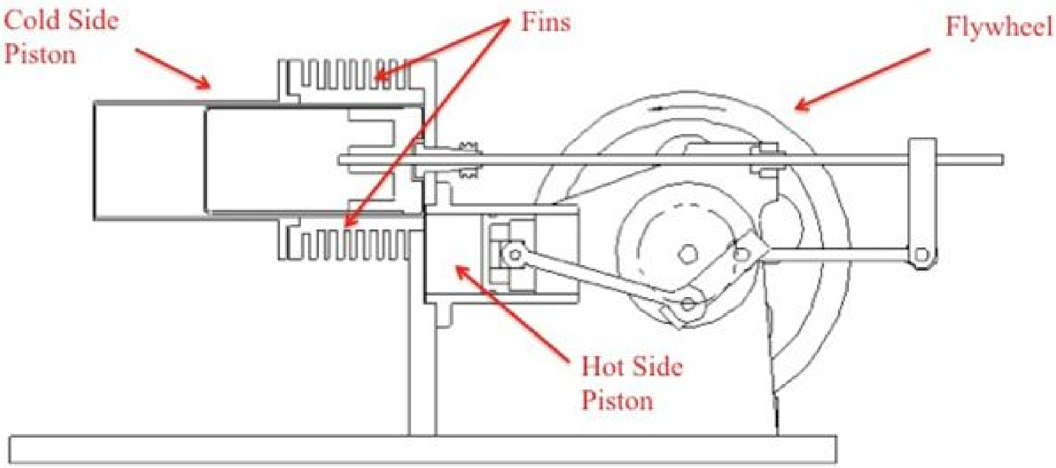


Figure 18: Beta-Style Stirling Engine

The beta style engine operates similarly to the alpha style engine, using 2 different pistons that are connected to a rotating flywheel. The engine's pistons are aligned parallel with one another and are positioned horizontally with respect to the base. A single power piston is arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston has a loose fit and doesn't extract power from the expanding gas, but only exists to move the working gas between the hot and cold heat exchangers.

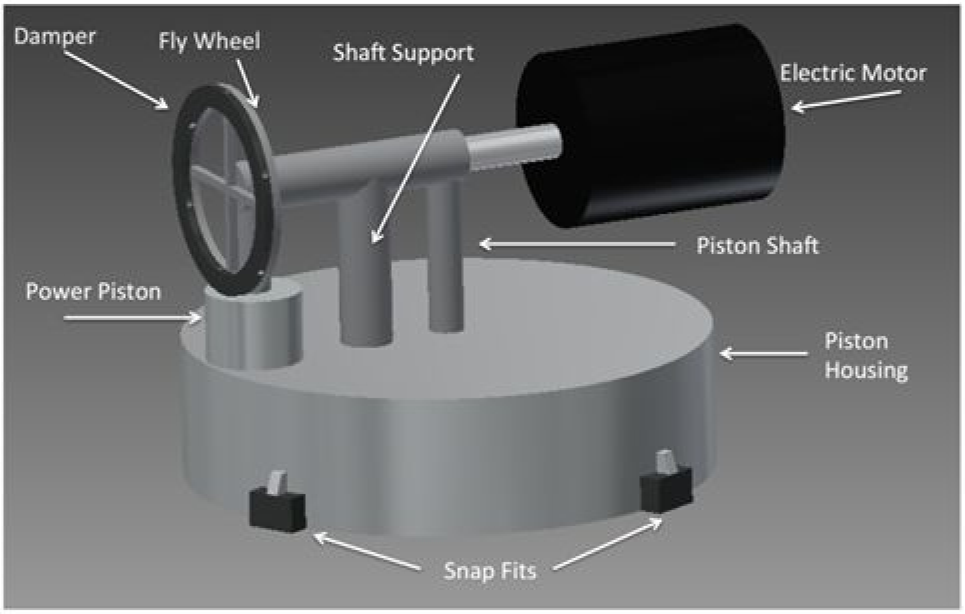


Figure 19: Gamma-Style Stirling Engine

The gamma style engine features two vertically aligned pistons that are contained within the same housing. One disadvantage to this engine design was poor energy consumption because rather than being physically separated, the hot and cold pistons are housed within the same material, making it more difficult to efficiently harness both hot and cold temperatures.

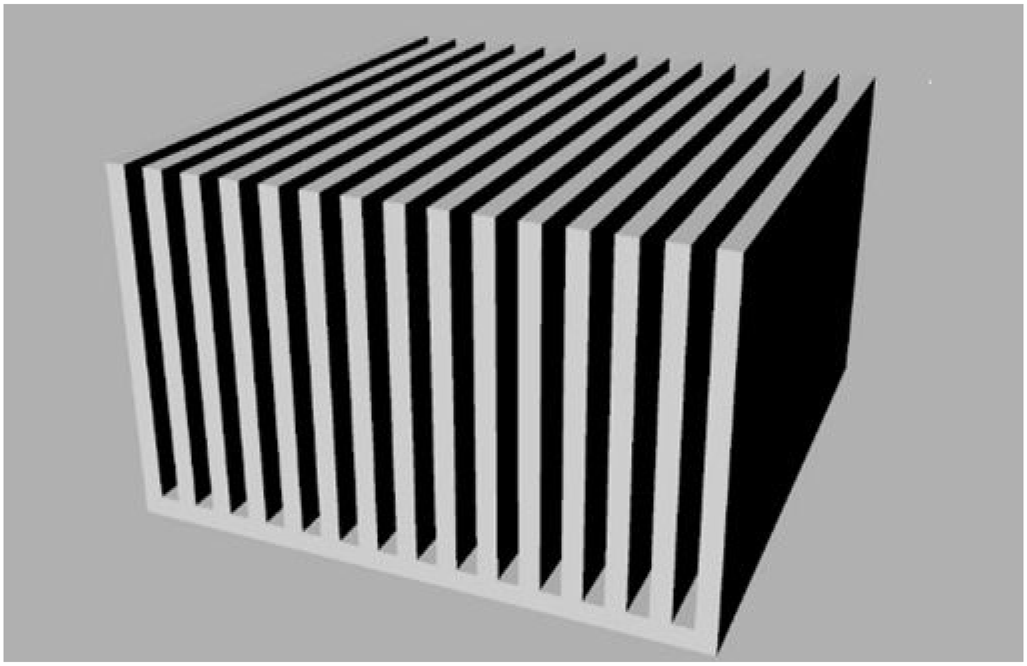


Figure 22: Finned Heat Sink

Figure 22 depicts a standard heat sink with various fins in addition to a fan. This preliminary engine attachment design is intended to move air across the chilled and heated fins on each side of the engine and then transport the cooled and heated air into the refrigerator's interior and out the back respectively. If this design were to be pursued, a network of various heatsinks and fans could be investigated in order to increase cooling efficiency.

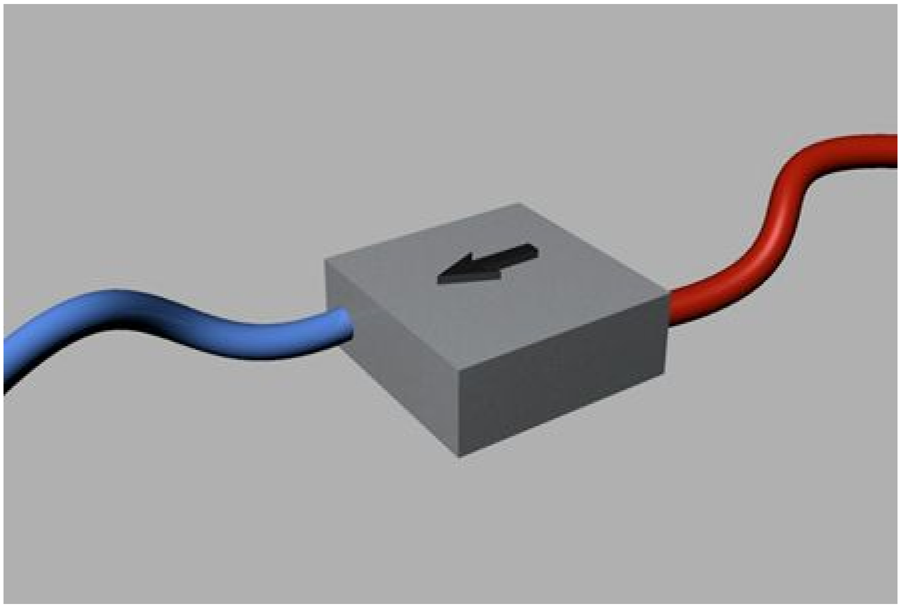


Figure 23: Heat Exchanger and Coolant Fluid (Water)

Figure 23 shows a conceptual diagram of a heat exchanger, which would be used to pump a coolant liquid (possibly water with salt or a particular alcohol content to prevent freezing) across the cold portion of the stirling engine's piston housing, then pump the chilled liquid throughout the refrigerator's pre-existing tubing in order to reduce the interior temperature. The heat exchanger would likely include fins and a standard pump to propel the coolant liquid.

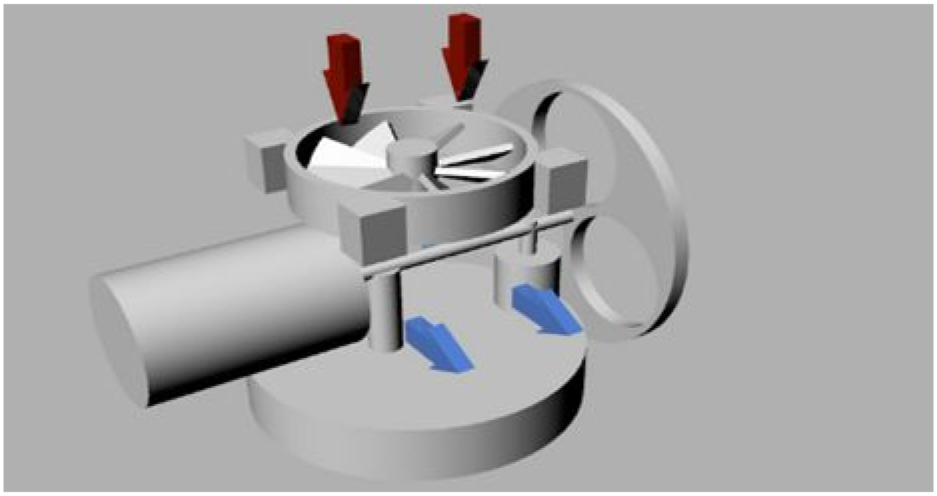


Figure 24: Flat Engine Body and Fan

Figure 24 models a potential design in which the surface or base of the stirling engine body will be designed to have a large surface area. The engine will be positioned such that the cold side of the engine body is in contact with the refrigerator's interior and will thus cool the internal temperature. The key aspect of this simple attachment is the precise positioning of the engine into the back of the refrigerator.

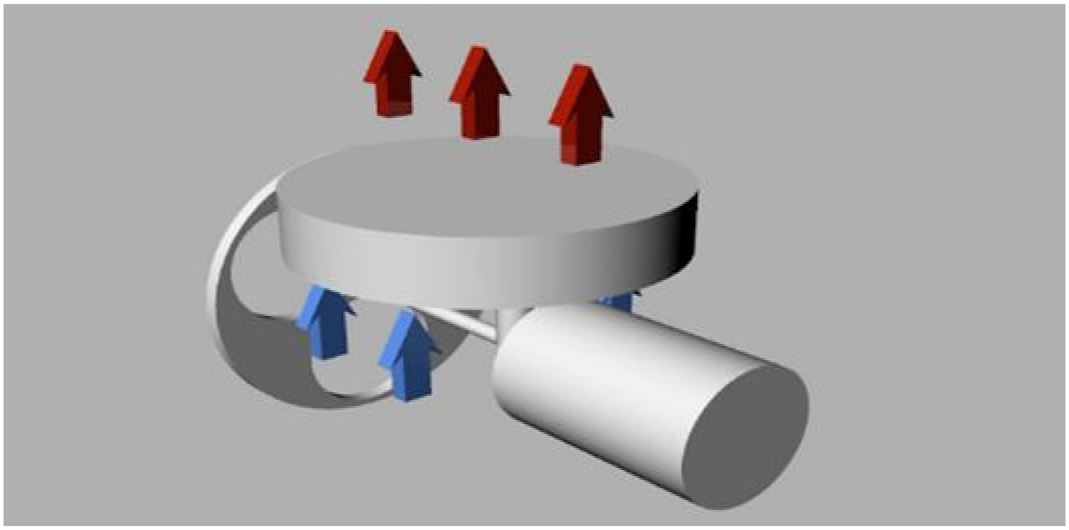


Figure 25: Flat Engine Body

Figure 25 portrays the concept of designing a cooling mechanism that has a large surface area where the pistons are housed. By maximizing this surface area, the cold temperatures can be carried into the refrigerator's interior and the hot temperatures can be extracted out the back.

