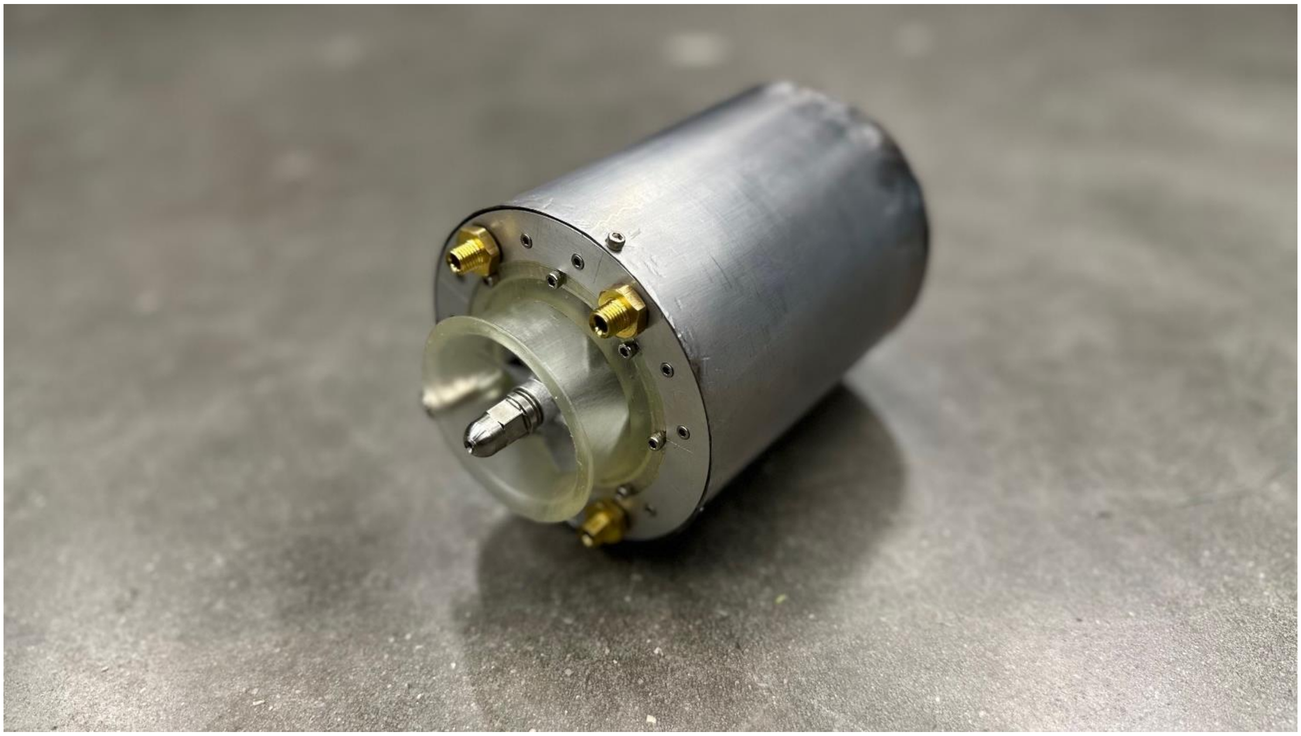

THE DESIGN AND MANUFACTURING OF A MINI JET ENGINE

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ME310

Table of Contents

Introduction

Theory and Background

This report discusses the design, manufacturing, and testing of a mini jet engine as part of the Design Elements course at The Cooper Union. Jet engines are ubiquitous in many jet-powered aircraft of all sizes and work from core thermodynamics and physics principles. There are various types of jet engines used, but the type of jet engine that will be discussed here is a turbojet. More specifically, the type of jet engine that we will be designing and manufacturing are mini jet engines that are used for small RC aircraft applications. These are on the order of 6-7 inches in length with a 3-inch radius.

The basic goal of a jet engine is to produce thrust. The generation of thrust results from the expulsion of high-speed exhaust gases opposite the direction of motion. This works under Newton's Third Law and more specifically, the conservation of momentum principle. To get the air moving at high speeds, it is combusted in the jet engine. The thermodynamic cycle that is employed in a jet engine is the Brayton Cycle.

The Brayton Cycle has three steps or components. These are a compressor, the combustion chamber, and a turbine. A schematic of the cycle is shown below. In the first step, ambient air is drawn into the system and compressed by the compressor. The compression increases the pressure and temperature of the air, preparing it for combustion. The compressed air enters the combustion chamber, where fuel is injected and ignited. This process releases a large amount of thermal energy, increasing the temperature and pressure of the air. The high-pressure, high-temperature air from the combustion chamber is directed to the turbine. As the air expands through the turbine, it performs work on the turbine blades, extracting energy to drive the compressor and provide thrust as it is expelled out of the engine. This expansion process lowers the temperature and pressure of the air.

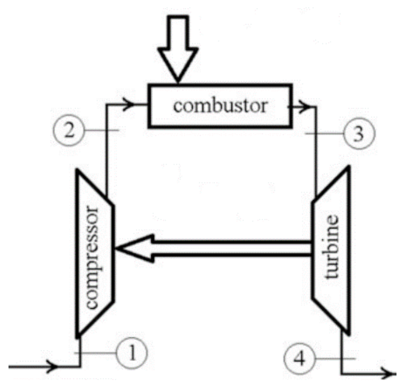


Figure 1: Brayton Cycle Diagram

Motivation

We were interested in working on a complex engineering challenge involving manufacturing, vital material selection, a data acquisition system, and an intricate assembly to challenge ourselves during senior year. This project incorporates all of these and therefore we chose to attempt building it.

We hope our jet engine will be used as a platform for data collection and analysis in Cooper. It can be further modified for additional experiments by changing various components including the compressor shape, the intake fuel, or the fuel delivery system. We also hope future classes can use our mini jet engine as a demo for combustion as it is very useful to have hands-on experience when exploring new concepts.

Component Breakdown

Many of the parts have been inspired by Thomas Kamp's *Model Jet Engines* book [1]. This book goes through the history and practical designing of a small model jet engine on the scale that we are looking at. The book's detail and comprehensive explanations have been useful as a guide for our designs. Someone created a blog detailing his build of Kamps' Jet Engine and it has been a good recourse to see what others have done as well [2]. We have also looked at many existing models for inspiration such as AMT's Mercury Engine. There are many YouTube videos that go through breakdowns of mini jet engines, and we tried to look at many designs to choose one that we thought would be the most practical to build. The following section goes through each component detailing the purpose and design constraints of each.

Rotary System

The rotary system is designed to rotate at a maximum of 140,000 RPM and requires high levels of precision to maintain balance. Any slight imbalance causes intense centrifugal forces which cause elastic deformation in the shaft, further increasing the imbalance. It is therefore critical that the RPM of the rotary system does not exceed its critical limit. [1]

Compressor

The compressor is the first component in the system and its function is to compress the incoming air to increase its pressure. It converts kinetic energy into pressure energy by accelerating the drawn air and then decelerating it rapidly, converting its speed into pressure and increasing the temperature and therefore enthalpy of the air. Model jet engines typically use single-stage radial compressors. Radial compressors have a spinning impeller with blades arranged in a radial configuration. Incoming air moves outward along the impeller blades centrifugally which increases its velocity. The high-speed air is then directed into a diffuser (see Stationary System) which directs the air into the combustion chamber and also slows it down to gather some of the kinetic energy. The blade design determines the pressure ratio of the compressor. The pressure ratio is the total pressure of air at the compressor discharge to the total pressure at the compressor inlet. It is a crucial parameter that influences the efficiency and performance of the engine. Efficient blade design ensures that the air is effectively compressed as it passes through the compressor stages. [1]

Shaft

The shaft connects the compressor to the turbine and holds the bearings allowing everything to turn smoothly. The shaft's natural rigidity counters the centrifugal forces caused by any imbalance to prevent substantial bending. However, as the speed of the rotary system increases, the rotational frequency approaches the natural frequency of the system, known as the critical speed. At critical speed, the system is in resonance, causing oscillations in the rotor system that the shaft's rigidity cannot prevent. This increases the deformation in the shaft uncontrollably, bending it significantly and causing significant vibrations. Therefore, engines must rotate below the critical speed. The critical speed depends on the mass, geometry, bearing placement and material of the shaft. As a general rule, the longer and thinner the shaft, the slower it can rotate before reaching the critical speed. [1]

Bearings

Efficient bearings allow the rotary system to maintain a high-speed rotation. Bearing selection is critical to the efficiency of the jet engine. The bearings must be rated for extremely high RPM (around 140,000) and therefore ceramic ball bearings are typically used in mini jet engine applications. Ceramic balls, typically made from silicon nitride, are incredibly hardness and have strong resistance to wear. Additionally, ceramic ball bearings have a lower coefficient of thermal expansion compared to traditional steel bearings, making them more dimensionally stable at elevated temperatures. To operate successfully, the bearings require lubrication and cooling, so they do not reach the incredibly hot temperature of the turbine located just below. The bearings are constantly lubricated with some of the fuel being routed to the bearings. [1]

Turbine

The turbine drives the rotary system. It extracts energy from the exhaust gases coming out of the combustion chamber (see below), causing the shaft and compressor to rotate. Exactly opposite to the compressor, the turbine reduces pressure and turns it into kinetic energy. The gases are directed into the turbine blades, exerting a force around the edges of the blades expressed as torque. From the combustion chamber, the gases move through the stationary Nozzle Guide Vane (see below) and into the turbine. The interaction between gases and turbine blades is nuanced. When the turbine wheel is already spinning rapidly, it's important to distinguish between absolute speed (relative to a fixed point) and relative speed (considering the motion of the turbine blades). The turbine blades shouldn't be set at right angles to the diffuser blades. While gases initially hit the blades at right angles when the turbine is at rest, this changes when it's in motion. The torque generated by the turbine results from a peripheral force acting on the blades. Gases are accelerated within the rotor blades and expelled at high speed in the opposite direction of rotation, creating thrust. The total peripheral force is the sum of these thrust forces working in the rotation direction. [1]

The turbine is the most stressed component in the system as it has to withstand high temperatures and centrifugal forces. Its design must consider the thermal expansion of the part and must be made from a material that can withstand these high temperatures and forces to ensure the engine continues to operate smoothly and efficiently. [1]

Stationary System

Inlet Cover

Adding an inlet cover helps direct air flow to the diffuser efficiently and prevents leakage. This cover is designed to sit right next to the impeller blades, but never touch it, avoiding friction and blade damage. This gap design incorporates expansion considerations and is recommended to be 0.4 mm to help with leakages while avoiding contact of the blades and the cover. [1]

Diffuser

The diffuser slows down the air after the impeller blades, converting the kinetic energy into pressure energy. Its blades must line up with the airflow coming out of the compressor’s blades. However, it is important that the diffuser blades don't begin immediately adjacent to the rotor system. This is because, at this point, the airflow speed is unevenly distributed. Allowing the flow to even out between the rotor wheel and the diffuser blades is ideal. In the context of a model jet engine, it's recommended that the diffuser blades commence after a gap equivalent to 1.15-1.2 times the wheel diameter to optimize the performance of the diffuser system. This allows the airflow to slow down and increase pressure before entering the combustion chamber. [1]

Diffuser Cover

The diffuser cover is designed to keep the redirected air inside the jet engine system. It plays a crucial role in minimizing turbulence and uneven airflow distribution as the gases transition from the rotating rotor to the stationary diffuser blades. It also includes a groove that is fitted with an O-ring which the outer casing slides over to ensure no air escapes. [1]

Shaft Collar

The shaft collar surrounds the central shaft. It houses the shaft bearings in line with each other and secures the shaft assembly to both the diffuser and Nozzle Guide Vane assembly. It acts as a structural component which centralizes the shaft and ensures the proper alignment of the rotatory system.

Nozzle Guide Vane (NGV)

Nozzle Guide Vanes are components designed to guide and control the flow of hot gases exiting the combustion chamber in a jet engine. As the gases leave the combustion chamber, they are at high pressure and temperature. As the high-velocity gases pass through the NGVs, the vanes work to accelerate the gases in the direction of the turbine rotor. The NGVs play a vital role in converting the thermal energy of the hot gases into mechanical energy that powers the turbine. As the gases pass through the NGVs, the pressure and temperature typically decrease from the conversion of thermal energy into kinetic energy. [1]

Outer Casing

The outer casing of the jet engine is the part which separates each of the moving parts of the jet engine from the environment, it also makes sure that combustion byproducts flow out of the system without it interfering with the rest of the system. The outer casing also comes into direct contact with the exhaust, which has the greatest temperature and flowrate, from the whole cycle, which means the material needs to be able to withstand great heat, and not warp too greatly. It also needs to be shaped in a way that makes sure that the pressure of the exhaust is not greater than what's in the system or there will be large back pressure which could cause problems with the flow profile. [1]

Combustion System

Combustion Chamber

The combustion chamber is where the air intake from the compressor is mixed with fuel and heated to the required temperature. The mixture of air and vaporized fuel must be stoichiometrically complete so that all the fuel is burned off while maintaining a large enough flame so that it is not extinguished. If the fuel is not completely burned away due to insufficient presence of oxygen in the mixture, the flame will reach through the turbine and soot will accumulate inside the engine. The temperature inside the combustion chamber can reach up to 2000°C. The air in the combustion chamber is cooled using holes to introduce cool air between the primary combustion zone and the turbine. The design goal of the combustion chamber is to achieve an even temperature distribution in the radial direction with the air being slightly cooler at the base of the turbine blades where stresses are higher.

Fuel Lines

The purpose of the fuel lines is to introduce fuel into the combustion chamber from an outside source. It was decided that the fuel should enter from the front of the combustion as it would be more problematic to design a system that wraps around to enter from the back, making the tubing more complex. Therefore, fuel will be entering from the front of the jet engine and be routed to enter combustion chamber from the top.

Vaporization Chambers

The vaporization tubing is added to the end of the fuel lines which enter the combustion chamber. These are needed to make sure the fuel is fully vaporized before entering the chamber, and therefore needs to be long enough for all the fuel to heat up to the proper temperature. This is the reason fuel is sometimes injected from the back of the combustion chamber and wrapped to front for the fuel to fully vaporize as seen in Figure 2.

