Thermodynamics Demonstration Unit 1B
Power Generating Turbojet Engine

Final Report

EGR 486C-01

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1. Background

The purpose of this report is demonstrate the project has been completed and the goals have been met to the clients standard. A discussion of previous semesters provide background and analysis towards the finished model. Reflecting on the end of the semester provides a post mortem analysis, where the team works through engineering issues encountered.

1.1 Introduction

The thermodynamic Brayton cycle has wide ranging applications from power plants to jet engines. Although courses of thermodynamics provide the necessary information for a Brayton cycle, they lack the physical demonstrations to portray the inner workings with respect to a jet engine. Stakeholders in the production and design are Northern Arizona University, David Willy, and staff; for the learning purposes. The Brayton cycle works in four stages: compression of the working fluid, introduction of heat within the heat exchanger, isentropic expansion through the turbine to produce work, then finally passes through another heat exchanger before starting again in the compressor. It was determined by the team that a power generating turbojet engine is a simple concept that illustrates aspects of introductory thermodynamics.

1.2 Project Description

The team was given the task of designing and building an educational model of the Brayton cycle for use in thermodynamic classes. The model is to demonstrate the compression, expansion, and heat addition principles shown in a classic Brayton cycle in a thermodynamic class. The ultimate goal is to collect real time data to display on T-s and P-v diagrams while the cycle is running. Through iterations of the project, the scope has been narrowed down to a power generating turbojet engine that will convert rotational energy into electrical energy to illustrate power output.

2. Requirements

Research performed required meetings with NAU staff to outline customer requirements and the engineering requirements associated with them. All requirements were assembled in a house of quality which provided insight into the most critical components of the project. Following research for requirements, the team outlined testing procedures for the quality check of the built project.

Updates regarding customer requirements included ignition system and power output type. Beginning the project, it was determined that air would be introduced in the compressor section, this idea was altered by the client upon witnessing the final product. Another discrepancy of the clients was the power output type to AC instead of the proposed DC power. The team had proposed the initial light bulb display with a brushless DC motor since the project's beginning; it was not mentioned again until witnessing of the completed project.

2.1 Customer Requirements

Based on the client suggestion, we met with the thermodynamic professors (Dr. Mazumdar, Dr. Nelson, Dr. Wade, and Prof. Willy) at Northern Arizona University to collect the customer requirements. The Responses of requirements can be seen in Table 1.

Table 1: Customer Requirements

Customer Requirements	Weighting	Justification
Collect Data	5	The fundamental principles behind teaching the Brayton Cycle to future students
Safety	5	No damage or deterioration of model over time to ensure functionality
Functionality	3	Must be operational for a maximum of 15 minutes to simulate a Brayton Cycle
Rigorous Design	4	Team designed blades, casing, and data acquisition
Analysis	5	Turbomachinery design and Brayton Cycle
Cost	3	Maintain low cost for entirety of project
Visibility	4	To visually illustrate the processes of a Brayton Cycle

2.2 Engineering Requirements

The team's engineering requirements can be found in Table 2. The team collected the customer requirements information from the client and customers to determine the required engineering requirements.

Table 2: Engineering Requirements

Engineering Requirements	Target	Units	Justification
Work Output	20 Watt	$Watt$	Production of power from turbines will turn on a light bulb connected to the system.
Aerodynamic	>.3	C_d	Minimizing aerodynamic drag will increase the power produced from turbines
Thermal Capacity	100	K/m^2	Implementation of a heat exchanger, will provide the data for interactive graphs
Volume	<.5	m^3	Constant volume measurements for each process of cycle is required for P-v diagrams
Data Acquisition	Pressure and Temperature	Pa, K	To create a realtime chart for T-s & P-v diagrams to simulate a Brayton Cycle

2.3 Testing Procedures

Testing procedures were generated for each main component, each procedure is related to the projects engineering and customer requirements while maintaining paramount safety. The purpose of the testing procedures is for two reasons, a quality check of the project and a operating manual for safe and reliable usage. Each component has been analyzed to create a specific quality check and operation.

Quality Check

Power Test

Tools: Multimeter

Procedure:

Measure motor resistance for quality assurance

Measure voltage and current generated from motor

Heat Test

Tools: Thermocouple

Multimeter

Procedure: Check heating element temperature is below 240° F

Check thermal fuse is operational with multimeter

Check Aluminum Shroud is safe to touch with thermocouple

Pressure Test

Tools: Multimeter

Computer

Procedure:

Measure Voltage generated from pressure transducer

Check all wires are connected and communicating to computer

Speed Test

Tools: Stroboscope

Procedure:

Measure rotational speed of shaft

RPM not exceeding 1500 for safe operation

Operating Procedure

Ignition Procedures

Plug in main power cable

Begin Air Compressor to 60 psi

Release Valve to Turbine Section

Turn Valve to Compressor Diffuser

Heating Element Operation

After Ignition is completed and running

Turn on heating system

Safe Run Time: 20 minute, continuous

Temperature Acquisition Operation

After LED system is continuously operating

Plug in Temperature position one

Acquire Data

Plug in Temperature position two

Acquire Data

Pressure Acquisition Operation

Plug in Pressure position one

Acquire Data

Plug in Pressure position two

Acquire Data

Shut Off Procedure

Turn off Heating system
Turn off Power System
Allow system to run until no movement
Unplug main power cable

Quality checks and operation procedures are necessary for the safety of the team and student body that will utilize the project. Simple procedures have been generated for each component that ensures all users have a safe and reliable method of operating the power generating brayton cycle.

2.4 Design Links

In this section, the design links from the customer requirements to the engineering requirements are analyzed in a simple Pugh chart in Table 3. The purpose of this analysis via pugh chart, provides the basics to which the team ignored in pursuit of having a rotating model built by the time of presentation. Instead of focusing on the final product, the team should have managed the foundation to build a working and elaborate project utilizing proper design links.

Table 3 : Pugh chart

		Stator Blade on casing	Stator Blade on shaft	Gear box	No Gear box	Pitot Static Tubes	Strain Gauges
		Concept 1	Concept 2	Concept 5	Concept 6	Concept 7	Concept 8
Criteria	Weight						
Work Output	5	S	S	+	-	S	S
Isentropic Efficiency	3	+	-	+	-	+	-
Thermal Capacity	2	S	S	S	S	S	S
Volume	3	S	S	+	-	S	S
Data acquisition	5	S	S	S	S	S	S
Cost	3	S	S	+	-	-	+
Aerodynamic	4	S	S	-	+	-	+
Internal Velocity	3	S	S	-	+	S	S

2.5 House of Quality

House of Quality can be seen in Appendix 11.1. The house of quality is a tool for understanding the relationship between the customer requirements and the engineering requirements. The QFD also allows us to understand how the design can be improved by knowing the most detail on our design. Based on the QFD we can decide or determine the most effective component in order to design an educational high bypass turbofan.

3. Existing Designs

3.1 Design Research

Current designs of a turbojet engine are only on jet engines reaching above mach 1. Also, the client has made requests that further separates out project from full size turbojet engines. Therefore, the research conducted incorporates the mathematical concepts behind the jet engines. Assumptions made to simplify the extremely complex equations include speeds much slower than mach 1, no blade vibrations, and including a generator behind the turbine to capture the rotational energy instead of thrust.

3.1.1 Power Research

The LED display consisted of 24 individual 24 Volt LED bulbs at 4.4 Watt per foot. A 4 pin connector is required to attach the brushless DC motor to the LED strip, as shown in Figure 1. Calculations from were utilized are provided to demonstrate the current required for two segments of LED lighting to be lit as.

Considering a 8 inch segment of lighting, the power required is 2.93 watt [1].

$$P = i \cdot V$$

$$i = \frac{24\ Volt}{2.93\ Watt} = 0.122\ Amps$$

A DC motor has been selected with a resistance of 5 Ohms and a torque constant of 21.1 mNm/A (milli-Newton meters per Amp).

$$V = i \cdot R + K_e \cdot \omega$$

$$\omega = \frac{24\ Volts - (0.122\ Amps)(5\ \Omega)}{21.1\ mNm/A} = 110.85\ rad/s$$

3.1.2 Casing Research

The purpose of designing a casing around a Brayton cycle, specifically at jet engine cycle, is to channel the working fluid through the system safely. This report will detail the material chosen as well as the rationale behind the design. A past option for a casing design was to form an acrylic tube to the shape the team decided. The design would not be time effective and was too expensive for the project's budget, however. The current design was chosen because of the time and cost effectiveness.

The material chosen for the casing is PLA 3D printer filament provided through NAU. PLA filament is a common material because of the applications of the prints. PLA filament does not need special equipment like other filaments would and has low warp qualities after prints. Unfortunately, the 3D printers provided through NAU do not allow teams to purchase specific filaments for use. The color of the team's design was supposed to be clear. However, current clear filaments have a milky white quality that does not allow much transparency. To account for this, the team decided to alter the design to allow visuals to the inside. This is discussed further in later sections.

3.1.3 Blade Research

Current rotor blade designs have been generated through many iterations to fit any and all situations. Utilizing Airfoil Tools [2], it is possible to examine blades that meet the speed and Reynolds numbers. For the project, there are two rotor blades in question: axial compressors, and axial turbines. To analyze the performance and outputs of the rotor blades, it is critical to apply the Euler Turbomachinery equations for the work output potential of the system [3].

Current rotor blade designs are complex and arguably the most important factor of the modern jet engine. The compressor blades are designed to slow and compress the incoming working fluid to a calculated internal pressure. To achieve this, the blades have a twisted contour design that helps direct the fluid flow towards the following compressor blades more efficiently than simply a blade with no twisted contour. This transfers the fluid's kinetic energy into usable potential energy. Following the compressor and combustion chamber, the turbine blades are used to direct the working fluid out of the system, providing thrust. The turbine blades are designed similarly to compressor blades, however turbine blades are designed with a more defined curvature to propel the working fluid out of the system at a higher velocity than it entered with.

3.2 System Level

The purpose of the project is to design and operate a power generating brayton cycle that allows for the education of introductory thermodynamic principles. The operating Brayton cycle is able to educate under three main parameters related to engineering and thermodynamics. The principles utilized for work production, is directly related to power energy analysis. The blades designed for the compressor and turbine sections are related to airfoil analysis relating to the flow of the fluid. Figure 1 shown below visualizes the process of the project.

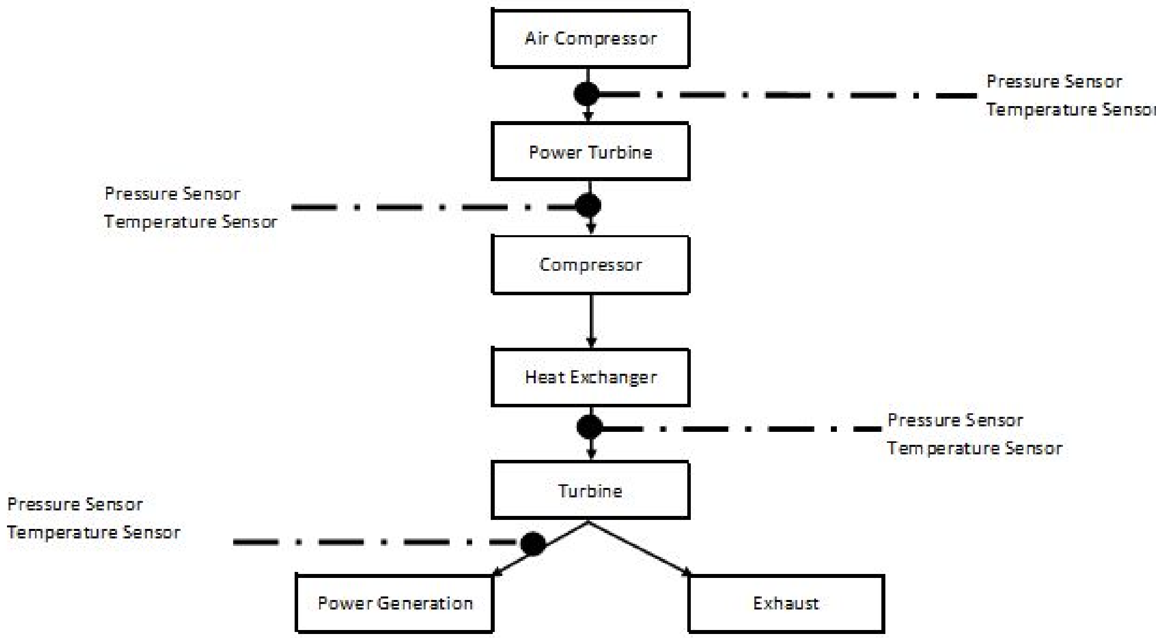

Figure 1: Project Decomposition

3.2.1 Thermodynamic Work Output Principles

The main importance of the project was to assist thermodynamic professors to teach students the Brayton cycle. In a Brayton cycle, a working fluid is initially compressed, then heat is added to the compressed fluid, leading into a turbine section which draws a work output form the fluid, before entering a compressor section again in a complete cycle. The project should be able to visualize these principles in a manor that students can understand.

