Takin' the Heat

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Abstract

The goal of this project was to design a Stirling engine that converts renewable energy into mechanical power while staying applicable to underdeveloped nations. The design choice is a gamma-type double cylinder Stirling engine that uses atmospheric air as its working fluid to produce 200W of mechanical power. It is designed to use solar power as its heat source and ambient air as its heat sink. The design reflects our core goals of simplicity, variability, stewardship and performance. We believe this project to be feasible given our engineering analysis, research, and budget.
# Table of Contents

1 Introduction .......................................................................................................................................... 6
2 Project Description .............................................................................................................................. 6
3 Project Requirements ......................................................................................................................... 6
   3.1 Project Wants ............................................................................................................................... 6
   3.2 Project Needs ............................................................................................................................... 6
4 Project Organization ............................................................................................................................ 7
   4.1 Design Team ............................................................................................................................... 7
   4.2 Client and Resource Interface ..................................................................................................... 8
      4.2.1 Clients ................................................................................................................................. 8
      4.2.2 Resource ............................................................................................................................. 8
5 Design Norms ....................................................................................................................................... 8
   5.1 Cultural Appropriateness ............................................................................................................. 8
   5.2 Transparency/Trust ..................................................................................................................... 8
   5.3 Stewardship ............................................................................................................................... 8
   5.4 Caring ......................................................................................................................................... 9
   5.5 Robustness ................................................................................................................................... 9
6 Background ........................................................................................................................................... 9
   6.1 History ......................................................................................................................................... 9
   6.2 Current Technology ..................................................................................................................... 10
   6.3 The Basics ................................................................................................................................... 10
7 Alternative Solutions ........................................................................................................................ 10
   7.1 Stirling Engine Types ................................................................................................................ 10
   7.2 Heat Source ................................................................................................................................ 11
      7.2.1 Solar Radiation .................................................................................................................... 11
      7.2.2 Fire ..................................................................................................................................... 12
   7.3 Cold Source ............................................................................................................................... 12
   7.4 Regenerator .................................................................................................................................. 12
   7.5 Construction Materials .............................................................................................................. 12
   7.6 Pistons ......................................................................................................................................... 13
   7.7 System Gas .................................................................................................................................. 13
   7.8 Pressurized Gas .......................................................................................................................... 13
   7.9 Output Function .......................................................................................................................... 13
   7.10 Starting Method ........................................................................................................................ 13
8 Research ............................................................................................................................................. 13
   8.1 Patents .......................................................................................................................................... 13
      8.1.1 Solar Collector ..................................................................................................................... 14
      8.1.2 Stirling Turbine .................................................................................................................. 14
      8.1.3 Piston Travel ....................................................................................................................... 14
   8.2 Engineering Index ........................................................................................................................ 14
      8.2.1 4-Cylinder Gamma-type Stirling Engine ........................................................................... 14
      8.2.2 TNT-1 ................................................................................................................................ 14
      8.2.3 Heat Pipe Receivers .......................................................................................................... 15
      8.2.4 Hybrid Stirling Engines ..................................................................................................... 15
   8.3 Web Sources ............................................................................................................................... 15
      8.3.1 Viebach ST 05 Stirling Engine ......................................................................................... 15
      8.3.2 Alpha Ross-Yoke and Alpha Rocker-V ................................................................. 16
9 Design Model for Feasibility ............................................................................................................ 17
   9.1 Project Scope .............................................................................................................................. 17
   9.2 Thermal Model .......................................................................................................................... 17
Table of Figures
Figure 1. Alpha Stirling Engine ................................................................. 10
Figure 2. Beta Stirling Engine ................................................................. 11
Figure 3. Gamma Stirling Engine ............................................................. 11
Figure 4. Solar Stirling Engine ............................................................... 12
Figure 5. Rocker-V Stirling Engine ......................................................... 16
Figure 6. Ross Yoke Stirling Engine ....................................................... 16
Figure 7. Conduction Flows ................................................................. 18
Figure 8. Convection Flows ................................................................. 19
Figure 9. Radiation Flows .................................................................. 20
Figure 10. Thermal Control Volumes ..................................................... 21
Figure 11. Slider Crank Design ............................................................ 22
Figure 12. Decision Matrix .................................................................. 24
Figure 13 Preliminary Prototype Design ............................................ 25
Figure 14. Wall Thickness and Resulting Pressure Drop .................... 26
Figure 15. Sink Thickness and Resulting Pressure Drop ..................... 26
Figure 16. Source Thickness and Resulting Pressure Drop .................. 26
Figure 17. Source and Sink Radii - Their Affect on System Performance 27
Figure 18. Displacer Radius - Its Affect on System Performance ........ 28
Figure 19. Pressure Drop as Wall Height Varies ................................. 28
Figure 20. Pressure Drop for Various Wall Materials ....................... 29
Figure 21. Inlet Radiation Magnification .............................................. 30
Figure 22. Fluid Parameters in Response to Various Engine Speeds .... 30
Figure 23. Pressure Change for 1 Cycle ............................................... 31
Figure 24. Offset Angle Optimization ................................................... 32
Figure 25. Piston Crank Arm Optimization .......................................... 32
Figure 26. Connecting Rod Optimization ............................................. 33
Figure 27. Piston Radius Optimization ................................................ 34
Figure 28. Impact of Mass on Power Output ....................................... 35

Table of Tables
Table 1. Summary of Tasks for Each Group Member ............................ 7
Table 2. Summary of Specifications for Viebach ST 05 Stirling Engine . 15
Table 3. First Law Breakdown on Control Volumes ............................... 21
Table 4. Decision Matrix ..................................................................... 23
Table 5. Summary of Estimated Costs for Different Components of Stirling Engine .......................... 36
Table 6. Breakdown of Total Labor Cost ............................................. 36
Table 7. Summary of Total Cost ............................................................ 37
1 Introduction
Calvin College is a liberal arts college located in Grand Rapids, MI. Among many other exceptional programs, its engineering program maintains an excellent reputation. The engineering program is accredited by the Accreditation Board for Engineering and Technology (ABET), and offers students a degree in Bachelor of Science in Engineering (B.S.E.) with concentrations in Chemical, Civil & Environmental, Electrical & Computer, and Mechanical engineering. To earn this degree, Calvin College requires that all senior engineers take a two course capstone sequence, ENGR 339 and ENGR 340. This report finalizes the requirements for ENGR 339, the first course in this sequence. In addition to this report, ENGR 339 also required all students to design project posters for their station, develop a team website, meet with an industrial consultant, attend frequent classroom lectures from a variety of speakers, manage time during several work sessions, read text material, setup a practice interview with career services, and construct a refined resume. Each member of Team 8 contributed to this final report. This report presents the project background, design process, and product implementation strategy for our senior design project.

2 Project Description
The project idea came from a third party. Matt Weeda, of Innotec Corporation, proposed the project during the summer of 2006 before ENGR 339 began. Innotec is credited with the project idea and project funds, however all work completed was and will be completely independent from them.