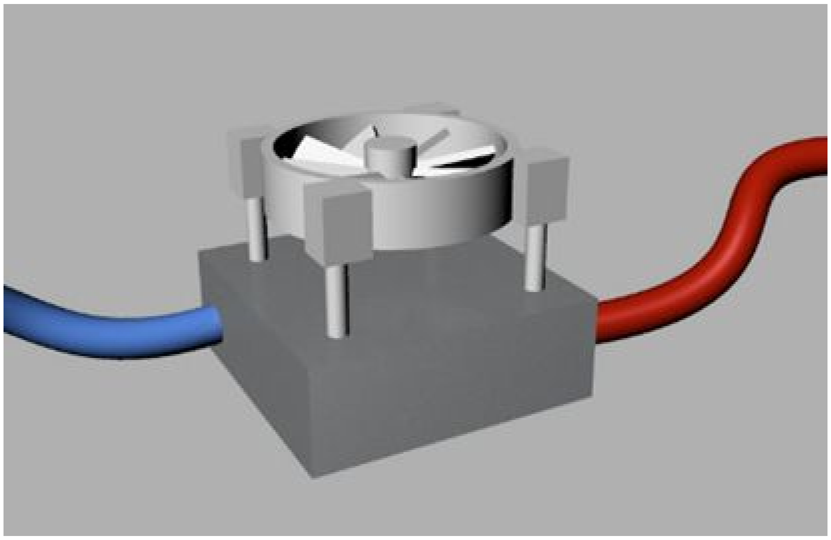


Figure 26: Heat Exchanger (with water) and Fan

Figure 26 shows a model of a fan, which is being used to move chilled air from the engine across the housing of a heat exchanger. A standard pump inside of the heat exchanger will then be used to move the fluid (likely water or other combination with salt or alcohol) through the housing, thus chilling it and pumping it throughout the pre-existing piping network to cool the refrigerator.

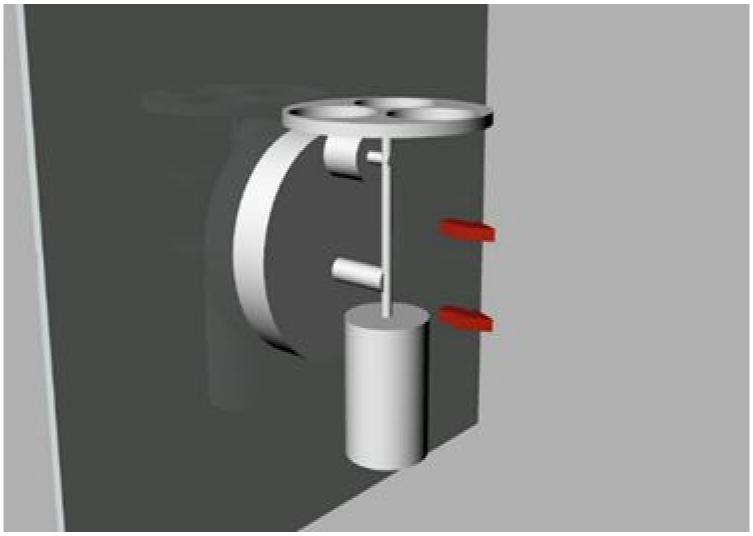


Figure 27: Inner Refrigerator Body as Heat Sink

Figure 27 depicts a model of the engine attaching to the interior rear surface of the refrigerator in order to dissipate the heat out from the inside of the refrigerator. Heat will be removed in the direction of the arrows shown above.

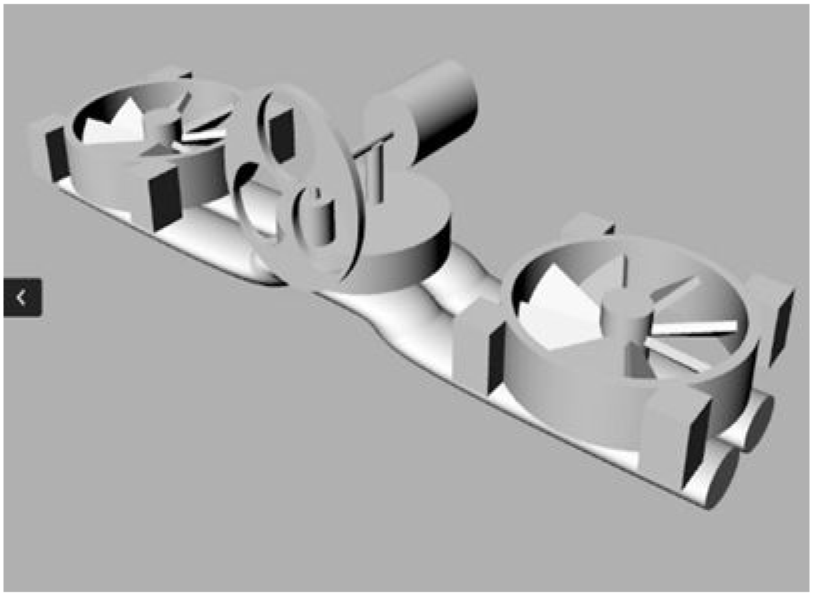


Figure 28: Solid Thermal Conductor and Fan

Figure 28 makes uses of fans as well as a solid thermal conductor material to remove heat from the inside of the refrigerator. This attachment is located underneath the engine, therefore as the engine heats up, heat is dissipated through the thermally conductive material and removed by the fans.

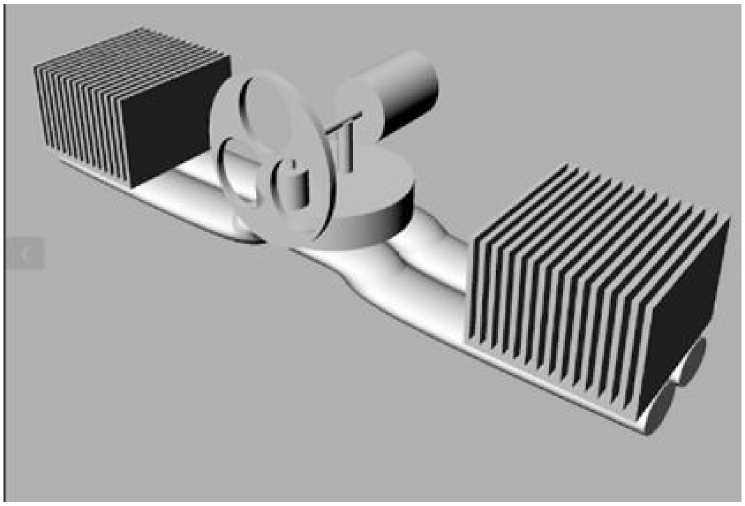


Figure 29: Solid Thermal Conductor and Heat Sink

A solid thermally conductive material is shown in Figure 29 that moves the heat created by the engine towards the heatsinks on either side. The two heat sink devices then remove the heat from the system.

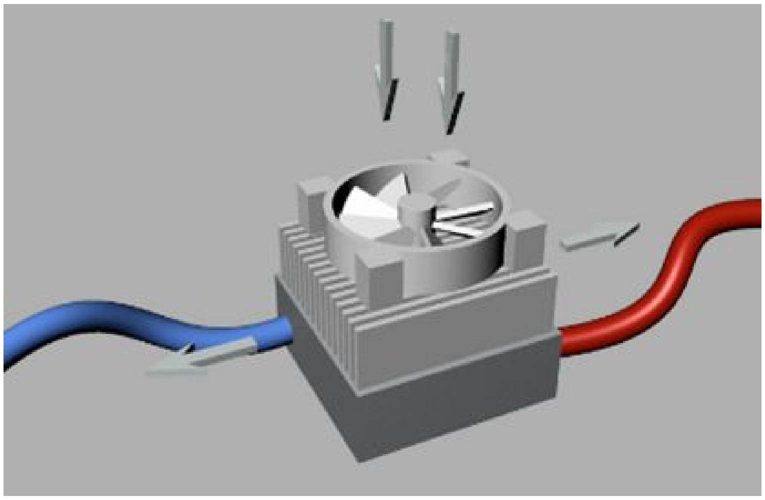
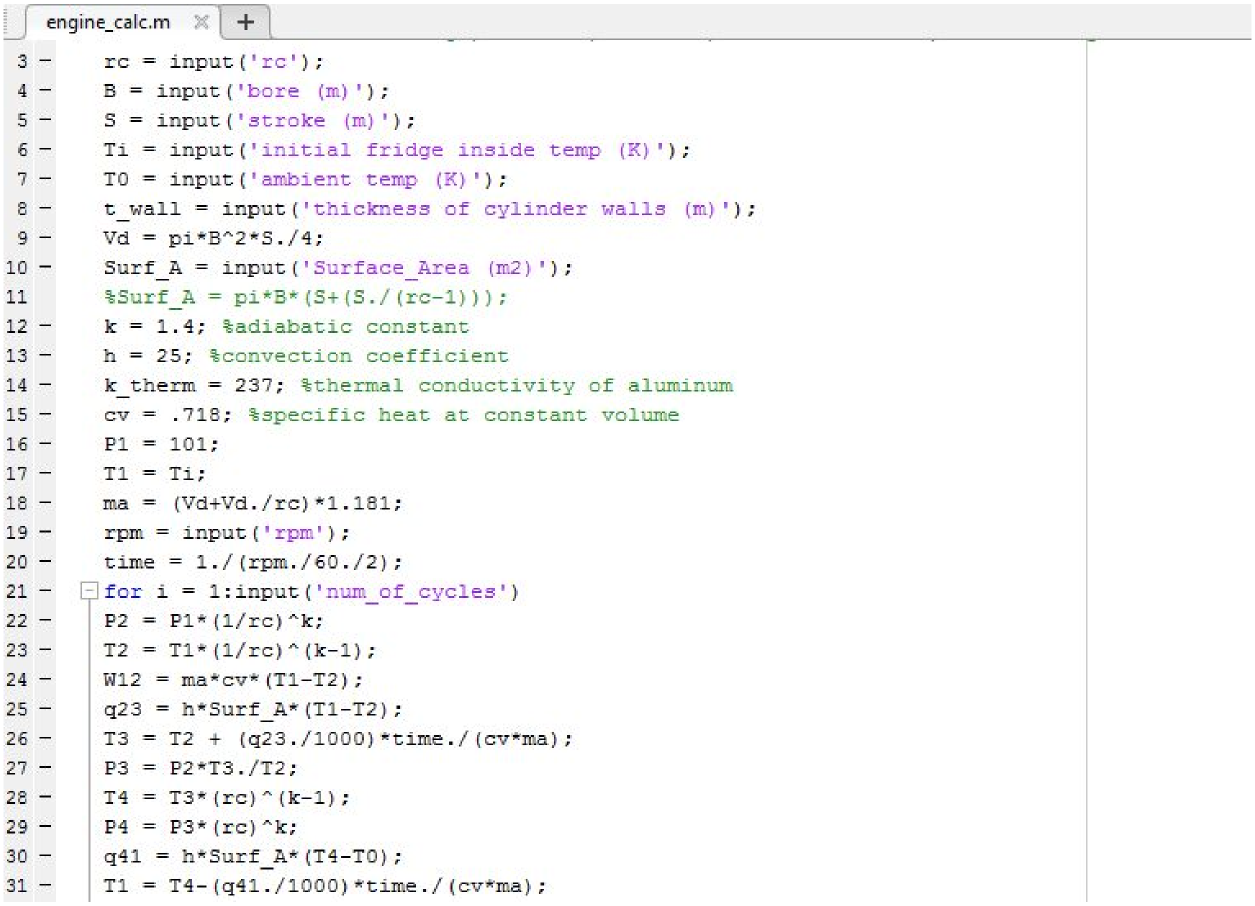


Figure 30: Heat Exchanger, Fins and Fan

Figure 30 depicts heat being removed from the system by entering the fan, and dissipating through the heat sink, effectively cooling the refrigerator interior. The fan moves the chilled air from the engine to the heat exchanger. The pump inside of the heat exchanger will then move the fluid through the housing, chilling it and releasing it to cool the interior of the refrigerator.