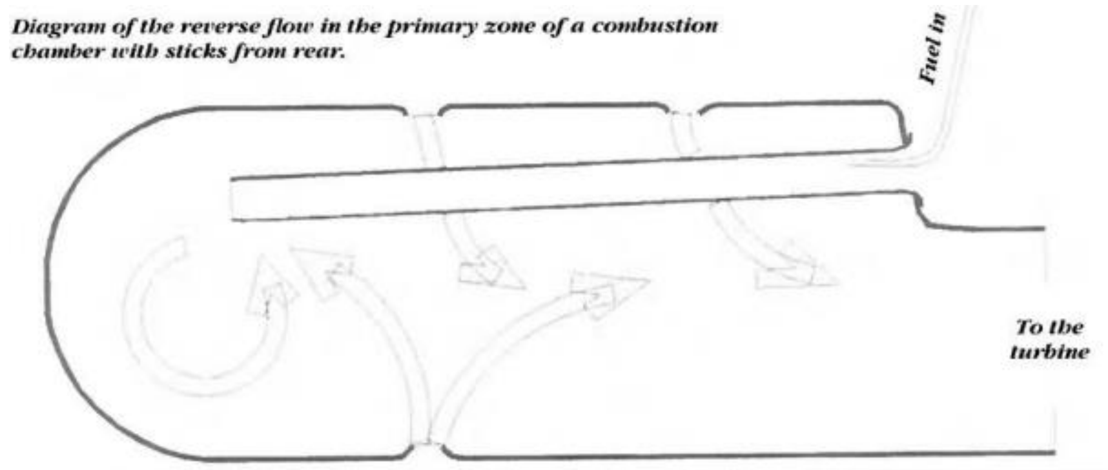


Figure 2: Fuel Entering from Back

The issue with this type of fuel injection is the need for the fuel lines to wrap around the combustion chamber on the outside, as fuel will be supplied from the front of the system, the front face of the engine. Therefore, the fuel lines were designed to be injected from the front of the combustion chamber, as shown in **Figure 3**.

Figure 3: Fuel Entering from Front

The diagram shown in Figure 3 also includes vaporization tubes which wrap in a U-shape, this allows for the fuel to fully vaporize and is used to make sure that the fuel enters directly from the front. This is especially necessary to make sure non-vaporized fuel is combusted by the recirculation zone created by the configuration of the front of the chamber. Also, in this configuration the fuel has a chance to mix with the air, as it does not directly enter the combustion zone. Unlike the method in Figure 2, the vaporizer will be under the same pressure as the combustion chamber, allowing for easier control of fuel injection. [1]

Starter Fuel

The engine requires a starter fuel to get the system to its operating temperature before the main fuel system is turned on. Without any starter fuel, the combustion chamber will not get to the right temperature for fuel vaporization. The starter fuel will be propane, a commonly used starter fuel in mini jet engines. Propane was chosen because it is readily available in most camping and hardware stores, and it is commonly used for a safe, controlled flame. A 16.4-ounce canister of propane can be purchased from REI for approximately $10, so the cost and accessibility of the fuel is not a concern. The gaseous fuel will be routed into the combustion chamber through separate fuel lines. The fuel will be attached to the test stand and have a manual valve to control the flowrate delivered to the engine.

Running Fuel

Once the engine is up to operation temperature, it is switched onto kerosene as the starter fuel. We chose kerosine since it is very similar to jet fuel but much more accessible. The fuel is liquid at room temperature and will be stored in a fuel container on the engine mount. The fuel is delivered to the engine using a fuel pump connected which is controlled by the ECU. Kerosene is readily available in most major retailers and is inexpensive. A quart sized container of kerosene can be purchased from Walmart for approximately $7, so the availability and cost of the fuel is not a concern.

Controls & Data Acquisition System

Engine Control Unit (ECU)

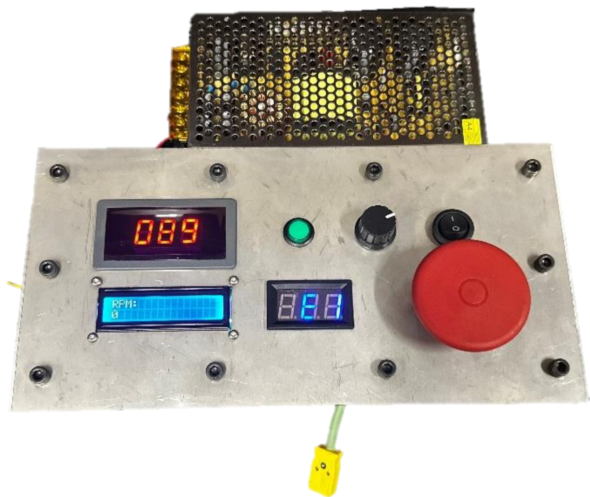


Figure 4: ECU

In order to run the engine, it is crucial to have a robust controller. To ensure this, the engine will be controlled using a control board. The controller is powered by the external power supply connected to the control panel. The power supply cord has an on/off switch to control ECU power input. The ECU is capable of reading engine RPM (bottom left display), fuel pump throttle (top left display), and engine temperature (bottom right display). The controller will allow for manual control of the throttle position (green on/off button & dial knob), as well as a solenoid for the starter fuel (on off switch). There is also an emergency stop button to cut off fuel pump power.

ECU Pannel Structure

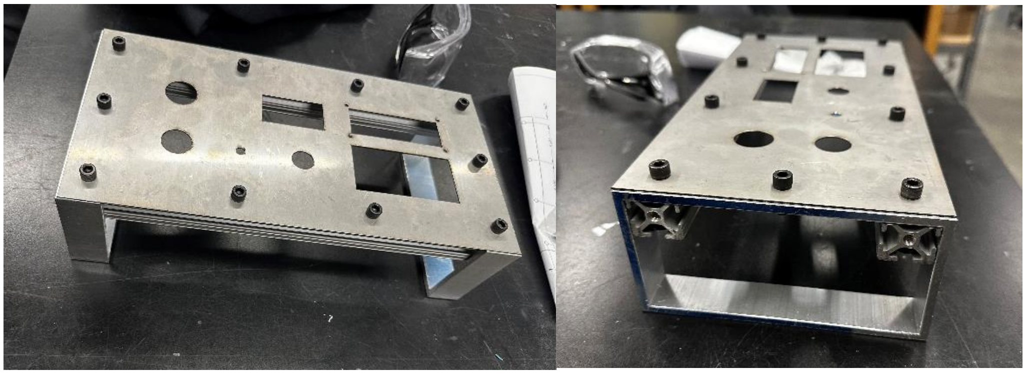


Figure 5: ECU Panel Structure

The ECU Structure was designed to withstand the unreasonably powerful impact of a future student slamming the emergency stop button in the event of a catastrophic event. The front of the panel was laser cut out of an 1/8” Stainless steel sheet. The sides of the panel is constructed out of aluminum rectangular profiles which were cut to length on a band saw. The span of the panel is constructed out of 1” square aluminum profiles, which were cut to length, and milled down 0.2” at the ends to account for the thickness of the rectangular profiles. Holes in the profiles were then added to connect ¼” machine hardware to connect all of the components together.

Fuel Pump

Figure 6: Fuel Pump

The fuel pump is used to control the rate of fuel entering the engine, which is controlled by the ECU. The fuel pump that was supplied with the original jet engine will be used since it is already mounted and has previously worked with the engine controller.

RPM Sensor

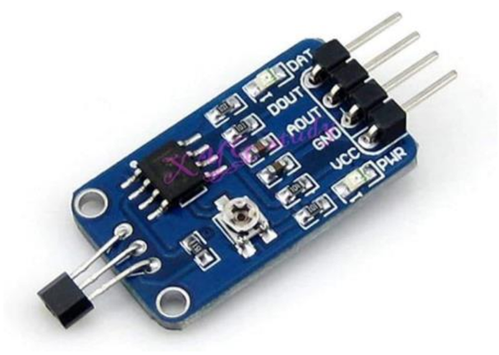


Figure 7: Hall Effect Sensor

It is important to have accurate measurements of engine RPM since it is the main system output. For this reason, hall effect sensors such as the one pictured above will be used. This sensor operates by detecting the frequency of an oscillating magnetic field. Designing the rotating assembly to have a magnetic field will allow the hall effect sensor to measure the rotational frequency which can be converted to engine RPM. To create this magnetic field, the hall effect sensor needs to be pointed directly at the magnetic component. In the design of this engine, a magnetized nut on the compressor end of the rotating assembly will be used for sensor measurement.

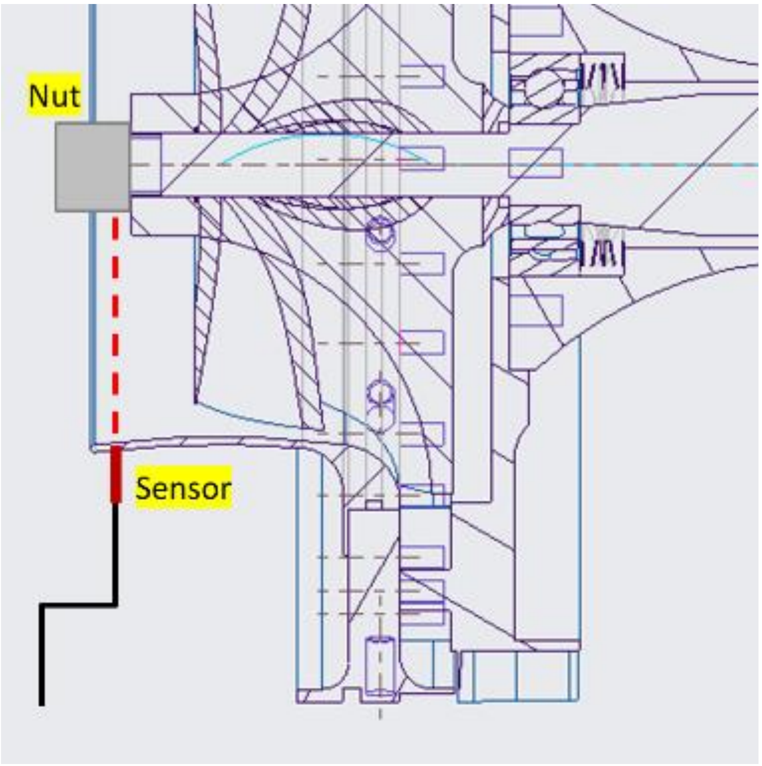


Figure 8: RPM Sensor Placement

As shown in the diagram above, the hall effect sensor will be mounted onto the compressor cover. A hole will be drilled through the housing for the sensor to take measurements. The magnetized nut will be attached directly in front of the sensor and will spin with the rotating assembly. The sensor shown in Figure 6 can detect the RPM and be adjusted for sensitivity before it transmits the data to an Arduino.

The hall effect sensor measurement is dependent on the distance between the sensor and the magnetic component, so the sensor will need to be calibrated to ensure the measurement is accurate.

Temperature Sensor

Figure 9: Temperature Sensor

Temperature of exhaust gases will provide useful data on combustion performance as well as give an indication of unsafe engine conditions, allowing the engine test to be aborted. Temperature will be read using a type K thermocouple, designed specifically for measuring exhaust gas temperatures. The sensor has a reading resolution of 1 degree Celius, and is connected directly to the display shown above.

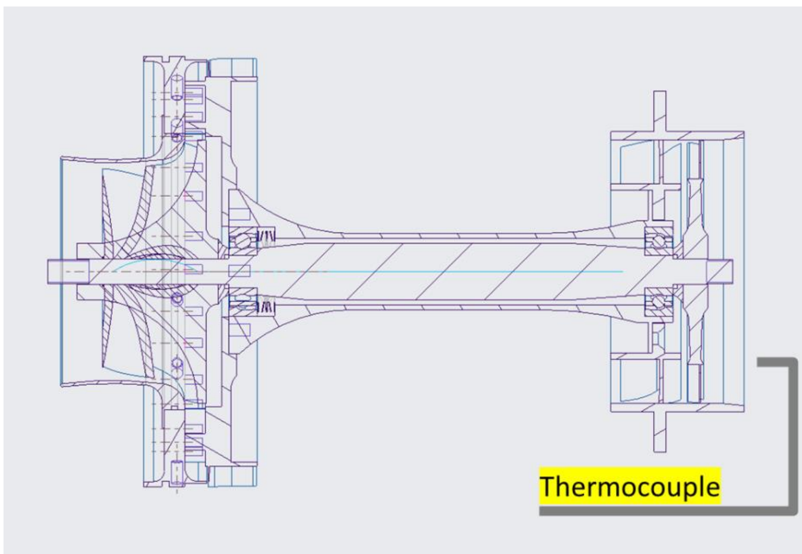


Figure 10: Temperature Sensor Placement

The thermocouple will be attached to the engine mount, and the end of the sensor will be placed just past the turbine exit, as shown in the diagram above. As with the other controls components, the thermocouple is from the old engine setup since they are available and are designed to work with the ECU.

Design and Manufacturing

All the parts to follow have been designed using PTC Creo. This is standard in many industries, especially aerospace, so it was a good opportunity to learn how to use this software.