3.2.2 Power Generation

Power from a Brayton cycle, specifically a turbo jet engine, is done through the use of turbine blades. The blades draw the rotational energy from the working fluid in the casing to a linear motion, therefore producing thrust. Instead of producing and measuring thrust, since it is not visible, the team decided to implement a generator to produce electricity. The electricity can be used in many different applications to show a visible work output.

3.2.3 Airfoil Analysis

The flow of the working fluid is crucial in creating the highest efficiency possible. The working fluid flows over the compressor and turbine blades, which needs to be redirected with as little inefficiencies as possible. Specific airfoil have a higher efficiency of lift vs drag, therefore must be chosen carefully.

3.3 Subsystem Level

3.3.1 Thermodynamic Work Output Principles

Expansion and Compression:
Compression in thermodynamic principles increases the temperature of the system, the purpose of this analysis is to demonstrate the efficiency of the compressor section. Calculating the pressure before and after the compressor section allows for the compression ratio necessary for the work output equations.

Heat Input:
Inputting heat into the system increases the energy of the system. The purpose of this analysis is to allow for the calculation of efficiency of the heater, as well as the efficiency of the entire system. The more heat put into the system, the better the cycle will operate.

3.3.2 Power Generation

Turbomachinery Analysis:
Utilizing the turbomachinery equations, it is possible to calculate the work output due to the decrease in rotation of the shaft. Although turbomachinery analysis does not occur in a elementary thermodynamic class, it is useful for Fluid dynamic analysis.

DC Motor Analysis:
To calculate the amount of power the DC motor can produce it is necessary to measure parameters of the system. Measuring the resistance of the motor and the torque characteristics leads to the induced voltage generated from the rotating shaft. By performing a DC motor analysis, fundamentals of electrical engineering are tested.

Power Analysis (Difference of input vs. output):
Following thermodynamic educational principles, a component efficiency analysis must be performed. Calculating the efficiency of the compressor and turbine sections will dictate the performance of the cycle and the amount of power generated. Problems from thermodynamic textbooks about Brayton Cycles with irreversibilities can be illustrated by performing a power analysis of the cycle.

3.3.3 Airfoil Analysis

Turbine Analysis:
Similar to calculating the efficiency of the cycle, it is imperative to measure the efficiency of the turbine stage. By minimizing irreversibilities, it is possible for future classes to inspect the project and analyze how to improve turbine blade design along with turbine efficiencies.

Compressor Analysis:
Compressor blade design is meant to compress the moving fluid into a higher state of energy before the input of heat. By analyzing the blades selected from the flow regiment, design and compression ratios can be calculated.

Flow Analysis:
Although not directly related to introductory thermodynamic classes, flow analysis is crucial for all engineering students. Flow analysis is the flow regime of the working fluid, i.e the reynolds number and turbulence of the fluid.

4. Designs Considered

Casing Reduction Alternative:

Original designs of the casing included placement wire filament to allow for constant area heating. Amount of compressor staging has decreased, and the air intake was in the clients intended ignition location. Figure 2 depicts the agreed upon design for research purposes.

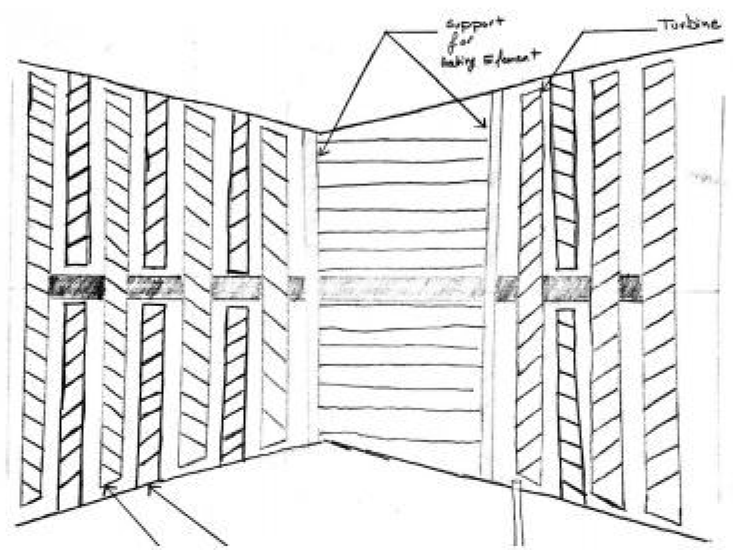

Figure 2: Original Design Iteration

Two Stage Ignition:

Initial designs in the summer semester worked on the previous idea of turbine ignition, as seen in Figure 3. Allowing the air to be switched to the compressor staging, the air compressor can operate at a lower pressure and still rotate the shaft.

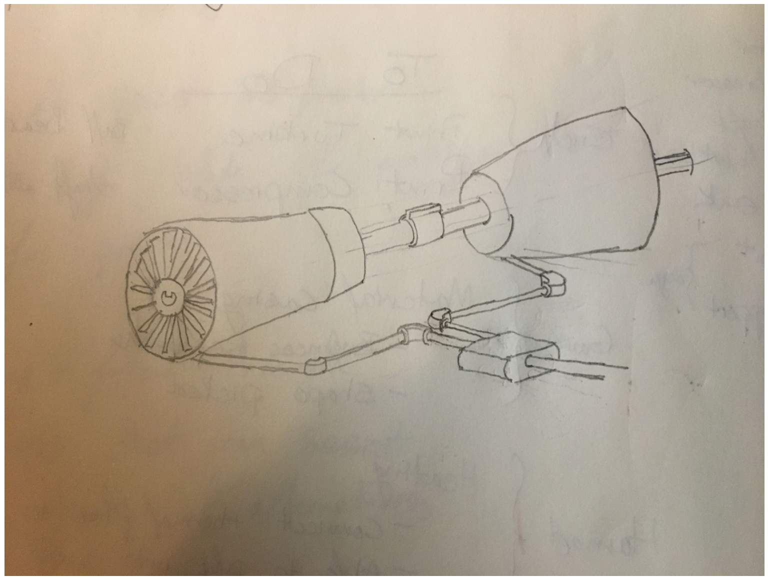

Figure 3: Summer Iteration One

Analog Pressure and Temperature Systems:

To meet the demands of the client, the team has focused on a digital system to acquire data from the working Brayton Cycle. The original idea of the team was to have manometers and temperature gauges on a wooden board behind the system that would physically illustrate the pressure and temperature states. This idea, as shown in Figure 4, would allow the entire project to be mobilized quickly without the need to set up a computer to run the data process.

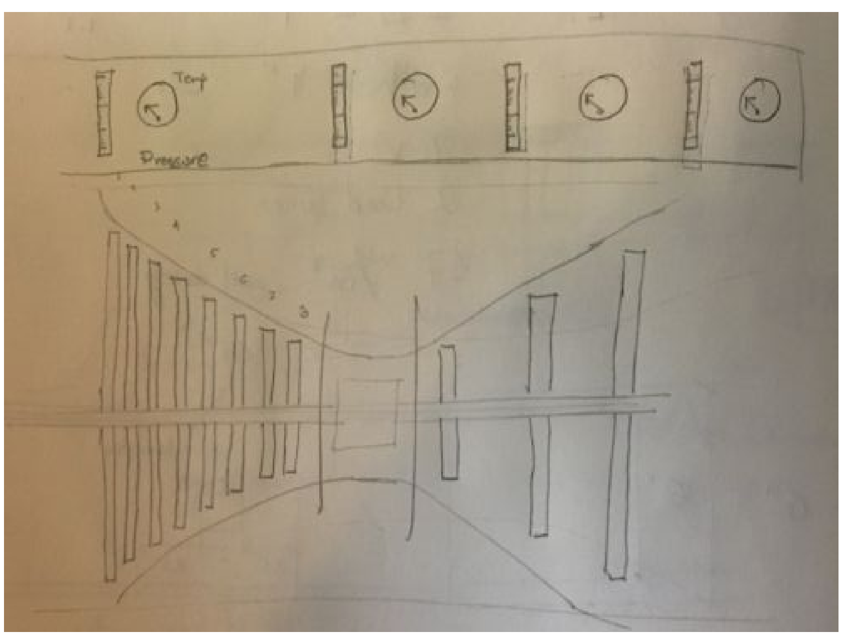

Figure 4: Analog Systems

Voltage and Current Output Sensors:

Similar to the analog temperature and pressure readings, a voltage and current meter was planned to be mounted at the end of the model. By presenting a analog system of reading, the project would allow quick and immediate power readings. This idea was not finalized out of the project. Figure 5 shown below displays an idea created for the analog outputs.

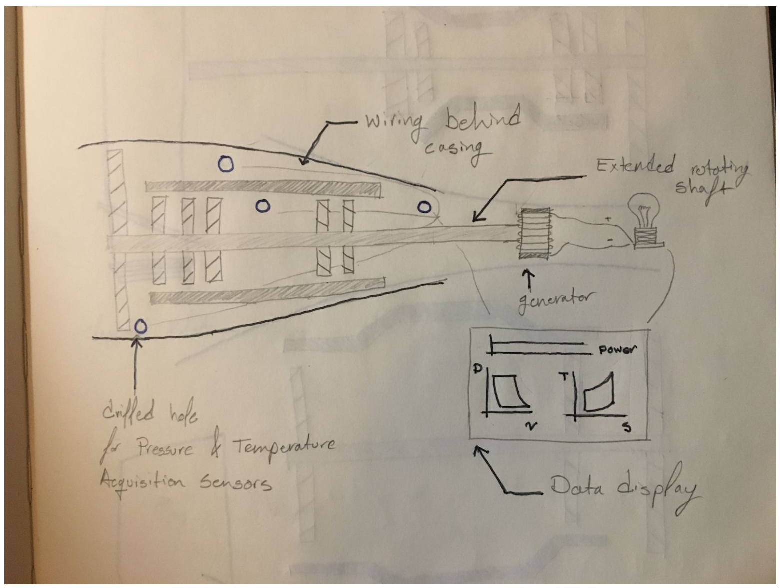

Figure 5: Turbojet Design Idea with Analog Outputs

5. Design Selected

5.1 Rationale for Design Selection

5.1.1 Power System

The power system was designed so that the rotating shaft would generate enough power to turn on a lightbulb. After research conducted to find a generator that will provide the lightbulb with power according to the power engineering requirement. After a quick search, a simple brushless dc motor will provide the project with a power output of 24 Watts, achieving the engineering requirement of 20 Watts.

5.1.2 Aerodynamic

After calculations for the Reynolds number were completed, a spreadsheet was made to analyze inlet velocities, angle of attack, and power output. These calculations were performed via the Euler Turbomachinery equations that produce the work output depending on the change of rotational speed and angles. Utilizing the mentioned equations, a inlet velocity was chosen to lock in the rotational speed with a selected diameter.

Calculating the tangential velocities from a range of angles and inlet/outlet velocities. Figure 6 shows how the power output increases from a increase of blade pitch assuming a set velocity. To illustrate the Euler Turbomachinery equations with a set of four turbines, it was determined that the power output would be 21.85 Watts [2]. Equations and calculations for the power output can be seen in the appendix.

Work output was calculated by iterating various angles with a selected inlet and outlet velocities. The spreadsheet that was used to calculate the power output with angles is attached to this report in the appendix. Additionally, figure 10 (located in section 8.2) shows a graph of various coefficient of drags with differing angles of attack. The coefficient of drag, unfortunately, is much higher than our engineering requirement hopes for.

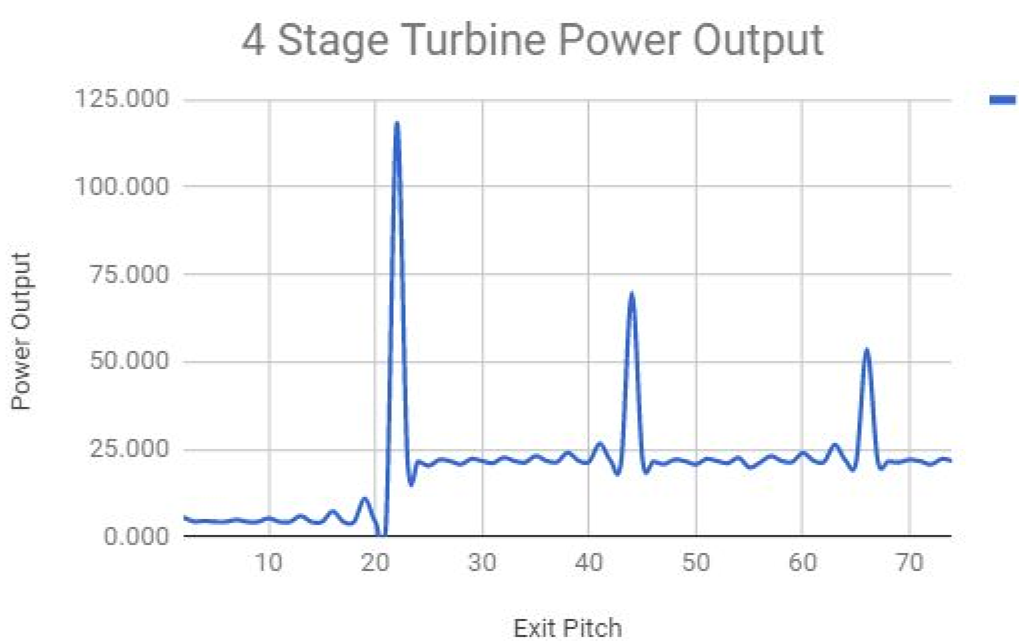

Figure 6: Power Output vs. Blade Pitch; at 20 ft/s

The importance of the Euler Turbomachinery equation for the analysis of the turbine is to demonstrate the relationship between the parameters that affect power output. The goal of the turbine is to steal as much kinetic energy as possible from the inlet velocity. Achieving reduced the speed per turbine stage as well as increased angles yields the highest work output.