****Insert Attachment Evaluation Matrix as Figure 31**



```
rc = input('rc');
B = input('bore (m)');
S = input('stroke (m)');
Ti = input('initial fridge inside temp (K)');
T0 = input('ambient temp (K)');
t_wall = input('thickness of cylinder walls (m)');
Vd = pi*B^2*S./4;
Surf_A = input('Surface_Area (m2)');
%Surf_A = pi*B*(S+(S./(rc-1)));
k = 1.4; %adiabatic constant
h = 25; %convection coefficient
k_therm = 237; %thermal conductivity of aluminum
cv = .718; %specific heat at constant volume
P1 = 101;
T1 = Ti;
ma = (Vd+Vd./rc)*1.181;
rpm = input('rpm');
time = 1./(rpm./60./2);
for i = 1:input('num_of_cycles')
P2 = P1*(1/rc)^k;
T2 = T1*(1/rc)^(k-1);
W12 = ma*cv*(T1-T2);
q23 = h*Surf_A*(T1-T2);
T3 = T2 + (q23./1000)*time./(cv*ma);
P3 = P2*T3./T2;
T4 = T3*(rc)^(k-1);
P4 = P3*(rc)^k;
q41 = h*Surf_A*(T4-T0);
T1 = T4-(q41./1000)*time./(cv*ma);
```

Figure 33: Matlab Code Used to Size Engine

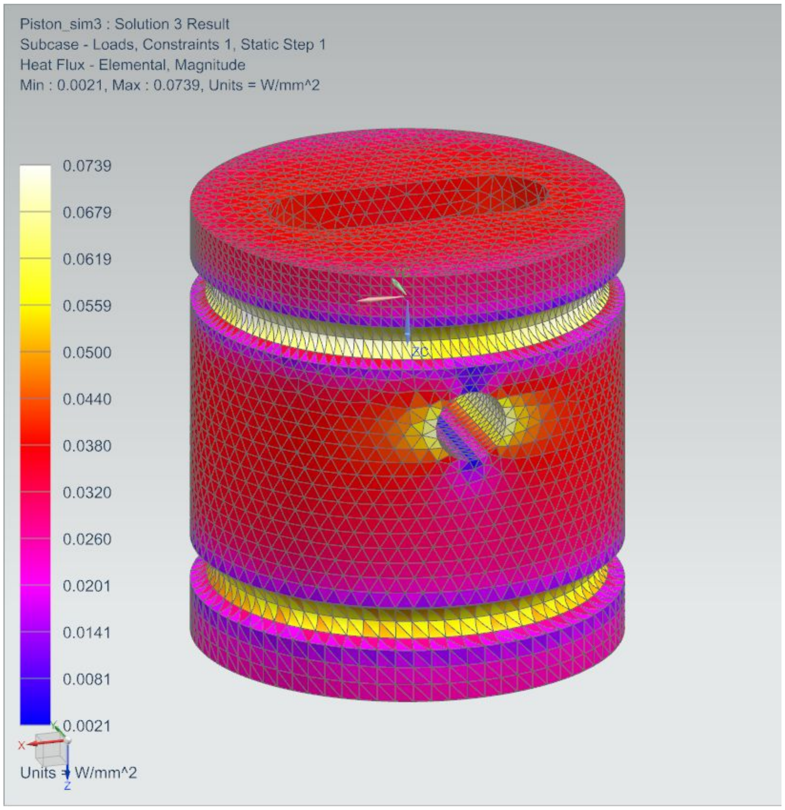


Figure 35: Finite Element Thermal Analysis: Heat Flux of Hot-Side Piston

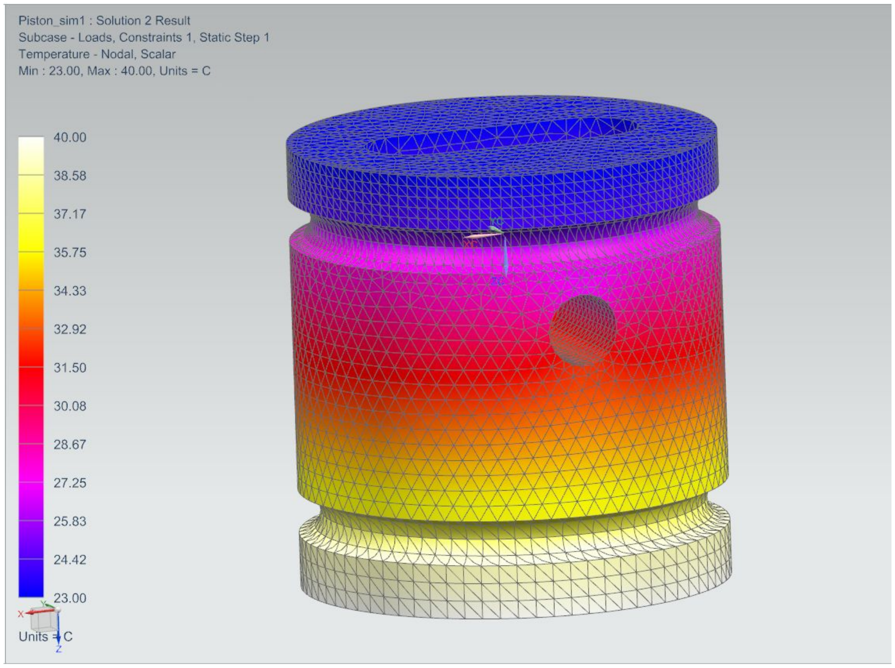


Figure 36: Finite Element Thermal Analysis: Temperature Gradient Through Hot-Side Piston

Thermal FEA Analysis- Hot and Cold Piston Heat Flux Verification Calculations

E=188 GPa
L=25 mm
D=25 mm
k^*= thermal conductivity =55,600 µW/ mm °C =0.0556 W/mm*K

$$A = \pi\left(\frac{D}{2}\right)^2 = \pi\left(\frac{25\text{ mm}}{2}\right)^2 = 490.874\text{ mm}^2$$

$$k = \frac{Ak^*}{L} = \frac{(490.874\text{ mm}^2)\left(0.0556\,\frac{\text{W}}{\text{mm}*\text{K}}\right)}{25\text{ mm}} = 1.092\,\frac{\text{W}}{\text{K}}$$

Hot Piston

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

T_1= 23°C = 293 K (room temperature)
T_2= 40°C = 313.5 K (hot temperature)

$$Q_1 = kT_1 - kT_2 = k(T_1 - T_2) = \left(1.092\,\frac{\text{W}}{\text{K}}\right) * (293\text{ K} - 313.5\text{ K})$$
$$= \frac{-22.38\text{ W}}{490.874\text{ mm}^2} = \mathbf{-0.046}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

$$Q_2 = k(T_2 - T_1) = \left(1.092\,\frac{\text{W}}{\text{K}}\right) * (313.5\text{ K} - 293\text{ K})$$
$$= \frac{22.38\text{ W}}{490.874\text{ mm}^2} = \mathbf{0.046}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

Cold Piston

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

T_1= 23°C = 293 K (room temperature)
T_2= 0°C = 273.15 K (cold temperature)

$$Q_1 = kT_1 - kT_2 = k(T_1 - T_2) = \left(1.092\,\frac{\text{W}}{\text{K}}\right) * (293\text{ K} - 273.15\text{ K})$$
$$= \frac{-21.68\text{ W}}{490.874\text{ mm}^2} = \mathbf{-0.044}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

$$Q_2 = k(T_2 - T_1) = \left(1.092\,\frac{\text{W}}{\text{K}}\right) * (273.15\text{ K} - 293\text{ K})$$
$$= \frac{21.68\text{ W}}{490.874\text{ mm}^2} = \mathbf{0.044}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

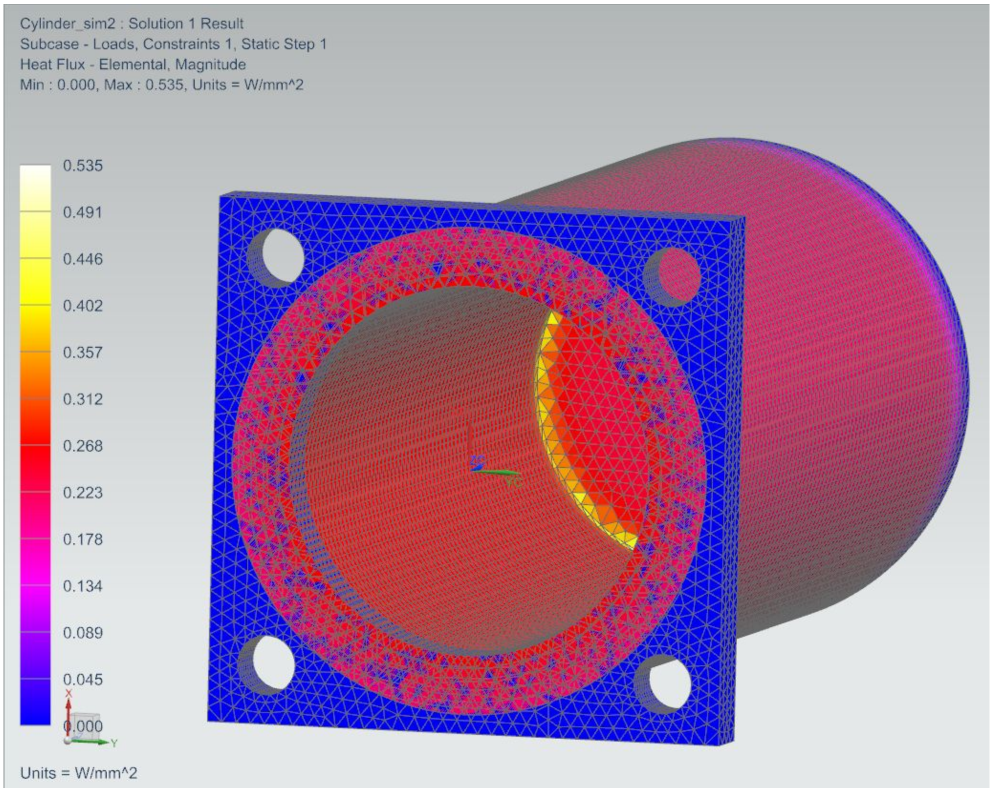


Figure 37: Finite Element Thermal Analysis: Heat Flux Through Hot-Side Cylinder

Thermal FEA Analysis- Hot and Cold Cylinder Heat Flux Verification Calculations

E=188 GPa
L=65 mm
D_o=33 mm
D_i=25mm
t=33mm-25mm=8mm
k^*= thermal conductivity =55,600 μW/ mm ℃ =0.0556 W/mm*K

$$A = \pi D_o L + \pi \left(\frac{D_o}{2}\right)^2 = \pi(33\ mm)(65mm) + \pi\left(\frac{33\ \text{mm}}{2}\right)^2 = 7{,}594.0148\ \text{mm}^2$$

$$k = \frac{Ak^*}{L} = \frac{(7{,}594.0148\ \text{mm}^2)\left(0.0556\,\frac{\text{W}}{\text{mm} * \text{K}}\right)}{65\ \text{mm}} = 52.778\ \frac{\text{W}}{\text{K}}$$

Hot Cylinder

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

T_1= 23°C = 293 K (room temperature)
T_2= 40°C = 313.5 K (hot temperature)

$$Q_1 = kT_1 - kT_2 = k(T_1 - T_2) = \left(52.778\,\frac{\mathrm{W}}{\mathrm{K}}\right) * (293\ \mathrm{K} - 313.5\ \mathrm{K})$$
$$= \frac{-1{,}063.48\ \mathrm{W}}{7{,}594.0148\ \mathrm{mm}^2} = \mathbf{-0.14}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

$$Q_2 = k(T_2 - T_1) = \left(52.778\,\frac{\mathrm{W}}{\mathrm{K}}\right) * (313.5\ \mathrm{K} - 293\ \mathrm{K})$$
$$= \frac{1{,}063.48\ \mathrm{W}}{7{,}594.0148\ \mathrm{mm}^2} = \mathbf{0.14}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

Cold Cylinder

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

T_1= 23°C = 293 K (room temperature)
T_2= 0°C = 273.15 K (cold temperature)

$$Q_1 = kT_1 - kT_2 = k(T_1 - T_2) = \left(52.778\,\frac{\mathrm{W}}{\mathrm{K}}\right) * (293\ \mathrm{K} - 273.15\ \mathrm{K})$$
$$= \frac{1{,}047.64\ \mathrm{W}}{7{,}594.0148\ \mathrm{mm}^2} = \mathbf{0.14}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

$$Q_2 = k(T_2 - T_1) = \left(52.778\,\frac{\mathrm{W}}{\mathrm{K}}\right) * (273.15\ \mathrm{K} - 293\ \mathrm{K})$$
$$= \frac{-1{,}047.64\ \mathrm{W}}{7{,}594.0148\ \mathrm{mm}^2} = \mathbf{-0.14}\ \frac{\mathbf{W}}{\mathbf{mm^2}}$$

