Design and Manufacturing of a Single Rotor Wankel Engine

A Major Qualifying Project
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Degree of Bachelor of Science

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Abstract

The purpose of this project is to design and manufacture a functional Wankel engine. A Wankel engine utilizes volume changes of an eccentrically turning rotor in a housing for power cycles. As the internal rotor of a Wankel engine rotates, the volume of its combustion chamber cyclically changes. The resulting volume changes of the combustion chamber create the intake, compression, combustion, and exhaust necessary for a thermal power cycle. The primary components of the prototype were designed by the team to be manufactured using the CNC machining equipment available at Worcester Polytechnic Institute. This Major Qualifying Project report outlines the team's process of designing, machining, and testing to produce a fully functional prototype of the engine.

Executive Summary

The goal of this Major Qualifying Project was to design and manufacture a single rotor Wankel engine. In addition to this, the team was tasked with incorporating unique design elements to improve on the common setbacks of the Wankel engine. For this project, the team purchased stock materials and used SolidWorks to design parts and manufacturing programs to machine and assemble an engine.

To achieve the set goals, the team utilized the engineering design process, incorporating several design and materials changes over the course of this past year. As a result of the teams research and advisor meetings, the team chose to address the following Wankel engine issues in effort to create a functional engine:

- Compression chamber sealing, side and apex
- Lubrication of rotating assembly
- Apex seal material selection for prototyping and wear resistance

Upon completion of the manufacturing and assembly of the designed engine, several results were observable. Firstly, sufficient compression was achieved in large part due to the apex seal spring constant, machining tolerancing and material selection, which were all carefully monitored to ensure a fully functional final product. Additionally, successful combustion cycles occurred as intake, compression and ignition were timed properly allowing for the cycle to occur. By utilizing the team's prototype brass apex seals, the seal longevity with the final cast iron seals has not yet been sufficiently proven. However, with the lubrication system functioning properly, engine longevity can be tested and refined by the future Major Qualifying Projects that have been planned to further this year’s team's work.

1.0 Introduction

Wankel engines, more commonly referred to as, “rotary engines”, are rotational engines that rely on rotors rather than pistons for power generation. A Wankel engine differs from a typical piston engine as the geometry is planar and not reciprocal, the piston is replaced by a rotating rotor. This rotor is triangular in shape, and undergoes a 4 stroke combustion cycle on each of its three faces each rotation (see Figure 1). This unique design was invented by German Engineer, Felix Wankel in 1954 (Sherman 2008). An in depth continuation of the origins of the Wankel can be found in section 2.1. For the purposes of the project, the team's design was based on existing models to utilize the complicated geometry calculations completed through generations of iterations completed by Felix Wankel’s successors. The team's model is considered a small engine at just 25 cubic centimeters of displacement. This was in an attempt to limit material costs, machining time, and allow for the prototype to be fully machined in the Washburn Shops available on the Worcester Polytechnic Institute campus.

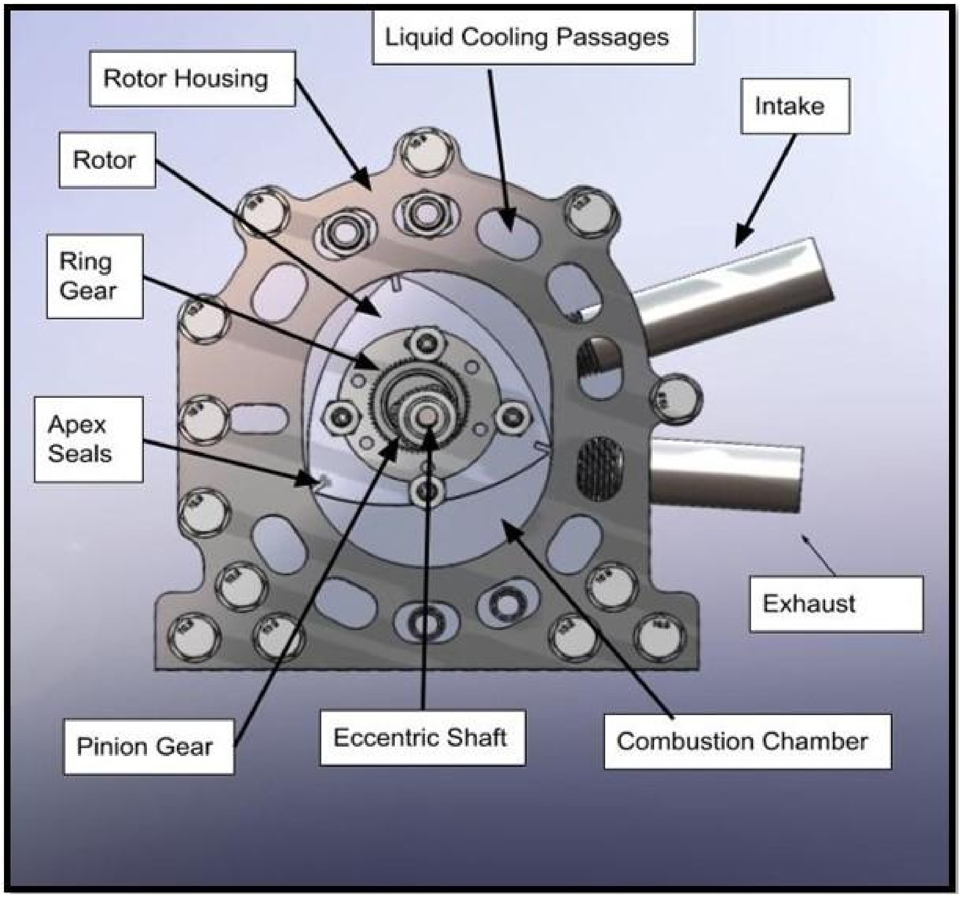


Figure 1. The basic theory and design of a Wankel rotary engine

1.1 Project Objective: Functioning Prototype

The overall goal of the project was simply to design, machine, and assemble a functioning Wankel engine before the presentation date. The underlying goals within the main project outline were to complete this task within the limit of the Grants supplied by the institute, and to incorporate design alterations to the existing Wankel engines available to create an original, unique engine. The team's design changes are explained in detail in section 3.0. To aid in reaching this goal, the team's project advisor, Professor Guceri, allowed the purchase of gears, bearings, pumps and a carburetor. This allowed the team to focus on the design geometry, machining, and required specifications to achieve full functionality of the prototype. The team's design utilizes a mixed two-stroke fuel, this means that the engine requires glow plugs as opposed to the more commonly used spark plugs in gasoline engines. It also requires a specially ported and jetted carburetor. Although these items were purchased, each item was customized for the specialty application.

2.0 Personal Life of Felix Wankel

Born in 1902, Felix Wankel firmly planted himself within many anti-Semitic organizations such as the National Socialist German Workers Party, which was also known as the Nazi Party within its first few years of inception in the early 1920s. Wankel's focus on technical advancements was not shared by his peers in the Nazi Party. As a result, he was offered an audience with Adolf Hitler and other leaders of the party to speak about the importance of technology and education. In 1932 Wankel was expelled from the Nazi Party due to in-fighting with other members. However in 1933, Wankel was set free due to intervention by Wilhelm Keppler and Adolf Hitler. He was also given state contracts and his own experimental workshop where he continued to work on his engineering projects.

At the end of the war, Wankel was imprisoned by the French and his workshop was dismantled. It was in 1951 that he received funding in order to start a new workshop. While his extremist views and involvement in one of the worst regimes ever seen should be condemned, this new workshop led him to create the first iterations of the Wankel engine (Sherman 2008).

2.1 History of the Wankel Engine

Felix Wankel was an engineer who was unable to afford a university education, but that did not stop him from pursuing a career in engineering. His career started with creating compressors for differing applications. One of these applications had the compressor being used as a supercharger for a small 0.05L 2 stroke engine. This supercharger used an internal triangular rotor and was the first application of Wankel's geometry that was later used in the Wankel engine. Soon after this compressor was designed, Felix Wankel realized that if he included intake and exhaust ports as well as spark plugs into his design it could be used as an internal combustion engine.

The original Wankel engine was created by Felix Wankel in 1957 and was called a "Drehkolbenmotor" or DKM for short. Both the internal rotor and the housing for the rotor would rotate with this design. Because these pieces of the engine rotated, it allowed the rotor to simply rotate around its center. The two would rotate at different speeds where the housing would rotate at a faster speed than the rotor. The ratio of angular speed between the two pieces was 2:3. This design had a couple of flaws that were addressed in later iterations of the Wankel engine. While the engine could reach very high speeds of up to 25,000 rpm, these high speeds caused the rotor housing to distort. Not only would the rotor housing distort at these high speeds, but it proved to be very difficult to cool the housing as it was rotating. The DKM engine can be viewed as a major success because it proved that Wankel's design would work to create a new type of engine that does not rely on pistons and cylinders in order to create compression and combustion (Hege, 2007).

In order to combat these issues with the original DKM engines, Hanns-Dieter Pascheke designed a modified version of Wankel's design that kept the rotor housing stationary while the rotor spun inside of it. This engine was called a "Kreiskolbenmotor", or KKM for short. The engine is the first design that most closely resembles the mass produced Wankel engines used today. Because the housing is stationary, the rotor cannot simply rotate around its center and instead has to follow the rotation of the eccentric shaft. There are advantages to the KKM engine. Because the rotor housing is stationary, it is considerably simpler to cool the engine as coolant passages can be cast or machined in the now stationary rotor housing, allowing for the implementation of a typical internal combustion engine cooling system. Power from the engine also gets transmitted through the eccentric shaft in this design. This means that the KKM engine can be used with typical automotive transmissions (Hege, 2007).

2.2 What is a Wankel Engine

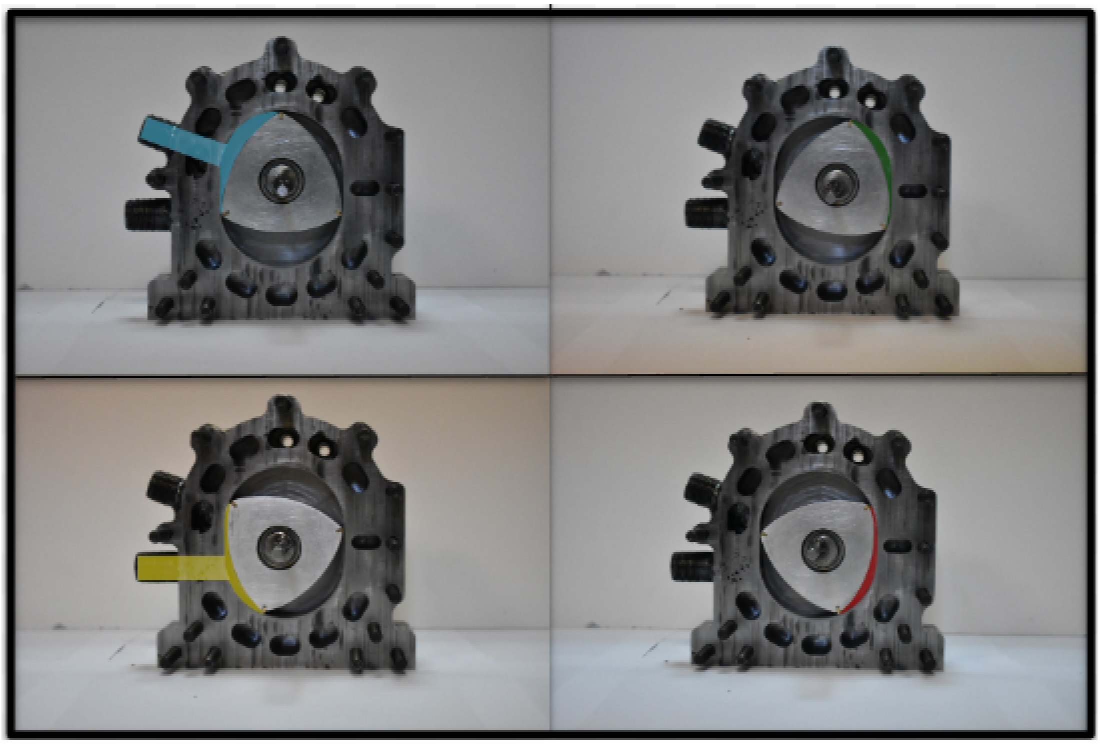


Figure 2. A sectional view of a Wankel Engine in the phases of the combustion cycle: Intake (blue), Compression (green), Combustion (red), Exhaust (yellow)

A Wankel Engine replaces the piston-cylinder style assembly used in most internal combustion engines with a three part, planar housing. For every rotor in the engine, a separate housing is required. These housings are bolted together and separated by a metallic gasket similar to a head gasket on a piston engine. A round-lobe crankshaft runs the length of the block through each rotor in the engine. The lobe, similar in geometry to a cam lobe, is directly contained within the rotor. Each rotor is paired with a ring and pinion style gear system, this system has a ratio of 3:2 meaning that for every three rotations of the rotor, the crank rotates twice. The reasoning for this ratio is due to the basic rotor geometry, the rotor is a three sided, curvilinear triangular shape.