5.1.3 Thermal Capacity

Energy outputs were previously assumed to theoretically calculate power outputs with achieved temperatures. Table 5 illustrates the assumed states that the operating system would achieve. All further design iterations were implemented in CAD using the property assumptions made.

Table 5: Thermodynamic parameters and their values

Sr. No.	Quantity	Value
1	Output Energy from Turbine	~20
2	Inlet Temperature Required	100 °C
3	Mass Flow Rate	0.00004 slug/sec
4	Atmospheric Temperature	75 °F

5.1.4 Volume

No previous research was performed for the necessary volume intake for adequate power output. Volume analysis began towards the end of manufacturing when internal volumes had been determined, and theoretical P-v diagrams were produced. The volume of air will be changing as it advances further into the compressor turbine sections. The engineering requirement made was unrelated to jet engine related Brayton cycles, as the volume of air will constantly be changing while in the open system turbojet design.

5.1.5 Data Acquisition

Measurement of temperature was to be measured through voltage using LabView. Translating the voltage into temperature through a calibration equation, it would be able to create temperature states of each subsection for the system.

Temperature is to be measured for record and generate T-S diagram on output. Required temperature measurement is performed with j-type thermocouple. J-type thermocouple are selected based on its greater accuracy in lower cost in our interested temperature ranges. In order to maintain the compaction, thermocouple legs are inserted in the casing while output reading are viewed outside of the casing. By change in composition at thermocouple legs, a voltage will be generated. Difference in generated voltage will exist at same temperature due to two different materials composition, which is then translated back to temperature as per calibration [4].

Preferably the required data for Brayton cycle, pressure and temperature readings, are taken at similar points. Therefore, along with pressure gauges, J-type thermocouples, shown in figure 7, were installed in the same drilled hole as it for pressure sensors. By choosing same drilled holes as of pressure sensor enables to plot P-V and T-S diagram at same reference points. Ultimately, real time data was obtained and stored with LabVIEW for record and generation of T-S diagram.

Figure 7: J-Type Thermocouple

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5.2 Design Description

Original iterations of the design were created to house equal size turbine blades in a solid case. Designs for heating had not been introduced at this time of design, focus was primarily on housing and blade placement. Figures 8 and 9 show the initial iterations of 3D designed assemblies.

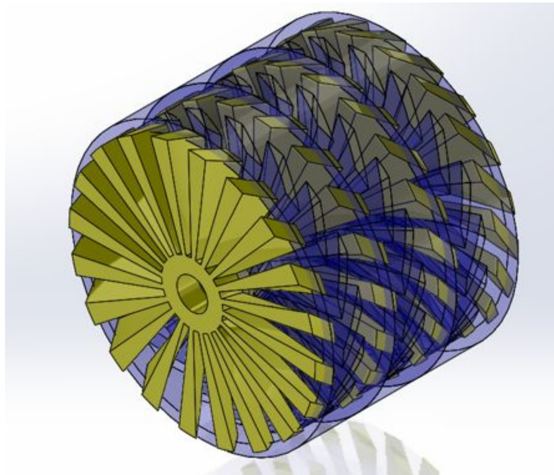


Figure 8: Fall Iteration Turbine Casing

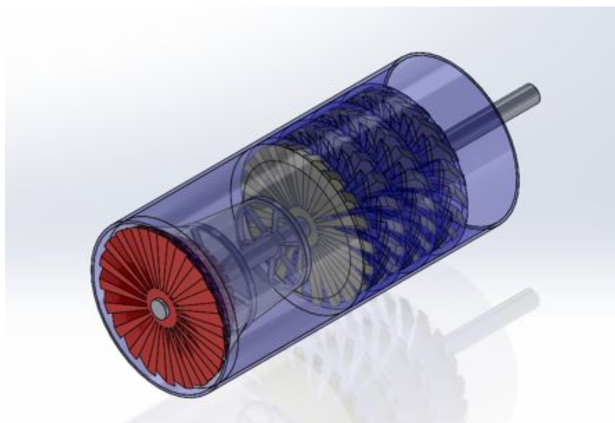


Figure 9: Fall Iteration Brayton Cycle Assembly

6. Proposed Design

CAD drawings were generated to allow the visualization of blade and stator placement. These iterations of drawings produced a pin slotted arrangement for casing that could allow for straight acrylic tubing to be used. Drawings found in appendix A11.3 demonstrate the future placements of stator and turbine blades that would develop the tolerances needed to maintain pressure.

7. Implementation

To manufacture the designed Brayton Cycle 3D printing, purchasing, and assembly are all required. Implementation of the manufacturing plan required key dimensioning off three critical parts: the keyed shaft, heat band, and radial ball bearings.

7.1 Manufacturing

Manufacturing the designed Brayton Cycle requires printing of the CAD drawings, purchasing of key components, and assembly. Table 6 provides a list of purchases, a list of 3D printed parts, and components for assembly. Each component has been segmented to display the purchasables, printing, and assembly features. Additionally, the Bill of Materials with pricing of all components can be seen in the Appendix section 11.5

Table 6: Task Management

Tasks for Team Members	Task Completed	Tasks to Complete
3D Print (Erich)	Ball Bearing Casing Designed CAD Printing Bearing Casing Printing Turbine Casing Printing Compressor Casing CAD update Keyed Shaft purchased Blade Staging Printed (9)	Future Team Redesign
Casing (Gavin)	Case Shape designed Purchasing Bolts Plywood Construction Purchasing Cart Material Selected Casing Assembled	Future Team Redesign
Heating System (Hamad)	Heat Band purchased Assemble safe housing and wiring Thermal Fuse Purchased Heat band power input built Power Switch assembled	Future Team Redesign
Pressure System (Abdullah)	Pressure Transducer purchased p-V & T-s diagram for power output ranging from 50 - 100 Watt Purchase Wire for pressure systems	Reacquisition of Pressure DAQ for future team
Work Output System (Erich)	LED strip purchased Purchase RGB Wiring Brushless Motor Selected Assemble Wiring system Motor hub designed and currently printing	New LED bulb attachment to DC motor Alternative to DC motor analysis
Ignition System (Gavin)	Air Compressor acquired Purchasing Tubing Purchasing Valve	Future Team Redesign

7.2 Design Changes

The heating element was originally presented to be a hot wire foam cutter, design iterations allowed for safety improvements. To allow the safe handling of the project, a thermal fuse was selected to close the circuit when the heating element reached a critical temperature. The implementation of the thermal fuse and wire band heater can be located in Appendix 11.2.

Power output was altered upon testing proof, to allow the reading of current and voltage through the use of a multimeter. Original designs included a LED strip or light bulb to demonstrate the power output generated by the rotating shaft. Currently the DC motor is attached to a multimeter that measures the current and voltage output.

Data acquisition was initially planned to allow any student or professor to plug in thermocouple and pressure transducer into a PC. upon learning from staff that LabView is not currently on any computers other than the ones located in the thermal fluids lab; it was determined to leave equipment for future teams. Future equipment must be handled accordingly with NAU staff to allow the borrowing of data acquisition tools.

Compressor blade manufacturing was too thin in the original prints from the RapidLab. Unfortunately the team could not iterate upon design and was forced to strengthen the material through epoxy. Fortunately the blades are flexible and durable enough to allow for easy positioning in the case and upon the shaft. All blades were coated in a thin layer of epoxy to toughen the outer layer.

An air diffuser was designed and constructed to allow a uniform flow of air into the compressor staging. Compressor blades were not strong enough to convert the force into rotation until epoxy was applied. The ignition system was then attempted to be implemented into the heating section of the model. The current system has to contain an air pressure of 80 - 150 psi in the air compressor and can now be introduced in the compressor staging. A compressor staging has been removed to allow for less stress on the shaft and for easier rotation.

The original casing design included a constant decreasing slope in the compressor section and equally a constant slope increasing for the turbine section. The final design of the casing contains a decreasing area with flat sections for the blade. This was to minimize air escaping around the space between the edge of the blade and casing. The steps help create a flat section that hugs the blade and allows for minimal space between the blades and casing. To allow the students to see the blades transferring energy into rotational energy, viewing sections were implemented for students to see the blades and shaft spinning.

The team initially ordered a band heater that was too small to fit the heat sink that was purchased. To fix this, the team returned the small band heater and purchased the larger band heater that was available. The new band heater reached higher temperatures quicker, which was beneficial to the project efficiency. The band heater would reach high enough temperatures to melt the casing. The team decided to purchase a thermal fuse that would shut the band heater off around temperatures of 110°C. Additionally, the team decided to incorporate a light switch that would also shut off the band heater if the thermal fuse did not operate correctly. This was to help keep the customer requirement of safety applicable. To make the project even safer for use, an aluminum duct was purchased that will fit over the heating section to prevent students from coming into contact with hot components.

8.0 Testing

Testing the power generating Brayton Cycle required the model to be fully operational. The majority of the engineering requirements are directly related to the subsections of the Brayton Cycle. Engineering Requirements were produced incorrectly at the beginning of the project, therefore the testing proof for each criteria does not accurately reflect the teams output. Upon reflection of the project, the engineering requirements should include the compression ratio, shaft rotation, and temperature achievement. Acquiring the proper engineering requirements would better illustrate the end state of the project.

8.1 Work Output

The LED strip shorted and was unable to operate from the DC brushless motor. A theoretical output was .46 kW. After putting the multimeter to the rotating DC motor, a voltage of 10 and amperage of 9 produced 90 Watts of power. This 90 Watts of power is significantly lower than the theoretical .46 kW, due to inefficiencies in the blades and the material not being able to withstand the forces to generate the power. To achieve the power output, a different material than PLA must be chosen.

8.2 Aerodynamics of Compressor Blades

Compressor blade 1:
Angle of attack: 52.51°
Coefficient of drag: 0.82

Compressor blade 2:
    Angle of attack: 52.51°
    Coefficient of drag: 0.82
Compressor blade 3:

    Angle of attack: 52.51°
    Coefficient of drag: 0.82

Compressor blade 4:
    Angle of attack: 37.62°
    Coefficient of drag: 0.57

Compressor blade 5:

Angle of attack: 30.74°

Coefficient of drag: 0.51

Compressor blade 6: 25.79°

Angle of attack: 25.79°

Coefficient of drag: 0.42

Upon creation of the Engineering Requirements, the team used drag coefficients to determine the blades efficiency. However, upon reflection the team should have used lift coefficients instead because the lift force from the blades is what determines the rotational speed of the shaft. A graph relating the angle of attack with the coefficient of drag is shown in figure 10.

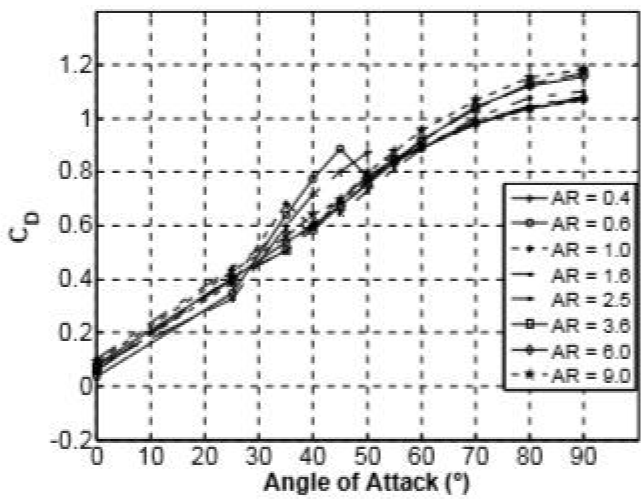


Figure 10: Angle of Attack vs Coefficient of Drag for a Flat Plate [7]

8.3 Thermal Capacity

During the initial creation of the Engineering Requirements, thermal capacity carried the incorrect units. Upon purchasing Mild Steel for the heat sink, it was researched to find that Mild Steel has a specific heat capacity of 510.7896 J/kg・K.