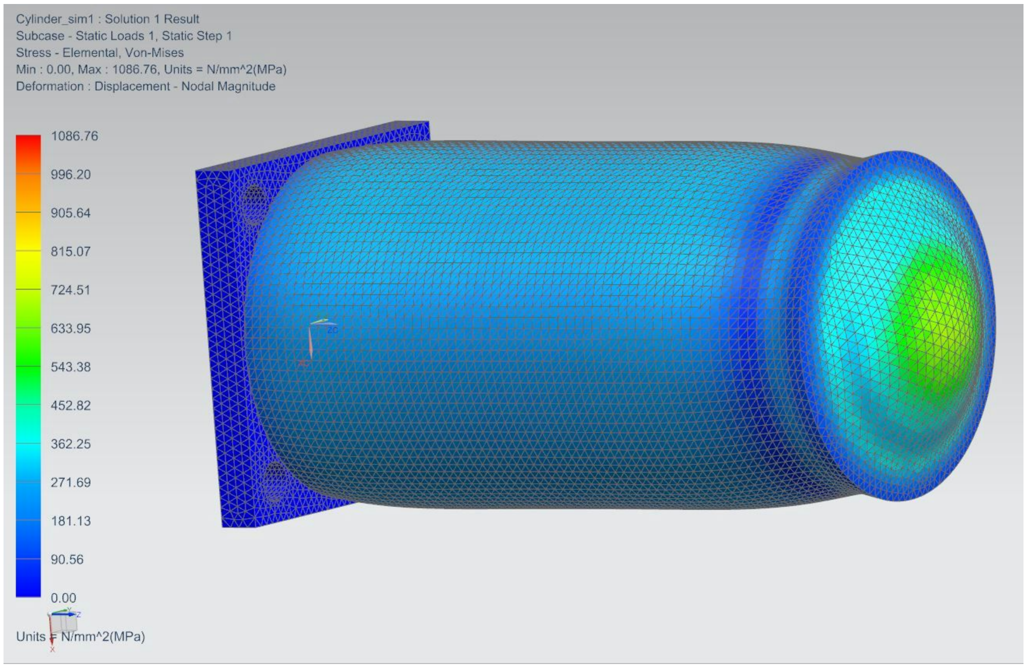


Figure 38: Finite Element Stress Analysis: Stress on Outside of Hot Cylinder

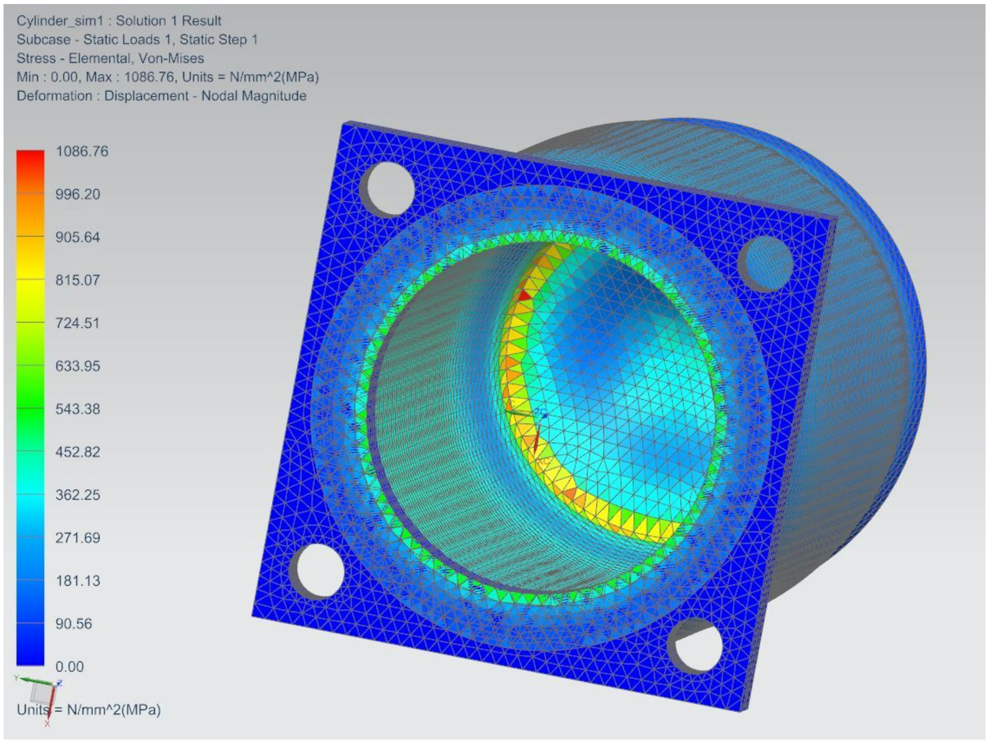


Figure 39: Finite Element Stress Analysis: Stress on Inside of Hot Cylinder

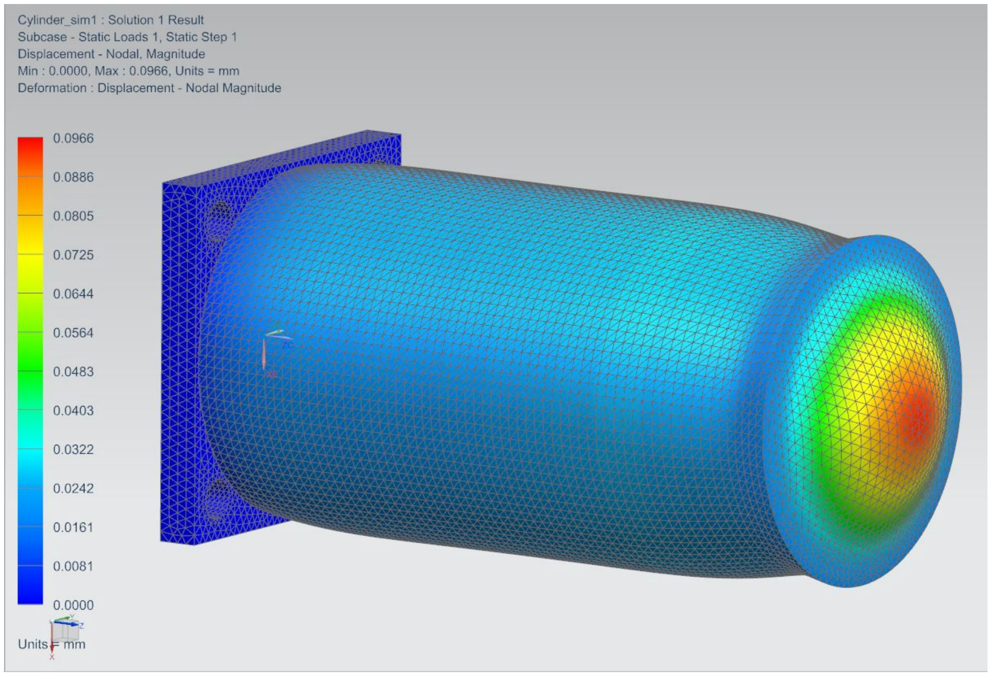


Figure 40: Finite Element Stress Analysis: Resulting Deformation on Outside of Hot Cylinder

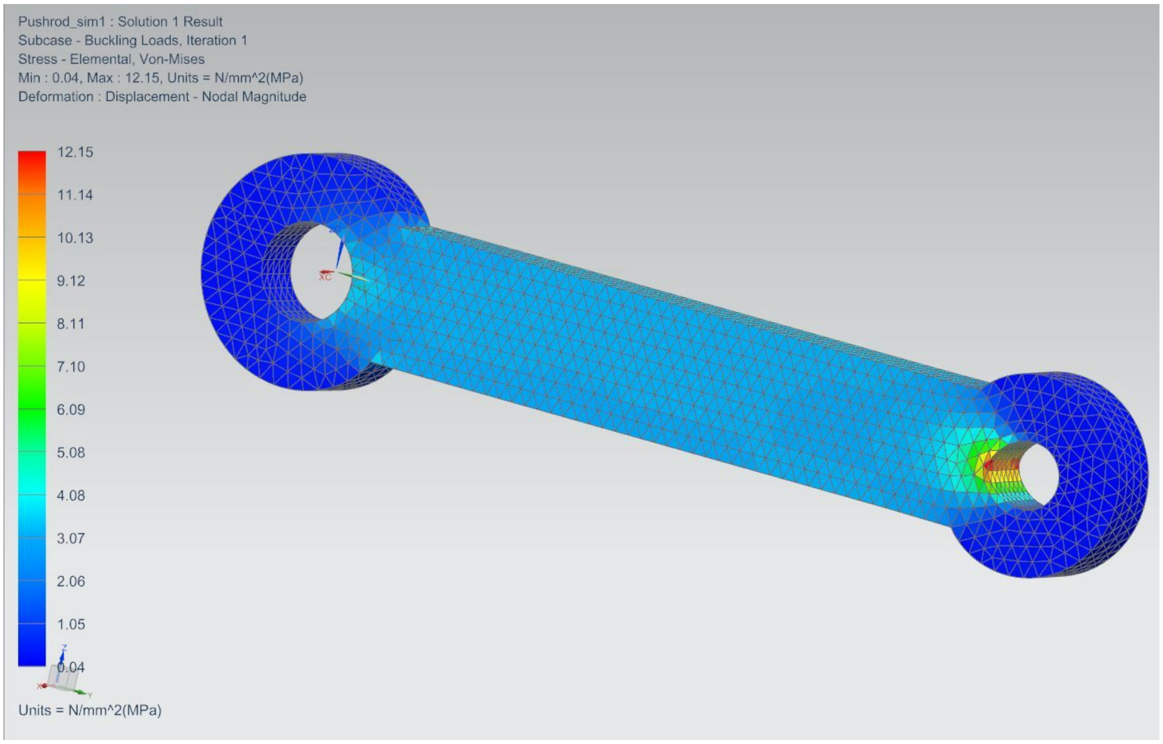


Figure 41: Finite Element Stress Analysis: Stress on Connecting Rod

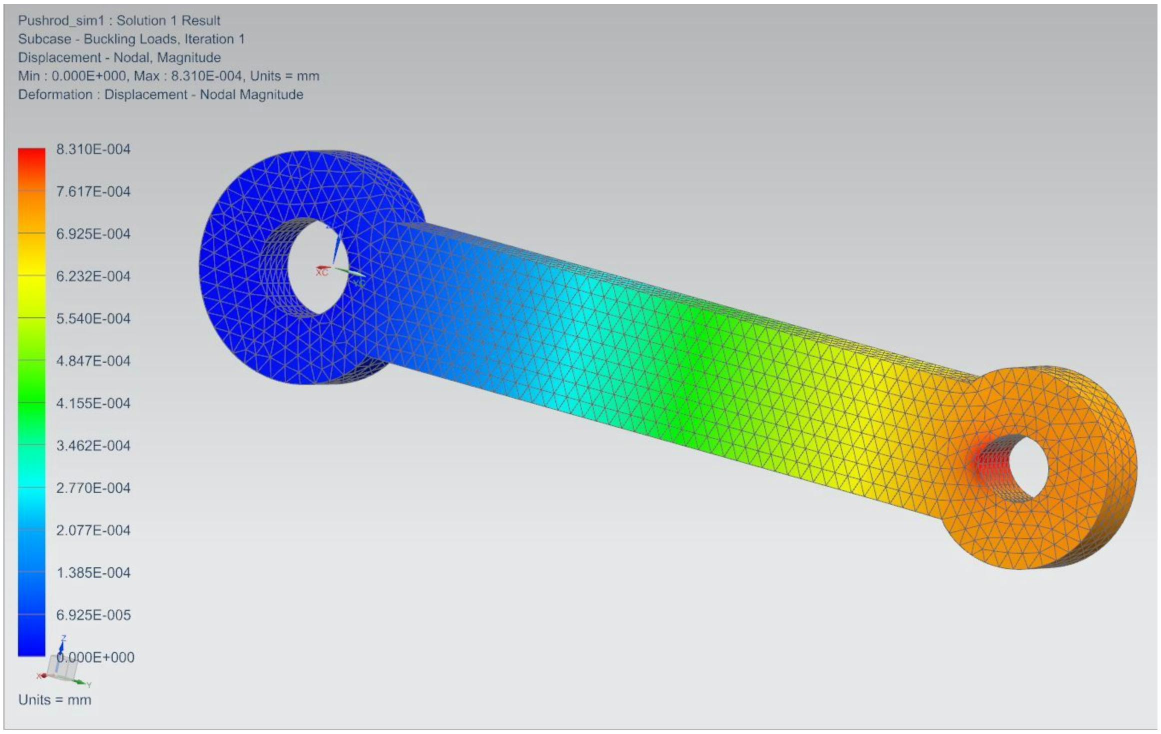


Figure 42: Finite Element Stress Analysis: Resulting Deformation on Connecting Rod