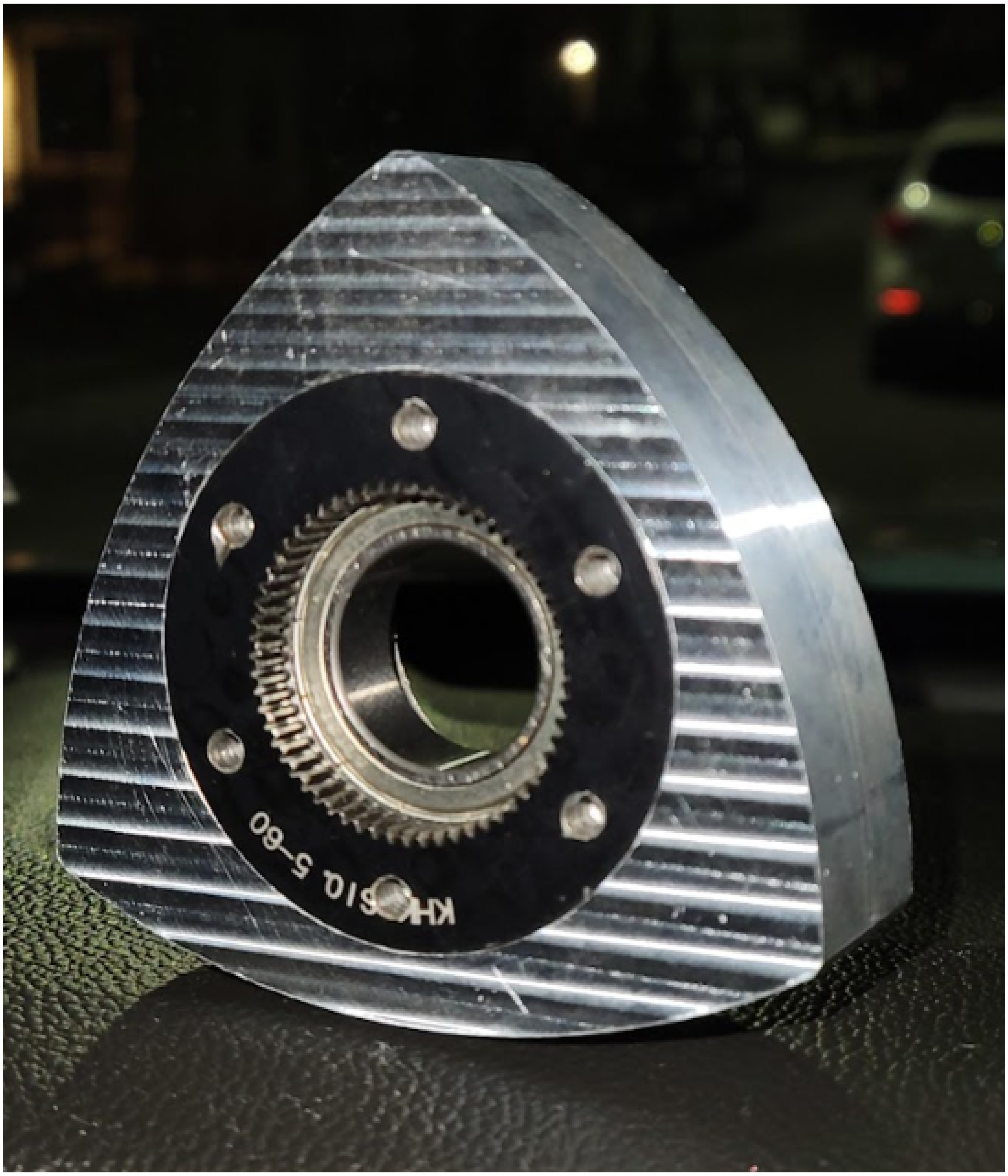


Figure 3. Image depicting the curvilinear nature of the Wankel rotor machined by the team

The housing is a shape called an epitrochoid, an epitrochoid is formed by tracing a point on a circle with a diameter with a ratio 3:2 of the circle its tracing.

Figure 4. Image depicting the meshing of the apex seals with the epitrochoidal housing on the teams engine

The eccentricity of the crank lobe is identical in phasing and diameter allowing the rotor to have each vertex in contact with the housing at all times. This contact is imperative to the sealing and compression of the engine and is aided by the incorporation of apex seals. Apex seals are similar in purpose to that of piston rings. In a Wankel however, each of the three faces are in separate phases of the combustion cycle at all times. In figure 5, the apex seals are the gold colored strips at each corner of the rotor, and complete the seal between the rotor (silver), and the housing (gray). This differs from a typical four-stroke engine in that all four phases of the cycle can be completed in one full rotor rotation and each face completes a full cycle each rotation. This ability lowers the amount of time that each rotor is making no power to approach zero, meaning the minimal possible power lag is achieved. In addition to this, Wankel engines operate at significantly higher revolutions per minute when compared to piston-cylinder engines. One of the great innovators of the Wankel engine was Mazda. The Mazda RX-7 used a 1.3 liter Wankel engine, called the 13B, a two rotor Wankel which produces 300 horsepower and revs to 10,000 revolutions per minute. This engine weighs only 330 pounds, giving it a power to weight ratio of 0.9 hp/lb (Thomson, 2020). Ability to run at higher speeds allows for high power to weight ratios, as the output of the engine can be geared down to produce more torque at a lower output shaft speed in relation to the engine's crankshaft.

2.3 Benefits and Drawbacks of Wankel Engines

The nature of Wankel engines is that there are 3 simultaneous combustion cycles per rotor at any moment resulting in an improved power to weight ratio over the standard piston engine. Complex geometries of the rotor and epitrochoidal housing account for both the major advantages and disadvantages of the engine. The elimination of need for a camshaft or similar valve timing system and valves means a Wankel engine has far fewer parts and less complexity than a piston engine. Timing is crucial in all engines as it is vital to whether the engine runs or fails, and in a Wankel engine the timing is dictated only by the position of the rotor and, as stated, does not require valves or camshafts like a typical piston engine would. Additionally, this elimination reduces materials and machining costs, reducing the price to the customer. A Wankel's planar nature however is a major flaw as well. Firstly, it separates the "block" into two faces and a housing, increasing the size of mating surfaces and required sealing for efficient compression and combustion. Sealing of the combustion chamber is an easy solution for the power cycle, cooling however is another issue.

When the coolant is flowing, the increased sealed area increases potential for gasket and seal failure, which often results in an engine needing to be rebuilt or replaced. Rotor housings themselves are the optimal shape according to Wankel's findings in section (2.1). The use of the epitrochoid increases compression and overall combustion to the maximal possible in the engine configuration. It also allows for three power cycles per rotation per rotor. Epitrochoids however are extremely difficult to machine with high precision compared to bored cylinders. This results in an increased difficulty of lining or "sleeving" the bore as it is called in typical engines. Lining, when necessary, would increase the manufacturing and parts costs but would be less necessary if machining plants were equipped with more expensive equipment. Both possibilities would increase costs to the customer.

2.4 Applications of the Wankel

Due to the properties of the Wankel engine, it received interest from several companies requesting licensing to use the engine in several obscure applications. Among this collection of interesting machinery is the Yanmar Diesel license issued in 1961. Yanmar is primarily an agricultural machinery company which also designs marine engines for light and heavy application. Yanmar was founded in 1912 in the Philippines, almost 50 years later in 1961 upon issuance of the license to use the Wankel engine, Yanmar began utilizing the design in several of its products. All over the world today, Yanmar agricultural machinery can be found with Wankel engines, as can heavy and light duty tractors, and inboard as well as outboard high and low output marine engines (Yamamoto, 1981).

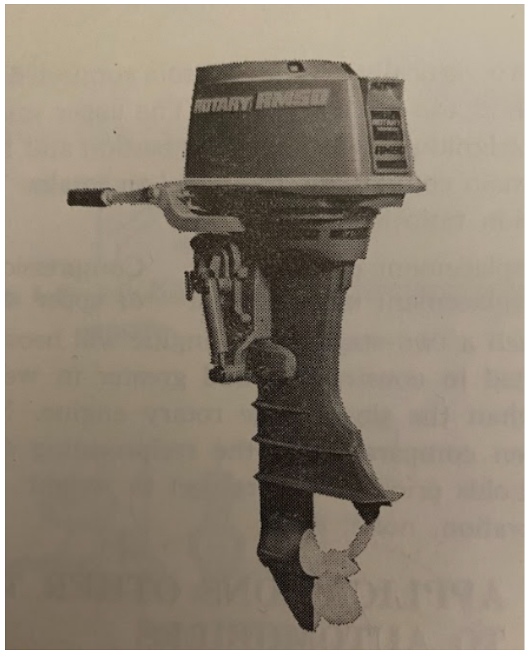


Figure 5: RM50 two-rotor marine outboard boat motor (Yamamoto, 1981)

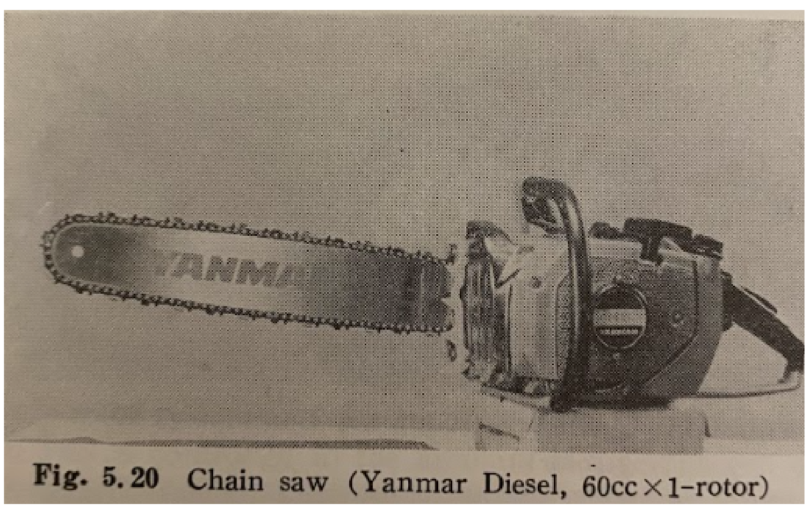


Figure 6: Yanmar Diesel Single Rotor Chainsaw (Yamamoto, 1981)

Applications of Wankel Engines outside of the automotive and aerospace industry quickly spread in the late 1960's through the early 1980's. The interesting design accompanied with the ability to produce more power, with a reduced weight compared to existing design made the expansion to the powersports industry a guarantee. Subsequently, this was an expansion into the western civilization with the existing widespread interest in powersports. Beginning with tractors and marine engines, an interest in use for jet skis, snowmobiles, as well as motorcycles. The Motorcycle industry welcomed its first example with the MZ-ES 250 in 1965, this motorcycle never went into series production. Perhaps the most available example of a rotary motorcycle is the Hercules W-2000, an air-cooled single rotary engine outputting roughly 30 horsepower. The W-2000 used a pre-built Wankel to drop into the frame of the motorcycle. The engine was originally designed as an engine for a snowmobile. Because of this, the full advantages of a Wankel engine were not able to be used in the Hercules. The engine's output had to be translated through a 90 degree bevel gear before reaching the transmission. This bevel gear and the size of the carburetor attached to the engine canceled any size and packaging benefits from Wankel engines. Because the engine was originally designed for a snowmobile, it did not have any oil sump and had to use pre-mixed fuel and oil in order to provide lubrication to the internal components. The W-2000 was produced from 1974-1977, production ceased due to low sales (Moto, 2022).

Figure 7. Image of a 1974 Hercules W-2000 motorcycle (Moto, 2022)

Wankel Engines first appeared in the automotive industry in 1967, 10 years after the conception of the first prototype. NSU, a German Automobile Company, or Neckarsulm, was the first company to put a Wankel in a car, the Ro80 sedan. Though the car was initially praised for its innovation, as time went on problems with the tip seals led to engine reliability issues, and it fell out of popularity quickly. Production ran for 10 years with less than 38,000 sold until NSU's parent company, Volkswagen-Audi converted the manufacturing plant into a Porsche 924 assembly building (Branch, 2022).

Figure 8. First Generation of a Wankel-powered NSU Ro80 (Kitman, 2023)

Perhaps the most prominent and famous example of the Rotary engine in the automotive industry was the Mazda RX-series of sports coupes. Mazda's first car with a rotary engine debuted in 1967 with the Mazda Cosmo Sport, though the car itself was in car shows as early as 1963. The Cosmo served as a halo vehicle for Mazda and was powered by a 0.982 liter two-rotor engine that produced 110 horsepower. Though the performance of the engine itself was adequate, however, the primary problem with the engine was scoring of the rotor housing, due to improper lubrication of the apex seals and inadequate tolerancing. Though this problem was solved with a change in apex seal material, it was not until the first RX model, the RX-7, truly popularized the rotary engine (Mazda, 2022).