Innotec Corporation is a manufacturing company located in Zeeland, MI. Innotec is primarily a Tier 2 supplier of automotive accessories. However, their product line extends to several other industries including office furniture and home appliance. Currently, Innotec is developing means for energy production that utilize renewable resources. One of these means is a cost-effective, mid-size Stirling engine. The current technology available has a limited customer base because its cost is greater than other comparable gas-powered electric generators currently on the market. The Stirling engine’s cost is driven high because of its complex design. Expensive modern Stirling engines are available primarily at a commercial scale, designed to be maximally efficient and made out of exotic materials.

The goal of this project is to develop a simple and inexpensive Stirling engine that converts heat energy from the sun into mechanical energy capable of generating 200 Watts of mechanical power. In addition, it is to be easily distributed and used in third world locations.

3 Project Requirements
For a project of this magnitude the project requirements must be separated into two different categories. The first is the project needs. These are the essential elements that our project must have in order to be considered successful. The second category is project wants. These are secondary elements of the project which are desired but may have to be sacrificed for the sake of money or time.

3.1 Project Wants
The goal of the project is to build a working prototype. For the prototype to be considered a success it must maintain its own motion and generate a useful amount of work. A useful amount of work has been defined as 200 W.

3.2 Project Needs
Ideally the engine should be robust to variation. To achieve this robustness it should be able to operate with many different heat sources such as solar, a hot fluid, or even an open fire. The engine should also be as easy to use as possible. This means keeping the design and materials simple so that parts are easily
repaired or replaced. The engine should be mobile, weighing less than 125 lbs and capable of fitting in the back of a pickup truck.

4 Project Organization

4.1 Design Team

We realized that it was important for us to divide up the project into different categories for each group member so that each one of us could focus on a certain task and get in done on time. Table 1 below shows the tasks that each group member completed.

Table 1. Summary of Tasks for Each Group Member

<table>
<thead>
<tr>
<th>Task</th>
<th>Group Members</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geoff</td>
</tr>
<tr>
<td>PPFS</td>
<td>P</td>
</tr>
<tr>
<td>Website</td>
<td>S</td>
</tr>
<tr>
<td>Mechanical Calculations</td>
<td>NA</td>
</tr>
<tr>
<td>Thermal Calculations</td>
<td>P</td>
</tr>
<tr>
<td>Design Model for Feasibility</td>
<td>P</td>
</tr>
<tr>
<td>Research</td>
<td>NA</td>
</tr>
<tr>
<td>Budget</td>
<td>NA</td>
</tr>
<tr>
<td>Alternative Solutions</td>
<td>NA</td>
</tr>
</tbody>
</table>

Key

- **P**: Task for Primary Person
- **S**: Task for Secondary Person
- **NA**: Not Assigned

The basis for our task breakdown was simple. The Myers-Briggs Type Indicator (MBTI) showed that Shalomel and Neil were ENTJ (Extraversion, Intuition, Thinking, and Judging) personalities. So, they were mainly in charge of managing the project besides other assigned tasks. On the other hand, Geoff and Ben were type ENFP (Extraversion, Intuition, Feeling, Perceiving) and ENTP (Extroversion, Intuition, Thinking, Perceiving) personalities, respectively. Accordingly, they were in charge of doing the calculations and other assigned tasks. For a more detailed list of tasks please refer to the schedule in Appendix. Having specific tasks for each group member helped each one of us make an equal contribution towards the project. It also helped us finish specific tasks on time and therefore increasing efficiency.
4.2 Client and Resource Interface

4.2.1 Clients
Our two main clients for this project are: (1) Innotec and (2) the end users of the Stirling engine. Since Innotec is funding our project we will share our results for the final product with them so they can further their research and development of Stirling engines. We also have to keep in mind the people who are actually going to use the engine. For further discussion on design considerations for developing areas refer to the Design Norms section.

4.2.2 Resource
Besides our own group members we had other people who helped us with the project. Professor Heun assisted Geoff with the thermal calculations and professor Ermer helped Ben with the mechanical calculations. Innotec is also helping us financially. They offered up to $5,000 for materials, and opened up their machine shop for the construction of the prototype.

5 Design Norms
One of the goals of this project is to integrate Christian principles into our design. We plan to do so by considering several important design norms listed below.

5.1 Cultural Appropriateness
One of the most important factors to consider is how well the design fits in with the culture where the final product is going to be used. Our goal is to make this design simple, yet effective. The Stirling Engine will be made as simple as possible while also meeting requirements of generating 200 W of mechanical energy. We assumed that 200 W is enough power to meet the basic needs of people living in under developed regions such as Africa. With this much power people can connect the Stirling engine to a small pump for mechanical power or use it to produce electrical power for lighting a small house.

The materials used to build the engine need to be easily available. Therefore, this engine is going to be made of materials that are easily accessible in developing areas so that people do not have difficulty in fixing any mechanical problems they might face. The engine will also be sized to be portable and easy to use in different locations. This will be one of the advantages of our design: people will have the freedom to use it in different locations instead of having a huge engine that is complex, stationary and limited to its uses.

5.2 Transparency/Trust
Transparency of the design is also very important. People in developing regions are in dire need of technology that uses their resources appropriately. However, technology cannot be of much help if the design is not transparent and trustworthy. Besides being simple and effective, the design will also be reliable. This means that the final product has to do what we say it can do. Transparency of the design will also be implemented by keeping well organized and clear documentation of the design so that the final product and its components can be reproduced easily. We also plan to use labels, pictographics and color coding for the Stirling engine to make it intuitive and easier for our customers to use.

5.3 Stewardship
As Christian engineers we are encouraged to strive for using earth’s resources carefully. The project design will account for environmental factors, the most obvious being pollution. By developing a Stirling
engine that utilizes renewable energy such as solar power means that there are no emissions produced by the Stirling engine. Therefore, the design will not have a negative impact of the environment.

Other factors that are addressed are the impact of different heat sources, the materials used, and the costs involved in building the engine. First, the different heat sources that can be utilized are: (1) Solar energy – using the heat energy from the sun and (2) Fire – many people in developing areas use fire as their main source of heat. When comparing these two heat sources it can be concluded that solar energy is a better option because it does not pollute the environment unlike using wood/coal to make fire. However, we have to consider situations when people need to use the engine during the winters. There are many areas in underdeveloped countries where there is minimum sunshine during the winter. In such environments, people are inevitably going to use fire to cook food as well as to keep warm. Therefore, it is important to have “fire” as the second option for the heat source in order to balance out the environmental effects and the basic needs of the people when there is no solar power available.

Lastly, the engine also needs to be affordable. Accordingly, we are making sure that the total cost of the Stirling Engine stays under our budget of $5,000. Our preliminary costs show that we are under budget. We intend to minimize the cost as much as possible in order to make this engine affordable.

5.4 Caring
In the context of underdeveloped nations, any technology that utilizes “free” energy is a big advantage for the people, especially in areas where electricity is a problem. In our design we plan to take advantage of renewable energy making our engine easily adaptable to developing regions where resources are scarce. The engine will be designed to be simple and effective so that it fulfills the need for reliable and inexpensive renewable energy in underdeveloped countries.

5.5 Robustness
We are also trying to make this design robust by making the Stirling engine multi-purpose. The two main sources of heat that can be used are solar energy and fire as discussed in the Stewardship section. Even though we are designing the engine to be used with different heat sources, we are not going to actually build all the physical parts that would go with each heat source. That would over complicate our design. However, to balance simplicity and robustness we will design the engine so that additional parts can be added to it depending on what heat source people are interested in using.