Table 7: Specific Heat Capacity of Selected Metals [8]

Specific Heat Capacity of Metals Table Chart				
Metal	**Btu/(lb-°F)**	**J/(kg-K)**	**J/(g-°C)**	**Btu/(lb-°C)**
Steel, Mild	0.122	510.7896	0.5107896	0.2196
Steel, Stainless 304	0.120	502.416	0.502416	0.216
Steel, Stainless 430	0.110	460.548	0.460548	0.198

8.4 Volume

The engineering requirement that the team chose, was that the total volume of material printed would be less than .5 m^3. The choice for volume implementation was for the reduction of cost for material to be printed. A more important engineering requirement that could have been utilized instead of the volume of material printed, is the compression ratio necessary for real work output. Current methods of measuring volume of the print included SolidWorks to measure the mass properties of the prints.

Total Volume: 53.73 in^3 = .00088 m^3 << .5 m^3

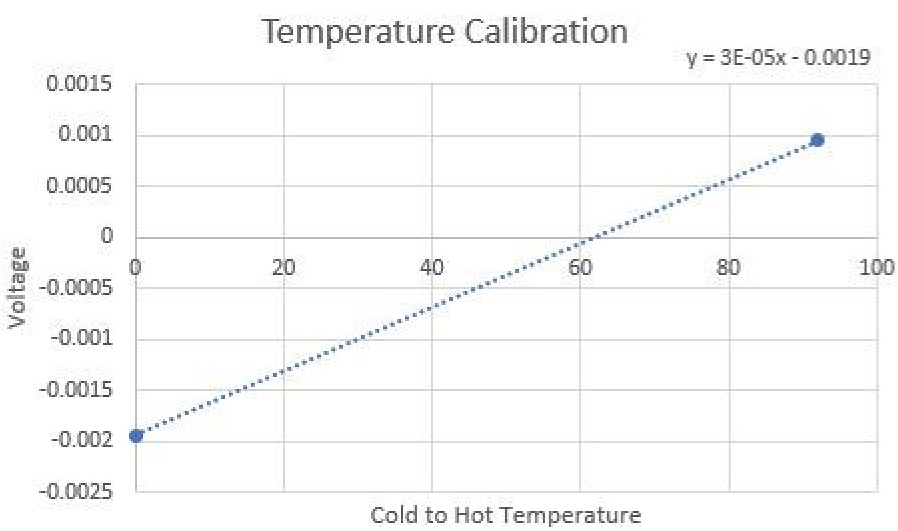
8.5 Data Acquisition

Table 8: Temperature Voltages

Time	Voltage_0	Voltage_1	Voltage_2	Voltage_3	Voltage_4	Voltage_
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95
#########	17.6743	-2455.95	-2455.95	-2455.95	-2455.95	-2455.95

Equation for temperature calibration: $y = 3E\text{-}05x - 0.0019$

Table 9: Temperature Calibration



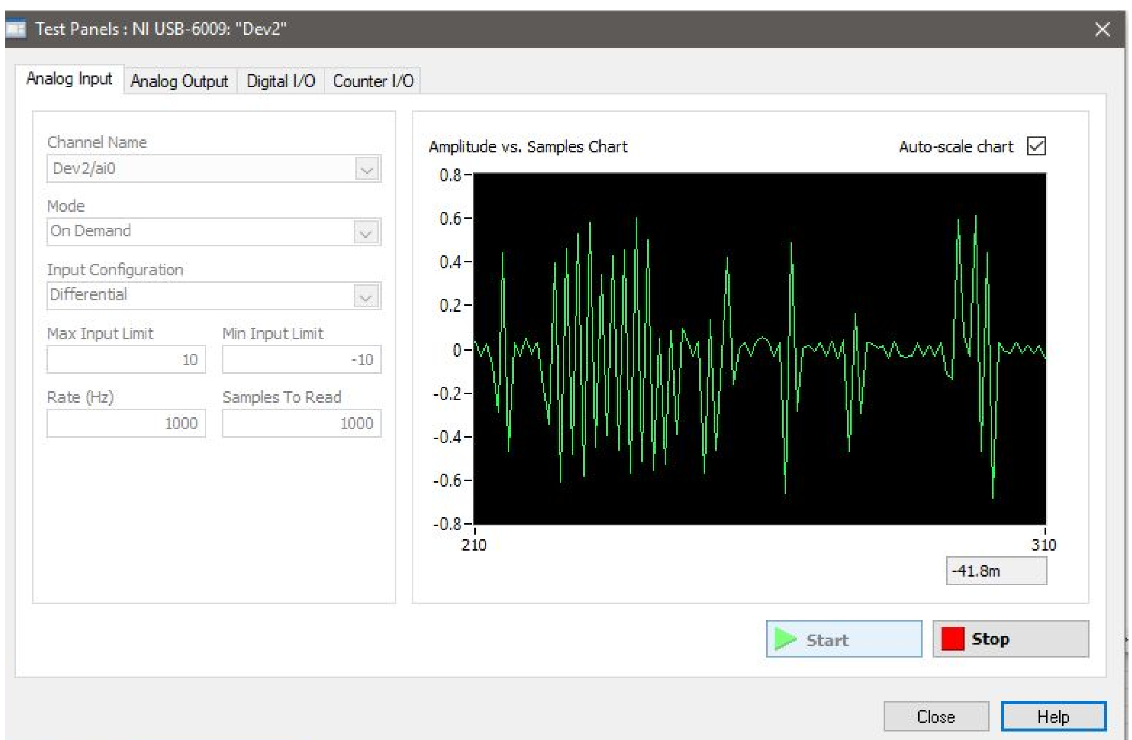


Figure 11: Pressure Transducer Voltages

Completing the testing proof for the final product yielded inconclusive results for the success of the project. Problems encountered for the testing proof included, faulty materials and incorrect engineering requirements. There should have been plans implemented to address the change in the necessary engineering requirements, as well as method for implementation.

9.0 Conclusions

The problem statement assigned to the team at the beginning of the project was to design and fabricate a working Brayton cycle for use in a Thermodynamics classroom to provide visual aids to students. The team went through several iterations of designs before deciding on a power generating turbojet engine. This specific style of a Brayton cycle was chosen because of the simplicity of the cycle for viewing purposes. Simply, air enters the system and is compressed, then heat is applied to the air over a small cross sectional area, the resulting hot air enters the turbine section to produce a work output. The team decided to connect a small generator to the end of the shaft that would convert the energy from the spinning shaft into electricity that would power a LED light bulb. The team believes the project accomplishes the problem statement assigned to construct a teaching device for use in a Thermodynamics classroom.

Following the completion of the project, the team gained communication and time management skills associated with operating in a professional group environment. Rather than being instructed what to work on from a professor, the team needed to take initiative and decide which assignments needed to be completed within a reasonable time.

9.1 Contributions to project success

A considerable amount of the project was designed using a 3D program and needed to be fabricated based on exact dimensions, therefore were 3D printed. Fortunately, the team was able to print the compressor and turbine blades with a 3D printer provided by the NAU RapidLab. However, due to the material used and limited time, the team needed to use the MakerBot 3D printers in the NAU library to complete the printing of the casing. The RapidLab is available to NAU capstone projects and provides high quality prints at no additional costs outside of course fees. The MakerBots, however charge $0.10 a gram of 3D filament and are of lesser quality than the RapidLab printers. The decision to 3D print the major components of the project instead of machining the components with metal significantly lowered the production costs. This allowed the team to focus a larger portion of the budget on other components, such as LED lights and an air compressor.

Additionally, the team stored all the documents for the project on a Google Drive with success. Every member could view and download the documents that were being worked on. This allowed the documents to be completed from separate locations without needing to exchange flash drives. Minimizing opportunities for a document to become corrupted or altered helped the team contribute to finishing the documents on time. Outside of the team, various professors located in the Engineering building assisted in the completion of certain subsystems. Dr. Sagnik Mazumdar allowed the team to borrow a temperature DAQ system and his ME 495 lab TA Jose assisted in the correct calibration of the thermocouples. Dr. John Sharber assisted in the correct configuration of the wiring for the heat section. Dr. Sarah Oman assisted in the 3D printing of the casing subsystem. The team greatly appreciates the help provided to complete the project in working condition.

9.2 Opportunity for improvement

In respect to the Brayton Cycle project, there are fundamental changes that should be considered that will improve the work output. The material of the blades should be changed from 3D plastic filament to a light alloy that is capable of producing the theoretical power analyzed. PLA, the 3D printing material used, is cheap and efficient for prototyping, but does not retain the structural integrity for realistic use. Additionally, a single keyed shaft is the simple solution to make axial blade forces rotate it, a single shaft does not accurately represent how a Brayton Cycle operates. An orbital gear system which rotates at different speeds between the compressor and turbine stages would allow for substantial work output.

The ignition subsystem was designed to initiate the compressor blades to spin the shaft, therefore spinning the turbine blades and producing work output. However, on the day of presentation, the client described how the ignition system should have been separated into two stages. The first stage included having the working fluid initiate the turbine section, then the second stage would initiate the compressor section. This type of ignition is realistic to modern day turbojet engines, however these engines have separated shafts with an orbital gear box to allow for maximum thrust (work output). To accommodate the client’s idea, the team would need a larger budget to include multiple shafts and a gear box.

Additional corrections to the success of the project include proper handling and storage for delicate subsystems. The compressor and turbine blades were moved constantly and stored where blades could crack easily. Also, all the 3D printed casing subsections were warped slightly, most likely because of improper storage and heat. The warping could also have been a result of inconsistent printing. The blades were printed using the NAU RapidLab while one section of the casing was printed by Dr. Oman and the other casing sections were printed using the NAU library’s MakerBots.

10. References

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11. Appendix

11.1 House of Quality

Brayton Cycle Educational Model											
	Work output (more is better)			+	-	+	0	+	+	+	+
	aerodynamic	+		0	+	0	-	+	+	0	0
	thermal capacity (more is better)	+	0		-		-	0	0	+	
	isentropic efficiency (more is better)	+	+	+	0	+	0	+	0	+	+
	Volume (less is better)	-	+	-		0	0	0	0	0	-
	Data Acquisition	+	0	0	0		0	0	0	0	0
	opacity (less is better)	0	0	-	+	0		0	0	0	-
Customer Requirements	Weighting	Power output	aerodynamic	Thermal Capacity	Volume	Data Acquisition	opacity	$\eta_{thermal}$	$\eta_{propulsive}$	$\eta_{thermal}$	$\eta_{isentropic}$
Collect Data	5	2	1	3	1	3	2	3	3	3	3
Safety (more is better)	5	2	1	3	3	1	1	3	3	3	3
Functionality	3	3	3	1	2	2	1	1	1	1	1
Rigorous Design	4	3	3	2	2	3	1	2	2	2	2
Analysis of Brayton cycle	5	2	1	2	1	3	1	2	2	2	2
Cost (less is better)	3	3	2	3	3	3	1	3	3	3	3
Visibility (more is better)	4	1	2	2	2	1	3	2	2	2	2
Technical Requirement Units		[W]	C_d	[K/m^2]	[m^3]	[K],[Pa],[N]	[%]	[%]	[%]	[%]	[K]
Technical Requirement Targets		20 Watt	0.4	756	<.5	378	<20%	>80%	>80%	>80%	>80%
Absolute Technical Importance		64	50	68	56	66	42	68	68	68	68
Relative Technical Importance		10.3559871	8.09061489	11.00323625	9.06148867	10.6796117	6.7961165	11.0032362	11.003	11.003	11.003