Stress FEA Analysis- Connecting Rod Deformation Verification Calculations

$E = 188$ GPa

$A = 32\ \text{mm}^2$

$L = 50$ mm

$$k = \frac{AE}{L} = \frac{(32\ \text{mm}^2)(188{,}000\ \text{MPa})}{50\ \text{mm}} = 120{,}320\,\frac{\text{N}}{\text{mm}}$$

$$\begin{bmatrix} f_{1x} \\ f_{2x} \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} d_{1x} \\ d_{2x} \end{bmatrix}$$

$$f_{1x} = 100\ \text{N}$$
$$f_{2x} = 100\ \text{N}$$
$$d_{1x} = 0\ \text{(fixed)}$$

$$\begin{bmatrix} 100 \\ 100 \end{bmatrix} = \begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} 0 \\ d_{2x} \end{bmatrix}$$

$$100\ \text{N} = (120{,}320\ \text{N/mm})\, d_{2x}$$
$$d_{2x} = \mathbf{8.3112 \times 10^{-4}\ mm}$$

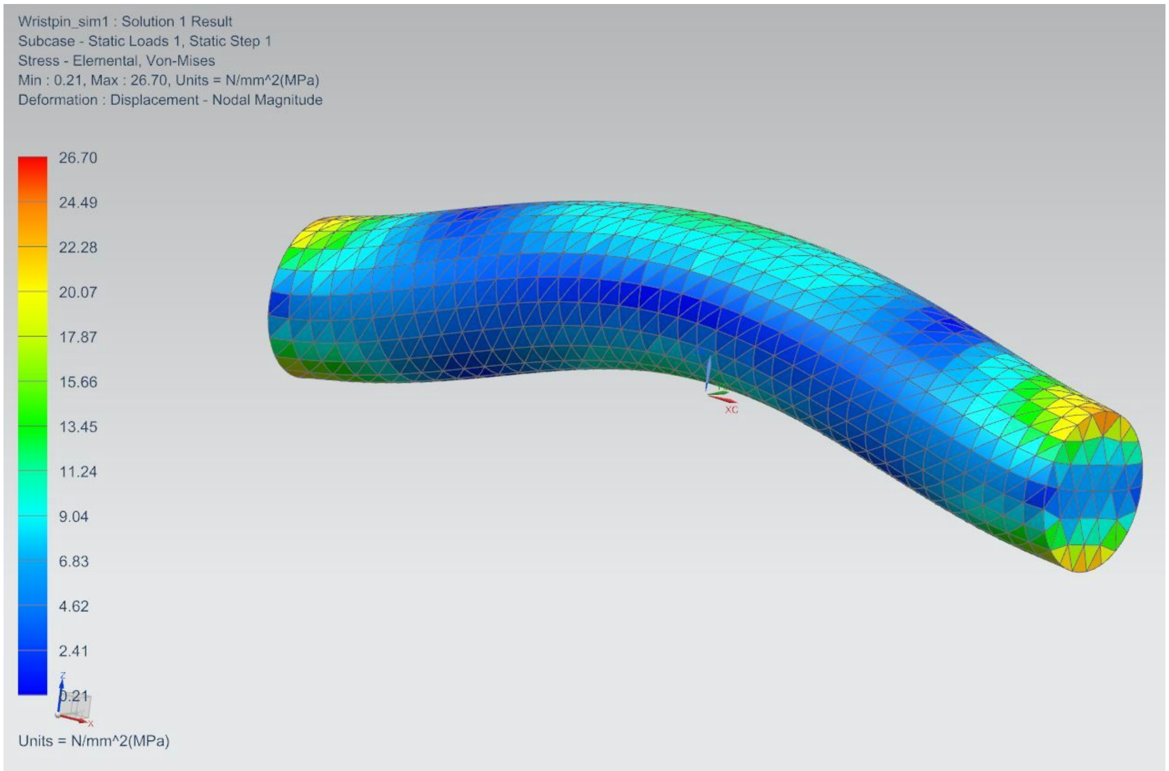


Figure 43: Finite Element Stress Analysis: Stress on Wrist Pin

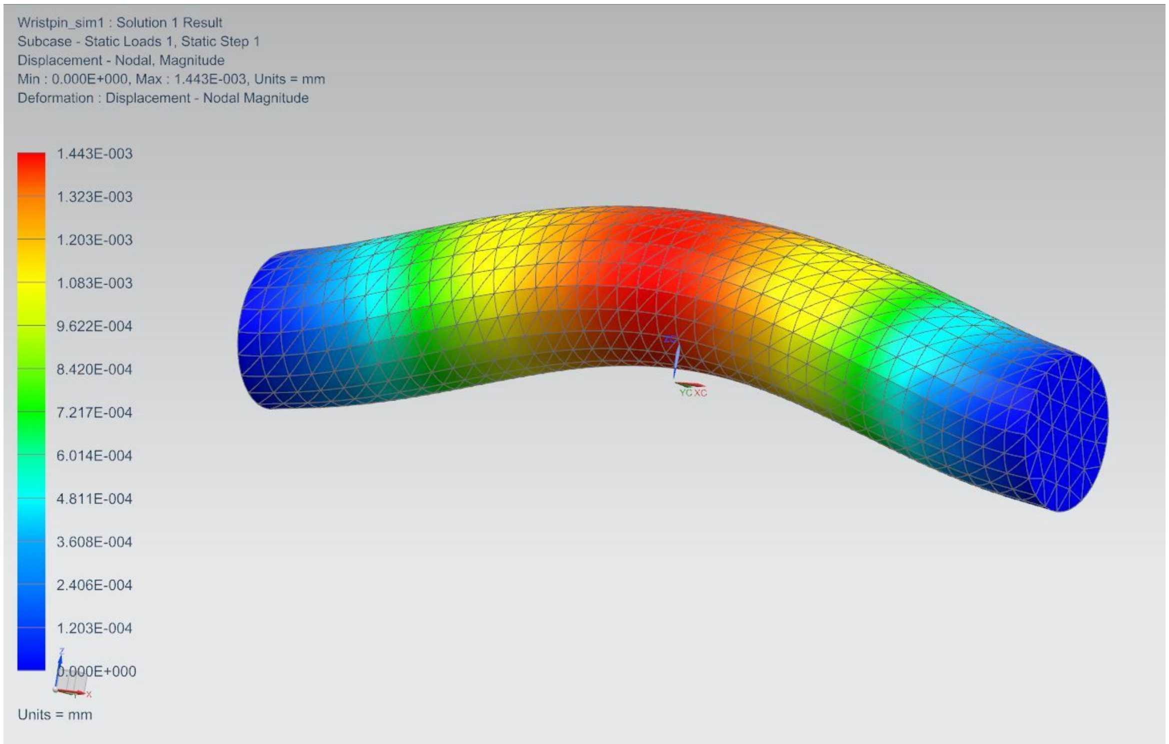


Figure 44: Finite Element Stress Analysis: Resulting Deformation on Wrist Pin

Stress FEA Analysis- Wrist Pin Deformation Verification Calculations

E = 188 GPa
L_{total} = 25 mm
$L_{1/2}$ = L = 12.5 mm
$\rho_{\text{Steel}} = 7.829\ x\ 10^{-6}\,\frac{\text{kg}}{\text{mm}^3}$

D = 4 mm
$V = \pi r^2 L$ = 157.0796 mm^3
$m = (\rho_{\text{Steel}})(V)$ = 1.229 g

$$I = \frac{mL^2}{3} = 64\ \text{gmm}^2$$

$$\begin{bmatrix} f_{1y} \\ m_1 \\ f_{2y} \\ m_2 \end{bmatrix} = \frac{EI}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix}\begin{bmatrix} d_{1y} \\ \phi_1 \\ d_{2y} \\ \phi_2 \end{bmatrix}$$

$$\frac{EI}{L^3} = \frac{188{,}000\,\frac{\text{N}}{\text{mm}^2}(64\ \text{gmm}^2)}{12.5^3\ \text{mm}^3} = 6160.384\,\frac{\text{Ng}}{\text{mm}^3}$$

$$f_{2y} = 100\ \text{N}$$
$$m_2 = (100\ \text{N})(12.5\ \text{mm}) = 1250\ \text{Nmm}$$
$$d_{1y} = 0\ \text{(fixed)}$$
$$\phi_1 = 0\ \text{(fixed)}$$

$$\begin{bmatrix} f_{1y} \\ m_1 \\ 100\ \text{N} \\ 1250\ \text{Nmm} \end{bmatrix} = \frac{EI}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ d_{2y} \\ \phi_2 \end{bmatrix}$$

$$f_{1y} = 6160.384\ \frac{\text{Ng}}{\text{mm}^3}\ (-12d_{2y} + (12.5\ \text{mm})\phi_2)$$
$$m_1 = 6160.384\ \frac{\text{Ng}}{\text{mm}^3}\ (-6(12.5\ \text{mm}) + 2(12.5^2\ \text{mm}^2)\phi_2)$$
$$100\ \text{N} = 6160.384\ \frac{\text{Ng}}{\text{mm}^3}\ (12d_{2y} - 6(12.5\ \text{mm})\phi_2)$$

$$1250\ \text{Nmm} = 6160.384\ \frac{\text{Ng}}{\text{mm}^3}\ (-6(12.5\ \text{mm})d_{2y} + 4(12.5^2\ \text{mm}^2)\phi_2)$$

$$\boldsymbol{d_{2y} = 0.0135\ \textbf{mm}}$$
$$\boldsymbol{\phi_2 = 0.0019\ \textbf{degrees}}$$