Introduced in 1978, the RX-7 replaced the Cosmo as the only rotary powered car in Mazda's lineup, but redesigning the RX-7 as a pure sports car instead of a mix between a luxury sports crossover did wonders for the rotary engine's reputation as a car engine, primarily due to its high power to weight ratio. The RX Series was Mazda's most impactful model being sold from 1978-2002. When it was first released, the RX-7 was sold with the 12A twin-rotor engine. This engine was 1.2 liters and produced around 100-130 naturally aspirated horsepower depending on which application it was being used for. The engine was also fitted with a turbocharger sometimes and could produce 160 horsepower with the aid of forced induction. Due to Wankel engine's tendencies for high RPM and low torque, turbochargers are preferred over superchargers in order to aid with forcing air into the engine to produce more power. The RX-7 was also available with the 13B, Mazda's most successful Wankel engine (Mazda, 2022).

The 13B was first seen in 1973 and was another twin-rotor design from Mazda. Each chamber had a volume of 0.654 liters and relied on two spark plugs in order to ignite the fuel inside. The 13B was used by Mazda for over 30 years and served as the blueprint for many different Wankel engines created by Mazda. As it was used for more than 30 years, there are many versions of the 13B, ranging from naturally aspirated to sequentially twin turbo. As a naturally aspirated engine, the 13B could produce 120 horsepower in cars such as the RX-4. Later in the development of their most successful engine, Mazda was able to turbocharge the 13B for the RX-7 and produce 180 horsepower. Near the end of its life, Mazda showed what the

13B was truly capable of and decided to sequentially turbocharge the engine. The first turbo would provide forced induction at around 4500 RPM, while the second turbo was reserved for higher RPM to help the engine provide its peak power of 280 horsepower in the RX-7. This was also the first time that a production vehicle had been equipped with sequential turbos (Mazda, 2022).

The Wankel engine has drawbacks that cause most people to ignore them and for manufacturers to avoid spending resources in creating them. These drawbacks include replacing the apex seals, burning oil, and poor fuel economy. In the world of automotive racing, these drawbacks are not seen as dealbreakers and are par for the course. Racing engines require new rebuilds frequently and the amount of power that they produce results in very poor fuel economy already. The main advantages of Wankel engines are the size and weight to power ratio that is possible. This is a major advantage to racing teams who are always trying to create lighter and faster cars in order to gain an edge on their opponents.

Mazda, being very well aware of the advantages and drawbacks of Wankel engines, decided to create the 787 in 1990 and the 787B in 1991 (Irimia, 2022). Both race cars had no purpose other than speed and reliability for endurance racing supremacy. The 787B was entered into the 24 Hours of Le Mans, a 24 hour race with long straights which many cars have failed to finish. Racing classes within the 24 Hours of Le Mans are dictated by vehicle weight and volume of the engines being used (Irimia, 2022). Because of this, Wankel engines are at a massive advantage here as they can create more naturally aspirated power than their piston engine counterparts in the same volume. The 787B ended up winning the race due to its reliability and power. Since then, no Wankel engine has been used in the 24 Hours of Le Mans again as the rules had to be changed after regulations changed the specifications that engines had to meet (Irimia, 2022).

The engine powering the 787B was an R26B. This Wankel engine, designed by Mazda for prototype race cars, had 4 connected chambers each with 0.654 liters of volume. This engine uses the same dimensions and component shapes as the 13B. The whole engine had a total displacement of 2.616 liters and was able to produce 700 horsepower for the 24 hour race (Irimia, 2022). The engine produced its max power at 9,000 RPM without the need for any forced induction. In order to create such an engine, Mazda used tricks such as variable length intake manifolds for the engine, upgraded fuel injection system, and added another spark plug to each chamber (for a total of 3 per chamber) (Mazda, 2022). As of now, Mazda no longer makes a rotary powered car, though in 2021 Mazda announced that a smaller rotary engine would be used to recharge batteries in a hybrid version of the MX-30 (Szymkowski, 2021).

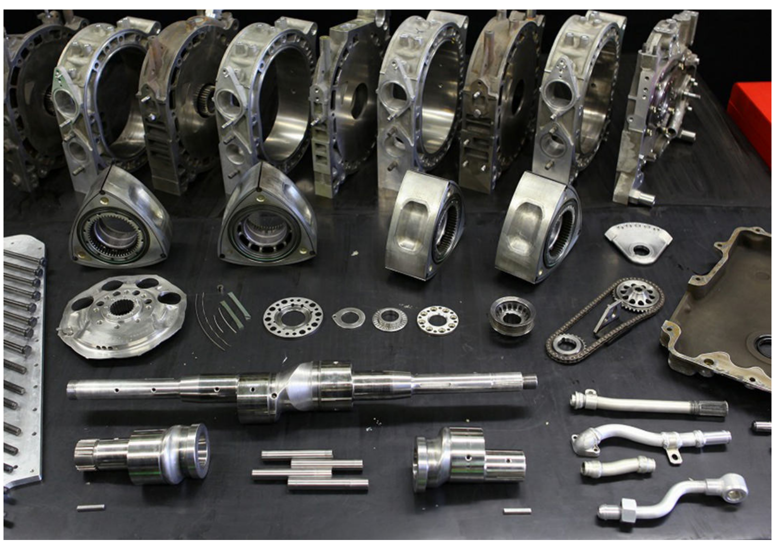


Figure 9. Transformation of the Racing Rotary Engine (RE) (mazda.com)Mazda R26B 4 Rotor Wankel Engine Parts explosion

3.0 Geometric Modeling and Design Considerations

The geometry of the Wankel engine is critically important because unlike a normal piston-powered engine, there are less parts that go into motion when the engine is started, meaning that any imperfections that could hinder the performance of the engine are amplified due to the Wankel engine's greater dependence on each individual part. In order to choose the shape of the rotor itself, the compression ratio of the engine must be considered. The compression ratio is the ratio of the volume when the rotor begins its compression phase to when the rotor finishes its compression phase, and is calculated with the following equation:

$$Compression\ Ratio\ = \frac{V_d + V_c}{V_c}$$

Where V_d is the volume displaced by the rotor during its compression cycle and V_c is the volume remaining after the rotor finishes its compression cycle. The reason why triangular rotors are most frequently used for Wankel engines is because the compression ratio increases when the number of sides that the rotor has decreases. For example, for a rotor inscribed in a circle of radius R, the total remaining volume in the circle decreases as the number of sides on the rotor goes up, thus decreasing the compression ratio (Yamamoto, 1981). A visualization of this is shown in the figure below.

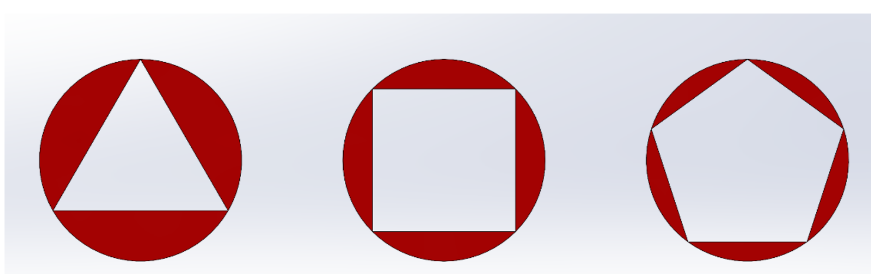


Figure 10. Visualization of Decreasing Compression Ratio due to Decreasing Displacement Volume Inside a Circle of Radius R (Red).

In addition to maximizing the compression ratio, the benefit to using a triangular rotor is so that the total volume necessary for the housing to envelop the motion of the rotor is significantly smaller compared to the other rotor geometries. A triangular rotor only requires two lobes, compared to a square rotor which needs three, and increases for every extra side the rotor has.

The total size requirement for this prototype would be quite small compared to some of the engines that car manufacturers like Mazda have made, but due to both size and machining constraints, it should be smaller than a car motor, but large enough that the combustion of the fuel forces the rotor to rotate. With this in mind, the rotor was designed to have a radius of 2 inches, which limits the material cost and machining time.

To generate the inner dimensions of the rotor housing, an epitrochoid graph was generated using the size requirements for this engine. An epitrochoid is generated when a "follower circle" is revolved around a main circle. As the follower revolves, it rolls around the circle in the same manner as a spirograph. A tracer point is contained within this circle and when the position of this point is traced, the epitrochoid is formed. The term epitrochoid simply refers to the process by which the shape can be formed; however the geometry of these shapes can vary infinitely depending upon the variables which define the epitrochoid equations.

$$x(\theta) = (R + r)cos(\theta) - d \cdot cos(\frac{R+r}{r}\theta)$$

$$y(\theta) = (R + r)sin(\theta) - d \cdot sin(\frac{R+r}{r}\theta)$$

Variables x and y are simply the dependent variables which plot the shape on the graph below. The main circle is defined by radius "R" and its follower circle has radius "r", the ratio of these radii determines the amount of lobes the effective epitrochoid contains. Variable "d", is the distance from the center of the follower circle at which the tracer point is placed. The ratio of the follower circle's radius to distance, d, determines the eccentricity of the epitrochoid (Yamamoto, 1981). It should be noted that for the circumstances of this project and its subsequent equations, the main and follower shapes are circles. In general however, these can take on any shape providing the follower can roll uninterrupted around the perimeter of the main shape. Felix Wankel was able to use his peers' attempts at rotating pumps to create the optimal epitrochoid for the engine housing. His optimization was centered around manufacturability and maximization of the resulting compression ratio. The specific epitrochoid he determined optimal is defined by the ratios below:

For two lobe, Wankel epitrochoid;

$$R = 2r$$

$$r = \frac{10d}{7}$$

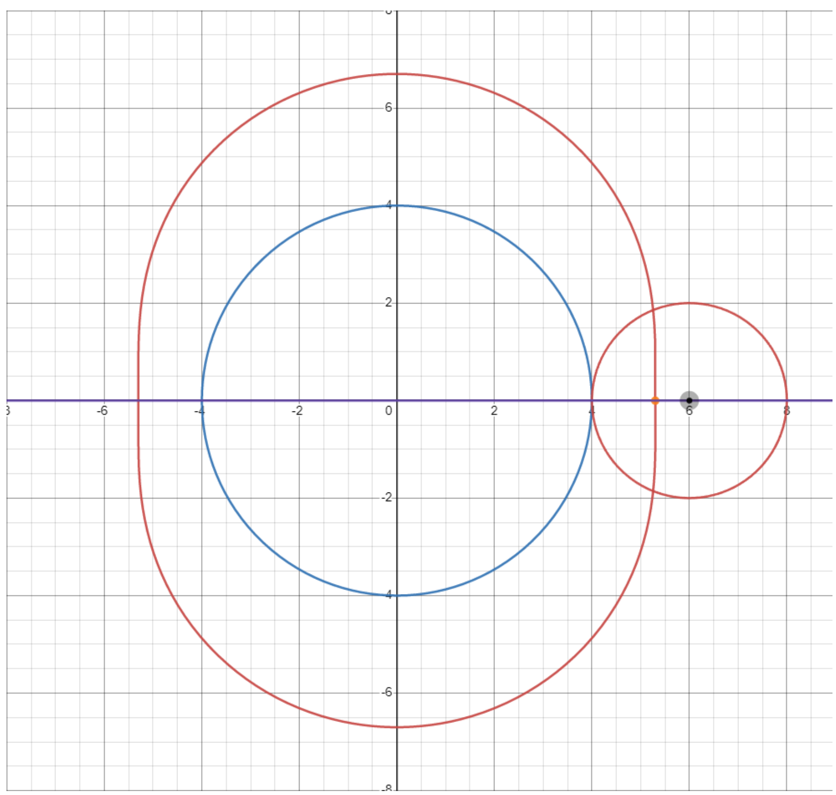


Figure 11: Epitrochoid generated using the above equations with R = 4, r = 2, d = 0.7.

For the gear ratio of rotor to axle drive, the ideal ratio for a 3-sided rotor is 3:2, with 3 teeth on the inner gear that is secured to the rotor for every 2 teeth on the outer gear that is secured to the housing. The reason the ratio is 3 to 2 comes from the transfer ratio equation

$i = Dg/Dr$, where dg is the radius of the outside circle, or the circle of the inner gear, and dr is the radius of the outer gear. Because this particular rotary engine will use a 3-sided, 2 lobe rotor and housing, the ratio of the gears should be 3:2.