Rotary System

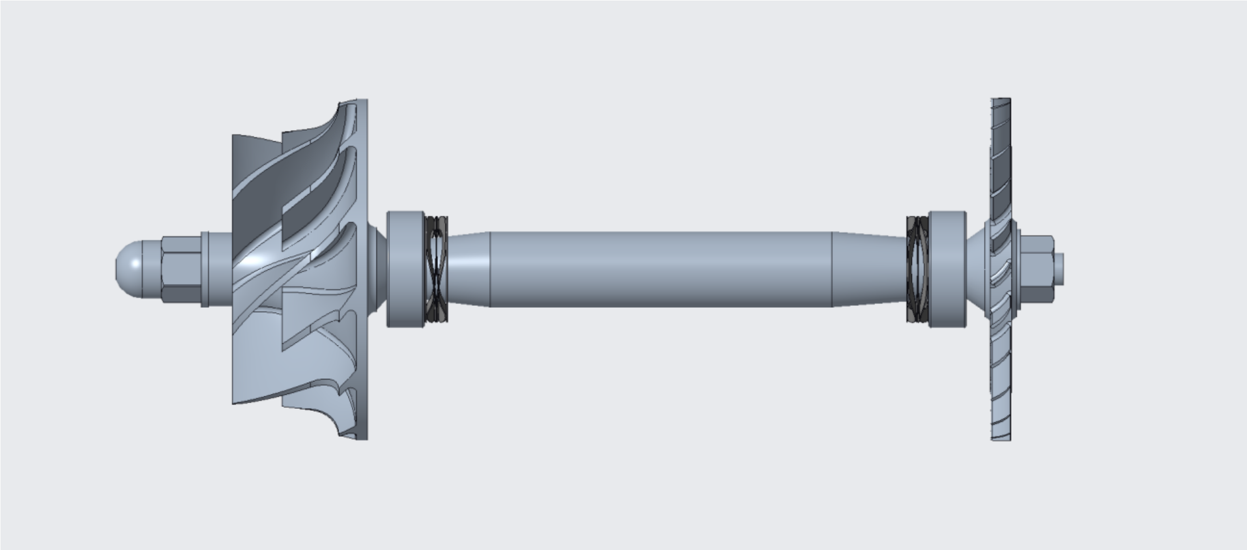


Figure 11: Rotary Assembly

Compressor

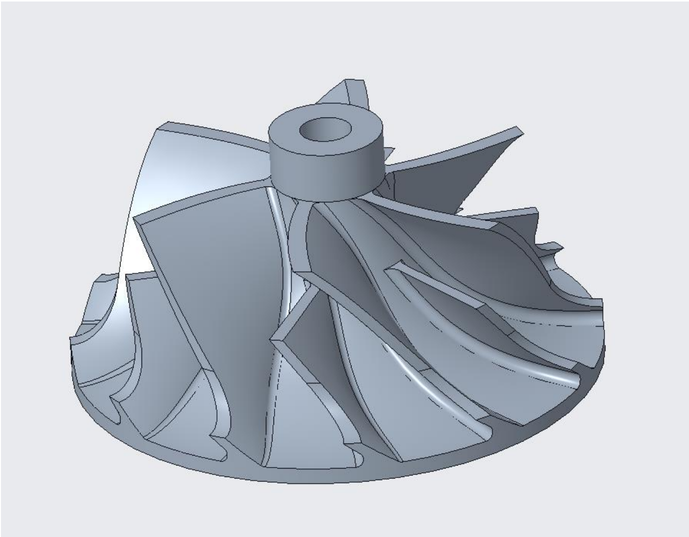


Figure 11: Compressor Design

The compressor can typically be made from aluminum, although it has a low melting temperature, as heat from the combustion chamber does not reach the compressor, and the air passed through the compressor constantly cools it. Aluminum is easy to manufacture as it is a relatively soft metal. Because of the complex geometry of the angled blades of the compressor, there are two methods for manufacturing. The first is the use of a 5 axis CNC. This, however, is a slow and difficult process to execute with the equipment available. The second option is to cast the compressor. With various methods of post processing, casting can yield strong and accurate parts with complex geometries making it a superior choice for us.

The process of casting starts with resin printing the desired geometry with castable wax (castable wax 40 was used). Curing is not necessary because the wax will melt out in the process. Then, the wax is placed into a flask where special plaster for casting is mixed and poured into the flask. After removing all the air bubbles with a vacuum chamber, the plaster is left out for 20 minutes to harden. Then, the flask is placed into a furnace for around 14 hours in a process called burnout. This burnout vaporizes the wax inside the flask, leaving an empty mold ready for casting. Finally, the flask is taken out at around 800-900 degrees Fahrenheit onto a special vacuum. When the molten aluminum is poured into the mold, this vacuum pulls the metal into all crevices of the mold to ensure a good complete cast. This is possible due to the porosity of the plaster allowing air to pass through. Once the metal has hardened (approximately 30 minutes), the flask can be placed in water to hasten the cooling process and the plaster can be broken away revealing the part. Images of the casting process are shown in Figure 14.

Two prototypes were made. In the first one, as shown in Figure 13 the blades were too thin and therefore would not function properly and were likely to break. They can easily be bent by hand. In addition, the curvature of the blades were not angled enough when compared to existing compressors for this application. Therefore, a second prototype was cast with thicker blades as shown in Figure 12. Supports along the blades in this second iteration were also taken off to avoid the need to machine down the blades after which would be a risky process.

Casting does not always enable the most precise tolerances (when compared to machining) for many reasons, one of which being shrinkage during cooling and another being the need to print the resin with supports which affect the part. We therefore turned the part on the lathe after casting to smooth out the diameter, remove the excess materials, and drill a hole through the center for the shaft. We used an indicator to check the alignment and concentricity of the blades and found that they were within 0.001 inches of each other, exceeding our expectations.

Figure 13: First Prototype of Compressor Wheel

Figure 12: Second Prototype of Compressor Wheel

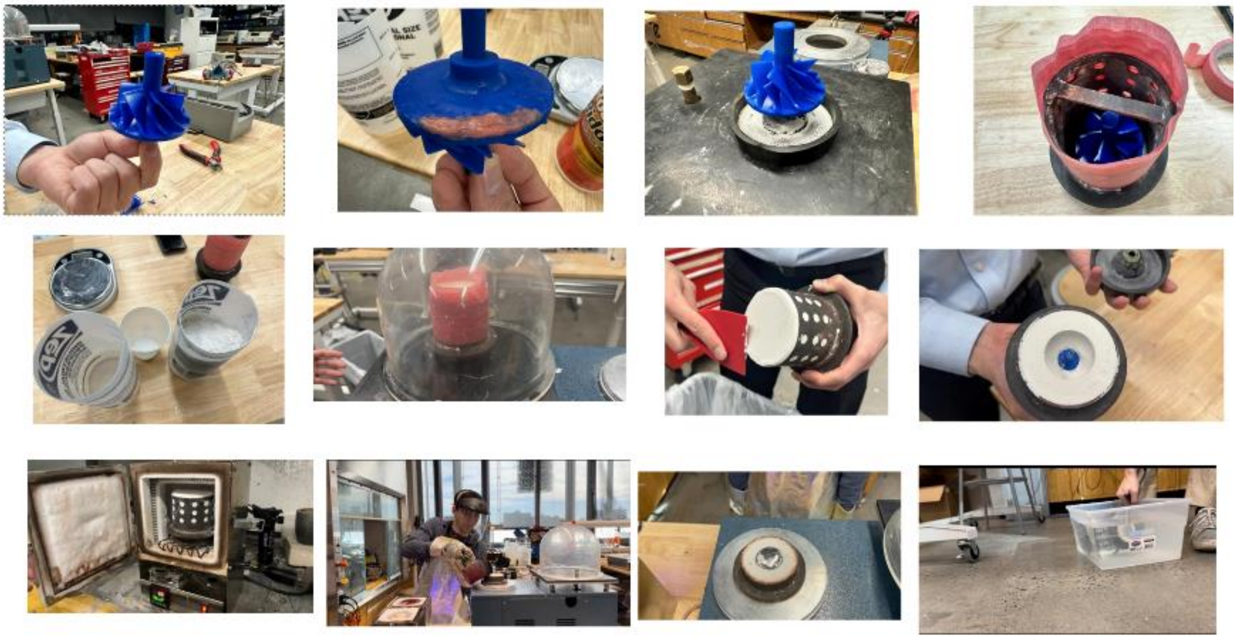


Figure 14: Casting Process

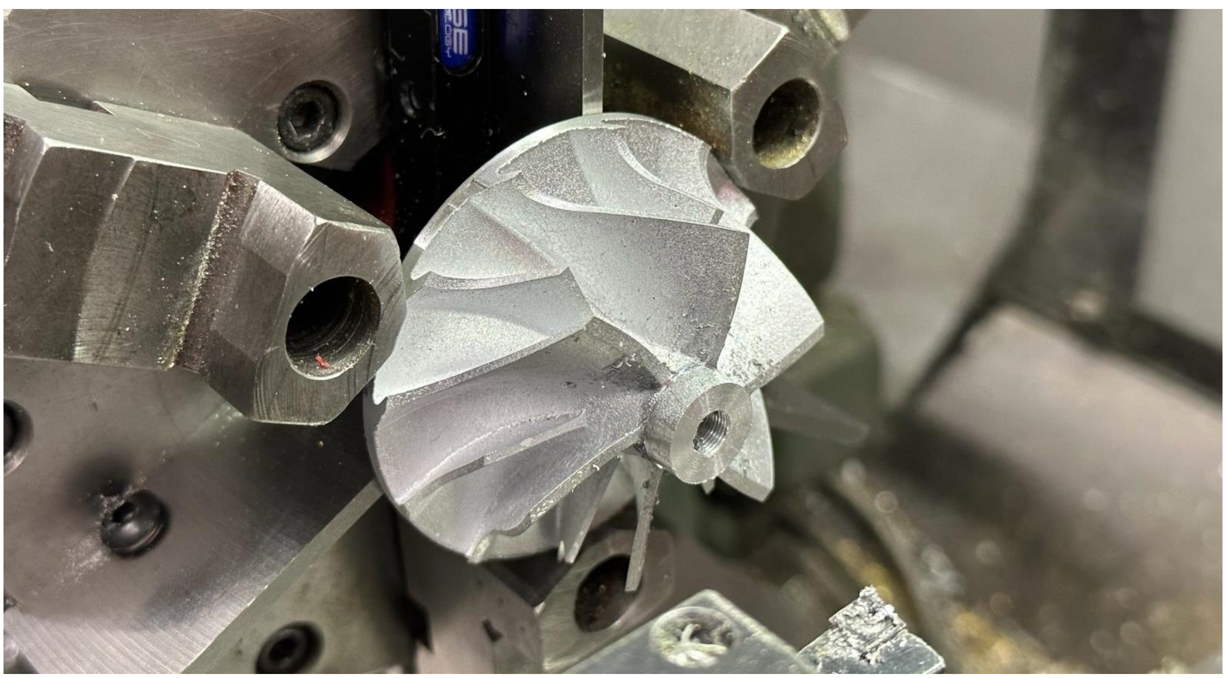


Figure 15: Finishing the Compressor on the Lathe.

Compressor Nut

The compressor nut secures the assembly of the compressor side by holding together the compressor, spacer, bearing and spring assembly. In addition, it houses the magnet used to measure the RPM of the jet engine. The nut was machined using the same 17-4 PH stainless steel as the shaft. Its design has three sections, the middle section for the magnet, the bottom section to thread onto the shaft, and the top section for a set screw. The set screw and shaft together are used to hold the magnet in place. The outside of the nut features the hexagonal shape for the wrength. The magnet being used is a 3/16” diameter 3/16” thick neodymium magnet[1] that is polarized radially. This way, the magnet can be placed right into the cylindrical slot and as the nut is rotated, the polarization will constantly flip.

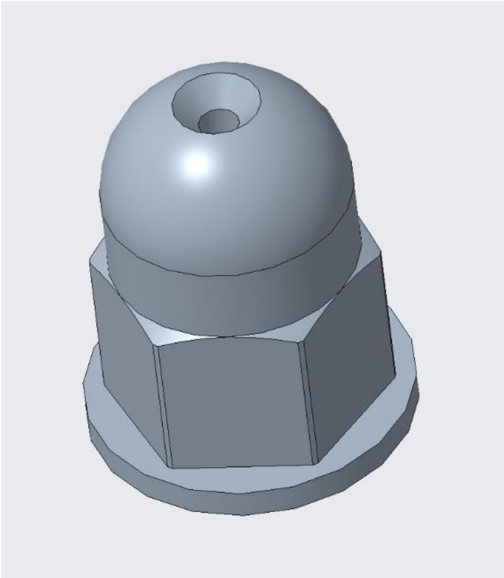
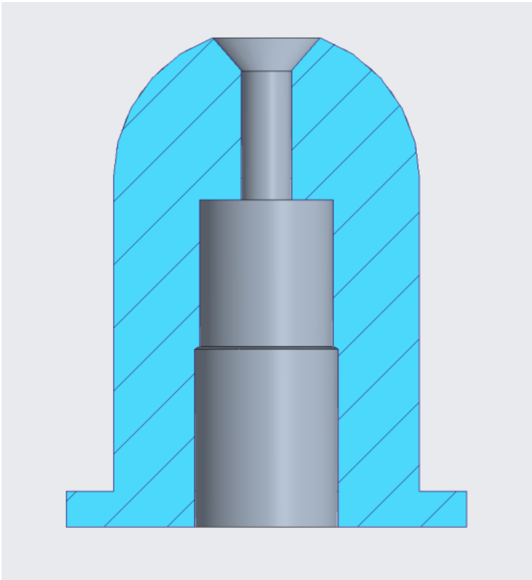



Figure 16: Compressor Nut Design (Left) and Cross Section (right).

The outer shape of the nut was turned on the lathe and the set screw hole was drilled. It was then removed, and the hexagonal nut profile was cut on the mill using a six-sided collet holder, making a pass along the surface of each side. The part was once again placed in the lathe to cut off, flip around and make the holes for the magnet and shaft. Finally, the bottom portion of the nut was tapped with left-handed ¼-20 threading for the shaft to go into.


Figure 17: Hexagonal Collet Holder (Left), Finished Outer Profile (Right)

[1] https://www.mcmaster.com/5862K418/

Figure 18: Finished Compressor Nut

Shaft

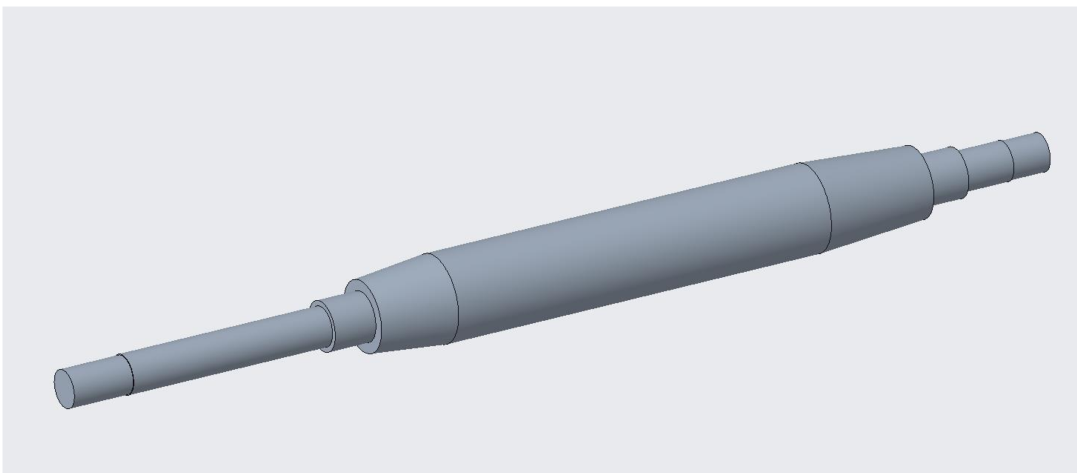


Figure 19: Shaft Design

The shaft was turned from 17-4 PH stainless steel due to its strength and heat-resistant properties. To obtain maximum circularity, each side of the shaft was completed without removing the part. Once the first side was done, the shaft was turned over and the other end is machined.