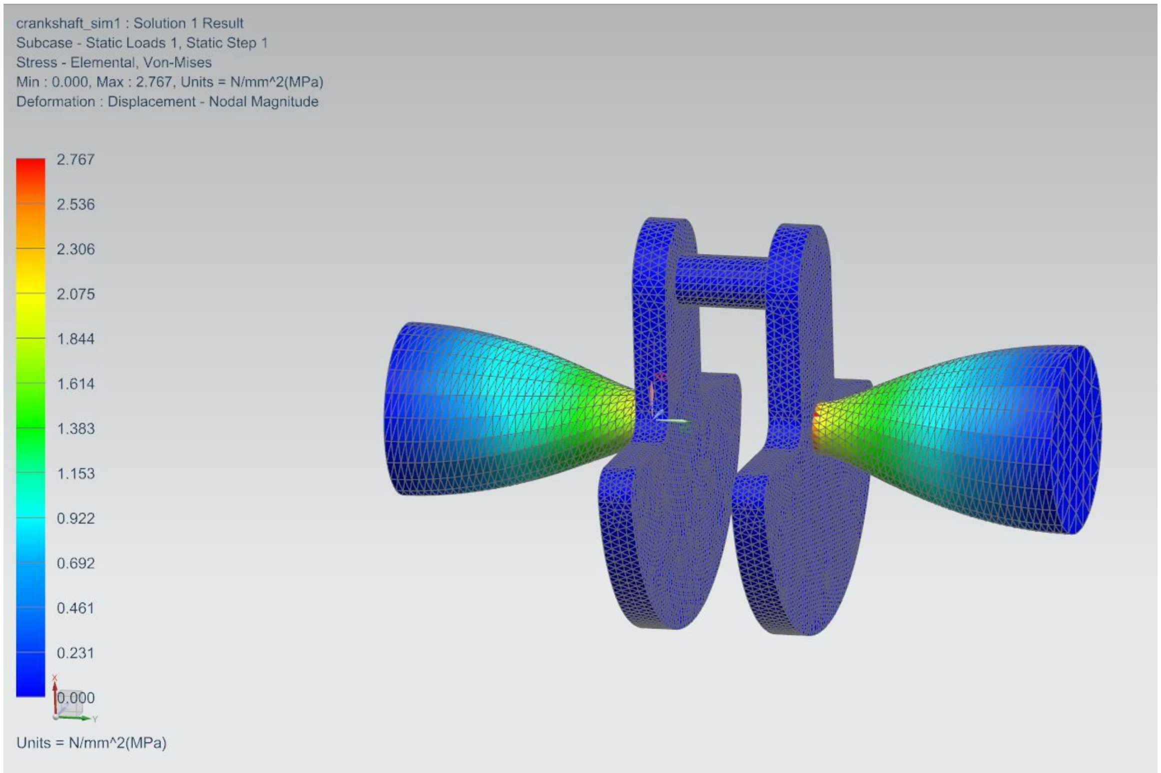


Figure 45: Finite Element Stress Analysis: Stress on Crankshaft

Table 4: Results from Testing

Engine Alone	Room Temp	Running Temp	Room Temp	Running Temp	Room Temp	Running Temp	T (F)	T (C)
Hot cylinder	24.4	50.6	23.9	46.7	26.7	47.8	16.133	8.963
Cold Cylinder	24.4	32.8	23.9	31.7	26.7	32.2		
Engine with fans	Room Temp	Running Temp	Room Temp	Running Temp	Room Temp	Running Temp		
Hot Cylinder	25	33.6	25.3	33.9	24.7	31.7	7.867	4.370
Cold Cylinder	25	26.4	25.3	24.8	24.7	24.4		
Engine with fans and insulation on cold cylinder	Room Temp	Running Temp	Room Temp	Running Temp	Room Temp	Running Temp		
Hot Cylinder	24.4	32.8	25	35.6	25	35.4	6.467	3.593
Cold Cylinder	24.4	29.4	25	26.9	25	28.1		
Engine with insulation on cold cylinder	Room Temp	Running Temp	Room Temp	Running Temp	Room Temp	Running Temp		
Hot Cylinder	23.6	39.6	23.6	41.1	24	39.4	11.933	6.630
Cold Cylinder	23.6	28.6	23.6	28	24	27.7		
Configuration	Average Room Temp (C)	Average Cold Temp (C)	Average Hot Temp (C)	Average Temp Diff. (Room - Cold Temp)(C)				
Datum	25	32.2	48.3	-7.2				
Insulated Cold Cylinder	23.7	28.1	40.033	-4.4				
Insulated Cold Cylinder and Fan	24.8	28.133	34.6	-3.333				