6 Background

6.1 History
The Stirling engine was first invented in 1816 by Robert Stirling a Scottish minister. Stirling intended to create a safe alternative to the explosive steam engines of his time. This dates the engine before the Diesel or gasoline engine. In 1850 J. Ericsson a Swedish inventor produced Stirling engines between the 0.5 and 5 hp range. However, the demand for more horsepower gave way to the Otto engines that were capable of producing more power. Stirling engines gained attention in 1940 when Philips co. developed the Stirling engine as a portable electric power generator; however advancements in battery technology made them unpractical as a power source. Due to high oil prices in the 1970’s car manufactures Ford and GM spent millions of dollars developing Stirling engines, but due to the slow response time of the engine and decreasing oil prices by the 1980’s the Stirling engine was no longer considered as an alternative power source. Currently, Stirling engines are being substantially researched due to their potential for high efficiency, and their low to zero emissions output.
6.2 Current Technology
Solar powered Stirling engines have been developed in California that can produce up to 25 kW of power at an astounding 30% efficiency from solar to electric. This makes Stirling engines more efficient than any other solar technology. The Stirling Energy Systems company signed an agreement with Southern California Edison in August 2005 to build an array of these solar Stirling engines capable of producing a combined 500 MW of power. Stirling engines are also currently being used in submarines due to the quite operation needed for military stealth. Some smaller versions of the Stirling engine can also be bought for sail boats and RV’s or other mobile applications where remote locations and quite operation are desired.

6.3 The Basics
Stirling Engines come in all shape and sizes but they all generate power on the same principle – using temperature difference. A Stirling engine is unlike a conventional combustion engine in that the fluid never leaves the engine. It uses an external heat source which can be anything: the sun, fire, steam, or natural gas. One side of the engine is heated using an external heat source which causes an increase in temperature and expansion of gases in the cylinder. The gases are then cooled on the other side of the engine by using a heat sink such as ambient air or water. This change in pressure difference between the inside cylinder and atmospheric air causes a piston to move creating mechanical power.

7 Alternative Solutions

7.1 Stirling Engine Types
Stirling engines have three main configurations: Alpha, Beta and Gamma. Each of these engines has advantages and disadvantages. Alpha contains two pistons, one for the heat source and one for the heat sink. The system is a completely closed system with a pressurized fluid. The engine has a very high power-to-volume ratio, but has many technical problems due to the high temperature of the piston and its seals.

![Alpha Stirling Engine Diagram](image)

**Key**
- H = Hot
- C = Cold
- R = Regenerator
- Ve = Vol. Expansion
- Vc = Vol. Compression

Beta has a single power piston that is coaxially arranged with a displacer. The displacer moves air from the hot side to the cold side. No power is extracted from the displacer. Alternatively, the displacer’s job is to move air from the hot to cold side creating a pressure difference inside the cylinder which causes the piston to move. The displacer needs no seals which make for a simpler design. The engine can achieve high compression ratios because the piston and displacer can overlap in motion.
The gamma design is essentially the same as the Beta however; the piston and displacer are not aligned coaxially. This makes for a mechanically simpler design; however the configuration produces a lower compression ratio.

7.2 Heat Source
A Stirling engine can use a wide variety of heat sources because the heat is produced externally. Heat sources such as solar, gasoline, fire, nuclear, steam, and geothermal are some of the more common types, but others such as buffalo chips, trash, and vegetable oil have also been used. Currently one of the most researched heat sources is solar because it is renewable, has no emissions, is easy to maintain, and is applicable to a wide variety of locations. Gasoline is usually used in conjunction with solar to provide power in times when no sun light is available such as at night, or on cloudy days. Geothermal is more practical in places like New Zealand where there is a higher geothermal gradient. Fire has been used sparingly because it creates high emissions, but for smaller scale purposes that have a readily available source of wood available it can be practical.

7.2.1 Solar Radiation
Solar radiation offers an abundant supply of energy that is renewable which makes it the most popular heat source for modern Stirling engines. Solar Stirling engines use an array of mirrors in the form of a parabolic dish to focus the sun’s rays at the receiver where temperatures can exceed 1300 °F. This heat is
then transferred through a fluid, usually oil, used to run a conventional steam generator for electricity production. One solar dish with a diameter of 10 m can convert 1000 W/m\(^2\) of incident solar radiation at ground level into 25 kW of electric power. Although solar power works well, the systems are very complex and require exotic materials to reduce size and weight so the engine can be positioned above the dish.\(^8\)

![Figure 4. Solar Stirling Engine\(^9\)](image)

7.2.2 Fire
The burning of wood is also a viable means for achieving the necessary temperatures required to power a Stirling engine. Wood fires typically burn between 900-1200°F although they can reach temperatures of 2000°F.\(^{10}\) Although burning wood reaches similar temperatures to solar it produces pollutants and requires a constant supply of wood which takes time and effort to prepare for burning. Wood also produces an uneven temperature and heat supply which results in a less efficient engine. Typically the hot side of a Stirling engine is placed above the fire and convection and radiation transfer heat through the walls of the cylinder. The cold side of the engine is placed away from the fire and shielded to avoid radiation effects.

7.3 Cold Source
Stirling engines must have some kind of heat sink. Most often ambient air is used to displace the heat. Fins, a radiator, or a fan are often used to increase the rate at which heat is removed through air. Cold water from a river or lake may also be cycled through to exchange heat. Some more complex Stirling engines incorporate refrigerators to increase the thermal efficiency.

7.4 Regenerator
Most Stirling engines use a component called a regenerator. A regenerator in its simplest form is a wire mesh that is used to temporarily store heat when air is moving from the hot side to the cold side. The large surface area of the wire allows for heat to be absorbed quickly when air is moving to the cold side, and also to release quickly when air is moving to the hot side, thus increasing efficiency.

7.5 Construction Materials
There is also a wide range of materials that are used to make Stirling engines. Materials such as steel or aluminum that have a high heat transfer coefficient are desirable for the sides that interact with the heat source and heat sink. Materials such as plastic or wood are desirable for the walls of the cylinder because they have a low thermal conductivity. The color also plays an important part due to thermal radiation.
hot plate should be black to absorb as much radiation as possible. The cold plate and cylinder should be white and/or reflective to decrease thermal radiation. The thickness and density also play a role in the design choice. A heavy plate will weigh more and transfer heat more slowly, but will be stronger and capable of holding higher pressures. A larger plate would cost more, weigh more, and take up more space, but would be able to provide more power.

7.6 Pistons
Many Stirling engines used in industry use a four cylinder arrangement. Four cylinders reduce vibrations and provide a smooth torque delivery and lower the starting torque requirement. However, more cylinders increase the complexity of the engine due to issues in timing and more parts. A one piston design is usually chosen for less complex designs. A fly wheel is used to minimize vibrations and to provide a smooth torque output. However, one piston designs are usually less efficient.

7.7 System Gas
A few common gases are used in Stirling engines, including: air, nitrogen, helium, and hydrogen. Engines using anything besides air must be completely sealed to prevent the gases from escaping. This makes the engines more complex and difficult to fabricate. Also, gases besides air must be replenished regularly to the system because of inevitable leaks due to the tiny molecular structure of the gas. This adds to the cost of maintenance. Since hydrogen is the lightest it creates the least amount of friction drag in the cylinder and transfers heat the quickest, making it the most efficient. Helium, however, is usually used instead because it offers similar efficiencies to hydrogen but is non-explosive and easier to maintain.