For this rotary engine, the peripheral port intake system will be used, as machining a side port intake system would be extensively difficult given the tools at the teams disposal. On the side of the rotor housing, the inlet port for the fuel and the exhaust port for the combusted gas should be on the same side, so that as the rotor revolves around the chamber, the incoming fuel does not exert as large of a force opposing the rotor. This leaves a space on the other side of the epitrochoid for the glow plugs to ignite the compressed fuel. In addition, water cooling canals were added in order to cool the engine in order to prevent the rotor from overheating and fusing with the sides of the engine.

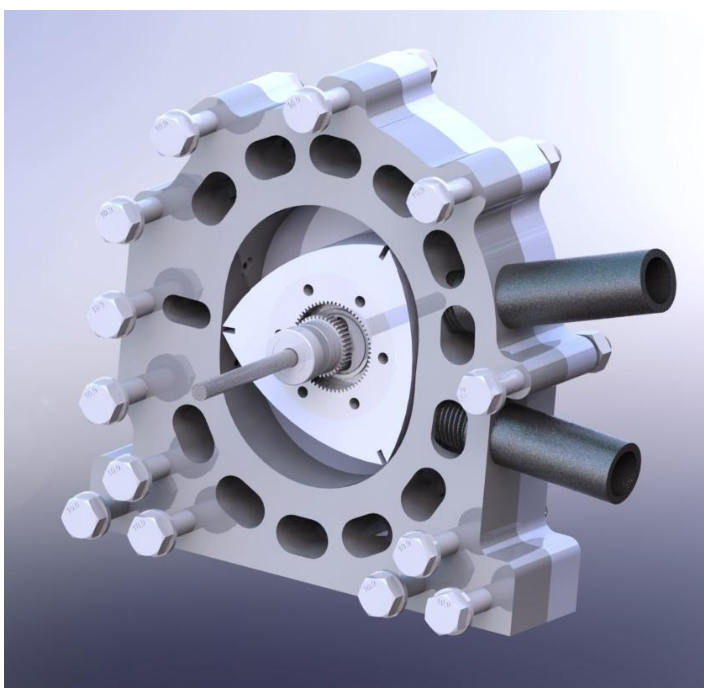


Figure 12. Sectional view of the MQP Single Rotor Wankel engine as designed in SolidWorks

3.1 Material Selection

One major issue with the Wankel engine is the sealing of the rotor within the housing to allow for a pressure build up in the compression chamber. For the team’s engine, the only mechanical sealing component of the rotor are the three apex seals, which are each located at the three tips of the rotor and seals between the rotor and the housing. Sealing components are exposed to heat and high pressures from combustion, as well friction from mating and rotation. To ensure the material selected for the team's engine would perform as intended, two tests were performed on apex seals from an existing Wankel engine the team had disassembled. The first test was a hardness test performed on a Wilson VH3300, several impressions were placed in 11 locations on the seal. The second test was a material composition test to find what alloy the seals were made of, completed in the Washburn materials testing lab with the help of graduate researchers.

Figure 13. Wilson VH 3300 Hardness testing machine located in Washburn Laboratories

The compression force of the diamond imprinting on the seal as well as the dimensions of the impression left allow for calculations to determine the Vickers hardness. This process began with creating a phenolic puck containing the seal using a phenolic powder and a Buehler press.

Figure 14. Buehler Phenolic resin puck-press located in Washburn Laboratories

The seal was then lapped down to a 0.5 micron finish using an AutoMet 250, shown in figure 16. This Machine had a pre-existing lapping system for unknown alloys, which was selected to polish the seal. After several cycles, the puck was examined using a microscope to ensure the surface roughness was able to be tested on the hardness tester. The result of each of these processes yielded the seal depicted below in figure 15, which shows the puck created to affix the seal in the hardness tester, and the test seal in the middle of the puck, which was taken from the working model Wankel engine.

Figure 15. Polished Apex seal in Phenolic resin

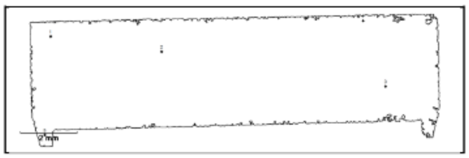
Figure 16. AutoMet 250 polishing and lapping machine located in Washburn Laboratories

Point	Hardness	Converted	Diagonal X	Diagonal Y	Comments	Magnification	Indenter
1	290 HV 0.2	28.46 HRC	35.7 µm	35.8 µm		40X	Vickers
2	267 HV 0.2	25.19 HRC	35.6 µm	38.9 µm		40X	Vickers
3	240 HV 0.2	20.44 HRC	39.4 µm	39.2 µm		40X	Vickers
4	279 HV 0.2	27.06 HRC	36.2 µm	36.7 µm		40X	Vickers
5	316 HV 0.2	31.78 HRC	33.5 µm	35.0 µm		40X	Vickers

Date: 20-02-2023

Figure 17. Apex seal hardness test 1 results with 0.2 kilogram force

Job data



Mean	Minimum	Maximum	Range	Std. deviation
279	240	316	76	28

Hardness Trace

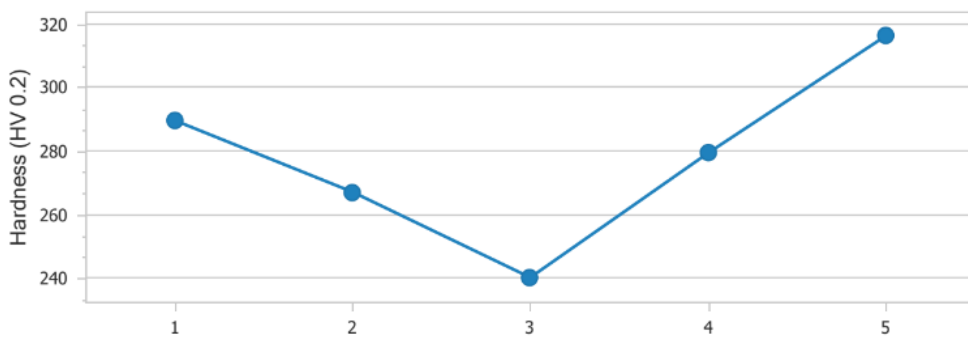
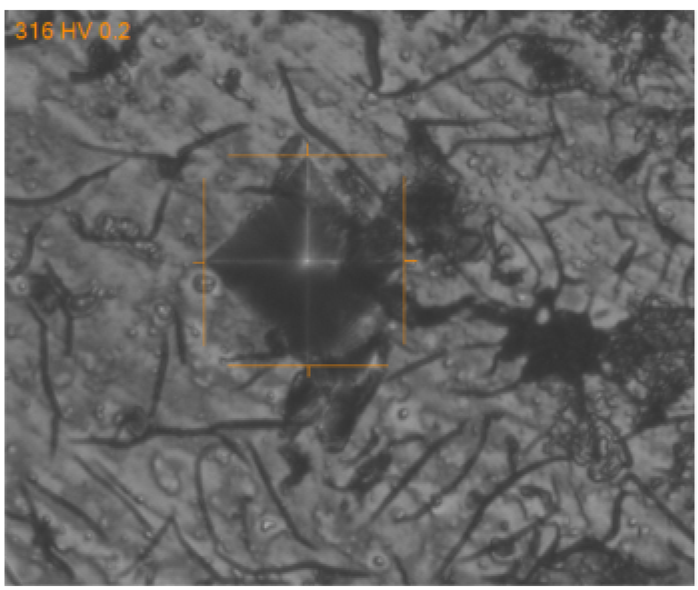


Figure 18. Map of seal as seen in Hardness tester as well as the Hardness (Vickers) plotted against the impression number

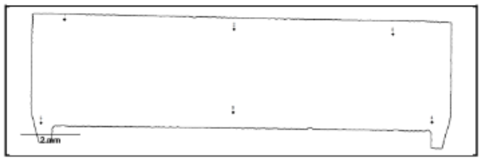
Figure 18. shows the data taken from the seal by the hardness tester at five different locations along the seal. The machine gave data in terms of Vickers hardness, which is the metric given for this specific type of testing. The size of the indentations left by the machine, shown in diagonal x and diagonal y, are used by the software to calculate the hardness at each point. The magnified indentation made by the machine at each point is depicted below in figures 19 and 21. Figure 17 shows the data output by the hardness testing software, where the outline of the seal tested is shown, a graph of the hardnesses at each location is given, and the mean hardness of 278 HV is given. In figures 20, 21, and 22, the hardness was tested five more times at different locations along the seal to ensure an accurate reading. In this job, the mean hardness was slightly higher at 294 HV, which could be attributed to the work hardening of the seal as it makes repeated contact with the sealing surfaces through its rotation in the engine.



5

Figure 19. Image describing how impression dimensions are collected to calculate hardness

Job data



Mean	Minimum	Maximum	Range	Std. deviation
294	211	384	173	61

Hardness Trace

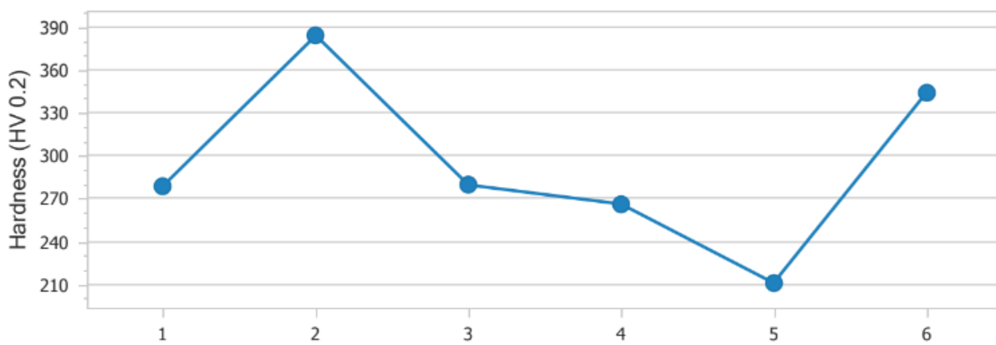


Figure 20. Map of seal as seen in Hardness tester as well as the Hardness (Vickers) plotted against the impression number

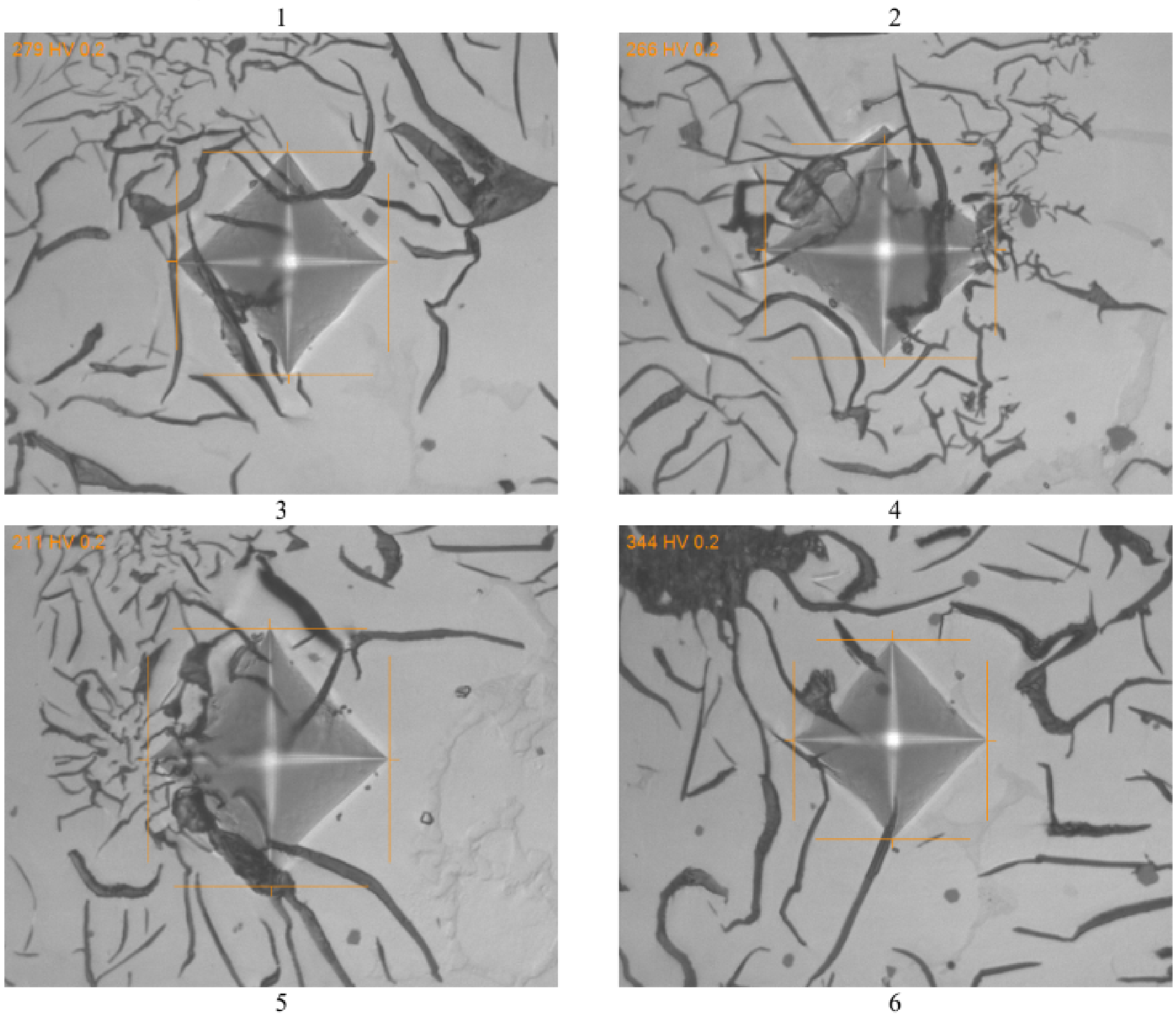


Figure 21. Image describing how impression dimensions are collected to calculate hardness