11.2 Fall Iteration CAD

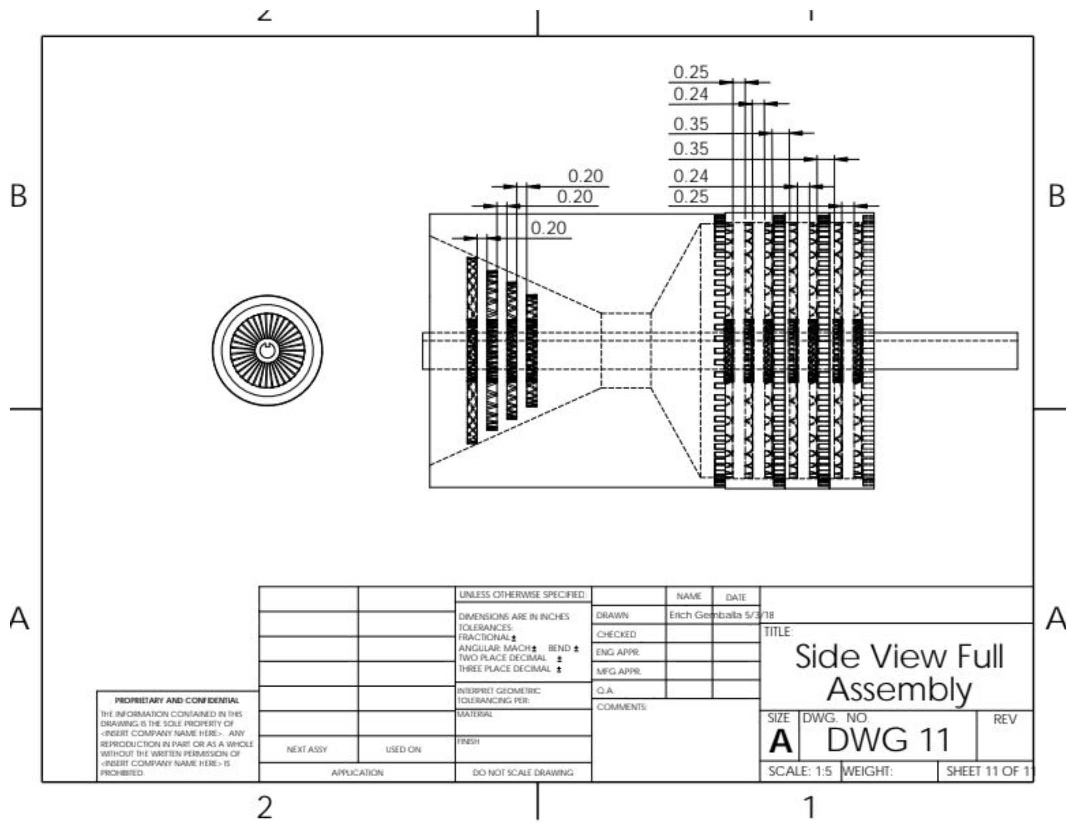

Figure A11.2.1: Fall Iteration Side CAD Drawing

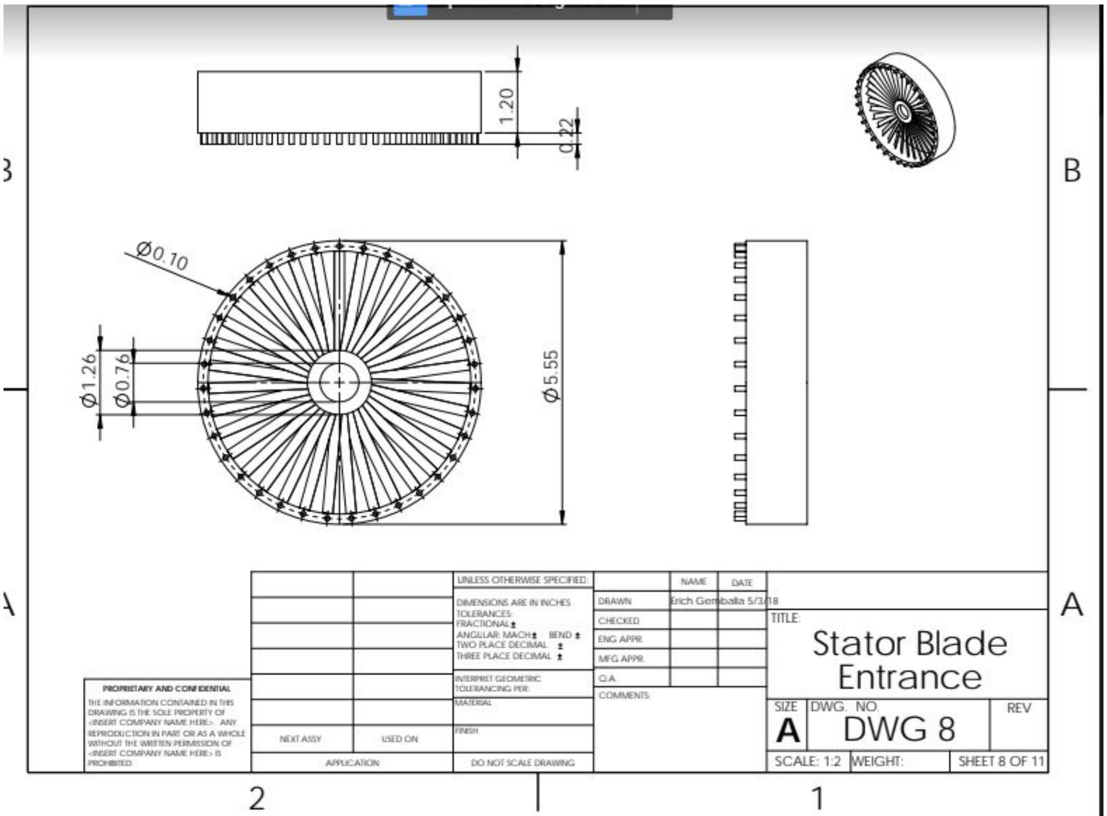

Figure A11.2.2: Fall Iteration Stator Blade CAD Drawing

11.3 Code for IT Thermo

```
T1 = 294.261
T2s = 355
T2 = 356.7
T3 = 400
T4s = 328.35
T4 = 336.8
p1 = 100
p2s = 200
p2 = 200
p3 = 200
p4s = 100
p4 = 100


s1 = s_Tp("Air",T1,p1)
s2s= s_Tp("Air",T2s,p2s)
s2 = s_Tp("Air",T2,p2)
s3 = s_Tp("Air",T3,p3)
s4s= s_Tp("Air",T4s,p4s)
```

```
s4 = s_Tp("Air",T4,p4)
v1 = v_Tp("Air",T1,p1)
v2s = v_Tp("Air",T2s,p2s)
v2 = v_Tp("Air",T2,p2)
v3= v_Tp("Air",T3,p3)
v4s = v_Tp("Air",T4s,p4s)
v4 = v_Tp("Air",T4,p4)
h1 = h_T("Air",T1)
h2s = h_T("Air",T2s)
h2 = h_T("Air",T2)
h3 = h_T("Air",T3)
h4s = h_T("Air",T4s)
h 4= h_T("Air",T4)
```

11.4 Equations for power from turbine blades

Power for Turbine 1

$W = 0.00004\, slug/s \cdot (20\, ft/s \cdot 19.83\, ft/s - 21\, ft/s \cdot 20.83\, ft/s)$ = 2.24 Watts

Power for Turbine 2

$W = 0.00004\, slug/s \cdot (18\, ft/s \cdot 17.83\, ft/s - 19\, ft/s \cdot 18.83\, ft/s)$ = 2.016 Watts

Power for Turbine 3

$W = 0.00004\, slug/s \cdot (17\, ft/s \cdot -0.16\, ft/s - 18\, ft/s \cdot 17.83\, ft/s)$ = 17.6 Watts

Overall Power

2.24 Watts + 2.016 Watts + 17.6 Watts = 21.85 Watts

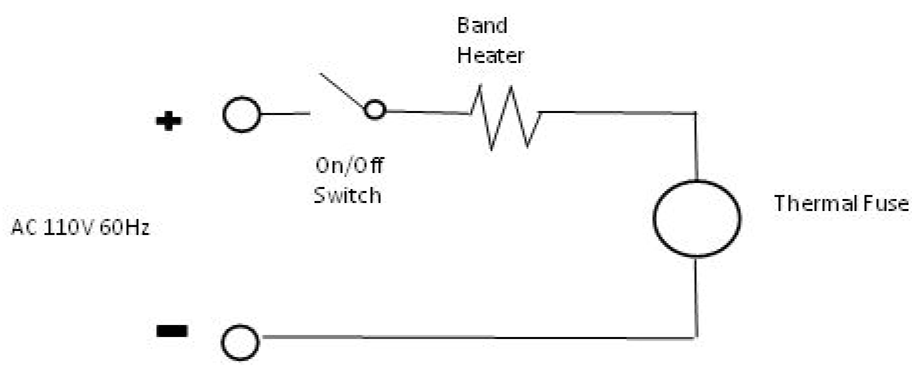

Figure A11.4.1: Band Heater Schematic

11.5 Bill of Materials

Table A11.5.1: Bill of Materials

	Vendor	Part #	Part Name	Qty	Description	Cost Per Unit	Total Cost + Tax
	Project Name	Thermodynamic Demonstration Unit 1B					
	Team	Erich Gemballa, Gavin Geiger, Hamad Almutairi, Abdullah Albdulghafour					
Structural/ Data Collection	McMaster-Carr.com	1	Keyed Shaft	1	3/4" Dia, 2 ft long Keyed Shaft	$ 47.50	$ 41.68
	HomCo	2	Ball Bearings	3	Radial Bearings	$ 4.95	$ 14.85
	Home Depot	3	Pressure Transducer	2	Pressure Collection	$ 49.00	$ 119.98
	Home Depot	4	Pressure Transducer Wire	2	Wiring for Transducer	$ 15.00	$ 30.00
	Home Depot	5	Thermocouple Wire	2	J Type Thermocouple Wire	$ 4.00	$ -
	Home Depot	6	Duct Tubing	1	Sleeve Over Heating Section	$ 10.48	$ 10.48
	TransducersDirect.com	7	Bolts	12	1/4" Diameter, 1" long	$ 0.63	$ 7.56
		8	Nuts	12	1/4" Locking Nuts	$ 1.18	$ 14.16
		9	Washers	12	1/4" Diameter	$ 0.10	$ 1.18
	Home Depot	10	Wires	1	Various wiring	$ 10.00	$ 10.00
		11	Wire End Caps		Plastic Wire connectors	$ 2.58	$ 2.58
					Total	**$ 145.42**	**$ 252.47**
Heat	Home Depot	12	Heat Sink	1	1.5" x 5" Steel Pipe	$ 5.99	$ 6.93
	Tempco	13	Band Heater	1	Collar Heater	$ 32.30	$ 45.09
	Grainger	14	Thermal Fuse	1	Temperature Regulator	$ 17.60	$ 29.57
	Home Depot	15	Switch	1	Emergency Shutoff Switch	$ 0.69	$ 0.83
	Home Depot	16	Thermal Tape	1	Thermal Tape for Insulation	$ 4.98	$ 4.98
					Total	$ 61.56	$ 87.40
Compressor	CPOOutlets.com	17	Air Compressor	1	6 gal 150 PSI Compressor	$ 89.00	$ 96.90
	Home Depot	18	Recoil Hose	1	25 ft Compressor Hose	$ 14.98	$ 16.10
	Home Depot	19	Ball Valve	1	Compressor Connector	$ 8.98	$ 9.70
	Napa Autoparts	20	Funnels	1	Standard funnels for diffusion	$ 3.50	$ 3.50
					Total	**$ 112.96**	**$ 126.20**
Power		20	Brushless DC Generator	1	Power Generation	$ 20.00	$ 20.00
	SolidApollo.com	21	LED Light Strip	1	Light Strip	$ 14.00	$ 15.00
					Total	**$ 34.00**	**$ 35.00**
3D Prints	NAU	22	Comp Casing 1	1	3D Print	$ 15.00	$ -
		23	Comp Casing 2	1	3D Print	$ 10.00	$ -
		24	Turbine Casing 1	1	3D Print	$ 10.00	$ -
		25	Turbine Casing 2	1	3D Print	$ 15.00	$ -
		26	Turbine Casing 3	1	3D Print	$ 15.00	$ -
		27	Comp Blade 1	1	3D Print	$ 10.00	$ -
		28	Comp Blade 2	1	3D Print	$ 10.00	$ -
		29	Comp Blade 3	1	3D Print	$ 10.00	$ -
		30	Comp Blade 4	1	3D Print	$ 10.00	$ -
		31	Comp Blade 5	1	3D Print	$ 10.00	$ -
		32	Comp Blade 6	1	3D Print	$ 10.00	$ -
		33	Turbine Blade 1	1	3D Print	$ 10.00	$ -
		34	Turbine Blade 2	1	3D Print	$ 10.00	$ -
			Turbine Blade 3	1	3D Print	$ 10.00	$ -
					Total	**$ 155.00**	**$ -**
			Blue Paint	1	Blue spray paint	3.98	3.98
			Yellow Paint	1	yellow spray paint	3.98	3.98
			White Primer	1	white primer spray paint	3.98	3.98
					Project Total	**$ 520.88**	**$ 513.01**