7.8 Pressurized Gas
Pressurizing the gas in the engine raises the amount of energy that can be transferred. However heavier more robust materials must be used and gas must constantly be added to maintain pressure due to losses through the seals.

7.9 Output Function
We would like to attach various devises to the shaft of our engine including: pumps, alternators, and grain mills. According to various resources a 200 W alternator’s input angular velocity ranges from 500-1500 RPM and its efficiency from 50-70 percent. The angular velocity required for a 200 W pump and grain mill ranges from 500-1000 RPM and 600-3000 RPM respectively.

7.10 Starting Method
Most Stirling engines are not self starting and require some sort of starting device to begin the Stirling cycle. This project has selected a hand crank for starting the Stirling engine.

8 Research
Research is an integral part of this project. We have looked into several sources for researching the different types of Stirling Engines, different energy sources, output function, and other pertinent information for the project.

8.1 Patents
Stirling engine patents where researched on the U.S. Patent website. Many U.S. patents reference very specific and complex components. The ones discussed below are more general ideas used to make Stirling engines more efficient.
8.1.1 Solar Collector
One solar Stirling engine uses a unique fluid absorption receiver to collect solar radiation. It uses a blackbody receiver to absorb thermal energy and then heat is transferred to a sodium steam super heater. This allows the working fluid to absorb relatively large amounts of solar energy at high temperatures, while the blackbody absorber remains at relatively low temperatures. This minimizes energy losses through re-radiation and increases efficiency.\(^{19}\)

8.1.2 Stirling Turbine
One interesting design uses a turbine instead of a displacer, making the engine much more efficient because all power is translated tangential instead of linearly. This design decreases air friction because the air only has to move at half the speed since it has double the time to complete the cycle due to the constant power stroke.\(^{20}\)

8.1.3 Piston Travel
Another design patents a device for a double-acting, multi-cylinder, alpha configuration free-piston Stirling system, to control piston travel to prevent undesirable consequences of piston travel beyond predetermined limits. This increases efficiency by balancing vibrations, maximizing expansion of gases, and reducing friction.\(^{21}\)

8.2 Engineering Index
Another source of research was the Engineering Index. It was mainly used for ordering articles that gave specific details about different types of engines.

8.2.1 4-Cylinder Gamma-type Stirling Engine
Even though this engine has 4 cylinders it has a fairly simple drive because, the drive of each of the four displacers is attached to the top of each of the four power pistons, with a sealed bulkhead between them.\(^{22}\) Moreover, each cylinder is connected to the power piston cylinder that is phased 90° behind it. This is an advantage because it reduces the number of crank throws from 8 to 4. The design of this engine also includes oil-free Teflon cup seals, a regenerator made up of stainless steel mesh and a closed crankcase. With a displacement of 37.66 cc, this engine gave a maximum output of 40 W with helium and 20 W with air as the working fluids. The biggest advantage of the regenerated 4-cylinder gamma-type engine is that it can be used for a variety of different applications such as sewing machine, electric typewriter, lawn mower, weed trimmer, electric generator, etc.

8.2.2 TNT-1
TNT -1 is a type of Stirling engine that has a transparent quartz glass on its top through which a concentrated solar beam passes directly heating the mesh layers inside the cylinder space.\(^{23}\) Using the quartz glass is advantageous because it enables the working gas to receive more efficiently and makes the heater system simple and light. This system can be used for any type of Stirling engine including multi-cylinder engine, free piston engines or space engines.\(^{24}\)

For the glass used, quartz is a good choice because it strong enough even at temperatures up to 1300°C. Quartz also does not drop transparency until about 1100°C, which would affect how well the solar beams are being converted to heat and work. One disadvantage of using quartz is that it is quite expensive compared to other materials that are going to be used for the engine. Therefore, it is unlikely that quartz will be used in our project but it is recommended for people who can afford it. However, leaving a space for glass on the top of the engine will be considered for the final design.
8.2.3 Heat Pipe Receivers

A heat pipe receiver is another component that needs to be considered in our design because it essentially increases the efficiency of the heat being transferred. Many companies working on Stirling engines use heat pipe receivers because (a) it leads to uniform thermal distributions on the heater head tubes of the Stirling engine, (b) permits use of relatively low-cost concentrator that inherently provides non-uniform flux distributions on the absorber surface, and (c) allows for independent optimization of the receiver and engine designs. However, the authors of this article found heat pipe receivers to be “problematic” because of space, thermal and physical constraints. They overcame this problem by using increased receiver size and improved concentrator size.

8.2.4 Hybrid Stirling Engines

Hybrid Stirling engines can be used year round even when there’s no sun because they can run on gas during winters. However, they are more expensive and complex than other Stirling Engines.

8.3 Web Sources

Internet websites were also used in our research. We came across several useful websites for small scale Stirling engines. The following information was found from various sources on the internet.

8.3.1 Viebach ST 05 Stirling Engine

This engine is designed and produced in Germany. It is a gamma-type Stirling engine that consists of a crankcase with the displacer cylinder and power cylinder offset by 90° to each other. The engine is based on a set of 8 sand castings. The ST 05 G engine has been developed over a number of years and has been designed to form part of an integrated home heat and power system and can provide most of the domestic heating and electrical power requirements. One of the advantages of this engine is that it can run on gas, solid fuels, oil/paraffin, biomass or combustible industrial waste such as wood chips or sawdust. Table 2 below gives the specifications for this engine.

<table>
<thead>
<tr>
<th>Working Gas</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>10 Bar</td>
</tr>
<tr>
<td>Working piston bore</td>
<td>80 mm</td>
</tr>
<tr>
<td>Displacer Diameter</td>
<td>96 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>75 mm</td>
</tr>
<tr>
<td>Rotating Speed</td>
<td>600 rpm</td>
</tr>
<tr>
<td>Torque</td>
<td>8 Nm</td>
</tr>
<tr>
<td>Mech. Power Output 300-500W</td>
<td>0.4 to 0.67 hp</td>
</tr>
<tr>
<td>Power at 10 bar</td>
<td>355 W</td>
</tr>
<tr>
<td>Gas Consumption (for 300W output)</td>
<td>225 g / hour Propane</td>
</tr>
<tr>
<td>Heat Input (for 300W output)</td>
<td>2,862 W</td>
</tr>
<tr>
<td>Thermal Mechanical Efficiency</td>
<td>10.47%</td>
</tr>
</tbody>
</table>
8.3.2 Alpha Ross-Yoke and Alpha Rocker-V

The Alpha Ross-Yoke and Alpha Rocker-V were two other designs that were interesting. Not much information is available on these designs because they are still in the development stage. The advantage of these designs is that unlike other Alpha-type Stirling engines, these designs make it easier to seal the pistons that contain the working gas. Figures 5 and 6 show diagrams of the Alpha Rocker-V and the Alpha Ross-Yoke Stirling engines.

In conclusion, we kept track of the feasibility of different options by listing the basic concepts, design variables, and the pros and cons of each design for all three research categories. This has helped us...
identify weaknesses in our design and therefore, we were able to make continuous improvements on our
design by using ideas from multiple sources.