We began by reducing the shaft to its maximum thickness of 0.5625 (9/16”) which fit in a collet of that size to get a better hold on the part and turned each section to the correct thickness. One critical surface on the shaft is the section where the bearing sits. This needs to have a very particular tolerance so that the bearings can go into the shaft easily, but not have any significant room to move around. Therefore, after each pass on that surface, we tested the fit by sliding on the bearing until we brought it down to the exact diameter needed. After flipping to the other side of the shaft, the concentricity was checked with an indicator and the shaft was shifted around the collet to find the position with the least runout. Finally, each side of the shaft was threaded using a left-handed ¼-20 die. Overall, the shaft was within ±0.0005” for each dimension which is necessary to ensure that the shaft is well balanced.

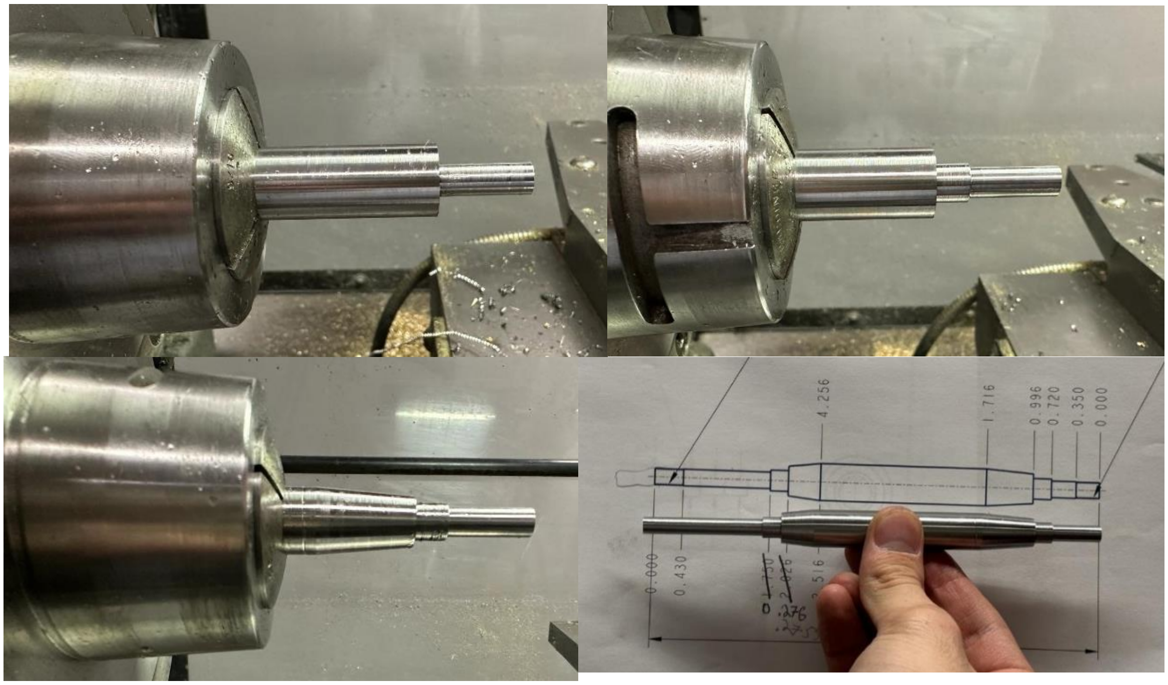


Figure 20: Shaft Making Process. Machined Shaft (Bottom Right)

Bearings

Figure 21: Bearing (Left), Waves Spring (Right)

The bearings have been purchased from GMN bearings (Model HY S 608 C TA Angular Contact Bearings [2]) and have steel racers, with ceramic balls. These bearings are rated for 140,000 RPM with grease lubrication and are rated for almost 400 degrees Fahrenheit. The bearings should not get too hot, as air and lubrication will be constantly passed through it during operation. These bearings also have a polyetheretherketone (PEEK) cage. It is recommended that cages aren’t used for jet engines as any deformation or failure of the cage can cause failure and possible damage to the engine. However, since they seem viable given their ratings and they were given as a donation for the project it was decided to use these bearings in the jet engine.

Angular contact bearings are used as they are optimal in high speed and precision applications; however, they do require preload to operate. The schematic below describes the preload procedure. Manual

[2] GMNBT.COM

preload is applied either with a spring or a wave washer (it can be also be applied by torquing the nut to a specified value but this is less forgiving and requires more precise instrumentation). This allows for a consistent force applied onto the casing and balls and ensures proper contact. It also is important in this application to allow for any axial thermal expansion of the parts. A spring is therefore placed behind each bearing.

The wave spring we are using [3] is made from 17-7 PH stainless steel and can provide 7.5 lbs. of force at full compression. The desired preload force is 17 N = 3.8 lbs. Therefore, the shaft collar is designed for this in mind and will compress the spring to 50 percent of its maximum compression. Using the spring dimensions and specification this means that the compressed length of spring should be 4.52 mm = 0.178 in.

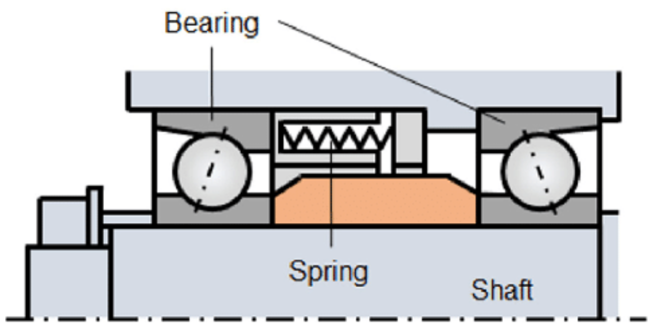


Figure 22: Pre-Load Diagram

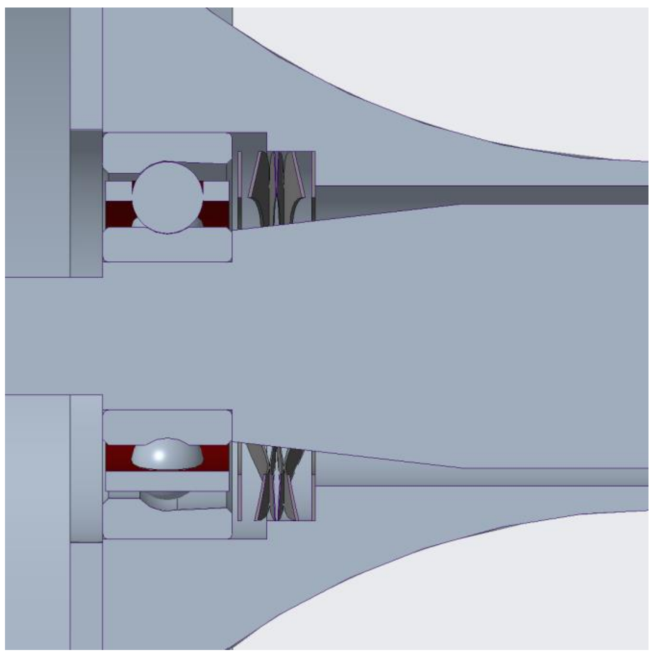


Figure 23: Bearing and Spring Assembly

[3] https://www.mcmaster.com/3726N622/

Turbine

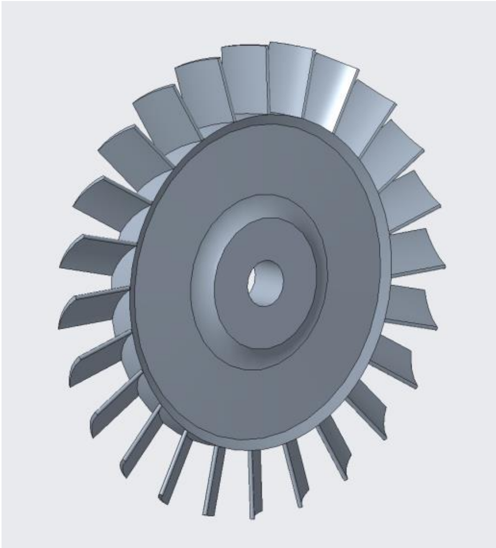


Figure 24: Turbine Design

The turbine needs strength and the ability to handle extremely high temperatures as it is spinning up to 140,000 RPM. It is therefore common to use Inconel in turbine manufacturing. Inconel is a nickel and chromium based alloy that has extreme properties. We are using Inconel 718 as it was given as a donation from Altemp Alloys. It can be cast if the right equipment is available (need high temperature furnace), but since that equipment is not available, it will be made on the CNC instead. Due to its complex shape, a four axis CNC is necessary with a trunnion that will rotate the part in the CNC to machine each blade the same.

To manufacture the turbine, we turned its profile on the lathe.

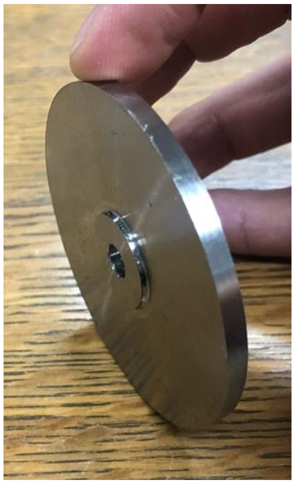


Figure 25: Turned Turbine Profile

The complex blade shape was then formed using the CNC mill. Some post processing was necceacry to take off burs on the blades. This was done with some sandpaper and a Dremel.

Figure 26: Turbine in the CNC Mill. **Figure 27:Final Turbine**

Turbine Nut

The turbine nut holds the turbine side of the engine in place. This was machined using the same 17-4 PH stainless steel as the shaft.

The process of machining is very similar to the compressor nut, however it is less complex since this one is just a regular nut with a flange. It was machined by turning it to the necessary diameter and drilling a hole through the center for the ¼ - 20 threading. It was then removed, and the hexagonal shape was cut on the mill using a six-sided collet, making a pass along the surface on each side. Next, it was placed back on the lathe and the remainder of the rod was removed using a cut off tool. Finally, it was tapped with a ¼-20 left-handed thread on the lathe to the tap is concentric with the rest of the piece.

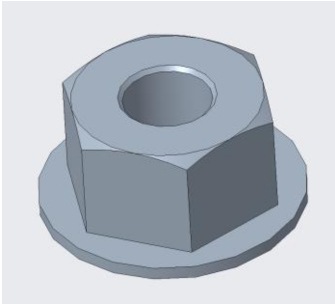


Figure 28: Nut Design

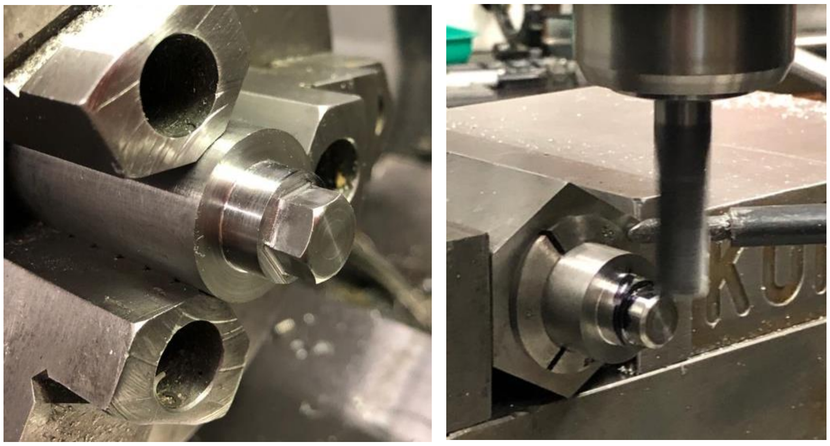


Figure 29: Machining the Nut.

Stationary System

Inlet/Compressor Cover

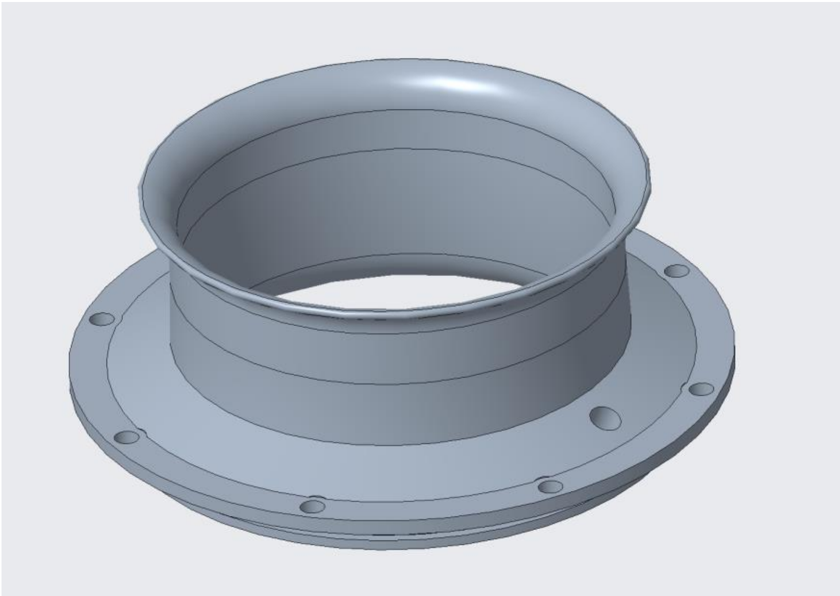


Figure 30: Inlet Cover Design

The cool incoming air enters the jet engine through the inlet cover. Since it will remain cold while the jet engine is running, it can be made from clear Resin which is easy to manufacture and can be reprinted as needed. The inlet cover features holes to screw it into the diffuser cover, and it also features a airline connector that allows compressed air to be fed into the compressor. This will be for the startup procedure to get the engine running.