Point	Hardness	Converted	Diagonal X	Diagonal Y	Comments	Magnification	Indenter
1	279 HV 0.2	27.00 HRC	36.4 µm	36.5 µm		100X	Vickers
2	384 HV 0.2	39.19 HRC	31.4 µm	30.8 µm		100X	Vickers
3	279 HV 0.2	27.07 HRC	35.5 µm	37.3 µm		100X	Vickers
4	266 HV 0.2	25.03 HRC	38.8 µm	35.9 µm		100X	Vickers
5	211 HV 0.2	-	40.7 µm	43.2 µm		100X	Vickers
6	344 HV 0.2	34.86 HRC	32.3 µm	33.4 µm		100X	Vickers

Date: 20-02-2023

Figure 22. Apex seal hardness test 2 results with 0.2 kilogram force

Test Report Summary:			
Trial number (report #)	Minimum hardness value (HV 0.2)	Maximum hardness value (HV 0.2)	Mean Hardness value (HV 0.2)
1	240	316	279
2	211	384	294
Mean Values From Test 1 and 2:			
Parameter:	Mean minimum hardness value (HV 0.2)	Mean maximum hardness value (HV 0.2)	**Mean hardness value of trials 1 and 2 (HV 0.2)**
value:	225.5	350	**286.5**
Seal Sample Elemental Composition:			
Element	% of seal alloy material	+/- 3 sigma	
Fe	87.34	0.49	
Al	4.14	0.47	
Si	6.52	0.2	
Mn	0.574	0.081	
Ni	0.342	0.07	
Cu	0.107	0.047	
P	0.208	0.045	
Cr	0.058	0.032	
Zn	0.059	0.03	

Table 1. Results of Hardness testing and XRF plotted in Excel

Table 1 shows the results of the hardness and composition testing. The mean values of each test were averaged again to give an overall average hardness of the test seal of 286.5 HV.

3.2 Apex Seal Material Chemical Composition

In effort to determine the material properties of the seals, the term concluded an X-ray fluorescence Spectroscopic (XRF) test would benefit the determination of the alloy used in the sample seal. The XRF used was supplied by Washburn Laboratories and was executed by Materials Science graduate candidates. The results of the test are found in Table 1 (above), and were used to search which alloy fits this composition. The composition testing yielded that the material was an alloy consisting mostly of iron, aluminum, and silicon. Further research revealed that this is not a known alloy and was likely proprietary and or not a readily available material. Given this data, the team opted to create two sets of apex seals, one set made of cast iron, the industry standard, and one set made of brass.

The cast iron was selected for the seals because of its high strength and resistance to high temperatures. It has similar hardness properties depending on its manufacturing, with a Vickers Hardness of approximately 300. It is also easier to machine tight the tolerances needed for this application (*The Online Materials Information Resource - Cast Iron*). Cast iron is the final material selected for the engine's apex seals because it provides the properties and machinability required. Brass was also chosen as a sacrificial seal to be used during testing of the engine. Brass has a HV of about 100-120, which is far softer than the aluminum and steel rotor and housing (*Overview of materials for Brass*). Because the team wanted to limit scoring and damage to the engines components in the initial trials, brass seals would be destroyed well before the rotor and housing if there were issues while testing. The brass seals are far easier to machine and far cheaper than the rotor and housing, which was the main factor in deciding to use them for testing the engine's performance.

3.3 Rotor Material Selection

The material selected for the rotor was T6 6061 aluminum. This aluminum alloy is commonly used in automotive applications. One advantage of 6061 aluminum is its high fatigue strength, which is a measure of a material's ability to endure repeated loading over time without deformation. 6061 aluminum can endure 96.5 Mpa (14,000 psi), calculated with 500,000,000 cycles of cyclical loading under the yield strength . This metric is important for a rotor because it will be experiencing over 10,000 combustion cycles per minute, and a material with a low yield strength could deform while transferring the combustion forces to the eccentric shaft. A deformed rotor could seize the engine during operation, and could also cause improper sealing leading to lower compression and premature detonation of the air fuel mix. The relatively low density of 6061 aluminum, 2.7 g/cm^3, allows the rotor to have a lower mass, therefore decreasing the rotating mass of the engine and contributing to smoother engine operation and minimal engine vibrations (*All About 6061 aluminum (properties, strength and uses)*).

3.4 Spring Force Calculations

To properly seal the compression and combustion chambers, the force the apex seal exerts on the housing must be properly determined. The spring force must entirely seal each chamber while not over-exerting force to a suboptimal level where the kinetic friction is dramatically increased by the normal force between the housing and seal. In effort to determine this value for the custom application, the team tested existing seals out of a Mazda RX-7 as seen in Figure 23.

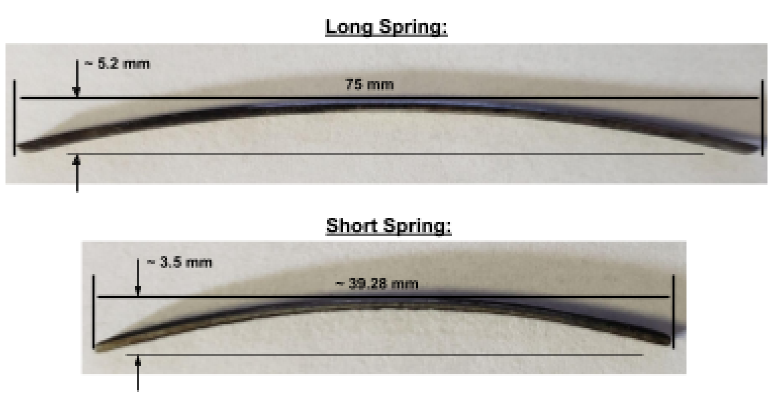


Figure 23. Leaf Spring dimensions used for spring constant calculations

Using the dimensions of each of these springs, the spring constant is calculable by the following equation:

$$F = k\Delta y$$

Spring	Travel distance	Force to fully compress	Approximate spring constant (K)
Short Spring	3.5 mm	2.5 Kg	714.285 Kg/m
Long Spring	5.2 mm	2.5 Kg	480.769 Kg/m

Table 2. Calculated spring constant values of apex seal leaf springs

Following the calculation of the spring forces for these springs, the team had to determine the force per unit length the seal exerted on the housing to apply these results to the team's design. Figure 24 below depicts the profile of the seals backed by the springs used in the above calculations.

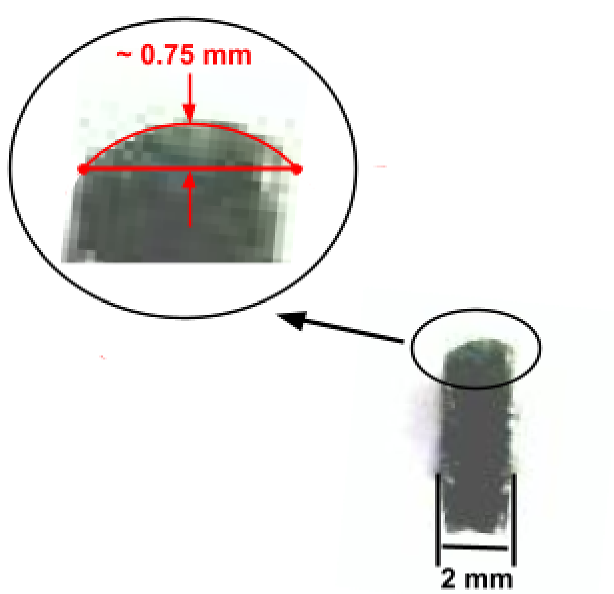


Figure 24. Contact profile of an Apex seal's mating face

Using the curved arc length and the flat seal width as well as the length to calculate contact area. Then, by dividing the maximum spring force by the contact area, the contact pressure can be found. Lastly, by dividing the contact pressure by the seal length, the pressure per unit length can be determined. These values can be found in Table 3, below.

Contact profile	**Minimum contact area**	**Maximum contact area**	**Maximum spring force**	**Minimum seal contact pressure**	**Maximum seal contact pressure**	**Approximate average seal contact pressure per mm compressed**
Flat	0.00016 m^2	0.00016 m^2	5.0 Kg	**44.4479 psi**	**44.4479 psi**	**10.056 psi/mm**
Rounded	0.00025639 m^2	0.00034186 m^2	5.0 Kg	**20.8330 psi**	**27.7367 psi**	**5.457 psi/mm**

Table 3. Calculated values of contact pressure per unit area. Note: Seal contact pressure is in PSI per millimeter to use metric units as in the team's design process.

From these calculations, the team was able to locate coil springs which had acceptable travel and spring force to allow the proper contact pressure per unit area.

3.5 Machining process

The process from idea to part begins with the completion of an agreed upon design, for this project, the team used SolidWorks 2022-2023 with the licensing provided by Worcester Polytechnic Institute. The tolerancing required for engine components is beyond that which manual milling can achieve unless performed by trained professionals. To meet the tolerance requirements, Computerized Numerical Control (CNC) milling was performed. CNC mills require an input called "G-code", this code defines the initial stock boundaries from which the part will be created, the tools used, the work offset, tool offsets, tool path, and the spindle speeds and stock feeds at every moment. To generate this code, SolidWorks has an "add-in" called SolidWorks CAM, this tool allows the user to define the tool and postprocesser to create a code compatible for the specific machine. Once the user selects a machine and the tooling they plan to use based on the part design stock size is defined as is the work offset. The Work offset describes the initial location from which the path coordinates can be generated. This location is called the G54 and is essentially the origin of the three dimensions in which the machining occurs. Next, features are "extracted" and SolidWorks can then create an acceptable tool path. The user then verifies the spindle speeds and stock feeds based upon the path and tooling. These values are determined mostly by the add in but can be verified by tables within Washburn, experience, as well as the lab monitors on duty. Once each feature has an acceptable path definition, the path can be sent to the post processor which turns the path into a compatible code for the machine. Many parts require multiple operations, a multi operation part can be created within the same file by creating a "new set-up" within the tool and repeating the process above. Once each feature is completed, the machine set up can begin.

To set up the machine, the user must power on and allow for the machine to warm up. During this time, the selected tooling can be assembled with the compatible tool and collet. Each chuck and nut must be torqued to 90 pound feet with the torque wrench at the workbench. Tools can then be loaded into the machine turret. The G-code defines the tool number associated with each tool and turret location, the user must insert the tool in the respected turret location using the prompts on the machine. Stock can then be loaded into the vice, stock must be placed on parallels which allow the machining operations to be completed without the tool hitting the vice while maintaining proper clamping force. At this point each tool can be touched off, by editing the "tool offsets" in the machine, tool lengths can be defined for each tool. This process defines the length of the tool to fully describe the location at which the tool will begin interfacing the part. Next, “work offset” must also be defined by using the probe in the machine, by editing the machine memory, the G54, or origin, as described in the paragraph above can be located. By touching the probe off the three planes of the stock, the X,Y, and Z positions of the pre-defined origin can be created.

Lastly, the user must drag the G-code into the machine via the program list tooling prompt. By searching the code’s name and selecting it, the machine can then add the code to its internal memory. The user can then “cycle-start” the tool paths and begin cutting. During the operation, the user should be observing spindle speeds, stock feeds, and spindle loads to ensure all of which are safely within the acceptable ranges as defined in the G-code and machine interface. Once the first operation is complete, if a secondary operation is required, the user can then orient the part in the vice as defined by the G-code. Definition of “work offset”, would have to be re-created for the new operation, “tool offsets” however will remain in the machine memory. Once all part operations are complete, any required post processing can be completed by hand. Due to limitations of machining, all parts were deburred. Parts that required further machining were the housings, while all other rotating and sealing parts required hand finishing.

Limitations of surface roughness from the milling operation as well as the end mill used enforced the requirement for the housings to be surface ground. A surface grinder has a flat magnetic work holder and a grinding wheel which, at high RPM contacts the part. The grinding head remains in place as the operator utilizes handles which jog the part in the X, Y and Z directions.