11.6 CAD Models & Drawings

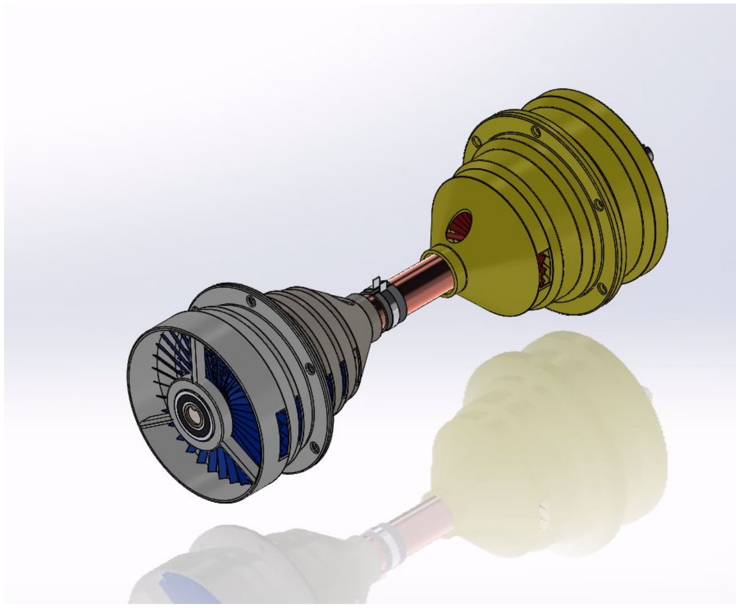

Figure A11.6.1: Assembled Cad Model Isometric

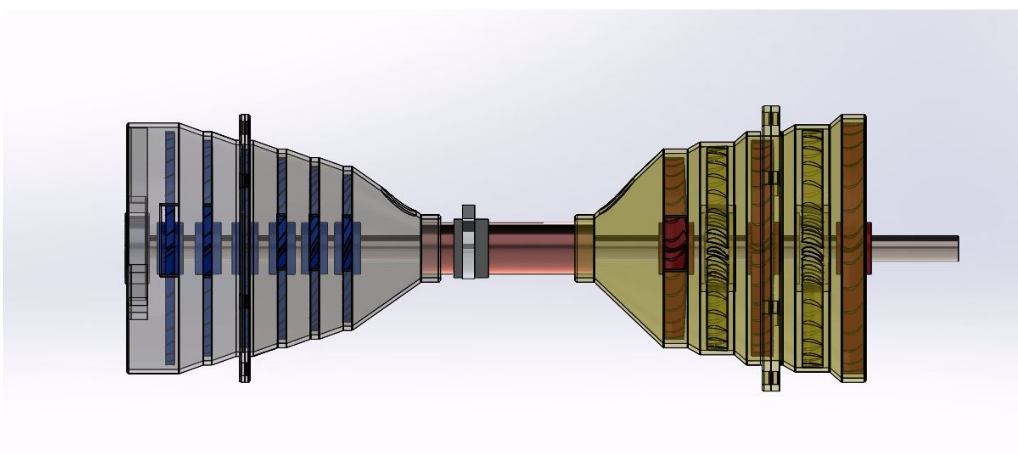

Figure A11.6.2: Assembled CAD Model Side

Figure A11.6.3: Exploded CAD Model

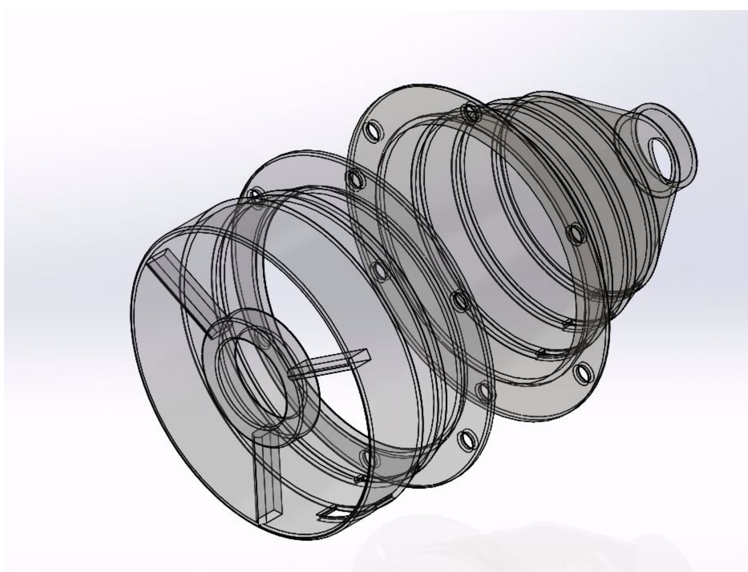

Figure A11.6.4: Compressor CAD Model

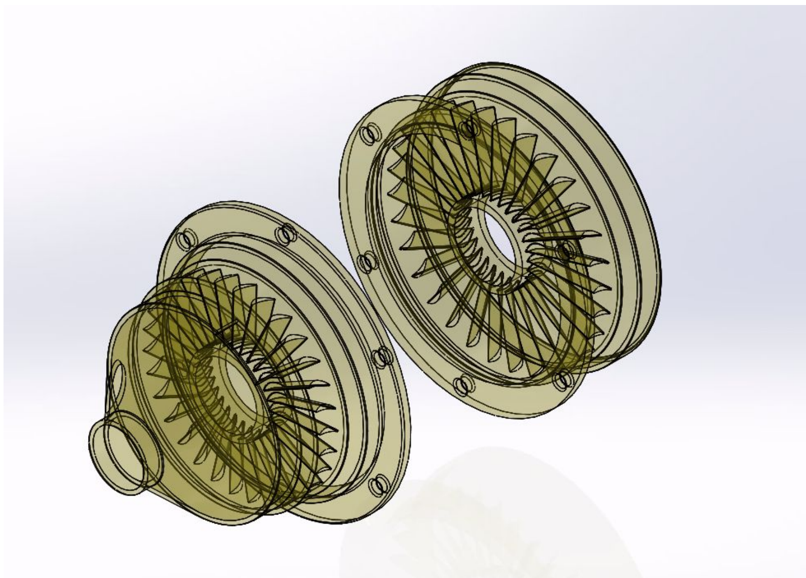

Figure A11.6.5: Turbine CAD Model