We printed the inlet cover using a Formlabs printer using clear Resin. After it was washed, we left it out for two hours before hardening it in the UV curer for 30 minutes at 60 degrees C. We then tapped a 10-32 hole for the airline connector piece.

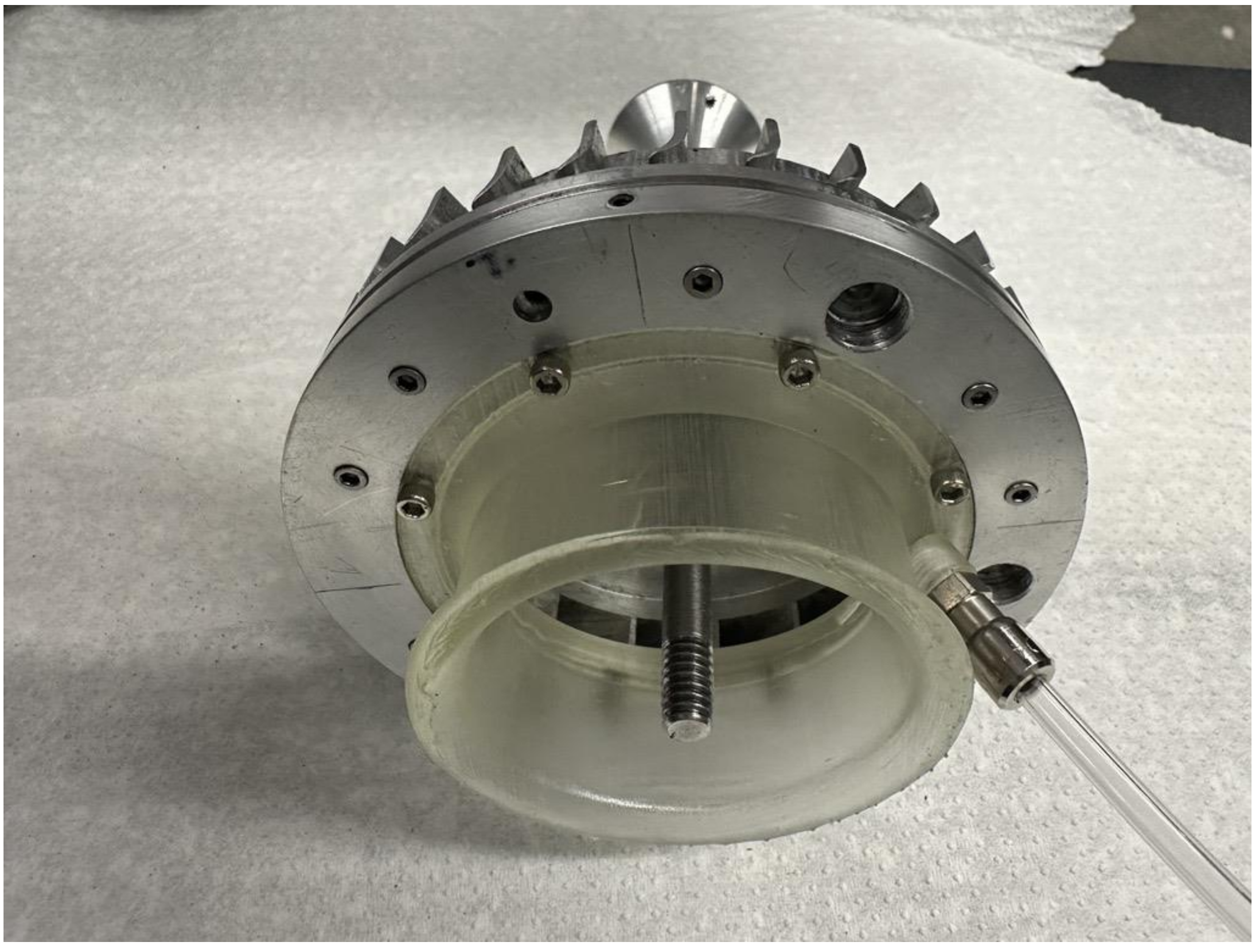


Figure 31: Resin Printed Inlet Cover with Air Line Fitting

Diffuser and Diffuser Cover

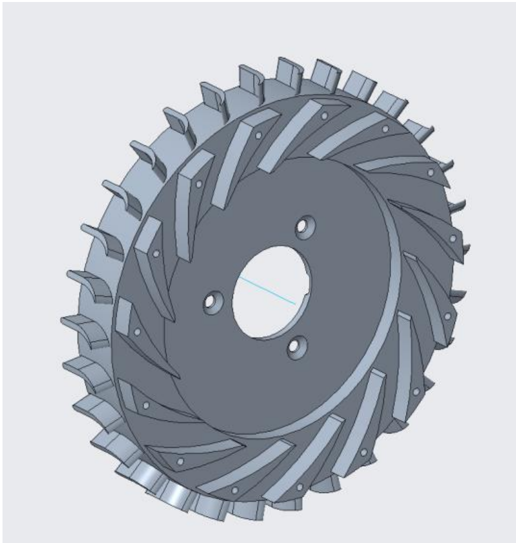


Figure 33: Diffuser Design

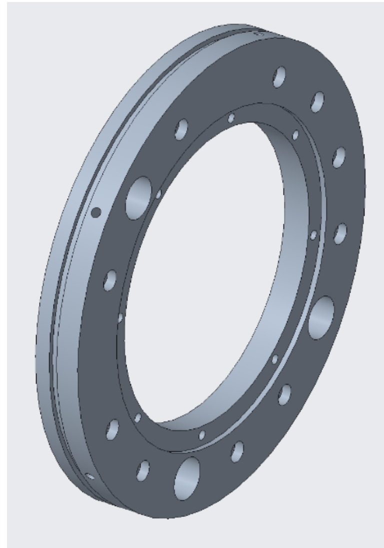


Figure 32: Diffuser Cover Design

The diffuser and diffuser cover were machined on the CNC lathe and CNC mill due to their complex geometry. It is made of aluminum since it is on the cold side of the jet engine. The hole pattern for each was made on the manual mill. The diffuser cover has a counter bore hole pattern on top which goes into the hole pattern on the diffuser which was taped with a 3-48 screw size. The diffuser cover also has a hole pattern around its sides which screw into the outer casing.

The O-ring that goes around the diffuser cover for the outer cover to go onto, was made using a 1.5 mm diameter O-ring piece and glued together using an O-ring kit.

Figure 34: Diffuser Profile

Figure 35: Diffuser Right: Top, Left: Bottom

Figure 36: Diffuser Cover

Shaft Collar

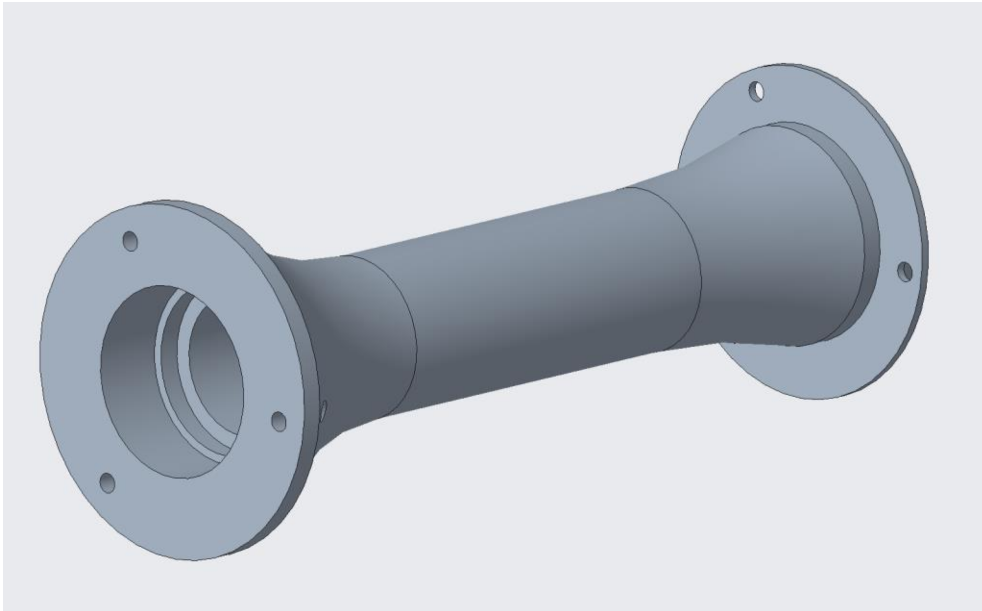


Figure 37: Shaft Collar Design

The shaft collar is also made from aluminum since it does not need to withstand loads and should not get too hot. Cold air will be passing around the combustion chamber, cooling the surrounding components such as this one making aluminum a viable material.

It was machined on the CNC lathe. To obtain maximum circularity, each side of the shaft collar was completed without removing the part. Once the first side was done, the shaft collar was turned over and the other end was machined. As with the shaft, the critical surface of the shaft collar is the bearing seat. Therefore, this was machined precisely to the outer diameter of the bearings to allow for proper tolerancing. First a drill was used to hollow out the aluminum stock followed by a boring bar to get the inner profiles. Then the outer profile was created. It was necessary to machine a plug for the non-clamped end and hold it with the tailstock since there was a lot of material removal to make the outer profile.

Figure 38: Drilling out the Shaft Collar

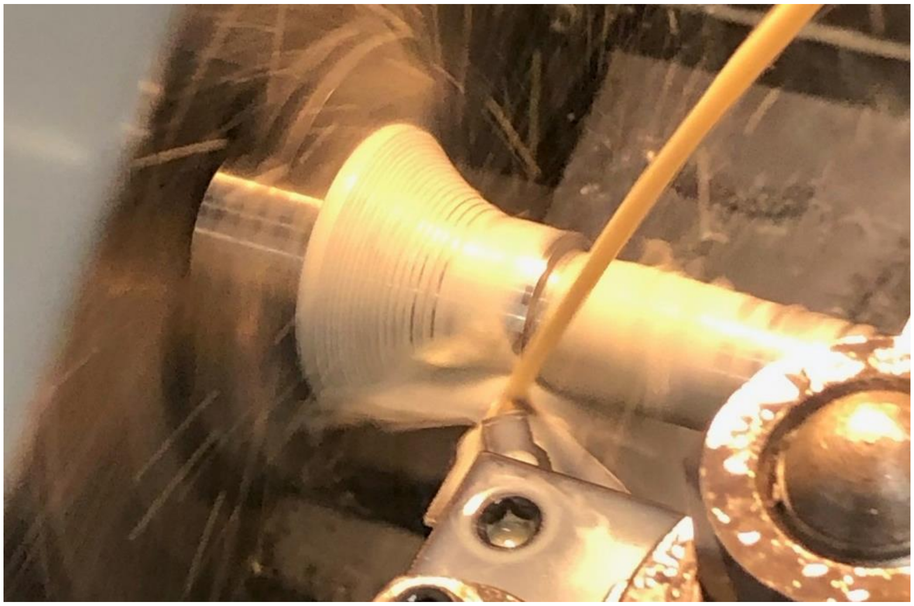


Figure 39: Turning the Curved Surface of the Shaft Collar

Figure 40: Final Shaft Collar

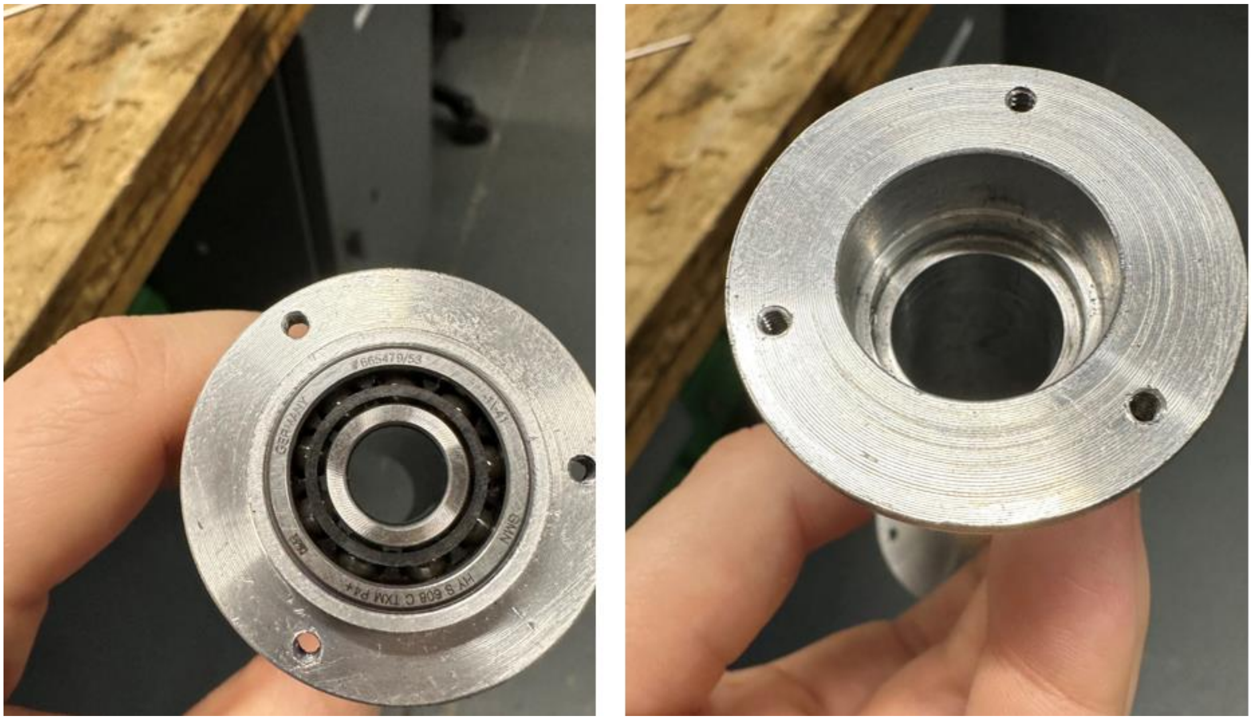


Figure 41: Bearing Seat in Shaft Collar

Nozzle Guide Vane (NGV)

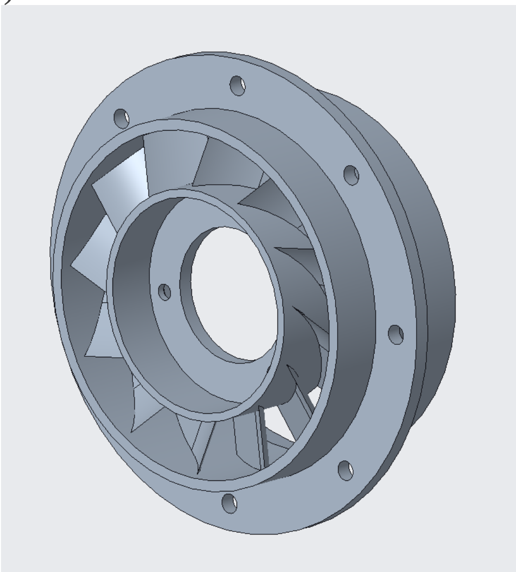


Figure 42: NGV Design

The nozzle guide vane is also taking a lot of heat and can therefore is made from stainless steel or Inconel. Since stainless steel is easier to machine and more accessible, it was chosen as the material for the NGV. The NGV was made in two parts on the CNC lathe and mill. Both parts were turned on the CNC lathe to achieve the overall profile. Then the parts were milled using the CNC mill, for the inner piece, the blade pattern was made and for the outer piece the negative blade pattern was made. They were then welded together. The hole pattern in the outer piece connects to the outer casing while the hole pattern in the inner piece connects to the shaft collar.