Figure 25: Rotor housing being surface ground in Washburn Laboratories

Once all surfaces of the housing were ground, this process was checked with a flat stone and a light. Ground surfaces were placed on a flat stone and a light was shined from all directions to determine the finish of these faces and validate the grinding process. This process consequently reduced the overall thickness of the center housing, requiring the rotor to be lapped to a smooth finish within the required tolerance. To accomplish this, a finishing paper of 220x was placed on the flat work holder of the grinder and the rotor was lapped by hand in a figure-eight pattern. The rotor was frequently flipped to even the material removal on each face and ensure the same finish on both sides. An engineering square was placed on top of the rotor inside the housing to verify the thickness of each component was uniform and within the tolerance of the copper gaskets being used.

The eccentric lobe and shaft also required post processing by hand in order to construct the eccentric shaft. The shaft was placed in the recess within the lobe and TIG (Tungsten Inert Gas) welded. This welding method was chosen to carefully control the puddle location as well as the assembly temperature to mitigate warping. Using the workholding available within Washburn, the runout of the eccentric shaft within the housing plates was negligible as no bonding occurred in any of the engine bearings. Apex seals required a less intensive filing procedure to remove the excess material required to hold the part in the mill. Once machining was complete, seals were held in a vice and the excess material was filed down to the specification of the seal's design.

The final processing tool used were the laser cutters available in Higgins Laboratories. To properly create a seal with the exact geometry of the housing, the face sketches of the housings were extracted as laser cutting files. These files were uploaded to the laser cutter, the gasket material and thickness were imported to the machine to determine the laser speed and temperature. Once the foil was placed in the machine bed, the corner was located by the operator using the bed corner and cutting could begin. These gaskets properly sealed the housing fluid paths in large part due to the accuracy and precision of laser cutting machines.

3.6 Engine Assembly

The assembly process of the engine is imperative to the operation of the rotating assembly. The process begins with pressing the shaft bearing and pinion gear into the housing; tight tolerances of these recesses required large amounts of force applied via a press. Next was the application of PTFE (Poly-tetra Fluoro-Ethylene) tape to each of the oil and water fitting threads, this tape seals the threads eliminating the helical fluid leakage path. Each fitting was then fastened in the proper location to the depth of the pipe thread on the fitting. With the housing nearly complete the rotor can be assembled.

The first step is to press in the bearing and ring gear. Force is again required and must be applied in a square, uniform manner. With the gear secured in place, the retaining screws can be threaded into the holes in the gear recess to fully secure the gear in place. Next, the coil springs were pressed into the spring recesses within the rotor, and the seals were added to each slot; it is important to ensure the springs are properly retained within the recesses of the seal. The rotor can then be hung on the pinion gear on the housing. Using the eccentric shaft to align the rotor and mesh the gears, the lobe can fit through the recess as the shaft slides through the shaft bearing in the housing. It is important to have the gasket on the face of the housing before aligning the middle housing with the endplate. By first adding the gasket to the remaining side and carefully sliding the shaft into the endplate the main assembly is mostly complete.

The final assembly of the engine requires two people, a one way bearing and three wrenches. With the one way bearing allowing the proper direction of rotor rotation, person one must continually spin the shaft while person two fastens all block bolts. Person two must use a head bolt with a washer on each side and a nut. By first putting each bolt assembly through the proper holes in a pattern which alternates the direction of the bolt and hand tightening each nut the torque procedure can begin. Starting in the middle, at the bolts inline with the shaft, fasten the bolts to 13 pound feet. Working in an alternating pattern across the face of the block, continue torquing while the rotor spins. The pattern is identical to that which is used in fastening head bolts. If at any point, person one feels binding of the rotating assembly, loosen each bolt in reverse order and assess the issue. Once all bolts are fully torqued, in a circular pattern, confirm all bolts are at the same torque. With the long block assembly complete, ancillary components can be added and test bed assembly can begin.

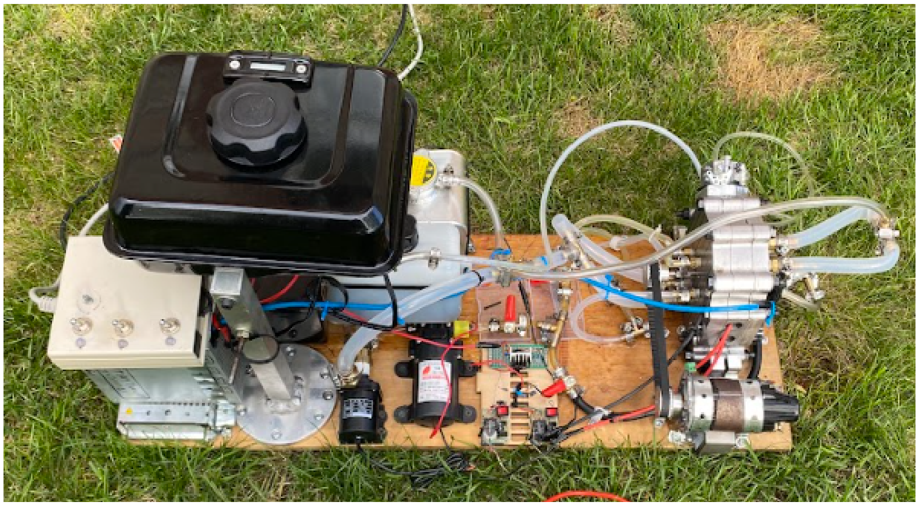


Figure 26: Complete Engine and Test Bed Assembly

3.7 Ignition System

Wankel ignition is dissimilar from piston-cylinder engines in that the compression and combustion strokes are combined. This in turn means each pass through the combustion chamber requires the spark plug to fire, as such this requires an ignition system similar to a two stroke engine with the additional consideration that each full rotation requires three spark cycles. To fully combust the fuel in the combustion chamber, there are two ¼-32 thread RC aviation spark plugs which fire simultaneously. These spark plugs can,with limited modification, can be timed to fire sequentially if further tuning is required in the future.

The operation and design of the ignition timing circuit is based on the use of semiconductors to smooth and amplify the changes in voltage produced by a hall effect sensor when a magnet is in close proximity. In this circuit, when switch (*d*) in the figure below is closed, current from the PSU (*b*) flows through the electromagnet windings in the relay (*e*) closing its contacts feeding 12V DC to one of the output terminals on the solid state relay (*g*).

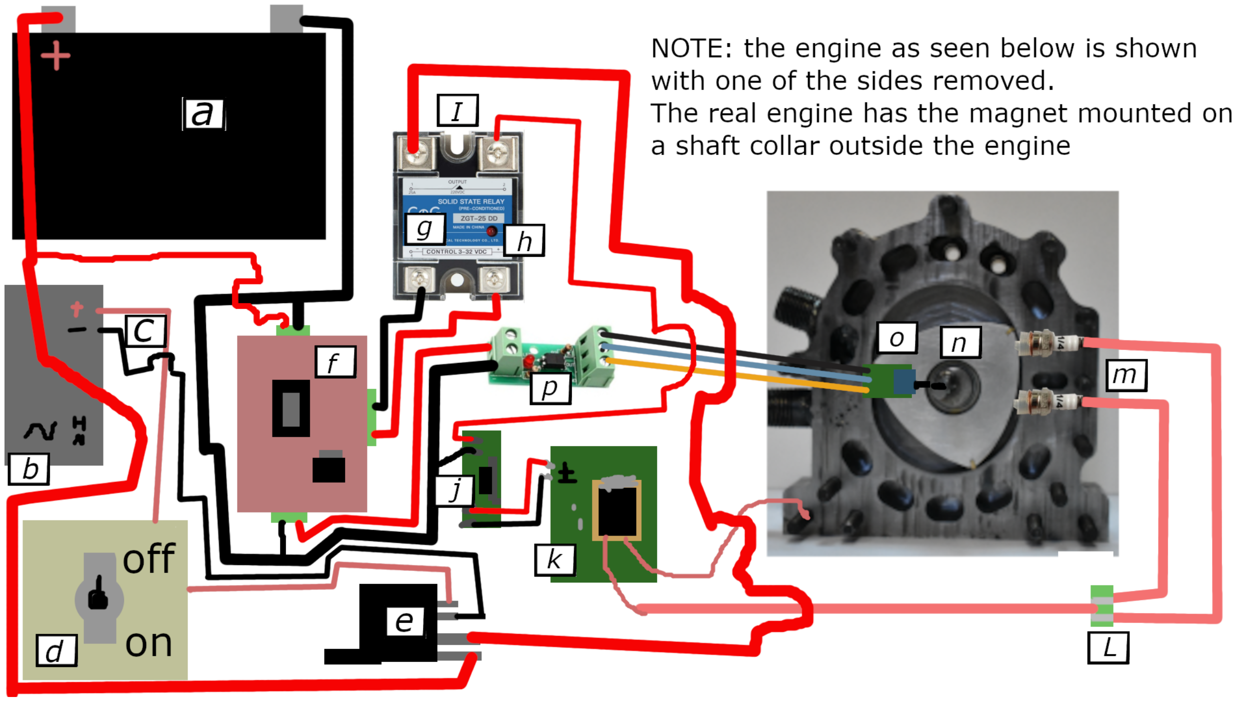


Figure 27. Component block diagram of ignition system

After powering up the system by flipping switch (*d*) in the bottom left corner of the figure above, the engine can be turned clockwise when facing the engine the same way as shown in the diagram above. With the shaft turning, the magnet will pass the Hall effect sensor, triggering a change in voltage at the optocoupler input which inturn turns the output of the coupler on and off as the magnet rotates with the shaft.

The next block in the circuit, the ignition signal amplifier, serves to correct the sinusoidal waveform of the raw output of the optocoupler. This block is based on a NPN transistor and an LM386 operational amplifier configured as a non-inverting comparator. The LM386 IC is provided with 12V DC and GND as its rail voltages and the reference voltages were set to the following: LOW<~1.5V, HIGH>~7.5V using the formulas and sample circuits provided in LM386's datasheet (*LM386 low voltage audio power amplifier datasheet (rev. C)*). The voltage vs time graph of the ignition trigger signal at the input and output of the LM386 IC is shown in the figure below.

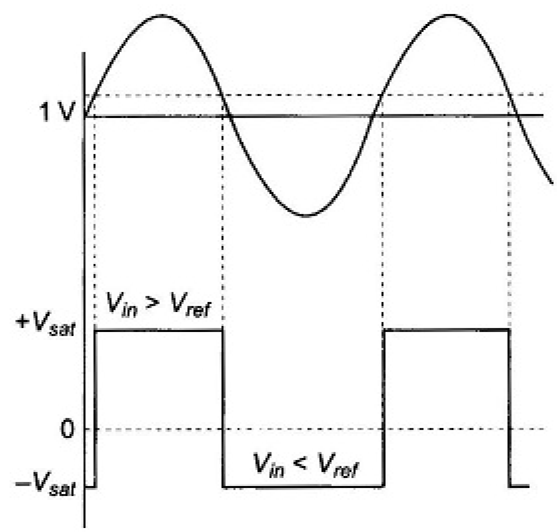


Figure 28. Graph of input to the ignition trigger signal amplifier (top curve) VS the output waveform (bottom curve) (Eeeguide, 2023)

The final stage of the ignition trigger signal amplifier is a 2N2222 based NPN transistor with +12V DC from the battery connected to the collector pin of the transistor and the final output signal wire connected to the emitter. The output of the LM386 is connected to the base pin of the transistor which inturn outputs the same waveform at the collector but with much more current and heat tolerance. The higher current square wave output is then utilized as the input signal for a self contained and internally isolated power transistor module (typically referred to as a solid state relay) which switches the main 12V supply to the voltage regulator and the ignition coil beyond it. A table describing the ignition system components, their function, and their connections to other components are listed in the table below.