9 Design Model for Feasibility

One requirement for this project is to develop a working model by May, 2007. Call this stage of success
“point B”. In September, 2006, our development began from only an idea. Call this stage “point A”.
There are many ways to get from point A to point B. As a design team, we must decide which way will
give us the largest chance for success. The purpose of this report is to discuss the feasibility of getting
from point A to point B throughout several months of part-time work from a team of non-experienced
engineers. Here are two examples of different approaches.

Innotec is concurrently working on a similar solution. Their approach to point B is to iterate their design
by prototyping. From their best estimate, they have the resources (time, competence, finances, and
potential) to accomplish an acceptable design in this way. On the other hand, our limitations require us to
use a different approach.

Using classroom knowledge from recent machine design and heat transfer courses, we created models of
our system. Using these models, we can iterate to find an optimal solution prior to actually building any
components. The following section describes this modeling process.

9.1 Project Scope

The scope of our project is the design and construction of the engine itself.
The engine accepts input heat energy and through a mechanical system produces an output torque. The
design of the engine involves defining the material, shape, and size of each element. Some of these
elements are the linkage bars, top and bottom plates, output shaft, bearing size, and shaft supports.

Harnessing, gathering, or transporting the heat energy to the engine is outside of our scope, however we
must ensure that our engine is capable of receiving the heat. In addition, the connection between our
engine’s output shaft and the machinery it powers is also outside of our scope. For Senior Design night
we will attach our engine to either a water pump or a small generator, but only for demonstration
purposes only.

9.2 Thermal Model

The thermal model was constructed because there was a need to calculate the pressure drop in the Stirling
engine cycle. This information is necessary to determine the power of the engine itself. Throughout the
engine’s cycle, the fluid pressure is constantly fluctuating between low and high pressures. During the
low pressure, the piston is driven down by atmospheric pressure. During the high pressure, the piston is
driven upwards by the fluid pressure inside the chamber. Thus, as the gap between these pressures
increase, the capability of the engine increase.

The inputs to this model are component dimensions and materials, inlet radiation energy, and surrounding
temperature, pressure, and wind conditions. The outputs are system temperatures and pressures at
different points during the Stirling cycle.

The thermal model consists of three main components: conduction, convection, and radiation. A thermal
model for this system is vital for two reasons. The first is that this system is completely driven by
transferring energy via a heat exchange from some abundant source. This model confirms the feasibility
of this system by calculating the effects of the surroundings on the system. These effects can be analyzed
to predict if a certain energy input can power the system.
The second reason why a thermal model is vital for this system is because it allowed for a comparison of design alternatives without expensive prototypes. Component material, dimensions, and properties can be varied thus allowing for quick adjustments and graphical comparisons of any desired calculation. Because the model is segmented into individual components, optimization can target specific parts of the design.

9.2.1 Conduction
The conduction model considers only heat flow through the material medium. This is the most basic form of the conduction equation used in this model.

\[ Q_{\text{Conduction}} = -kA \frac{\Delta T}{\Delta x} \]  

Eq 1)

In this equation, ‘k’ is the conductivity of the component material, ‘A’ is the cross sectional area of the energy flow, ‘\( \Delta T \)’ is the temperature difference between sides of the material, and ‘\( \Delta x \)’ is the thickness of the material.

In the gamma type Stirling engine, there are four main conduction flows. They are: conduction through the heat source, vertically through the fluid chamber walls, horizontally through the fluid chamber walls, and through the heat sink. The pairs of red arrows in Figure 7 represent these heat flows.

![Figure 7. Conduction Flows](image)

Negligible conduction heat transfers are from the heat sink to the mechanical components above the sink and from the heat source to the hardware that mounts the engine. These were ignored in this model. Also, the displacer is modeled as a lumped solid, wiping away the need to consider conduction in it.

9.2.2 Convection
The convection model considers only heat flow between a solid medium and a fluid. This is the most basic form of the convection equation used in this model.

\[ Q_{\text{Convection}} = h_{\text{conv}} A \Delta T \]  

Eq 2)

In this equation, ‘h’ is the convection coefficient, ‘A’ is the surface area of exposure, and ‘\( \Delta T \)’ is the temperature difference between the fluid and the surface.

There are several convection flows, each modeled as forced convection. The heat source has convection flows to both the ambient air and to the system fluid. Convection to the ambient air from the heat source is to be minimized, while convection to the system fluid is to be maximized to achieve maximum performance. The chamber walls also have convection flows to both ambient air and the system fluid.
Optimally, these are both minimized so the fluid keeps a maximal amount of energy. The heat sink has both convection flows; however these flows are both maximized to achieve maximum performance. The logic behind these initial assumptions is: as the fluid cycles up and down in the chamber, it carries energy from the heat source to the heat sink. Thus the energy flow is vertical. Any flow that is not upward is minimized. Figure 8 presents this idea: the large red arrows represent that most of the convective heat flow is vertical. Additional convection flows occur inside the chamber because the displacer constantly transfers heat in and out of the working fluid.

![Figure 8. Convection Flows](image)

Negligible convection heat transfers are from the displacer connecting rod to the fluid and from the piston (not pictured, but on top of the heat sink) to the fluid. These were ignored in this model.

9.2.3 Radiation

The radiation model considers only heat flow between a heat source and sink that are separated by a certain medium. This is the most basic form of the radiation equation used in this model.

\[
\dot{Q}_{\text{Radiation}} = \varepsilon A \sigma \Delta (T^4)
\]

Eq 3

In this equation, ‘\(\varepsilon\)’ is the surface emissivity, ‘\(A\)’ is the surface area of exposure, ‘\(\sigma\)’ is the Stefan-Boltzmann constant, and ‘\(\Delta (T^4)\)’ is the difference between two surface temperatures, each raised to the fourth power. Note that for incident radiation, the higher surface temperature is that of the ambient air.

There are several radiation flows. The driver of the system is the sun’s radiation heat flow to the system heat source. However, this heat source could also be an open flame or a geothermal source as described above. In addition, there is a radiation flow from the source to the chamber wall and to the displacer. The chamber walls have radiation flows from the sun on the outside, and radiation flows from the source and to the sink as well as to the displacer on the inside. The sink also has a radiation flow from the sun. The sink’s radiation flows are minimized in order to maximize its effectiveness as a heat sink. The sink also has radiation flows from the displacer and walls inside the chamber.
Negligible radiation heat transfers are from the ambient air to the sides of the source and sink and from the displacer to the displacer connecting rod. These were ignored in this model.

9.2.4 Model Flaws
This first thermal model not only utilized these three heat transfer types, it was completely constructed around them as well. (The model had three sections: conduction, convection, and radiation.) For instance, under the conduction section, all energy flows accounted for were listed at once, one right after another. This made the model impossible to compile. It couldn’t be broken down to calculate guess values because every variable depended on something else. A new method was necessary that utilize the same heat transfer categories, but allowed the model to be compiled in pieces.