Figure 43: NGV Inner Piece

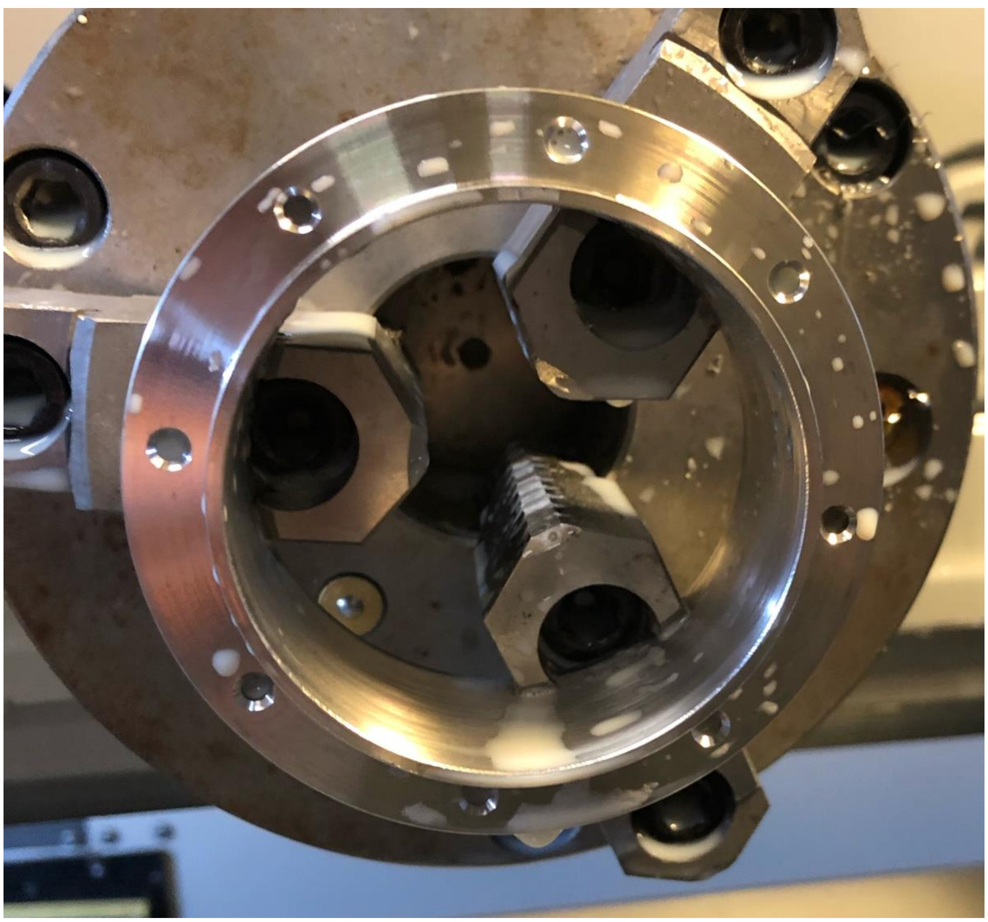


Figure 44: NGV Outer Piece

Figure 45: NGV Assembled

Outer Casing

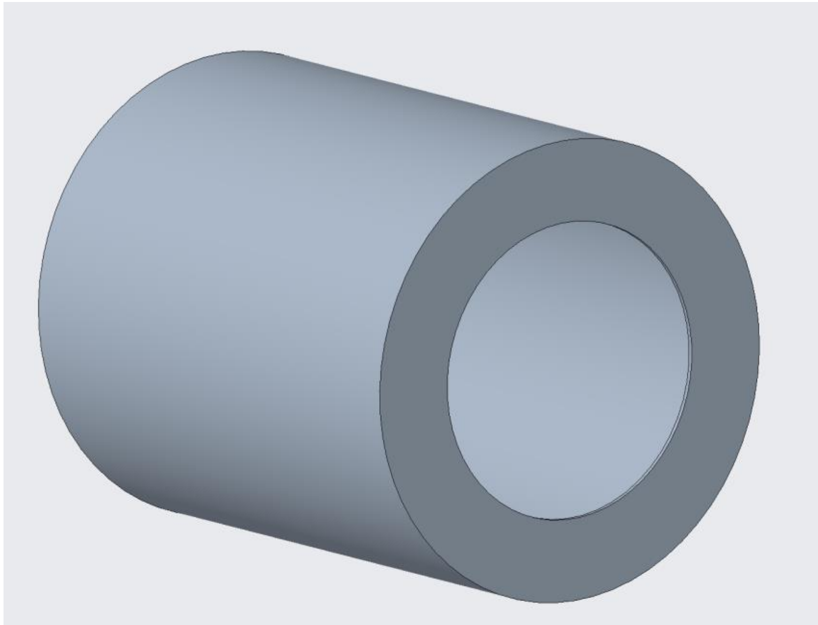


Figure 46: Outer Casing Design

The outer casing will be made from 1/8” stainless steel plates, which were rolled to the shape shown in Figure 46. The sheets were cut to size using a laser cutter and was rolled using the sheet metal roller in a cylinder based on a solid aluminum cylinder of the desired dimensions matching the diffuser diameter, and then spotwelded to keep its shape. To ensure this, an additional strip was added to the cylinder since the original sheet used was too small to fit the remaining parts. Then, a thicker stainless steel sheet was laser cut and welded to the back of the outer casing.

Figure 47: Outer casing: Cylinder Weld

Figure 48: Outer Casing: Circle Attached

Figure 49: Outer Casing Final Profile with NGV

Combustion System

Combustion Chamber

The combustion chamber is constructed from 1/8” stainless steel sheets. Although the temperature at the inside of the chamber is too hot for this material, the small holes in the front of the chamber cause the formation of a cooling barrier between the main combustion zone and the walls of the combustion chamber. The chamber will be constructed from five separate sheets of metal. The metal sheets were laser cut to size with holes for air flow and tubing. The inner and outer walls were bent into cylinder shapes and welded together. Also, the vaporization tubes are welded to the front piece of the chamber.

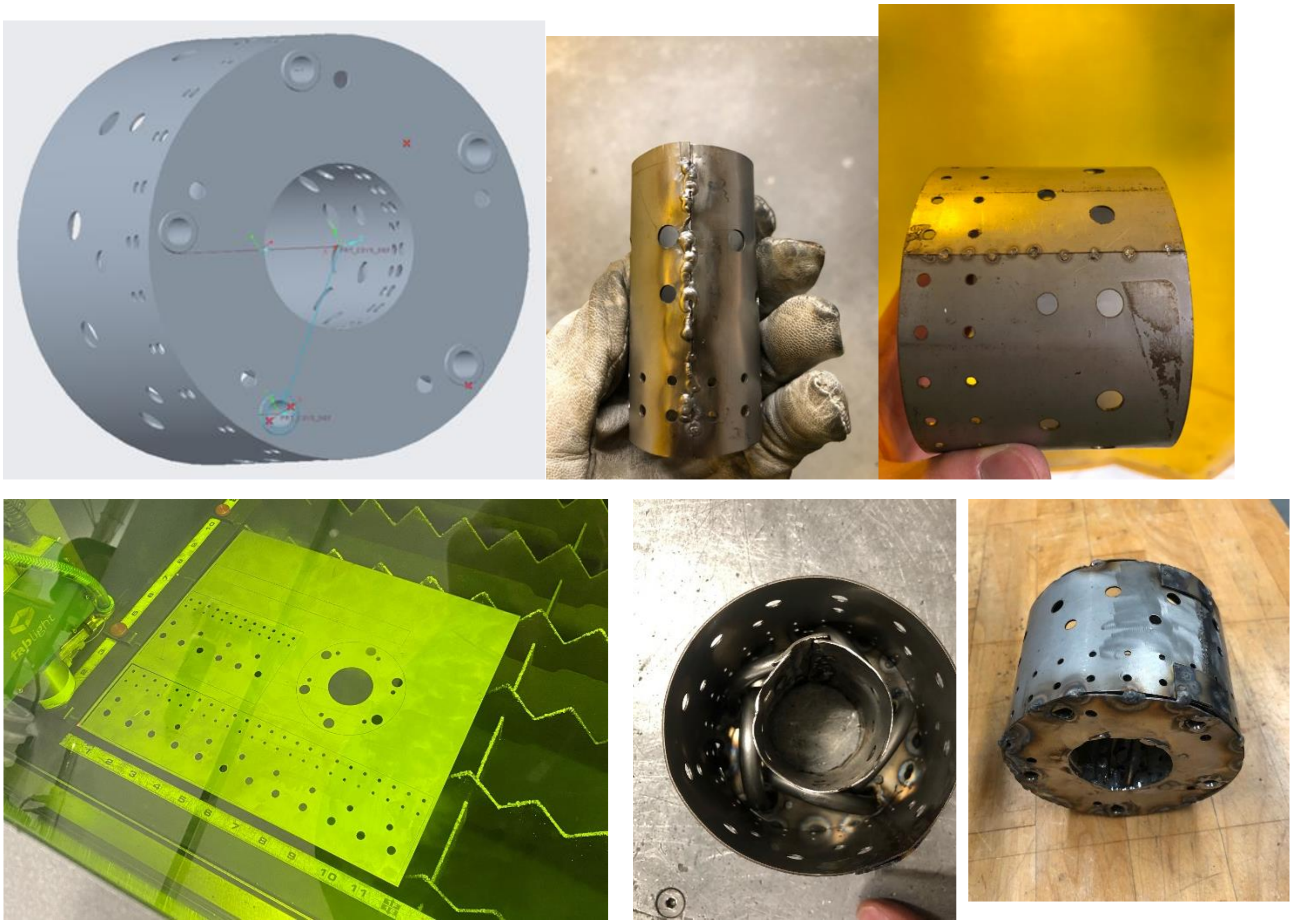


Figure 50: Combustion Chamber

Fuel Lines

The fuel lines are to be made of brass tubing, bent to the shape indicated in *Figure 51(a)*. The tubing is designed to have separated fuel lines: the first line to insert the starter fuel (Propane) and the second line to insert the fuel (Kerosine) in the front of the combustion chamber. These lines would then be welded to 12 stainless steel hypodermic needles, each cut to size. The brass tubing is seamless (not interior welds) allowing for unrestricted fuel flow. The brass tubing dimensions will be as follows: OD: 1/8", ID: 0.085" with a max pressure of 3,000 psi at 72°F. This tube also has a temperature range of -40° to 200° F [3]. The stainless-steel tubing can be sourced from the 7th floor bioengineering labs that have several hypodermic needles with the needed dimensions. Welding the stainless-steel needles with the brass tubing might be an issue though as they are known to have poor compatibility, due to galvanic corrosion. This can be dealt with by making sure the stainless steel for the tubing is a compatible type [301, 304 or 310 stainless steels] or by choosing to use silver soldering [4]. As shown in the final product, *Figure 51 (b)*, a silver soldering approach was chosen to connect these tube joints.

The bending process for the tubing consisted of creating a jig that was to the indicated diameters of the design, and then manually bending the tub along this jig on the lathe. The benefit of using the lathe was that with the precision of using the lathe's position control, a constant pressure was able to be used during the bending process, therefore allowing for a consistent bend. This jig is shown in *Figure 51(c).* The tube has a region of elastic deformation, meaning that there will always be some spring back. This was initially seen as not a problem as the tubes would be soldered together regardless, meaning that there would be no need to keep them in position beforehand. This was proven to be an issue during the soldering process though, as it left the part in a constant state of stress, making the soldering jig much more difficult to set up, and made the piece much more structurally fragile. The jig for bending was then designed to account for spring back, which made the soldering process far simpler.