Label Letter	Part or Setup Name	Part or Setup Function	Connections
a	12V lead acid battery	Main 12V DC voltage source	1.) Ignition trigger signal amplifier 12V power input 2.) GND 3.) Switched contact of relay (*e*)
b	110V to 12-13V DC PSU	Power pumps, charge battery when engine off	1.) Relay (*e*) coil pin connects to negative DC out 2.) second relay coil pin connects to DC GND terminal on PSU
c	12V control voltage power output terminals	Power to switch and main coil relay (*e*) electromagnet	1.) Spark enable/disable switch (*d*) 2.) coil pin on relay (*e*)
d	Spark enable/disable switch	Turns on and off source voltage to the solid state relay(*g*)	1.) Relay (*e*) coil input pin 2.) +12V DC output from PSU (*b*)
e	Main coil relay	Switches high current 12v battery connection to the ignition coil pack (*k*)	1.) Negative terminal DC output from PSU (*b*) 2.) positive DC 12v output from PSU (*b*)
f	Ignition trigger signal amplifier	Eliminate sensor noise, prevent voltage leak on low signal at the output of optocoupler (p) from triggering coils.	1.) GND 2.) +12V from battery 3.) optocoupler +12v (very low current) output 4.) +- trigger input on the solid state relay
g	Solid state relay	Turns on and off power to the HV ignition coil when hall sensor (o) is triggered	1.) +12V from relay (*e*) output pin 2.) 12V input on LM388T voltage step down circuit (*j*)
h	Solid State Relay 12V medium current input	Triggers solid state relay (g).	1.) +- DC 12V output signal of signal amplifier (*f*)

I	Switched output of solid state relay (*g)*	Provides power when triggered to the ignition coil.	1.) Ignition trigger signal amplifier output wired to input of solid state relay 2.) 12V input from relay (*e*)
j	LM388T voltage step down circuit	Steps down the 12v from the battery to the 3.7V required by the ignition coil.	1.) +- 3.7V DC inputs to ignition coil 2.) GND 3.) +12V from battery
k	High voltage ignition coil board	Steps up the 3.7V input voltage to 10-15 KV AC at the output to the	1.) Terminal block (*L*) 2.) neutral bolted to rotor housing 3.) GND 4.) switched 5V output from LM388T
L	Terminal block as plug wire splitter	Distributes the HV output from (*k*) to both of the sparkplugs	1.) spark plug hot terminals 2.) coil pack HV output wire
m	sparkplugs	Provides arc gap for spark inside the combustion chamber to jump and ignite the air fuel mix.	1.) High voltage AC hot wire from coil 2.) High voltage AC neutral wire bolted to rotor housing
n	Trigger magnet	Is fixed to the shaft so that the hall sensor is triggered whenever the rotor is oriented as it is in figure 27.	Mounted to the motor output shaft flange aligned with the sensor.
o	Hall effect sensor + sensor connector	Allows increased current flow across the sensor only when the trigger magnet is in very close proximity to the sensor.	1.) Optocoupler (*p*)
p	Optocoupler	Electrically isolates the hall sensor from the rest of the circuit and instead passes the signal from the hall effect sensor across the device to the signal	1.) Hall sensor leads 2.) GND 3.) Ignition trigger signal amplifier + voltage signal in

		amplifier using an internal LED and photoresistor.	

Table 4. Ignition system components, function, and connections to other components

3.8 Fuel and Fuel Delivery

Initially, the fuel for this engine was to be Nitro-methanol which was to be delivered via carburetion and ignited with the use of glow plugs. Upon arrival of several glow plugs designed for small engine applications, lack of reliability was evident. Also of issue was the inability to combust the fuel via the heat of the plugs with the compression of the engine. Due to these challenges, the team's design transitioned to gasoline fuel and thus, spark plugs. The carburetion delivery system remained carburetion to mitigate costs and complexities of designing optimal injector flow for the team's low displacement engine. Due to the oil-burning nature of Wankel engines, the team concluded a 2 stroke fuel-oil mix would be best to minimize internal friction and the chance of complications due to high heat. As this became the system of choice, Professor Guceri graciously supplied the team with a small engine two-stroke carburetor.

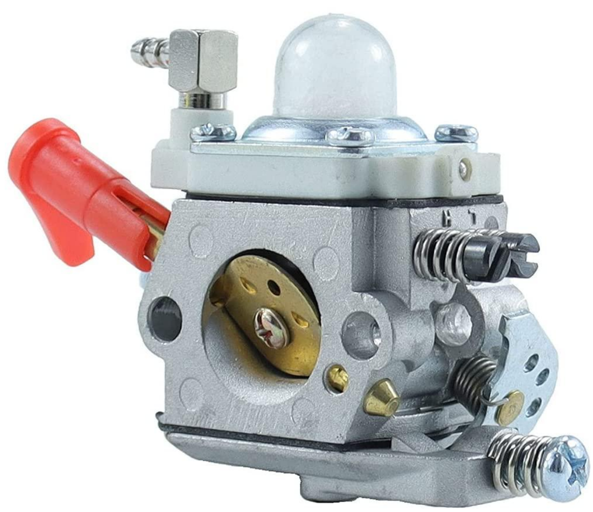


Figure 29. Carburetor model supplied by Professor Guceri which was used on the engine assembly (Amazon.com: Walbro Carburetor WT)

To ease the initial starting process and promote successful combustion, Di-ethyl ether was introduced to the carburetor along with the fuel. The purpose for this is the extreme volatility of this chemical compound. Di-ethyl ether is commonly referred to as starter fluid and is used as it is more volatile than gasoline, thus, reducing the octane level of the fuel below 87 (regular pump gas). The reduction in octane level results in a fuel which will combust at lower compression. Once the initial combustion occurs in the engine, di-ethyl ether is no longer sprayed in the carburetor as the combustion chamber is at an increased temperature allowing for combustion to occur more easily.

3.9 Testing Procedure

The first step to testing the engine was mixing the fuel needed to power the engine. Because the team was concerned about apex seal wear and proper lubrication of the engine, two stroke fuel was used, which is a combustible mixture of fuel and oil. The off-the-shelf two stroke oil was mixed with pump gasoline at a ratio of 32 parts oil to one part gasoline. The recommended ratios are usually 40:1 to 50:1, but the team decided to use more oil to greatly improve the lubrication and sealing of the combustion chambers.

Next, the team added the fuel to the fuel tank, and primed the carburetor by pressing the purge bulb. This bulb acts as a diaphragm pump, and circulates the fresh fuel mixture through the channels in the carburetor to be used by the engine. This step removes the air from the closed system of the carburetor, and acts to fill the reservoirs in the carburetor that allow the internal fuel diaphragm pump to continually supply the fuel mixture to the engine.

The team then adjusted the carburetor’s choke and idle. The choke on a carburetor restricts airflow during the starting of the engine, to provide a far richer fuel air mixture to the combustion chamber to aid in startup. Because this air fuel mixture only serves the engine at startup, the choke butterfly valve is opened to allow for more airflow after the engine first fires. This valve was actuated by hand based on the response of the engine, i.e. when the engine started to fire, the choke was opened.

After, the oil pump was run to lubricate the sides of the rotor against the housing. This was done before starting to prevent metal on metal contact during movement of the rotating assembly, as well as to seal the combustion chambers. A very heavy oil was used for this purpose, which was MasterPro SAE 85W-140 gear oil. Typical engine oil is around 30 weight, making this gear oil extremely viscous comparatively. A heavier oil was used because of its intended purpose of sealing the combustion chambers. A thinner oil would flow far more easily and therefore would be forced out of the injection area by gravity and the centrifugal forces of the rotating assembly. The heavier oil is far harder to remove from its injection points and therefore serves as a better seal. It is important to note that the pump should be run for a very short time, several seconds at most. Because this is an oil injection point and not a closed circuit, all oil pumped into the engine will stay in the engine. If the pump were to run for too long, the combustion chambers would fill with oil and the engine would not rotate because it is filled with an incompressible fluid. Ideally, this pump would run in pulses to supply oil to the engine based on the rpm’s and load placed on the engine.

The high and low idle screws on the carburetor were also adjusted. These screws serve to adjust the air fuel mixture being supplied to the engine at different rpm ranges, where the low idle controls the fuel delivery to the engine at low rpm’s and the high idle serves the engine along with the low idle at high rpm's. This is because as the rpm's are increased or more power is required, the two circuits within the carburetor respond to the changes in vacuum being created by the engine's intake. These screws were both turned all the way in until they bottomed out, and then were backed off by 1.5 turns each to open the fuel circuits. These screws were then microadjusted during operation of the engine until a smooth power delivery was achieved. The throttle valve was actuated by hand, which controls how much air fuel mix is able to enter the engine. At startup the choke is closed and the throttle is left fully open. As the engine starts to fire the choke is closed and the throttle is to remain open, only starting to be closed when the engines rpm's climb to the desired output. Because several of the team members were employed as mechanics or were very familiar with engines, all these decisions and adjustments were made based on past experiences and training, as well as the sound and output of the engine, which was used to determine the type of adjustments that needed to be made.

The next step in starting the prototype Wankel engine was to turn on the ignition circuit, which is item D in the figure above denoting the ignition system. After, a cordless drill was attached to the output shaft to rotate the engine in order to draw in air and fuel, and fire the spark plugs. When facing the engine with the carburetor and exhaust on the right hand side of the engine, the output shaft will rotate counterclockwise during engine operation. With the drill connected to the output from this side, it is important to spin the drill in the counterclockwise direction, otherwise the engine will not ignite and damage could be caused. When ignition begins, the drill should immediately be removed from the ¾ inch hex on the output shaft collar in order to prevent damage to the drill or engine.

4.0 Results and Findings

Engine Specifications

Housing Material	1045 Carbon Steel
End Cap Material	1045 Carbon Steel
Rotor Material	T6 6061 Aluminum
Apex Seal Material	Cast Iron
Side Gasket Material	Copper Foil
Gasket Thickness	0.5 Millimeters*
Rotor Side Sealing Oil	MasterPro SAE 85W-140 Gear Oil
Ring to Internal Gear Ratio	3:2
Coolant	Water
Mass of Assembly	~40 lbs.
Displacement	~25 Cubic Centimeters
Fuel Type	Gasoline
Fuel Mix	32:1 (2 Stroke Small Engine)
Spark Plugs	RC EXL ¼-32 (QTY: 2)
Base Carburetor	Walbro WT-997, Zenoah CY RCMK Losi
Power Supply	12 Volts

Table 5. List of single rotor Wankel engine specifications

4.1 Challenges

The limitations of the team's design fell into one of each of the following categories; stock availability (size and price), machinability with Washburn tooling, and maintaining geometric requirements to achieve combustion. Limitations the team first addressed were in the project outline, keeping the engine to approximately the “size of a watermelon” as proposed by professor Guceri. To remain within this requirement, the team had to scale down the engine while maintaining the strength required to withstand the internal forces of an engine. The next most impending issue was the housing material selection and machining. Housings of Mazda Wankel engines have a chrome lining within the epitrochoidal recess, this however was not within reason for the teams timeline and budget. To meet this, the team elected to use a much more available A36 steel, which is both budget friendly and machinable with the tools accessible in the machine shop. This choice however became a drawback as automotive grade T6-6061 aluminum was selected for the rotor material. The choice to use aluminum, along with those outlined in section 3.3 was due to the ease of machining. Several rotors were machined as prototypes and to refine the machining process. Bi-metal corrosion between the steel housings and aluminum rotor became a topic of interest, this was addressed with proper side sealing.

Side sealing is of the utmost importance, especially in large scale Wankel engines. Both to enclose the chambers within the housing as well as maintain the perpendicularity between the rotor and the eccentric shaft. A secondary benefit of side sealing is that the rotor never contacts the housing. In the prototype engine, the team elected to use an injected oil film. This effectively removed the issue of bimetal corrosion, has an effective sealing ability between chambers, and maintains the proper angle between the shaft and rotor. The additional mitigation of internal bimetal corrosion is the oil mixed into the fuel; use of a two-stroke mix introduces a lubricating film within the engine removing any contact of the rotating assembly with the housing.

The challenges associated with determining the proper material for the apex seals of the engine were covered in section 3.2, the next issue associated with sealing was the method by which to apply the contact pressure, and the retention of both the springs and the seals. After the calculations in section 3.4, the team concluded the more commonly used leaf springs would be impossible to source at the custom sizing of the rotor within the time allotted. To match the required contact pressure, coil springs were implemented. The springs used would be in pairs for each seal. One coil spring was placed at each edge of the seal slots in the rotor. The first step in the machining for this process being to make the slot for the seal, locating the vertices of the rotor required precision in fixturing and probing as discussed in section 3.5. Though this process was time consuming, the drilling for the spring recesses was even more challenging. Holes had to be machined with tight tolerances within the existing slots at a diameter of two millimeters at a precise depth for the springs chosen. The team used lengthy two millimeter end mills to bore these holes and suffered one instance of wobble where the spindle speed was too high with too low of a feed. This resulted in a recut of chips within the slot leaving a small marring on the rotor. To amend this, the rotor was lapped by hand which both removed any such burrs as well as brought the rotor down to final surface finish and thickness.

After the retention bores were completed, the issue of finding the correct travel distance and keeping the spring compression linear became the next project. Once the determination of coil springs was finalized, the seal design was fitted with small recesses on the inner edge to receive the top of the spring. The recess both aligns the spring at the top as well as keeps the seal mechanically fixed to the spring which is pressed into the respective bore. Travel and seal dimensions were constrained to the dimensions of the slot within the rotor. To fit the seal thickness, each seal was lapped by hand to perfectly fit within the slot. Travel however was determined to be imperative for the brass seals which will wear at a much higher rate. After several trial fittings. Trials determined that the smoothest rotation of the rotor while maintaining proper contact pressure was where the seal would have five millimeters of travel and wear between the spring and seal. This however is just the initial iteration, as the engine continues to be used, contact pressure will change over time and seals should be changed before the full wear is achieved.