9.2.5 Thermal Model #2: Control Volume
After re-examining the system, a different approach was used. Instead of breaking the system down strictly by heat transfer (i.e.: conduction, convection, and radiation), a control volume process was used. First, all control volumes were identified. Then, the first law of thermodynamics was applied by establishing energy accounting equations on the control volumes one by one. To find these energy terms, certain variables were given reasonable guess values until another control volume solved for that variable. In this way, the thermal model assuredly solved for every energy term, leaving no thermal guesses.

The second model has only dimension, material, and mechanical assumptions. Each of these can be varied to produce estimates for an optimal solution. Please refer to the Analysis section below for these results.

Note that this second approach still utilized the same heat transfer means as the first. However rather than compiling the entire system at once, one control volume was compiled at a time. Below, figure 10 depicts these control volumes, each separated by blue borders. Table 3 breaks down the heat transfer terms that are included in each control volume.
Figure 10. Thermal Control Volumes

Table 3. First Law Breakdown on Control Volumes

<table>
<thead>
<tr>
<th>CV</th>
<th>Energy Accounting Equation – (In’s = Out’s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\dot{Q}<em>{\text{Rad, Incident→Source}} = \dot{Q}</em>{\text{Conv, Source→Air}} + \dot{Q}_{\text{Cond, Source}}$</td>
</tr>
<tr>
<td>2</td>
<td>$\dot{Q}<em>{\text{Cond, Source}} = \dot{Q}</em>{\text{Cond, Wall Vertical}} + \dot{Q}<em>{\text{Conv, Source→Fluid}} + \dot{Q}</em>{\text{Rad, Source→Displacer}}$</td>
</tr>
<tr>
<td>3</td>
<td>$\dot{Q}<em>{\text{Rad, Incident→Wall}} + \dot{Q}</em>{\text{Cond, Wall Horizontal}} = \dot{Q}_{\text{Conv, Wall→Air}}$</td>
</tr>
<tr>
<td>4</td>
<td>$\dot{Q}<em>{\text{Rad, Source→Wall}} + \dot{Q}</em>{\text{Conv, Wall→Fluid}} = \dot{Q}<em>{\text{Cond, Wall horizontal}} + \dot{Q}</em>{\text{Rad, Wall→Sink}}$</td>
</tr>
<tr>
<td>5</td>
<td>$\dot{Q}<em>{\text{Rad, Source→Displacer}} = 2 \cdot \dot{Q}</em>{\text{Conv, Displacer→Fluid}} + \dot{Q}_{\text{Rad, Displacer→Sink}}$</td>
</tr>
<tr>
<td>6</td>
<td>$\dot{Q}<em>{\text{Cond, Wall Vertical}} + \dot{Q}</em>{\text{Conv, Fluid→Sink}} + \dot{Q}<em>{\text{Rad, Displacer→Sink}} = \dot{Q}</em>{\text{Cond, Sink}}$</td>
</tr>
<tr>
<td>7</td>
<td>$\dot{Q}<em>{\text{Cond, Sink}} + \dot{Q}</em>{\text{Rad, Incident→Source}} = \dot{Q}_{\text{Conv, Sink→Air}}$</td>
</tr>
<tr>
<td>8</td>
<td>$\dot{Q}<em>{\text{Conv, Source→Fluid}} + 2 \cdot \dot{Q}</em>{\text{Conv, Displacer→Fluid}} + \dot{Q}<em>{\text{Conv, Wall→Fluid}} = \dot{Q}</em>{\text{Conv, Fluid→Sink}}$</td>
</tr>
</tbody>
</table>

In Table 3:
- $\dot{Q}_{\text{Rad}}$ refers to radiation heat transfer. $A \rightarrow B$ refers to a transfer of energy from component ‘A’ to ‘B’.
- $\dot{Q}_{\text{Conv}}$ refers to convection heat transfer. $A \rightarrow B$ refers to a transfer of energy from component ‘A’ to ‘B’.
- $\dot{Q}_{\text{Cond}}$ refers to conduction heat transfer for a particular component.
- Each term represents a red arrow from one of the above figures.

9.3 Mechanical Model

The purpose of the mechanical model is to calculate the amount of shaft work that the engine is capable of producing. The pressures determined from the thermal model are used as inputs for the mechanical model. There are two reasons for creating a mechanical model. First, it calculates the output power for a specific pressure curve. Secondly, the mechanical model can be used to optimize the power output by changing the link lengths, masses, or timing.

9.3.1 Slider Crank Analysis

For the mechanical model two main approaches were used. The first is a Slider Crank Analysis. This model is used to find the position, velocity, and acceleration of each link throughout the engine cycle. The engine has two linkages that can be modeled as slider cranks, the piston and the displacer.
The base case Stirling engine calls for the piston and the displacer linkages to be connected to the same crank shaft, and as a result both crank arms move at the same speed. Since the two links are running at the same speed the only way to change the timing of the engine is to change the offset angle between them.

9.3.2 Linkage Force Analysis
The second part of the mechanical model is a Linkage Force Analysis on the piston linkage. Now that the location of each link is determined, the next step is to see how the forces are transferred through the linkage. This analysis is done on the piston and not the displacer because the pressure difference is only seen on either side of the piston. The displacer is enclosed in the chamber of our engine and therefore does not have a pressure difference.

The Linkage Force Analysis examines each link individually by summing the forces and moments acting on that link. To use this model some assumptions had to be made, however, these assumptions can be changed to more accurately reflect the actual parts. A piston diameter is chosen and the pressure is used as an input force on the bottom of the piston. This force travels through the piston linkage and creates a torque on the crank shaft.

9.3.3 Model Flaws
There are a few problems with the mechanical model. First, it does not take friction into account. One of the biggest problems when building a Stirling engine is overcoming the internal friction. The power output of the model is an extremely ideal case. The actual value will be quite a bit less. Secondly this model assumes the engine is moving at a constant rotational speed. In actuality an engine accelerates during its power stroke and decelerates the rest of the time. Using this ideal condition of a constant speed means that the model does not take into account the forces needed to sustain this motion. This approximation again overestimates the total power output. It is important to realize that the model is a completely idealized version of the engine and that the actual output will be considerably less than what is calculated.
9.4 Time Constraints

9.4.1 Senior Design
The Senior Design project schedule is the main time restriction on the project. The class began on September 5, 2006 and will finish with Senior Design Night on May 5, 2006.

9.4.2 Manufacturing time
The other potential time constraint comes from the need for custom parts. It can take anywhere from five to ten weeks to get custom parts machined by an outside contractor. We are using three strategies to avoid this time constraint. First, we will attempt to do most of the machining in house. Secondly, we will analyze our design and identify parts that will need to be ordered. Finally, we will adjust our design with this concern in mind thus minimizing the number of custom parts needed.

9.5 Knowledge Requirements
Being familiar with both thermal and mechanical concepts has helped us with this project. For instance, we have been able to use radiation, conduction and convection calculations for our thermal analysis. Similarly, we have used linkage force equations for our mechanical analysis. Familiarity with these concepts has also helped in our research by giving us a head start on knowing what to look for and understanding the basic concepts of articles and research done by other people. We also have two group members who are international students. This gives us an advantage as they know the situation in underdeveloped countries well.

10 Design Analysis
After developing the models described in the previous section, the optimization of our process could begin. Using these models to iterate the design we were able to adjust individual components before building any prototype. When we are ready to build the prototype at the completion of this analysis, we will have an accurate prediction of how the system will perform and what to adjust to improve its performance.