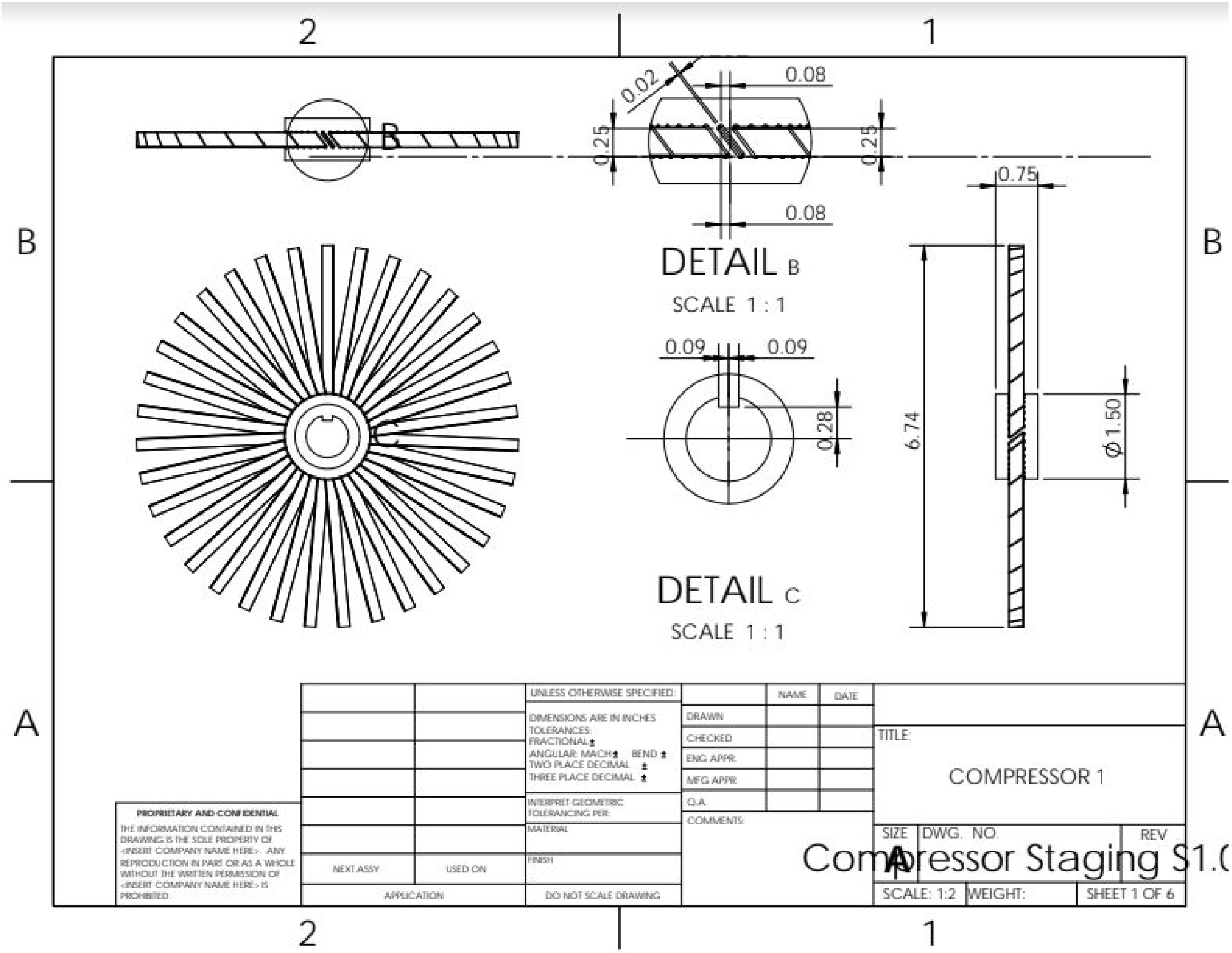

Figure A11.6.6: Compressor 1 Drawing

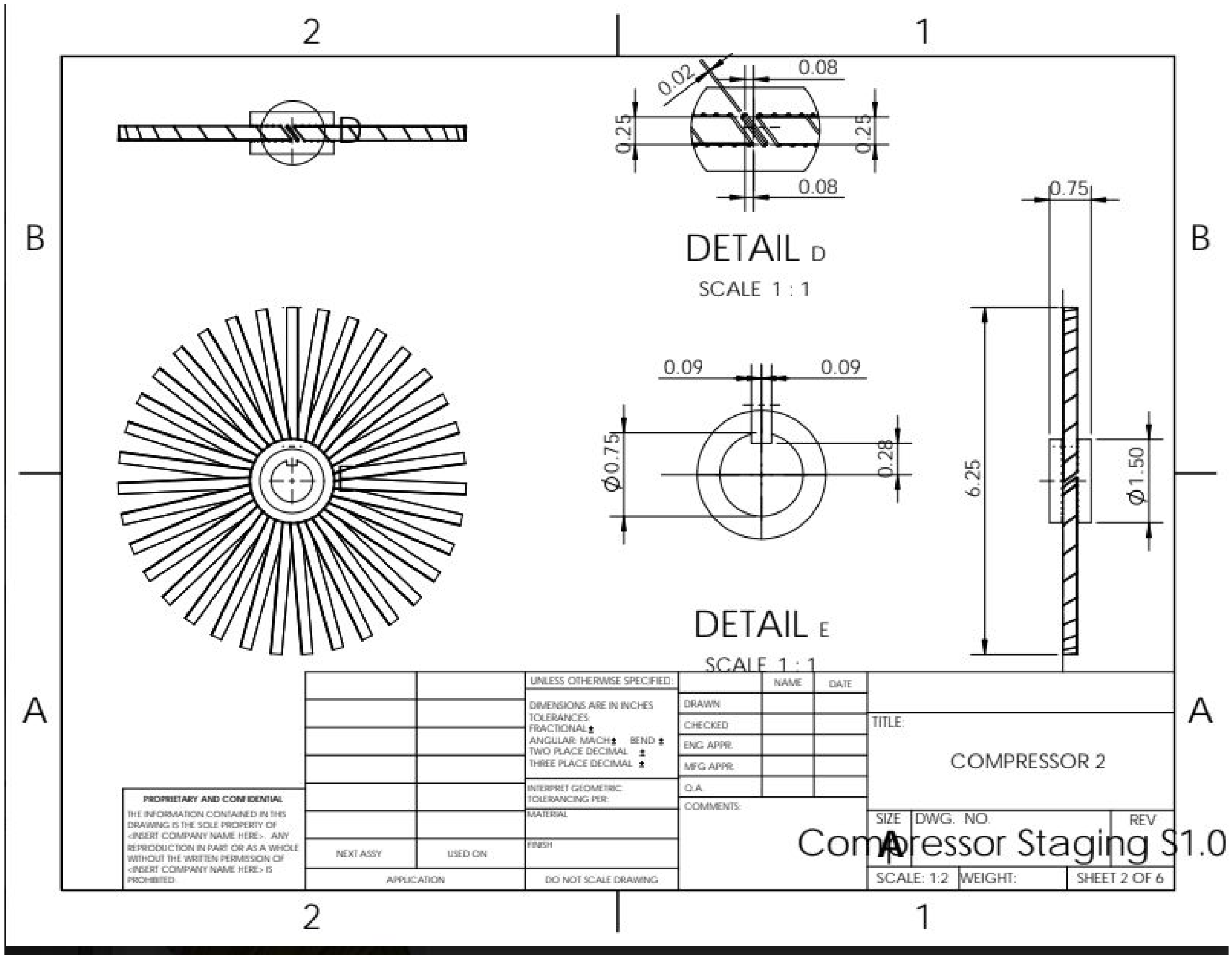

Figure A11.6.7: Compressor 2 Drawing

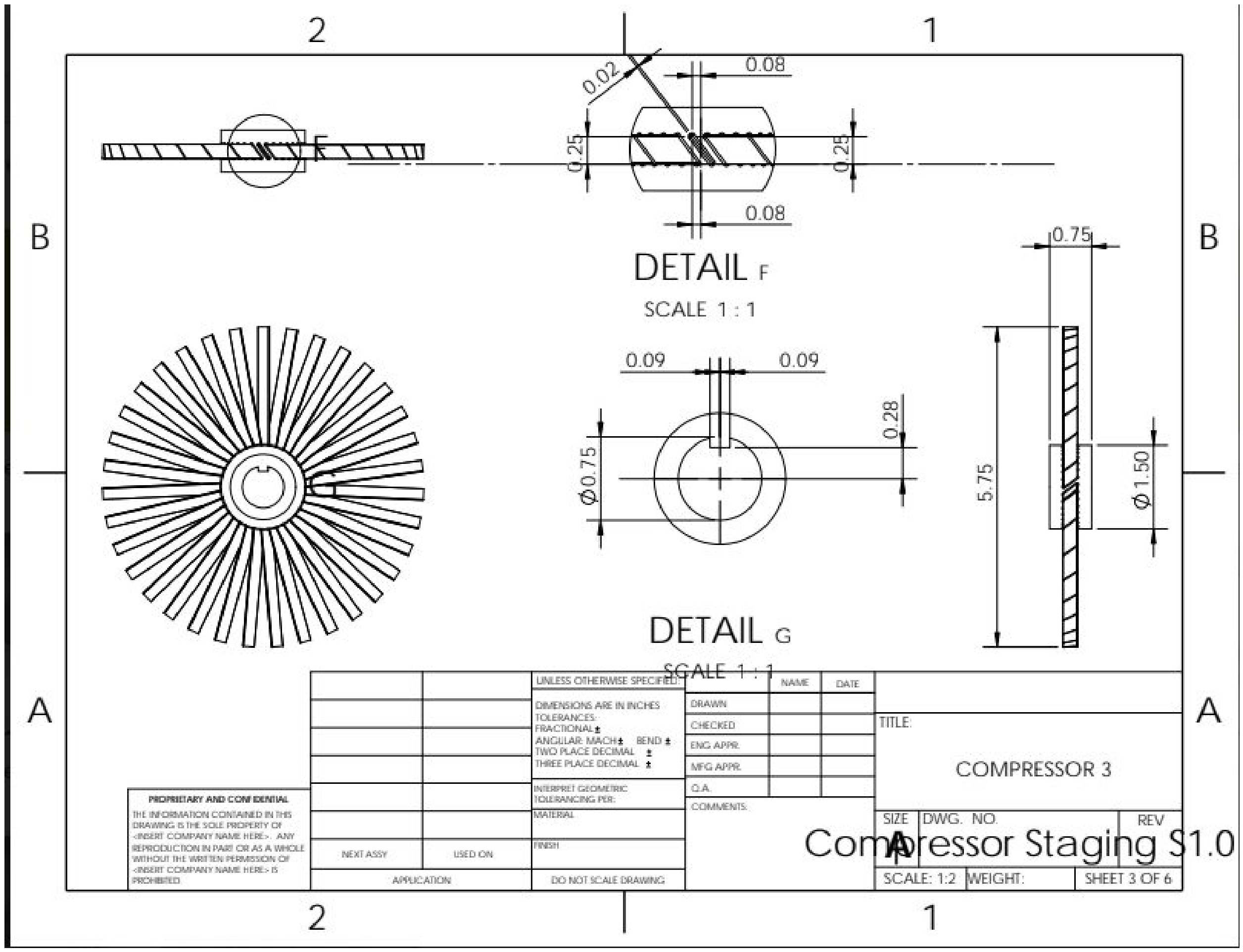

Figure A11.6.8: Compressor 3 Drawing

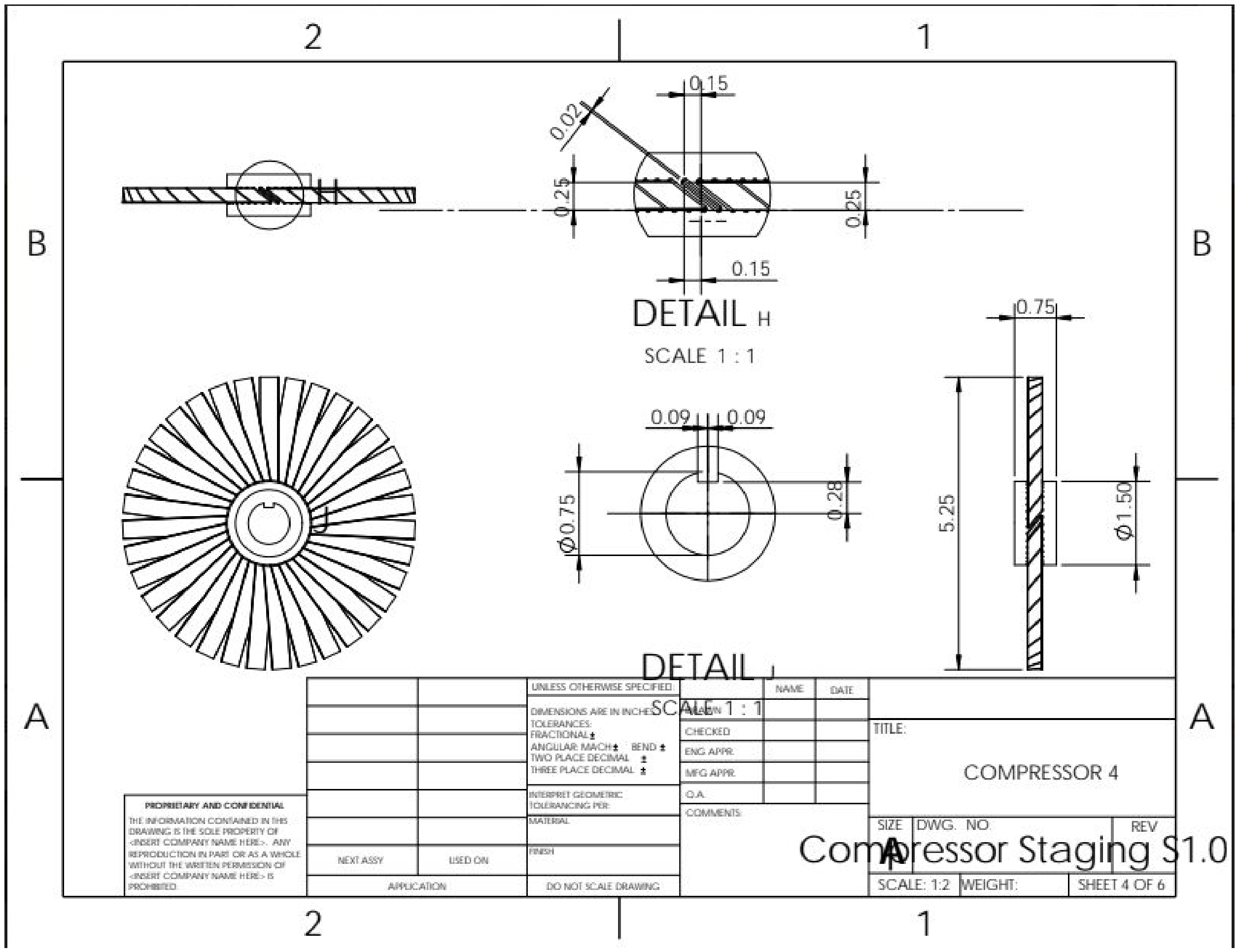

Figure A11.6.9: Compressor 4 Drawing

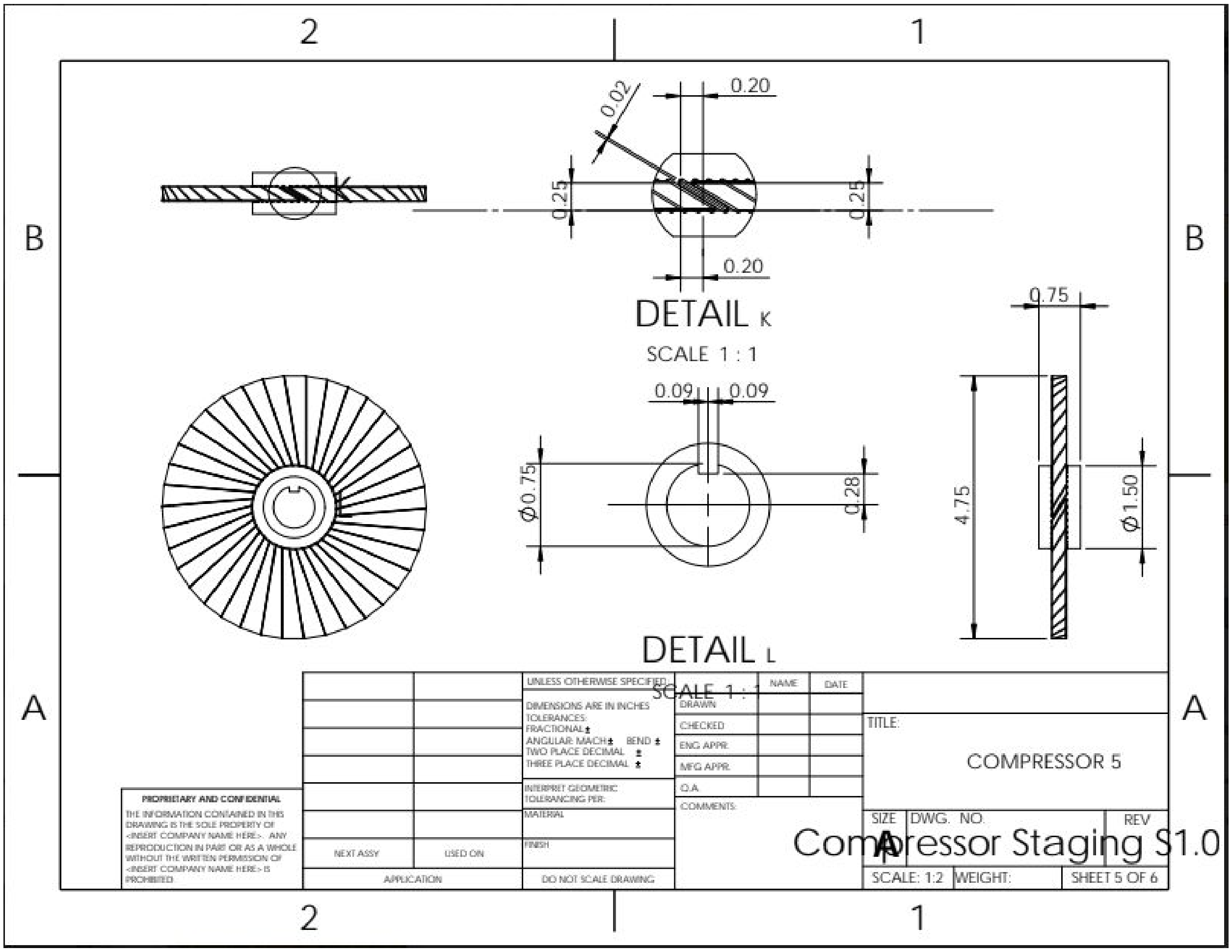