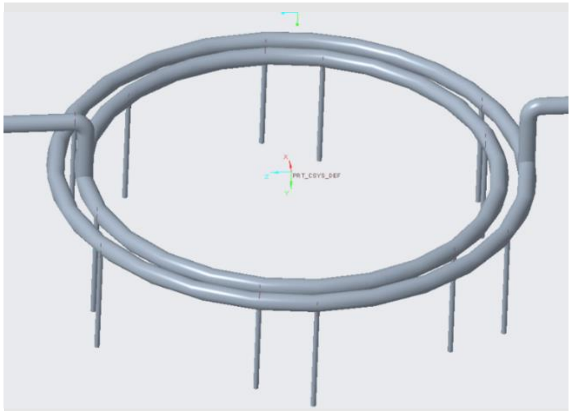
The hole in the brass tubing which would interface was designed to not interface with the tubes on the other side which would have the brass connection. This is because if they are on the same line, one of the joints will melt during the soldering process causing the piece to fail by filling up with solder. These tubes were made on the mill, at the diameter of the hypodermic needles (around 5 tau)

For silver soldering, a hand torch was used to heat the tubing and solder. To make sure that the brass would be heating up quick enough, the tip of the blue part of the flame (the hottest part) was always placed directly on the tubing during the heating up process. This is because during the silver soldering process the joint needs to be as hot as possible, without any of the heat flowing to the environment, meaning a traditional clamp set up could not be used to keep the pieces in place. A brick used as an insulator was used to deal with this issue, where the piece was able to sit on during the entire process. Also as shown in *Figure 51(d)* wet paper towels were used to make sure that the other soldered joints would not heat up during this process.

The silver soldering process is also very time dependent – if the piece of brass oxidizes before the solder is heated, then the silver will not adhere at all the brass. Also, if the flux itself vaporizes before the solder is used, then the interface would quickly oxidize meaning the process would need to be restarted. But if everything is done correctly, the silver solder will adhere to both faces of the tubing, and the joint will be sealed without any obstructions on the interior.

To not waste any resources, there was also a process done if this failed. After the piece is heated up and the silver solder for some reason does not adhere to join the tubing, both pieces need to be filed or rubbed with sandpaper to remove any of the oxidization and/or silver on the pieces. This proved especially difficult if the solder made its way within the piece, which meant the tube either needed to be shaved down, cut with the band saw, or remade. If this is not the case, then the tube would just be sanded, and cleaned with acetone. This process was especially important as if the two interfaces were not clean then the silver solder would not adhere at all to the joints. Once this process was done, the silver soldering process could be reinitiated with the same pieces.

The final product in the assembly is shown in *Figure 51 (e)*. This was not able to in the full assembly as it did not directly line up with the holes in the diffuser, and because the tubes themselves had been clogged with solder. Rather than bending the tubes to match, new fuel lines will be made without these issues.



(a)

(b)

(c)

(d)

(e)

Figure 51: Fuel Lines – Design (a), Final Product (b), Tube Bending (c), Silver Soldering Setup (d), Assembly (e)

Fuel Fittings

The properly attached the fuel fittings to the diffuser cover without air leakage, a small groove was machined on the bottom and an O-ring was attached to compress around the fuel lines so all the fuel goes into the fuel lines and doesn't leak.

Figure 52: Fuel Fittings

Vaporization Tubes

The vaporization tubes will be added to the end of the fuel lines which enter the combustion chamber. These tubes will be bent in a U-shape allowing for the fuel to reach the necessary temperature to enter the combustion chamber fully vaporized, ready for combustion. These tubes will be made of *Smooth-Bore Seamless Steel Tubing* sourced from McMaster. The seamless tubing will allow for unrestricted flow of the fuel, and should be stronger than normally welded tubing, allowing for greater maximum pressure (3,400 psi at 72°F). This tubing will also have a 3/8" OD and a 0.245" ID, with a temperature range of -65° to 800° F which should be well in the range (with an expected temperature of 650°F) [5]. It is important to note that the vaporization tubes should only be needed for the main fuel line, since the starter fuel does not need to be fully vaporized before entering the system. Therefore, the vaporization tubes will be organized in the chamber in a circular manner (x5), as indicated in Figure 53. The vaporization tubes will then be welded into the combustion chamber. Figure 53 also includes images of the tubes which were originally bent in the tube bender to a set radius, which were then taped together and better tuned to match each other. The tubes were then cut to match and were sanded to have a smooth finish. The tubes might need to be further cut in order to reach a proper clearance for vapor to exit.

Figure 53: Vaporization Tubes Assembly

Glow Plug

A glow plug was selected and purchased based on the desired temperature at which the fuel combusts. The chosen glow plug was the Hobbypark N3, which has a similar heat addition to the OS #8 glow plug.

Figure 54: Hobbypark N3 Glowplug

A redesigned port for connecting the glow plug to the combustion chamber was required, as the sample examined did not have enough points of contact with the outer shell. This means that the nut could not be adequately tightened such that it did not loosen itself from the outer shell due to vibrations. A curved washer was laser cut and grinded which had a radius of curvature that matched the radius of the outer shell. The connection from the glow plug nut to the glow plug was manufactured using stainless steel. The top nut was cut to a desired height for access to the glow plug for electrical connection to the controls.

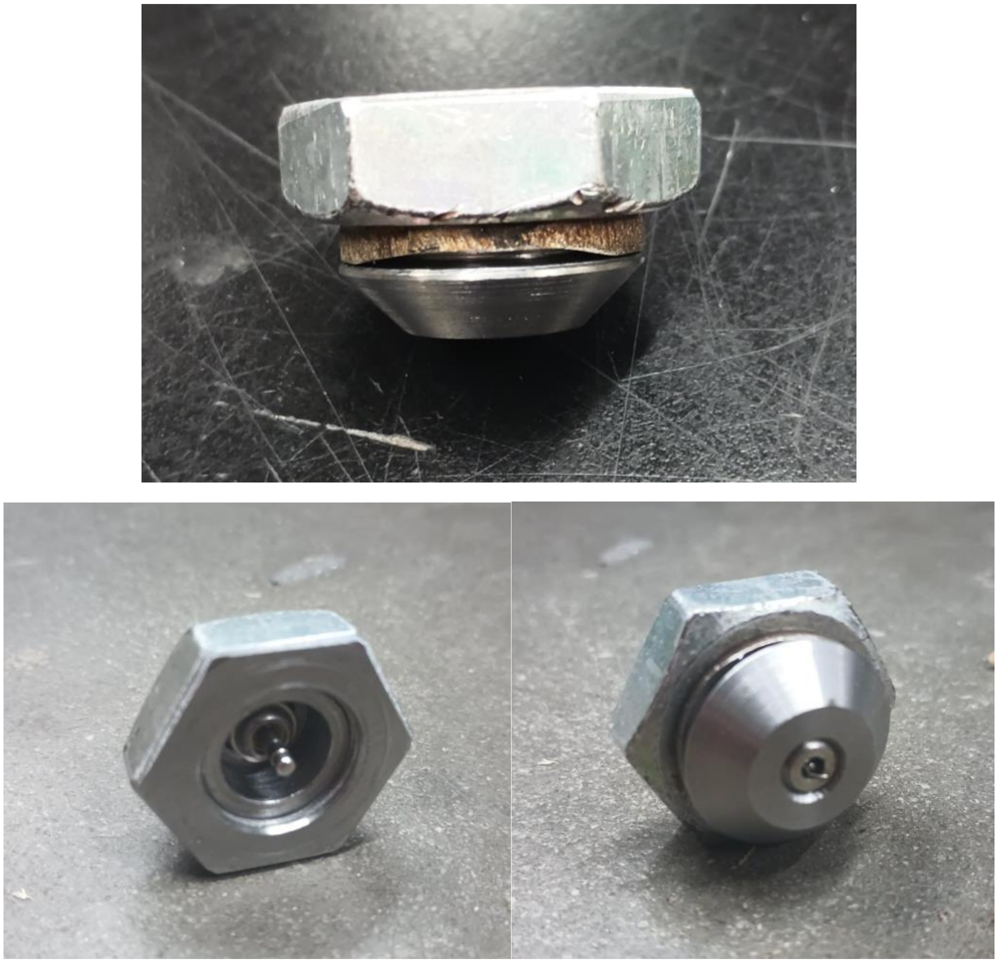


Figure 55: Glow Plug Nut and Washer Assembly with Glow Plug Installed

Assembly

The assembly of the jet engine begins with assembling the combustion chamber. The fuel lines with the needles attached are placed through the holes in the chamber. Then the chamber can be placed on the NGV and a hose clamp can be tightened to make sure it doesn't fall off.

Figure 56: NGV on Combustion Chamber

Once the combustion chamber is assembled, the shaft is inserted into the shaft collar and the springs and bearings are inserted into their slots.

Figure 57: Shaft Collar with Shaft

The diffuser is then screwed the shaft collar, and then the diffuser cover goes onto the diffuser.

Figure 58: Diffuser with Shaft Collar

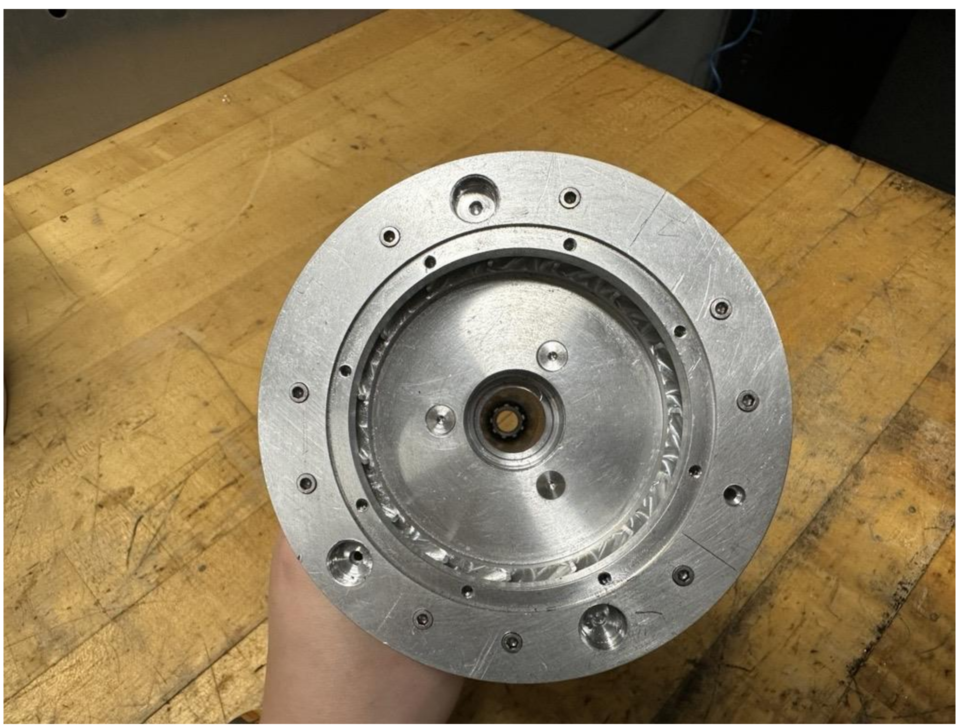


Figure 59: Diffuser Cover attached.

Finally, the shaft collar (with diffuser assembly attached) is screwed into the NVG (with combustion chamber attached).

Figure 60: Completed Stationary Assembly

Now that the stationary components are in place, the compression and turbine are screwed on. First the part, followed by a spacer, and finally a nut. The inlet cover is screwed around the compressor and the fuel fittings are added.