10.1 Final Design Decision
Simplicity was weighted most when reaching a final design decision. If these engines are to be used in third world applications, replacement materials must be easy to find. Also, tools required for its construction must be common and readily available. A simple design will allow any user to look at the components and know exactly how to replace them without looking at directions. Below is a summary of our decision matrix.

<table>
<thead>
<tr>
<th>Weight</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Simplicity</td>
</tr>
<tr>
<td>7.5</td>
<td>Material Cost</td>
</tr>
<tr>
<td>7.5</td>
<td>Variability</td>
</tr>
<tr>
<td>7.5</td>
<td>Stewardship</td>
</tr>
<tr>
<td>5</td>
<td>Efficiency</td>
</tr>
<tr>
<td>5</td>
<td>Weight</td>
</tr>
<tr>
<td>5</td>
<td>Cultural appropriateness</td>
</tr>
<tr>
<td>5</td>
<td>Open communication</td>
</tr>
<tr>
<td>2.5</td>
<td>Performance</td>
</tr>
</tbody>
</table>

Table 4. Decision Matrix
The final design choice is a two cylinder gamma type Stirling engine that uses atmospheric air as its working fluid. It is to be made from carbon steel, aluminum, and plastic drain pipe. We are beginning with this most simple of designs and plan to adjust the design accordingly to achieve the desired performance. These adjustments will be made following certain technological developments. We will take advantage of the specific developments by incorporating them into our design. Figure 13 below represents a preliminary design for our prototype.
Recall that the thermal model’s inputs are component dimensions and materials, inlet radiation energy, and surrounding temperature, pressure, and wind conditions. Each of these inputs was varied and the following are summarized results indicating how each component adjusts the system’s performance.

Be sure to notice the relationship between the system pressure drop and the system temperature drop. Interesting trends form for various tests that point out where turbulence takes over laminar convection in the system’s fluid.

10.2.1 Component Thicknesses
According to the thermal model, the source, heat sink, and wall thickness did not have any noticeable effects on the system’s pressure drop potential. The following figures show this conclusion.
Figure 14. Wall Thickness and Resulting Pressure Drop

Figure 15. Sink Thickness and Resulting Pressure Drop

Figure 16. Source Thickness and Resulting Pressure Drop
10.2.2 Component Radii
According to the thermal model, as the source and sink radii increase, the potential pressure drop decreases once the radius is over 25 cm. For several reasons this can be explained. As the radii increase, the volume of fluid in the chamber increases by a factor equal to the square of the radii change. This increase in fluid movement causes laminar forced convection to turn to turbulent forced convection, allowing more energy to be transferred to the displacer and walls. This decreases the pressure drop because it takes away energy from the working fluid (Figure 17). Optimally, the working fluid would carry all energy to the heat sink, not allowing any leaks to the displacer or chamber walls.

While the plate radii affect the system performance, the displacer’s radius does not. Figure 18 plots the displacer’s radius as a percentage of the plate’s radius. The displacer is always smaller because it must fit inside the chamber walls, which go around the perimeter of the plate.

![Figure 17. Source and Sink Radii - Their Affect on System Performance](image)

**Figure 17. Source and Sink Radii - Their Affect on System Performance**
10.2.3 Wall Height

Similarly to the plate radii, the wall height has a point where it forces the convection from laminar into turbulent flow. At this point, it has a lower system performance potential. According to the model, this happens at 50 cm (Figure 19). Anywhere below or above this height, the performance will be better. This is very convenient because it gives freedom of selection. Depending on size constraints, the wall height can be either tall or short and have the same performance potential. (These constraints pertain to component costs or overall dimensions.) See figure 19 below.

Figure 18. Displacer Radius - Its Affect on System Performance

Figure 19. Pressure Drop as Wall Height Varies
10.2.4 Component Materials
For wall materials, there was little differentiation between the metals, woods, and plastics. This is predictable because material adjustment would only affect the conduction through the wall, which is already minimized.

![Pressure Drop for Various Wall Materials](image)

**Figure 20. Pressure Drop for Various Wall Materials**

10.2.5 Magnification of Inlet Radiation
Initially, this Stirling engine was designed for a solar energy source. Although the source energy can vary, the thermal model assumed that the major energy source is indeed the sun. The average solar flux for sunny location in Africa or Southern United States is 1200 W/m². The maximum solar flux along the equator is 1373 W/m². Therefore 1200 W/m² flux was considered reasonable. For a solar application, a collection dish could be used to magnify this flux onto a desired surface. Most solar dishes are capable of reflecting 12-15 times the incoming energy flux. This magnification of 1200 W/m² was varied. According to the model, any noticeable change in system performance requires over 10 times magnification. Figure 21 presents these results.
10.2.6 System Angular Frequency

This Stirling engine will output torque at a certain frequency. This frequency can be predicted using the thermal model. Figure 22 below shows that at lower RPM’s, the system produces a large pressure drop. This large pressure drop will cause the engine to accelerate because it drives the engine. As the engine’s angular velocity increases this pressure drop decreases. Once it falls under a certain level, the engine will no longer accelerate. According to Figure 22 below, which represents the base case design, the running angular velocity is around 800 RPM.

![Figure 21. Inlet Radiation Magnification](image1)

**Figure 21. Inlet Radiation Magnification**

![Figure 22. Fluid Parameters in Response to Various Engine Speeds](image2)

**Figure 22. Fluid Parameters in Response to Various Engine Speeds**
10.3 Mechanical Analysis

The advantage of having a theoretical mechanical model is that lengths and weights can be easily changed without having to scrap a prototype and start over. The effort now will save both time and money in the future.

10.3.1 Timing

Timing is a serious issue for any engine. For an internal combustion engine if the fuel sparks too early the engine will waste potential power and experience what is called engine knock. If the fuel sparks too late the engine has lost the fuel compression and will produce less power. Similarly, a Stirling engine has many of the same issues.

Figure 23 above shows the change in pressure inside of the engine as the displacer moves through one full cycle. To optimize the power output of the engine the container must reach its highest pressure values while the piston is on an upstroke and its lowest pressure while the piston is on a down stroke. In order to obtain these conditions the timing of the engine must be altered.

Figure 23. Pressure Change for 1 Cycle
The timing of the engine is driven by the offset angle between the crank arms on the piston and the displacer. The optimum value for the offset angle is 90° in front of the piston. With this offset angle the engine runs in a counter-clockwise direction. The direction can be reversed by offsetting the displacer 90° behind the piston.

It is also important to note the engine cannot obtain a pressure lower than the pressure of the outside air. This is a result of using the outside air as the heat sink. When the piston is on a down stroke there will still be an added resistance from the pressure inside the engine. The resistance acts against the motion of the engine and reduces the power output.

10.3.2 Link Length

The engine consists of four different links. The first link to be examined is the crank arm for the piston. This arm controls the displacement distance between the piston at the top and bottom of its cycle.
Judging from Figure 25, the piston crank arm should be made as long as possible. In addition to the power output there are some other factors to consider. First, the crank arm will be rotating at approximately 800 rpm. If the link was 0.2 m long the tip would be traveling at approximately 17 m/s or 38 mph. The second factor is that the piston travels a distance of twice the arm length. Again, if the link was 0.2 m long the piston would travel 0.4 m vertically. Both of these may be acceptable situations; however, they will have to be accounted for in other areas of the engine such as overall size or strength.