Fan	25	25.2	33.1	-0.2				

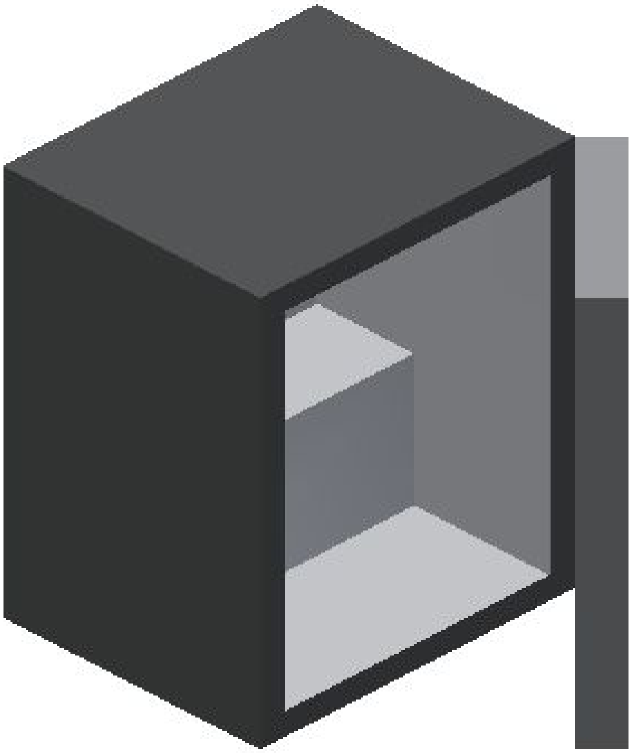


Figure 46: Isometric view of refrigerator model

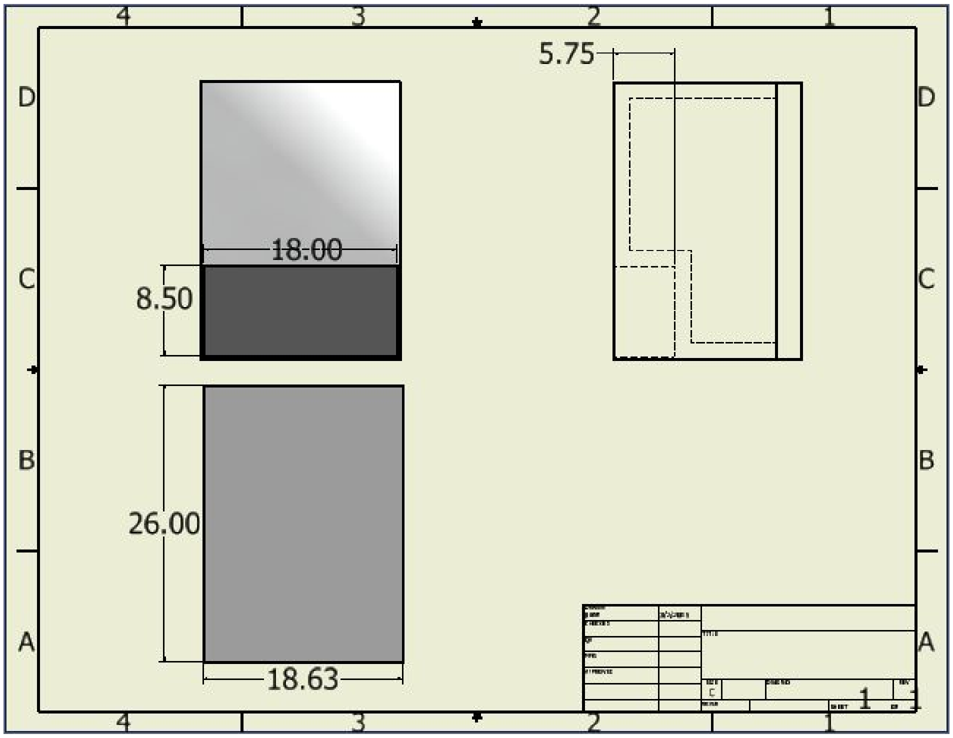


Figure 47: Side-view of refrigerator and interior volume

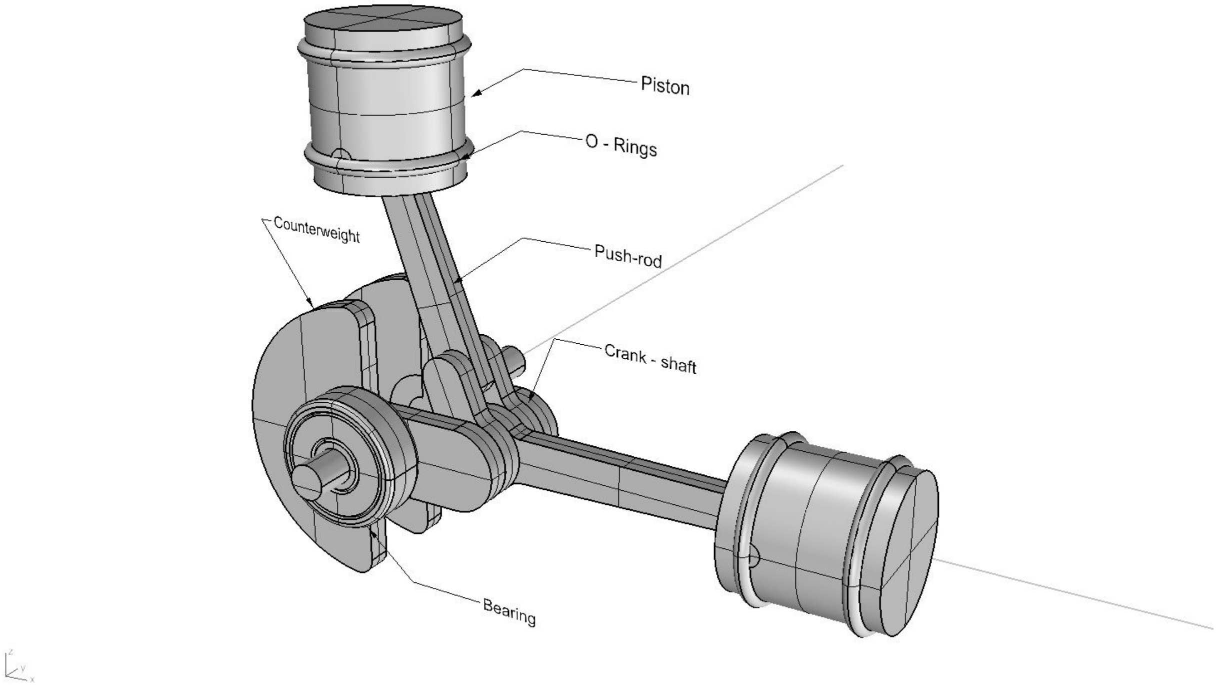


Figure 48: Isometric view of piston assembly

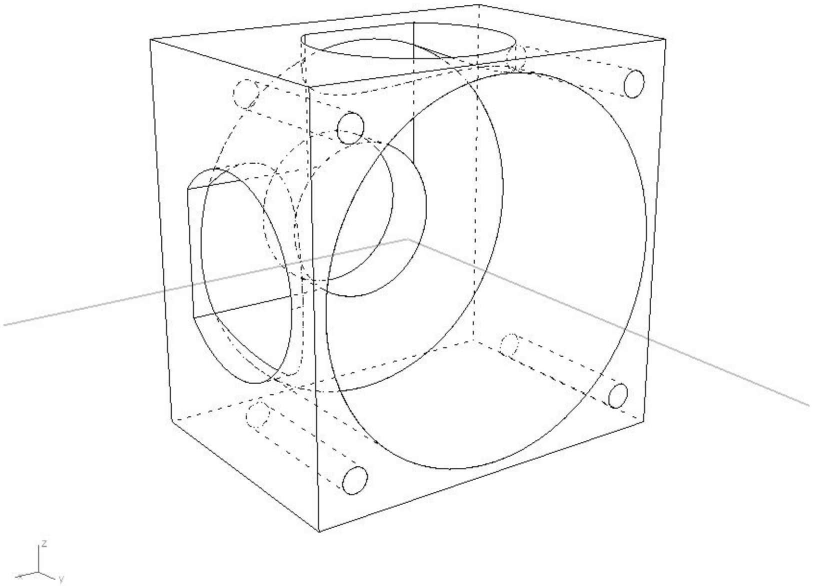


Figure 49: Isometric view of crankcase

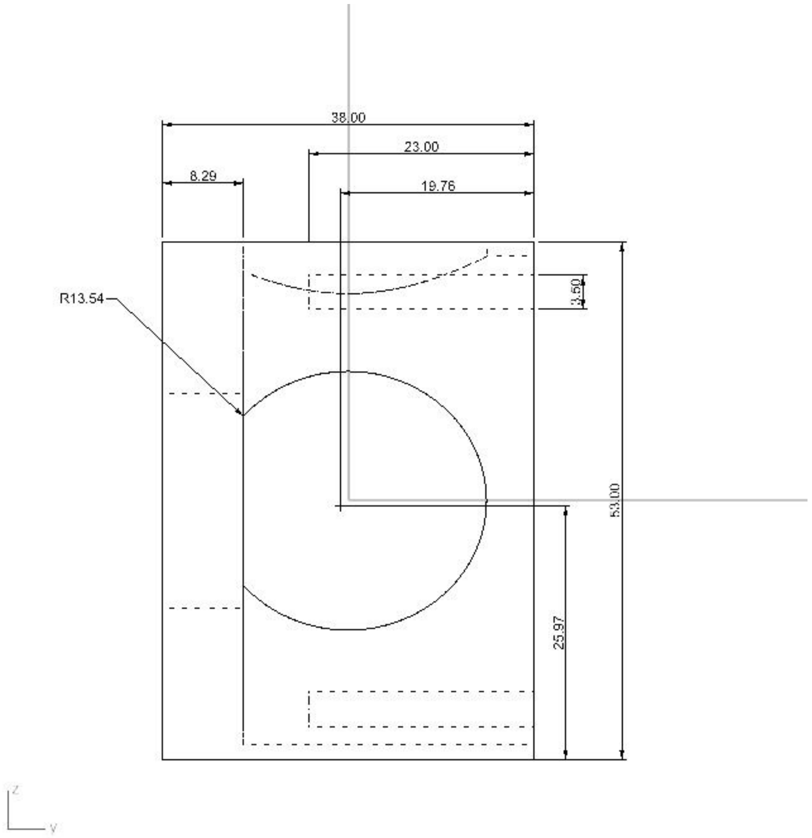


Figure 50: Right side view of crankcase

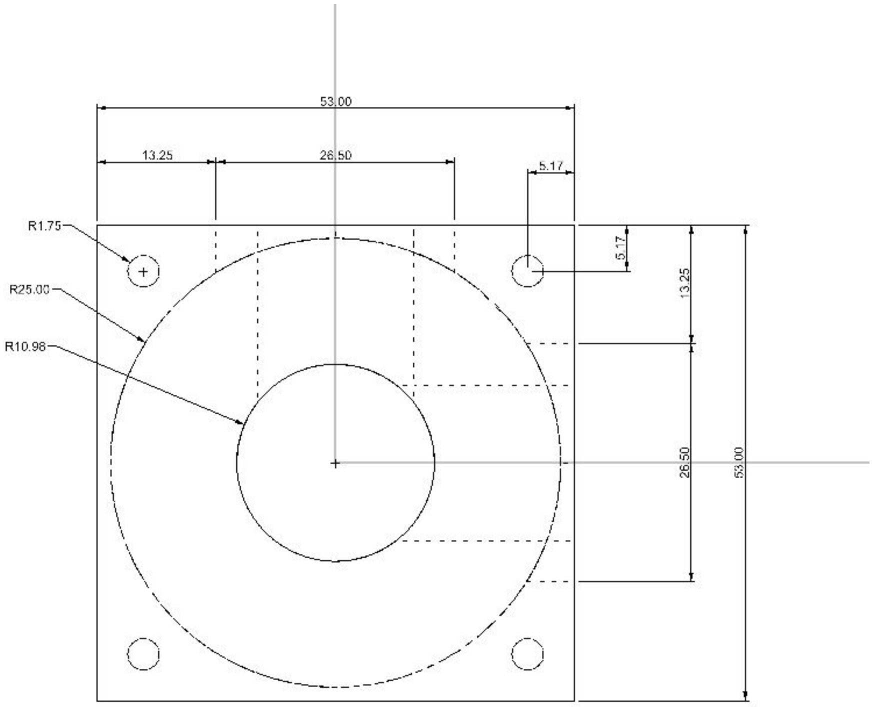


Figure 51: Front side view of crankcase

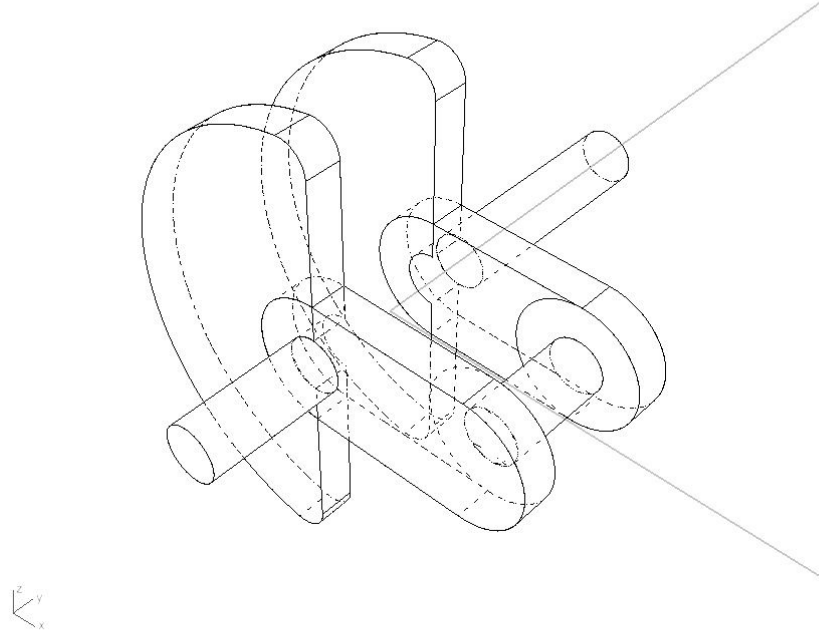


Figure 52: Isometric view of crankshaft

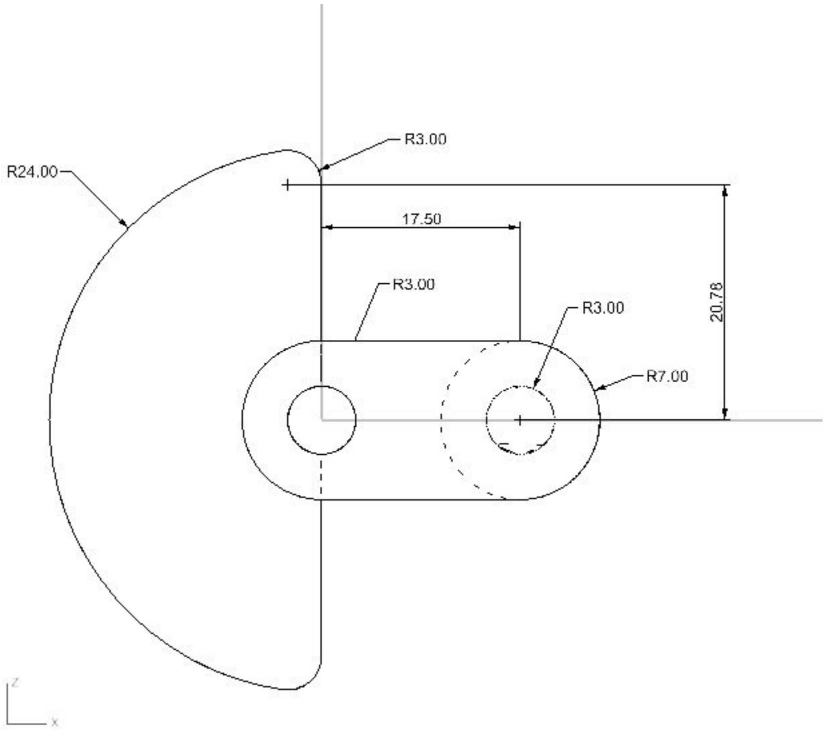


Figure 53: Right side view of crankshaft

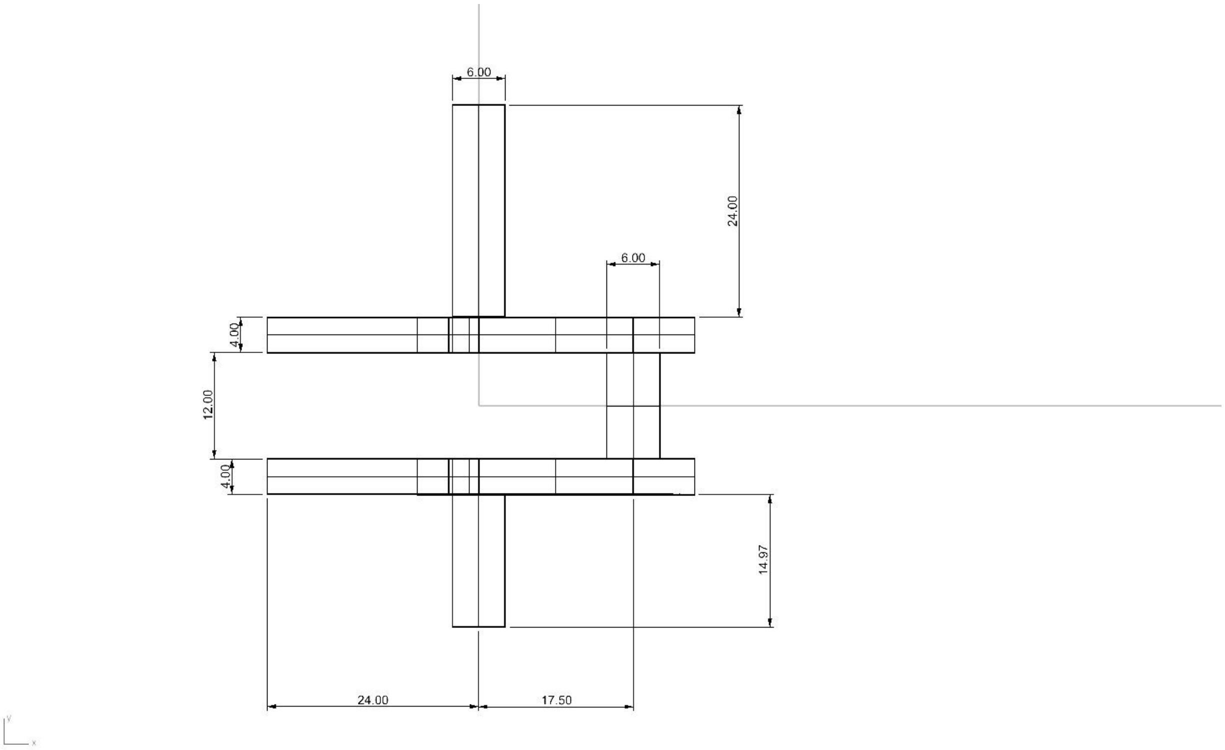


Figure 54: Top side view of crankshaft

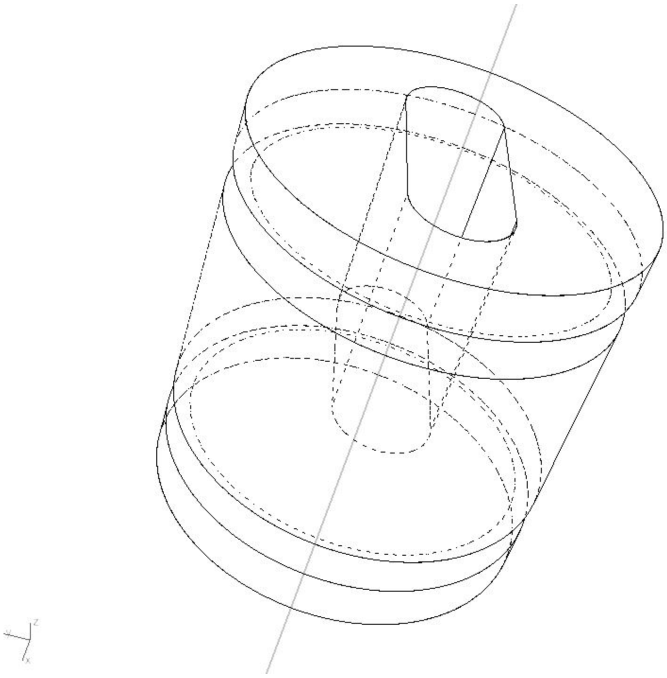


Figure 55: Isometric view of piston

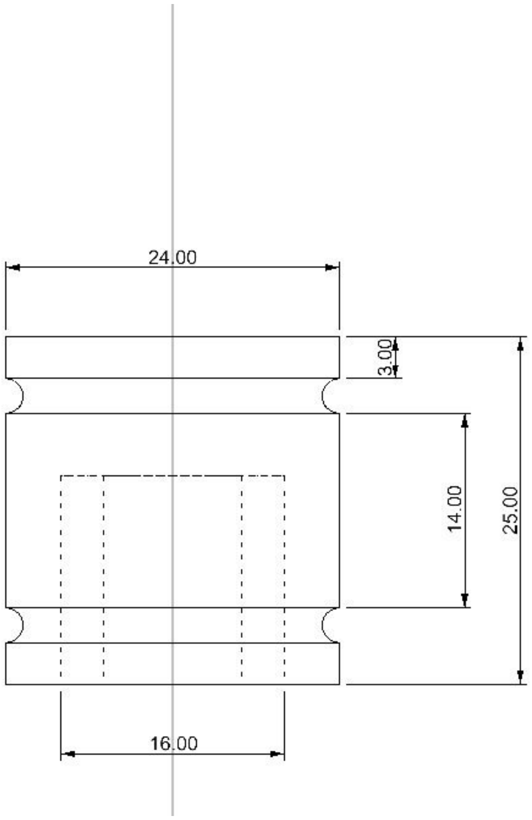


Figure 56: Right side view of piston

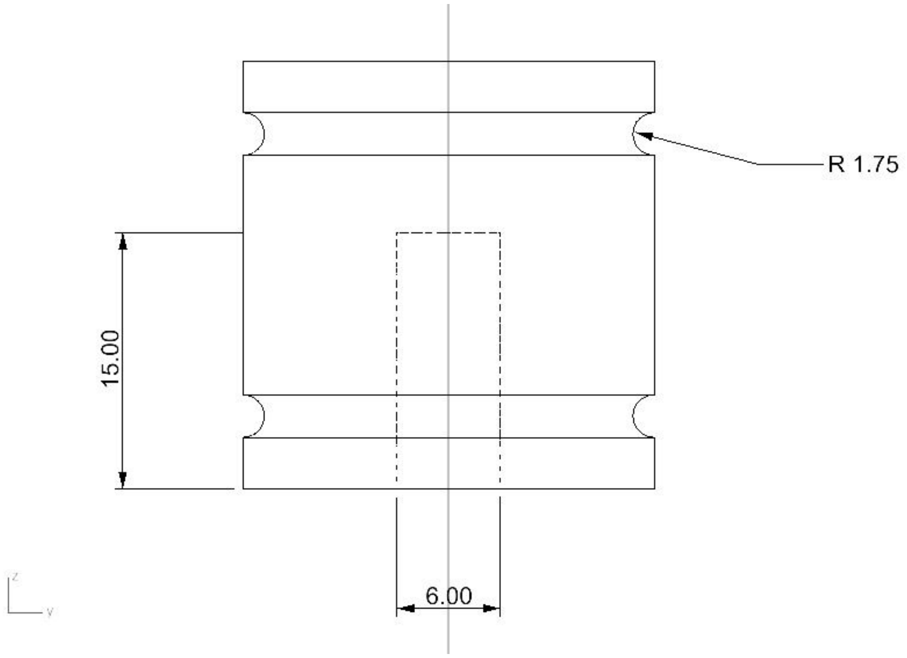


Figure 57: Top side view of piston

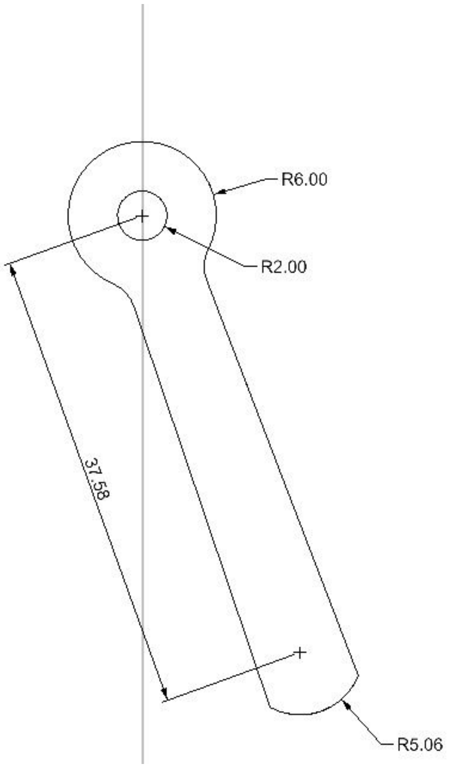


Figure 58: Front side view of short pushrod

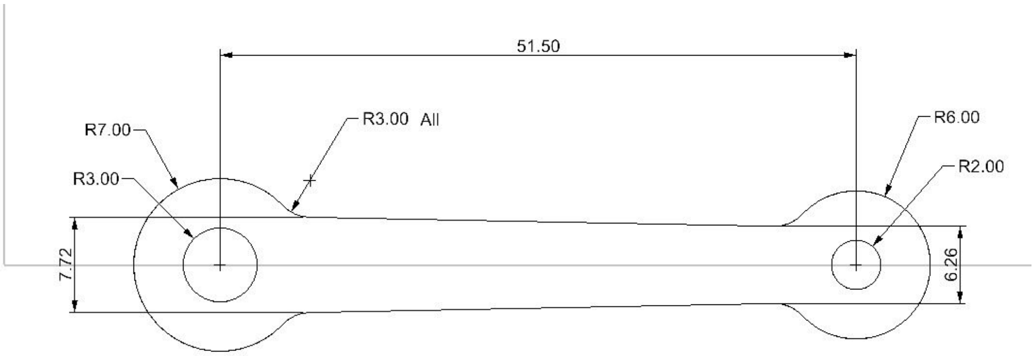


Figure 59: Front side view of long pushrod

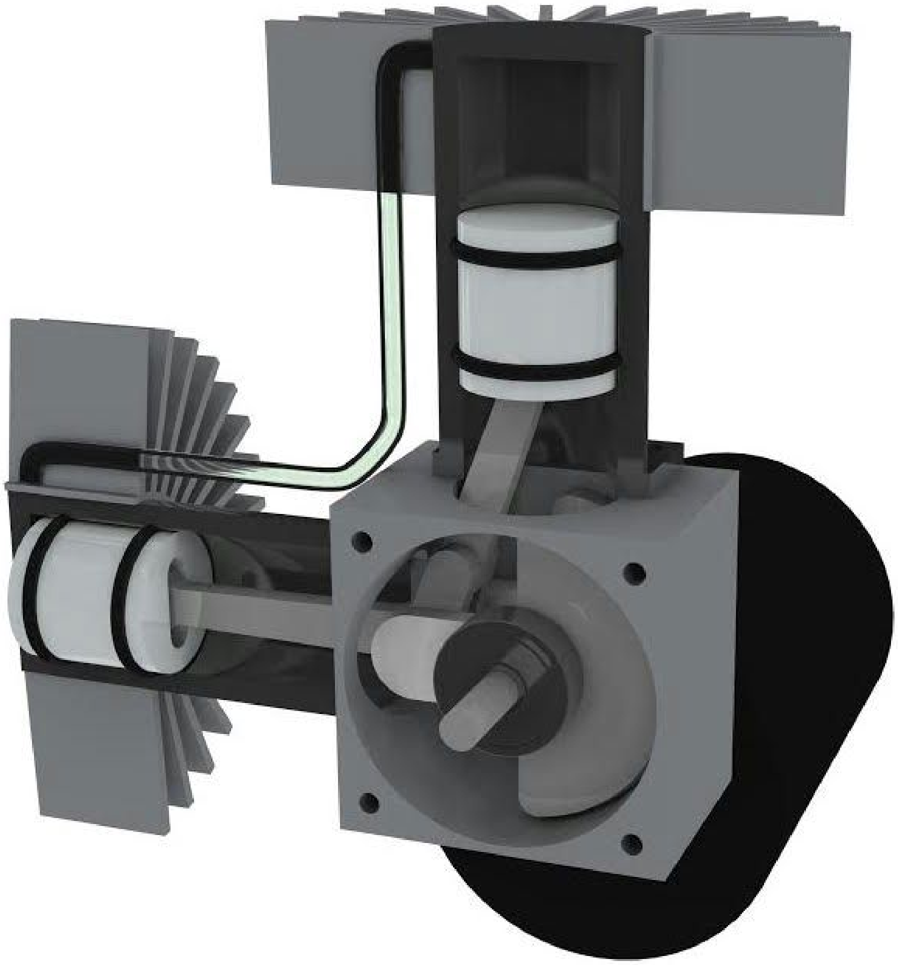


Figure 60: Isometric View of Final Stirling Engine Assembly

Table 6: Bill of Materials

Part	Material	Source	Price	Quantity	Material	Source	Price
Prototype				Mass Production			
Nipple	Brass	Home Depot	$1.00	2	N/A as will be machined along with cylinder		
Crankcase	ABS	Invention Studio 3D Print	$-	1	2'x2'x.25" aluminum plate	MetalDepot	$3.00
Crankcase Cover	ABS	Invention Studio 3D Print	$-	1	2'x2'x.25" aluminum plate	MetalDepot	$1.50