Due to the volume of the engine, it was originally designed to run on nitro fuel. Nitro fuel is composed of methanol, nitromethane, and oil (*Nitro fuel and gas for RC Cars: Buy Online: VP racing fuels, inc.*.). Oil is included within the mixture because the engine needs to be well lubricated internally without the additional complexity of an oil sump. Nitromethane is added in order to increase the rate at which fuel can burn within the engine. Methanol is the main source of ignition within the fuel mixture and can be easily ignited with glow plugs. Because nitro fuel was the original design for the engine, multiple types of glow plugs were purchased. Depending on the amount of nitromethane within the mixture, different glow plugs will work better. The additional advantage to nitro-methanol fuel with glow plugs is the subsequent elimination of spark timing. Similar to diesel, the fuel combusts from high compression and the addition of heat to the system via glow plugs. By heating the engine with glow plugs at start up and continually running, the engine will maintain a temperature and compression high enough to fully combust any fuel in the combustion chamber.

When selecting the external components that would actually make the engine run, the team initially had some problems with the ignition system. When the team was testing the feasibility of using glow plugs as the primary source of ignition for the rotary engine, the team discovered that the fuel mixture cooled down the glow plugs to the point where the heat from the glow plugs could not ignite the fuel mixture, despite numerous attempts and variations of fuel. With this discovery, the team made the decision to switch to spark plugs instead of glow plugs to ensure that the fuel mixture in the rotary engine will ignite. Because of the switch, an ignition system had to be created that would time the spark plugs in conjunction with the rotor turning at a slower rate than the axle. For the timing, a neodymium magnet would be attached to the eccentric shaft and would pass a hall effect sensor, which sends a signal to an ignition coil, which will activate the spark plug.

The final issue related to the build of this project came in the machining fixturing required to optimize the angle of the intake port. Our research and measurements based on existing models provided by Professor Guceri determined the location along the epitrochoid in which the center of the intake port should be placed is imperative. Our findings concluded that the port should be perpendicular to the tangential of the epitrochoid when the rotor is entering the intake phase. This allows the intake gasses to flow into the chamber as the rotor face breaks the plane of the intake port.

Broader Impacts of This Project

As the first generation of this Major Qualifying Project, a foundation has been laid by the two teams proving the concept of the goals and outline presented to us. Future seniors at Worcester Polytechnic Institute can continue the process of improving the Wankel engine design. The impact of optimizing the emissions and fuel consumption of a high power to weight ratio engine will have both financial and environmental impacts on the future of the internal combustion engine. Professor Guceri has voiced his concerns about battery powered motors and the advancements needed in the battery technology in order to make them a viable and environmentally friendly option for a wide range of uses. In the meantime, it is important to continue to innovate these gasoline powered engines to make them as efficient, reliable, and environmentally friendly as possible.

References

50 years of Rotary Revolution: We are Mazda. 50 YEARS OF ROTARY REVOLUTION | We are Mazda. (n.d.). https://www.mazda.com/en/innovation/mazda-stories/mazda/rotary_revolution/#:~:text=Mazda's%20rotary%20engine%20debuted%20in,automotive%20history%20in%20the%20process.&text=Without%20the%20rotary%20engine%2C%20there,production%20for%20nearly%2050%20years

All About 6061 aluminum (properties, strength and uses). Thomasnet® - Product Sourcing and Supplier Discovery Platform - Find North American Manufacturers, Suppliers and Industrial Companies. (n.d.). Retrieved May 2, 2023, from https://www.thomasnet.com/articles/metals-metal-products/6061-aluminum/

Amazon.com: Walbro Carburetor WT. Amazon.com. (n.d.). Retrieved May 2, 2023, from https://www.amazon.com/walbro-carburetor-WT/s?k=walbro+carburetor+WT

Branch, Ben. (2022). An NSU Ro80: The Rare Wankel Rotary-Powered Sedan That Killed Its Maker. *Silodrome.* March 11, 2022. https://silodrome.com/nsu-ro80-car/#:~:text=Fast%20Facts%20%E2%80%93%20The%20NSU%20Ro80&text=The%20NSR%20Ro80%20is%20powered,the%20era%20%E2%80%93%20just%200.355%20Cd

Eeeguide. (2023, March 6). *OP amp comparator circuit: Comparator Output Waveform*. EEEGUIDE.COM. Retrieved May 2, 2023, from https://www.eeeguide.com/op-amp-comparator-circuit/

Froede, Walter G. (1961). The NSU-Wankel Rotating Combustion Engine. *SAE Transactions. 69(*1). 179-193. https://www-jstor-org.ezpv7-web-p-u01.wpi.edu/stable/44553915?seq=3

Hege, J. B. (2007). *The Wankel Rotary Engine: A History*. McFarland.

Irimia, S. (2022, December 1). *The legendary Mazda 787B – the only rotary-powered car to win at Le Mans*. autoevolution. https://www.autoevolution.com/news/the-legendary-mazda-787b-the-only-rotary-powered-car-to-win-at-le-mans-205310.html

Kitman, Jamie. (2023, April 19). *The NSU Ro80 Was a Revolution (And a Total Failure).* Road & Track. Retrieved April 27, 2023, from https://www.roadandtrack.com/car-culture/a43643712/nsu-ro80-complete-story-book-review/

LM386 low voltage audio power amplifier datasheet (rev. C). LM386 Low Voltage Audio Power Amplifier. (n.d.). Retrieved May 3, 2023, from https://www.ti.com/lit/ds/symlink/lm386.pdf?ts=1612350151545

Moto. (2022, September 27). *Review of hercules W 2000 1974: Pictures, live photos & description hercules W 2000 1974 > lovers of motorcycles*. Lovers Of Motorcycles. Retrieved May 2, 2023, from https://loversofmoto.com/hercules-w-2000-1974/

Nitro fuel and gas for RC Cars: Buy Online: VP racing fuels, inc.. VP Racing. (n.d.). Retrieved May 2, 2023, from https://vpracingfuels.com/product-category/rc-hobby/car-blend/

Overview of materials for Brass. Overview of materials for brass. (n.d.). Retrieved May 2, 2023, from https://www.matweb.com/search/DataSheet.aspx?MatGUID=d3bd4617903543ada92f4c101c2a20e5

Sherman, Don (February 2008). "The Rotary Club" *Automobile Magazine* pp 32-79

Szymkowski, Sean (14 April 2021). "Mazda MX-30 EV lands in the US this fall, rotary engine revival to follow". *CNET*. Retrieved 15 April 2021.

The Online Materials Information Resource - Cast Iron. MatWeb. (n.d.). Retrieved May 2, 2023, from https://www.matweb.com/search/DataSheet.aspx?MatGUID=6291a24572754cae94ff365ed99b96f9&ckck=1

Thomson, L. (2020, February 18). *[video] listen to a Crazy Mazda RX-7 group B car rev to 10,000RPM: GRR*. Goodwood. Retrieved May 2, 2023, from https://www.goodwood.com/grr/race/historic/2020/2/video-listen-to-a-crazy-mazda-rx-7-group-b-car-rev-to-10000rpm/#:~:text=Based%20on%20the%20first%2Dgeneration,to%20a%20huge%2010%2C000rpm

Transformation of the Racing Rotary Engine (RE). Transformation of the racing rotary engine (RE). (n.d.-a). https://www.mazda.com/en/innovation/lemans30th/r26b/

Yamamoto, K. (1981). *Rotary engine*. Sae Soc Of Automotive Eng.

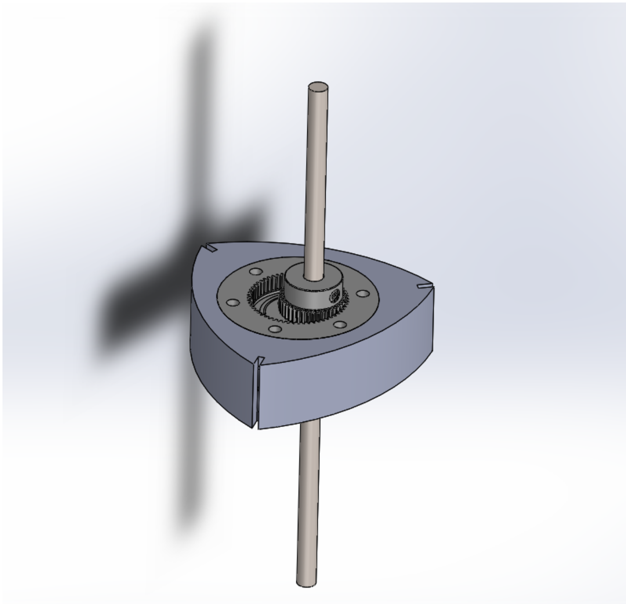
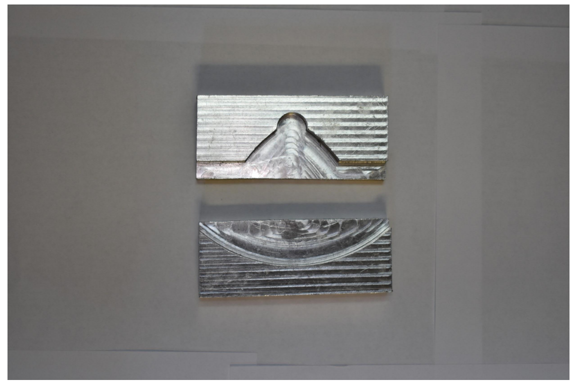
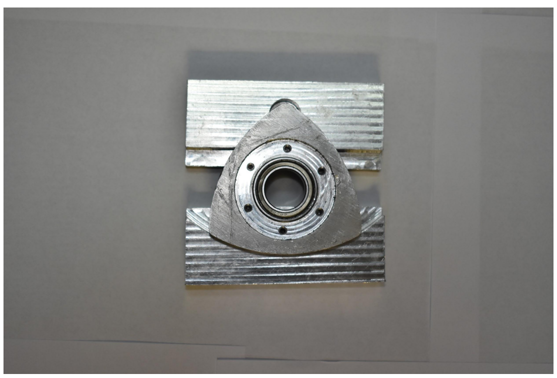
Yamamoto, Kenichi. (1971). *Rotary Engine.* Toyo Kogyo Co., Ltd.

Appendices

Component	Quantity
Rotor Housing	1
Housing Rear face	1
Housing Front Face	1
Rotor	1
Intake Port Pipe	1
Exhaust Port Pipe	1
Housing Bolts	13
Housing Bolt Washers	26
Housing Nuts	13
Internal Gear	1
Ring Gear	1
Rotor Ball Bearing	1
Housing Bearing for Eccentric Shaft	1
Eccentric Shaft	1
Copper Foil Gaskets	2
Male Brass Barb Fittings for Side sealing	8
Male Brass Barb Fittings for Coolant	8
Spark Plugs	2
Carburetor Flange	1
Carburetor Gasket	1
Carburetor	1
Fuel Line	3 Feet
Oil Line	1 Foot
Coolant Lines	1 Foot
Fuel Tank	1
Fuel Tank Stand	1
Water Pump	1
Oil Pump	1
Engine Block Tie Downs	4
Electrical Control Board	1
Ignition Coil	1
Ignition Circuit	1
12 Volt Battery	1
Power Supply	1

Female Brass Barb Fittings	2
Coolant Reservoir	1
Oil Reservoir	1
PTFE Tape	1 Roll
10-40 oil	1 Quart
Di-ethyl Ether	1 Can
Gasoline	2 L
Vibration absorbing Rubber Pads	4
Starter Motor	1
Timing Belt	1
Base For assembly	1 Board

Table 5. Final assembly materials list

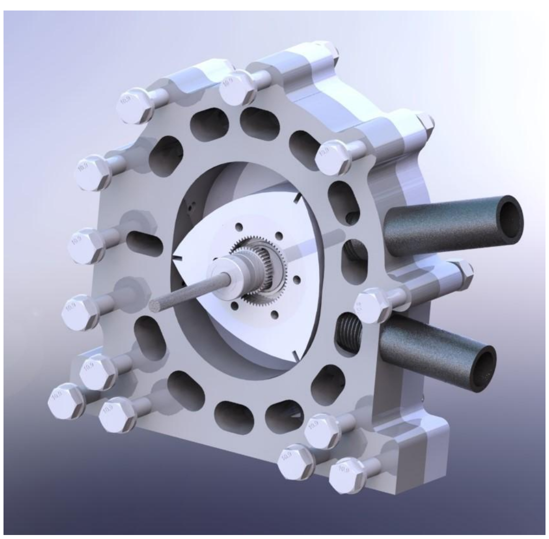


Figure 26. Custom machining fixture to properly align housing to bore the intake port

Figure 27. Custom machining fixture to bore the recesses for the ring gear and bearing as well as the crankshaft hole and ring gear retaining screws