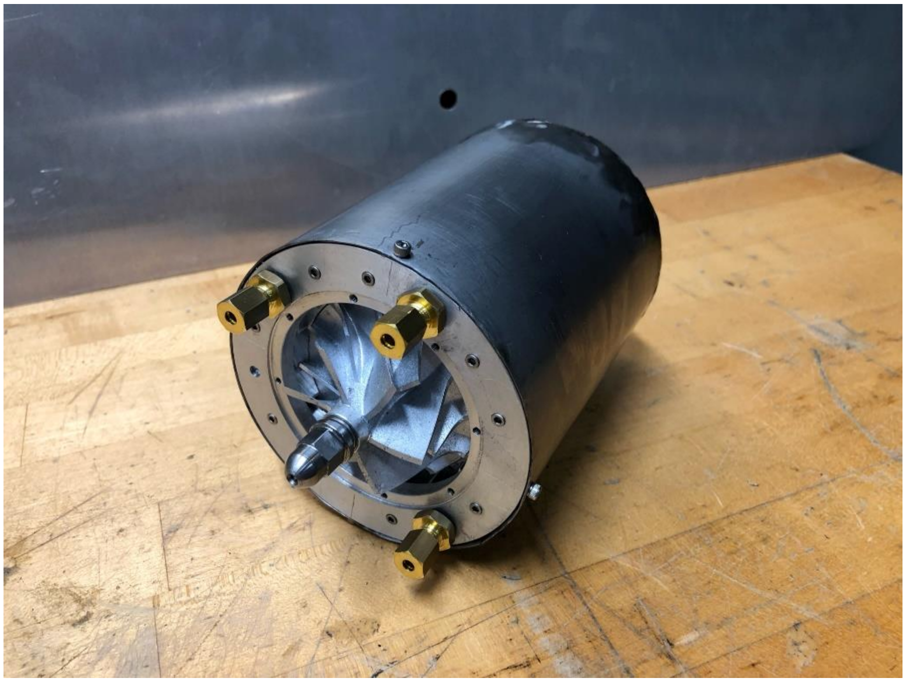


Figure 61: Assembled Compressor

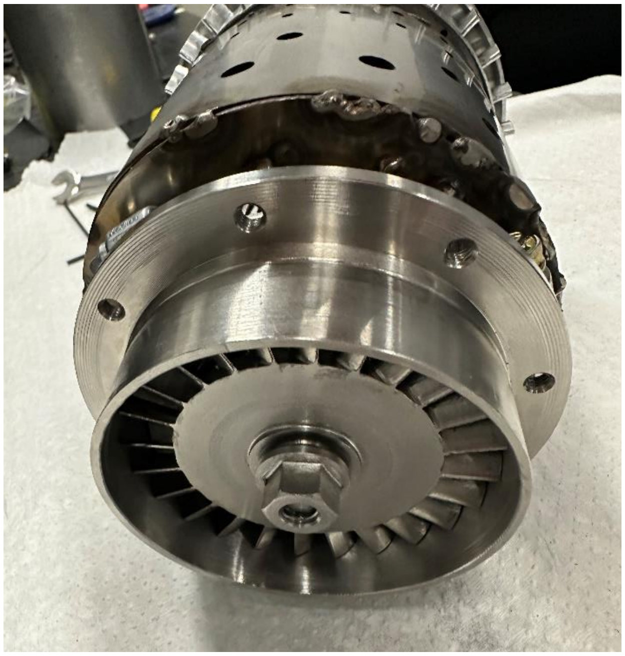


Figure 62: Assembled Turbine

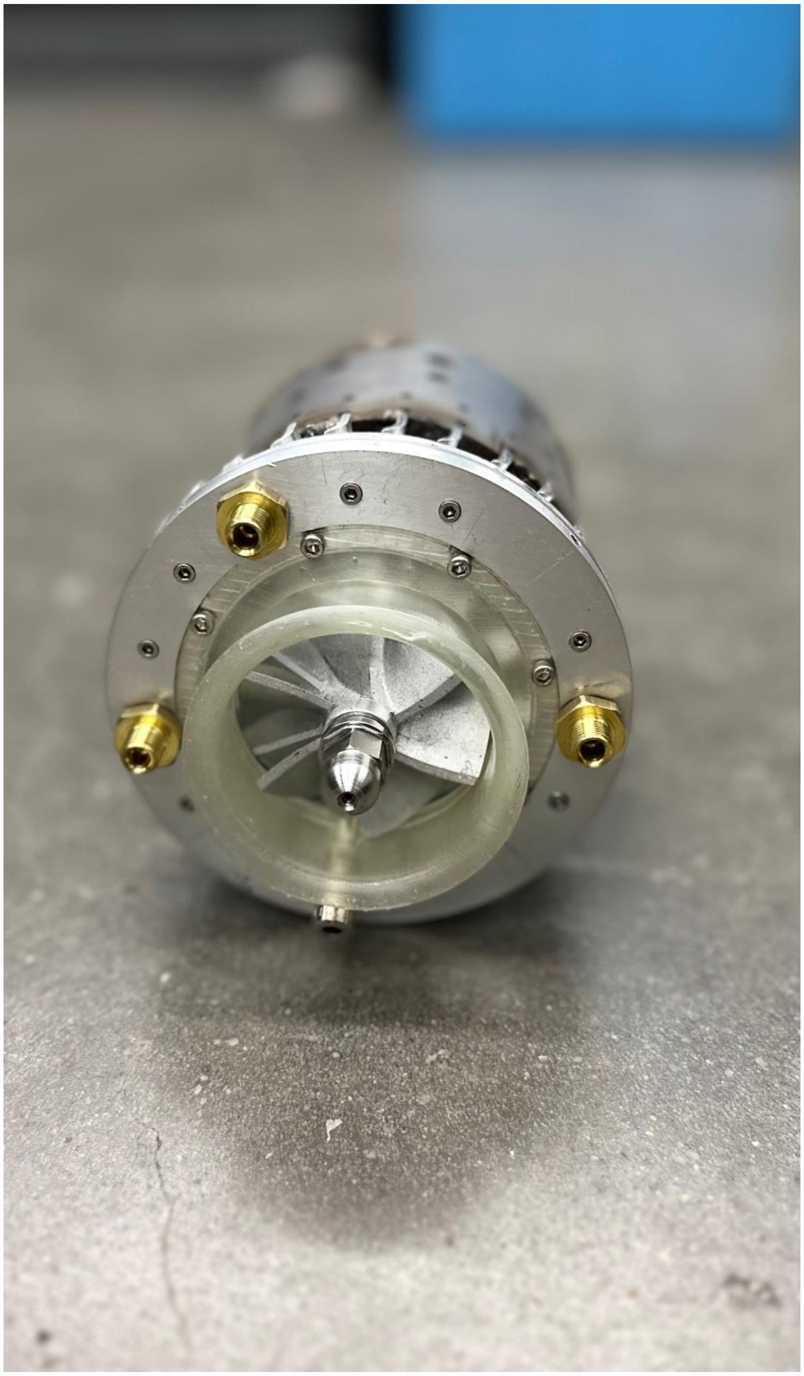


Figure 63: Fuel Fittings and inlet cover

Finally, the outer casing is put on and screwed into both the diffuser cover and the NGV.

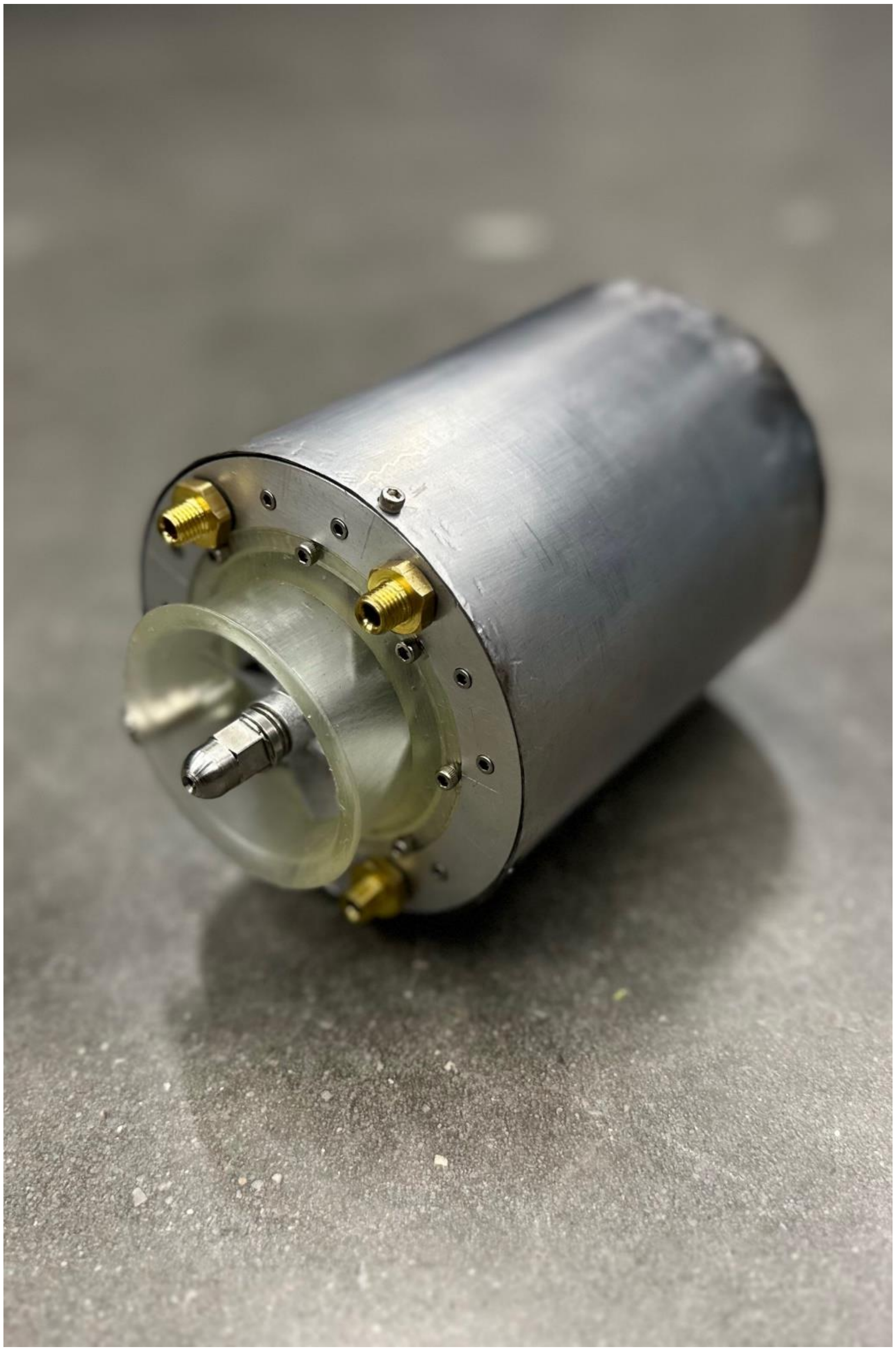


Figure 64: Final Assembly

Future Work

The engine ran really well on compressed air, and seemed well balanced. More rigorous testing will need ot be done to ensure that the rotational assembly is well balanced. Unfortunately, the engine was not able to be tested with fuel during the semester since the fuel lines were getting clogged during silver soldering. The next steps are to fix the fuel lines and then begin fuel tests.

Bill of Materials

The total price of all the materials used in this engine was $1470 but the actual price paid because of donations or spare parts around Cooper was $482.

Part	Part Number	Material	Dimensions	Process	Price	Actual Price	Time (Hours)
Rotary System							
Compressor	JE-R1	Aluminum		Casting/CNC Finishing	$ 40.00	$ 60.00	8/casting
Shaft	JE-R2	Stainless Steel	1" D x 7" Rod	Lathe	$ 20.00	$ 20.00	
Turbine	JE-R3	Inconell 718	3" x 1" Rod	CNC	$ 700.00	$ 80.00	
Bearings (x2)	JE-R4	Steel casing/Silicon	8x22x7 (mm)	Purchase	$ 148.00	$ -	
Spacers	JE-R5	Stainless Steel	3/4" x 2"	Lathe	$ 2.00	$ -	
Compressor Nut	JE-R6	Aluminum		Purchase	$ 2.00	$ -	
Turbine Nut	JE-R7	Inconell		Purchase/CNC	$ 2.00	$ -	
Pre Load Spring	JE-R8	N/A		Purchase	$ 10.00	$ 10.00	
Stationary System							
Compressor Cover	JE-S1	Resin Print		3D print	$ 7.00	$ 28.00	
Diffuser Cover	JE-S2	Aluminum	3" Rod	CNC	$ 15.00	$ -	
Diffuser	JE-S3	Aluminum	3" Rod	CNC	$ 15.00	$ -	
Shaft Collar	JE-S4		1.5" x 6" Rod	CNC/Lathe	$ 15.00	$ -	
Nozzle Guide Vane (NGV)	JE-S5	Stinaless Steel	3" Tube; 1" Tube; 1/8" Plate	Lathe/Welding	$ 100.00	$ -	
Outer Casing	JE-S6	Stainless Steel	1 mm Plate	Cutting/Rolling/Welding	$ 25.00	$ 10.00	
Combustion							
Combustion Chamber	JE-C1	Stainless Steel	.5 mm plate	Rolling/welding/Punching	$ 20.00	$ 10.00	
Fuel Lines	JE-C2	Brass	1/4"x0.065"x0.12"	Bending/welding	$ 15.00	$ 15.00	
Vaporization Tubes (x6)	JE-C3	Stainless Steel	3/8"x0.035"x0.305"	Cutting/(Bending)	$ 24.00	$ 24.00	
Fuel Injector Needles (x6)	JE-C4		.8 mm Needles		$ 15.00	$ -	
Fuel inlet Cap	JE-C5			Purchase	$ 20.00	$ 20.00	
Electronics							
Thermocouple + display	JE-E1			Purchase	$ 12.00	$ 12.00	
Fuel controller	JE-E2			Purchase	$ 13.00	$ 13.00	
Linear Hall Effect Sensor	JE-E3			Purchase	$ 10.00	$ 10.00	
LCD Displays	JE-E4			Purchase	$ 11.00	$ 11.00	
Emergency stop button	JE-E5			Found @ Cooper	$ -	$ -	
Arduino	JE-E6			Found @ Cooper	$ -	$ -	
12V Power Supply	JE-E7			Found @ Cooper	$ -	$ -	
Controller Pannel	JE-E8	Stainless Steel	1/8" plate	Found @ Cooper	$ 40.00	$ -	
Controller Base	JE-E9	Aluminum	Various profile	Found @ Cooper	$ 30.00	$ -	
Fuel							
Fuel	JE-F1	Kerosene		Purchase	$ 7.00	$ 7.00	
Starter Fuel	JE-F2	Propane		Purchase	$ 10.00	$ 10.00	
miscellaneous							
Fuel Fitting (x3)	https://www.mcmast	Brass		Purchase	$ 11.43	$ 11.43	
Fuel Fitting Tee Connector	https://www.mcmast	Brass		Purschase	$ 4.57	$ 4.57	
Air Fitting	https://www.mcmast	Nickel Plated Brass		Purchase	$ 10.62	$ 10.62	
Magnet	https://www.mcmast	Neodymium		Purchase	$ 1.48	$ 1.48	
1/8 BSPP Tap	https://www.mcmast	HSS		Purchase	$ 19.40	$ 19.40	
Semi Clear Tubing	https://www.mcmast	PTFE	2mm ID 4 mm OD	Purchase	$ 15.60	$ 15.60	
Clear Tubing	https://www.amazon	polyurethane	2.5 mm ID 4 mm OD (!0 meter	Purchase	$ 10.99	$ 10.99	
3-48 Screws	https://www.mcmast	18-8 SS	1/2" Long	Purchase	$ 14.02	$ 14.02	
8-32 Screws	https://www.mcmast	316 SS	5/16" Long	Purchase	$ 6.03	$ 6.03	
4-40 Screws	https://www.mcmast	316 SS	3/16" Long	Purchase	$ 5.67	$ 5.67	
4-40 Screws	https://www.mcmast	316 SS	5/16" Long	Purchase	$ 4.83	$ 4.83	
4-40 Screws (100 deg Flat)	https://www.mcmast	316 SS	5/16" Long	Purchase	$ 11.89	$ 11.89	
1/4-20 Tap (LH)	https://www.mcmast	HSS		Purchase	$ 7.62	$ 7.62	
1/4-20 Die (LH)	https://www.mcmast	Carbon Steel		Purchase	$ 16.70	$ 16.70	
O-ring Stock	https://www.mcmast	Buna-N	1.5 mm wide, 3 ft Long	Purchase	$ 1.92	$ 1.92	
Total							
					$ 1,470.77	$ 482.77	

Acknowledgements

Our group would like to thank several people for their assistance in making this project come together. First, we would like to thank Estuardo Rodas for teaching us and giving us many design principles and lessons along the way that have been informative in our designs. We would also like to thank Brian Yudin and Sinisa

Janjusevic for their machining expertise and their help in designing for manufacturability. Specifically, Brian has been a great mentor teaching us welding so that we can weld several parts of our jet engine and Sinisa for his time spent in CNC machining many of our parts that could not have been manufactured differently.

We would also like to thank GMN Bearings and Altemp Alloys for their generous donation of parts for this project. The project would not have been much more expensive and over our budget if not for them.

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