Counterweights	Steel Pieces	Wreck Racing Scrap	$-	2	3" x 6" steel rod	MetalDepot	$10.00
Crankpin	6mm bolt	Wreck Racing Scrap	$-	1	""	MetalDepot	$0.10
Connecting Rods	1'x1'x.125" steel plate	Wreck Racing Scrap	$-	2	""	MetalDepot	$2.00
Pistons	Wear-Resistant Nylon Rod 1" D, 1' L	McMaster Carr	$3.00	1	""	McMaster Carr	$3.00
Cylinders	6061 Aluminum Tubing, 1.125" OD, 1 "ID	McMaster Carr	$6.50	1	""	McMaster Carr	$6.50
Piston Rings	20mm x 2.5mm Fluoroelastomer	McMaster Carr	$0.75	4	""	McMaster Carr	$0.75
Pulley	ABS	Invention Studio 3D Print	$-	2	“”	McMaster Carr	1.5
Belt	Vacuum Belt	Walmart	$1.94	1	Steel Chain	Walmart	$1.94
Bearings	Roller bearings	McMaster Carr	$10.00	2	""	McMaster Carr	$10.00
Motor	AC Motor	Craigslist	$20.00	1	DC Motor	McMaster Carr	$100
Wrist Pin	Aluminum	Scrap Bin	$-	2	2"x2"x.25" aluminum rod	McMaster Carr	$0.20
Screws	1'x1'x.125" steel plate	Home Depot	$0.25	12	Steel	McMaster Carr	$0.25
Motor Mount	Wood	Scrap Bin	$-	1	2'x2'x.25" aluminum plate	McMaster Carr	$1.50
Engine Mount	Wood	Scrap Bin	$-	1	2'x2'x.25" aluminum plate	McMaster Carr	$2.00
Crankshaft Extension	1'x1'x.125" steel plate	Scrap Bin	$-	2	""	McMaster Carr	$2.00
Hose	6” L, 8” D Copper Wire	Home Depot	$3.94	1	Nylon	Home Depot	$3.94

	1’ L, ⅛” plastic						
Cylinder Cap	1'x1'x.125" steel plate	Scrap Bin	$-	2	""	McMaster Carr	$1.00
Cylinder Mount	1'x1'x.125" steel plate	Scrap Bin	$-	2	""	McMaster Carr	$1.00
Scythe Fan model : st1225sl12sh	4” x 4” plastic	Scrap Bin	$-	1	plastic	Home Depot	$10.00
Insulation	bubble wrap	Scrap Bin	$-	1 sq. ft	plastic	Walmart	$8.00
		Sum	$46.38	44		Sum(Discounted)	$55.67

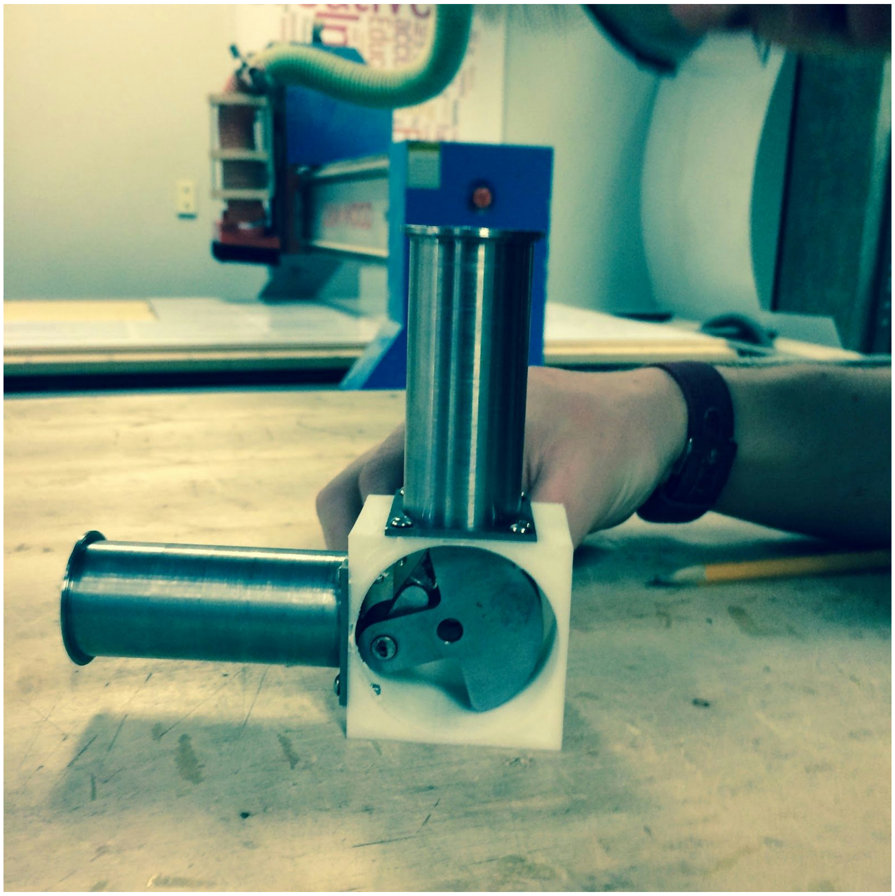


Figure 61: Prototype Engine Assembly