The second link is the connecting link between the piston and the crank arm. The length of this link has no impact on the total power output of the engine; however it must be longer than the crank arm for the engine to function. This link is also subject to large forces. Many of these forces do not act axially along the length of the link and thus create a bending moment. As a result buckling may become an issue in this link. The risk of buckling can be reduced by shortening the length of the link or increase the cross-sectional area.

The third link is the crank arm for the displacer. The displacer must sweep from near the bottom of the fluid container to near the top. The swept distance is controlled by the length of the crank arm. Since the container length is already specified by the thermal analysis it dictates the length of the crank arm. To function correctly the crank arm must be a little less than half of the container length.

![Figure 26. Connecting Rod Optimization](image)

The last link is the displacer connecting rod. The power output of the engine is actually greater when this link is shorter, however this does not yield an extremely significant change. Other considerations should be taken into account first. This link is connected to a rod which holds the displacer. When this rod is subjected to a tangential force it will have a tendency to in the worst case bind and at least severely increase the friction.

10.3.3 Piston Radius
The pressure in the engine is acting on the bottom face of the piston. If the area of this face is increased the force on the piston will increase by over two times the change. Therefore the radius should be increased to increase the power. There are, however, other issues involved with increasing the size of the piston. First of all an increase in the radius of the piston would increase the contact area between the piston and the wall. This would in turn increase the friction. Second the Piston would have to be made taller in order to stabilize it. This would again increase the contact area and thus the friction. The desire to increase the force on the piston will have to be balanced by the need to reduce friction.

10.3.4 Mass of Links
Along with varying the length of each component the mass can also be changed. This mass adjustment is a representation of changes in thickness and shape as well as in material chosen. When different masses were put into the mechanical model no changes in output power were seen. This is not entirely accurate because of the two assumptions inherent in the model; frictionless joint, and a constant rotational speed.
The main reason for designing an engine with a heavy piston is so that the weight of the piston powers the engine through the down-stroke. There are a few problems with this idea. The first is that the piston must change directions twice per cycle. In order to do this the piston’s inertial forces must be brought to zero twice per cycle. This puts a huge strain on the crank shaft and its supports. The second problem is that more energy had to be put into the piston to raise the extra mass on the up-stroke. At best, this results in a net zero power difference, but when including friction the total power output would be decreased.

There are two ways to accomplish this goal without running into these problems. The first is to attach a fly wheel to the shaft. A fly wheel stores kinetic energy and has a continuous rotary motion. Its continuous motion ensures that it will not produce an additional strain on the supports from a change in directions. A fly wheel would also gain its start up power from an outside source so the Stirling engine is only responsible for maintaining this motion. The second option is to build a multiple cylinder engine and offset the crank shafts such that when one piston is on its down stroke when another is on its up stroke. This produces a much smoother torque output. This requires a more complicated design but has the advantage of not wasting power by spinning a fly wheel.

10.3.5 Overall power
When reasonable assumptions are made for each dimension, the Stirling engine is capable of producing 200 W of power. Other considerations besides power output may influence the design choices and thus lower this value.

11 Budget

11.1 Funding
Innotec Corporation of Zeeland, MI, offered to support this project financially. They offered up to $5,000 for materials, and opened up their machine shop for the construction of the prototype.
11.2 Production Considerations

Several factors will effect the actual production of the Stirling Engine. First, the materials used need to be available and easily machined. For example, using an exotic material would not be feasible due to a lack of availability and high cost. Secondly, the components of the engine cannot be oversized. Having accurate dimensions for all the components will make the production process more efficient by avoiding re-manufacturing and physical problems such as fitting. Lastly, designing parts that are consistent with what is easily available in the market will help speed up the production process. This could also reduce prices since no parts will have to be custom ordered. The overall aim for the production process is to reduce the price and increase the efficiency to keep the design simple, yet effective.

11.3 Labor & Manufacturing Costs

Preliminary specifications and costs have been developed for the base case Stirling engine as shown in Table 5 below.

Table 5. Summary of Estimated Costs for Different Components of Stirling Engine

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Size [ft²]</th>
<th>Cost/Area [$/ft²]</th>
<th>Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Source</td>
<td>Hardened Steel</td>
<td>28.3</td>
<td>80.9</td>
<td>2,298.15</td>
</tr>
<tr>
<td>Heat Sink</td>
<td>Aluminum</td>
<td>28.3</td>
<td>23.1</td>
<td>652.15</td>
</tr>
<tr>
<td>Fluid Cylinder</td>
<td>Fiber Glass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacer</td>
<td>Aluminum</td>
<td>25.5</td>
<td>23.1</td>
<td>588.56</td>
</tr>
<tr>
<td>Hardware</td>
<td></td>
<td></td>
<td></td>
<td>150.00</td>
</tr>
<tr>
<td>Driveshaft</td>
<td>Steel rod</td>
<td>1.5&quot; OD</td>
<td>12&quot; length</td>
<td>18.36</td>
</tr>
<tr>
<td>Flywheel</td>
<td>Steel sheet</td>
<td>48&quot;X48&quot;</td>
<td></td>
<td>140.30</td>
</tr>
<tr>
<td>Piston Assembly</td>
<td>Bronze cylinder</td>
<td>3&quot; ID</td>
<td>4&quot;OD 13&quot; length</td>
<td>169.76</td>
</tr>
<tr>
<td></td>
<td>Steel rod</td>
<td>3&quot;OD</td>
<td>6&quot; Length</td>
<td>42.32</td>
</tr>
<tr>
<td>Total Cost [$]</td>
<td></td>
<td></td>
<td></td>
<td>4,649.60</td>
</tr>
</tbody>
</table>

Table 6 below gives estimates for the total cost of labor for this project.

Table 6. Breakdown of Total Labor Cost

<table>
<thead>
<tr>
<th>Total Days [days]</th>
<th>Average Work Day [hr/day]</th>
<th>Total Hours/person [hr]</th>
<th>Total Hours/group [hr]</th>
<th>Unit Price [$/hr]</th>
<th>Total Labor Cost [$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>236</td>
<td>3</td>
<td>708</td>
<td>2,832</td>
<td>100</td>
<td>283,200</td>
</tr>
</tbody>
</table>
11.4 Net Budget

Table 7 below summarizes the total cost of the entire project.

<table>
<thead>
<tr>
<th>Table 7. Summary of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing Costs</td>
</tr>
<tr>
<td>Labor Cost</td>
</tr>
<tr>
<td>Engine Model</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
</tr>
</tbody>
</table>

The total cost will be reduced mainly by the manufacturing costs, which will be less expensive because of smaller component sizes that will actually be used to build the engine.

12 Project Management

An adaptable schedule was made using Microsoft Office Project to give an overall vision of time and importance of the components of the project. At the beginning of the semester a preliminary schedule was made that outlined milestones such as, oral presentations, class assignments, and the Project Report Feasibility Study. The schedule was then changed to include all the detailed components of the project. The schedule gives key categories and sub-categories, a time frame for each task, percent complete of each task, and the person working on a task. See the Appendix for the Project Schedule.

13 Acknowledgments

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