Figure A11.6.10: Compressor 5 Drawing

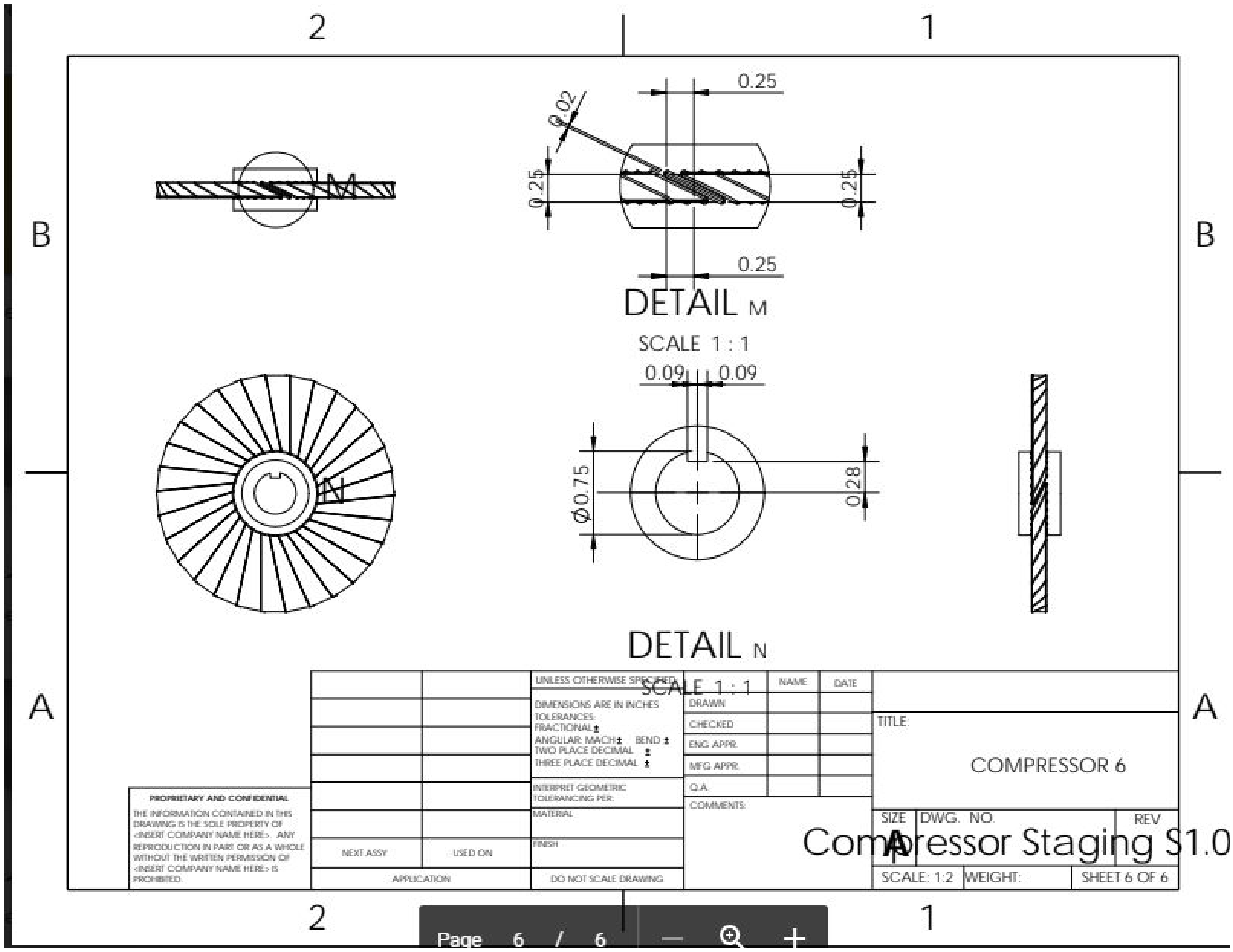

Figure A11.6.11: Compressor 6 Drawing

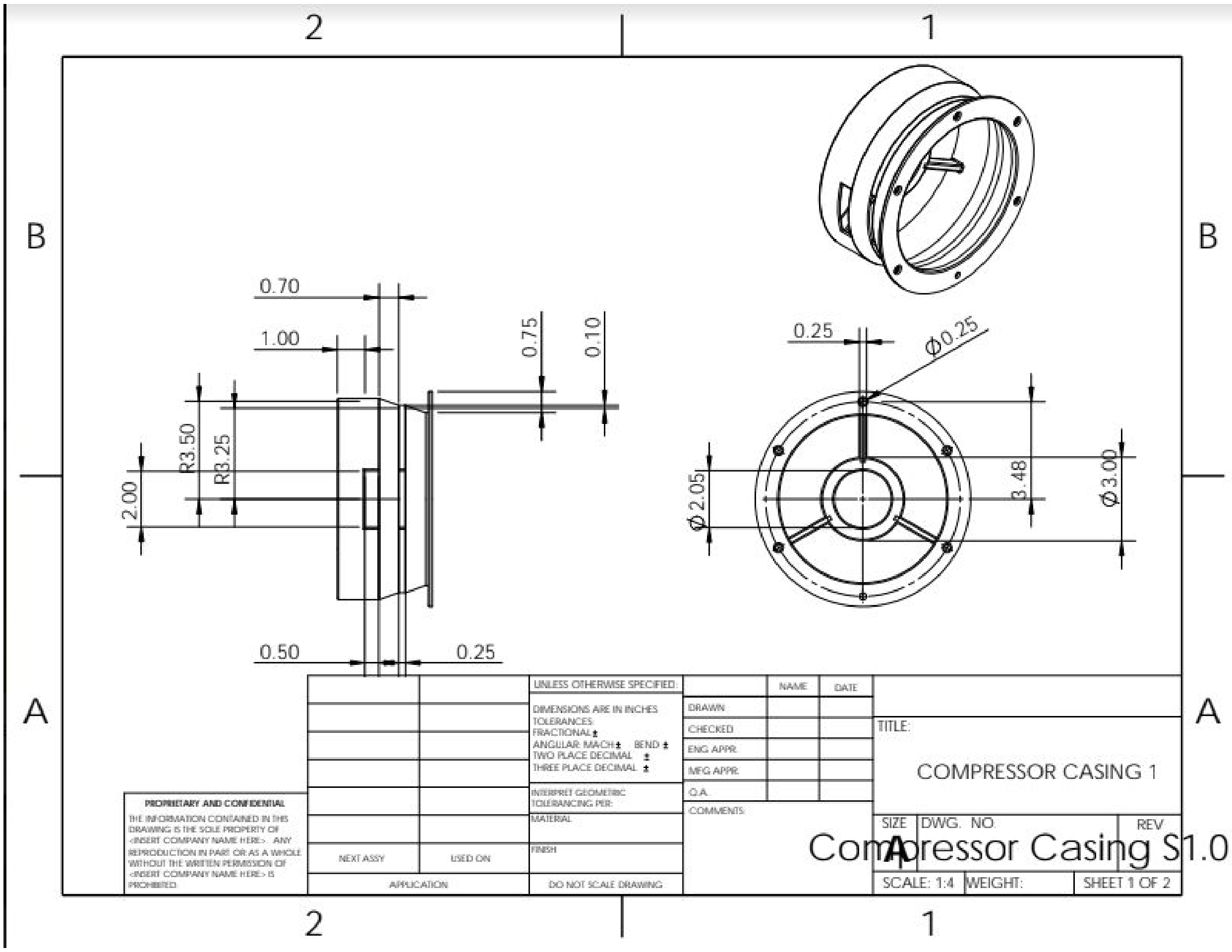

Figure A11.6.12: Compressor Casing 1 Drawing

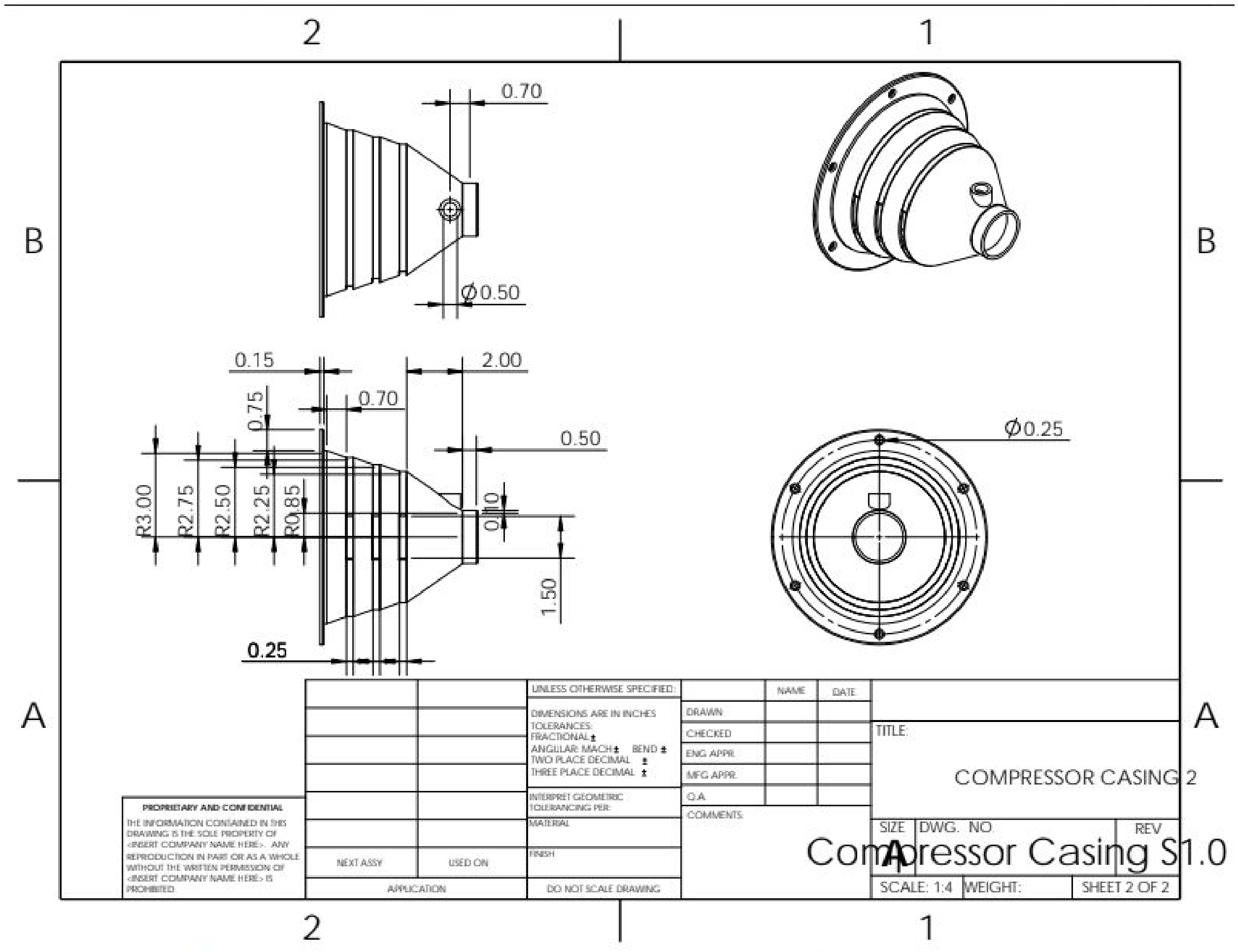

Figure A11.6.13: Compressor Casing 2 Drawing

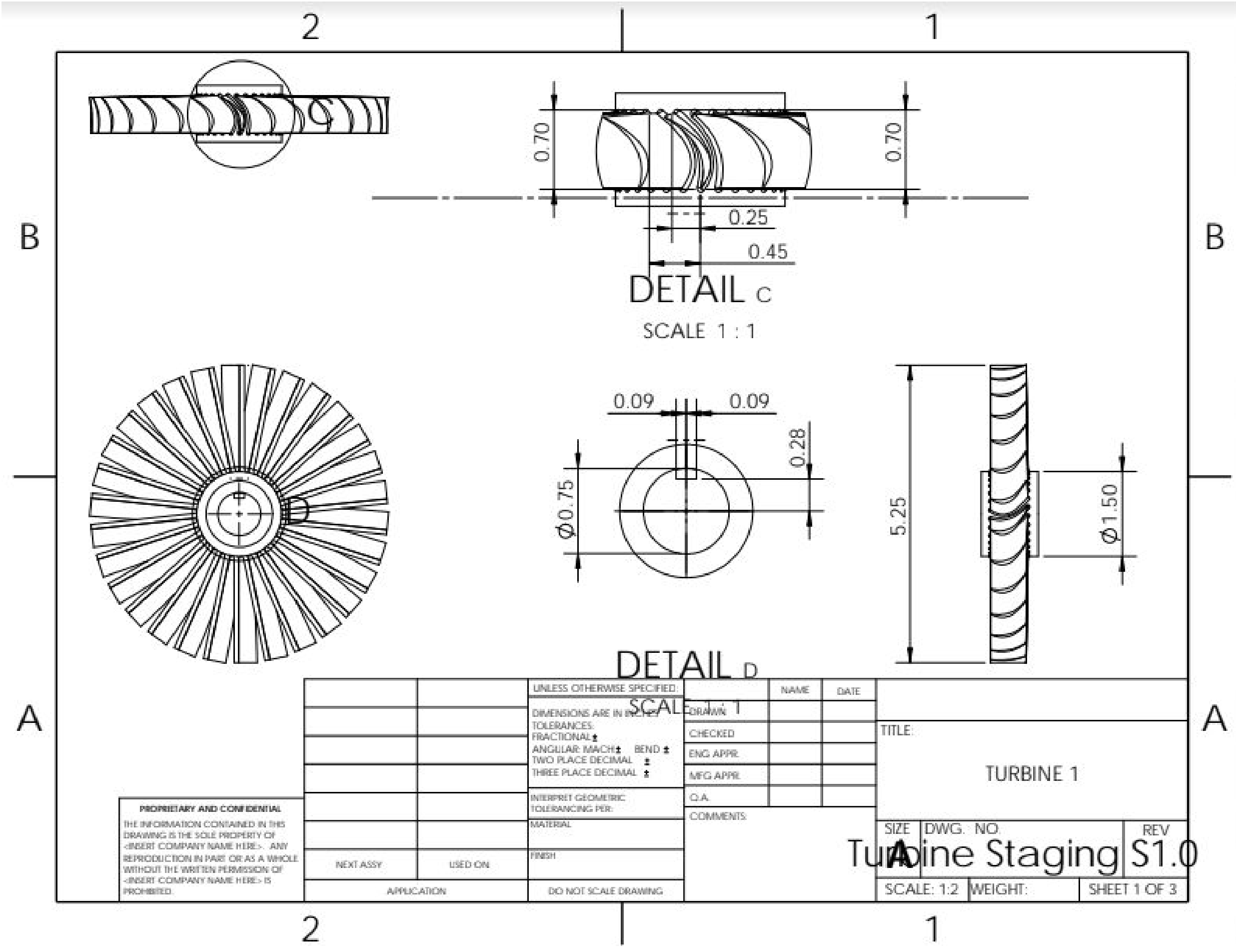

Figure A11.6.14: Turbine 1 Drawing

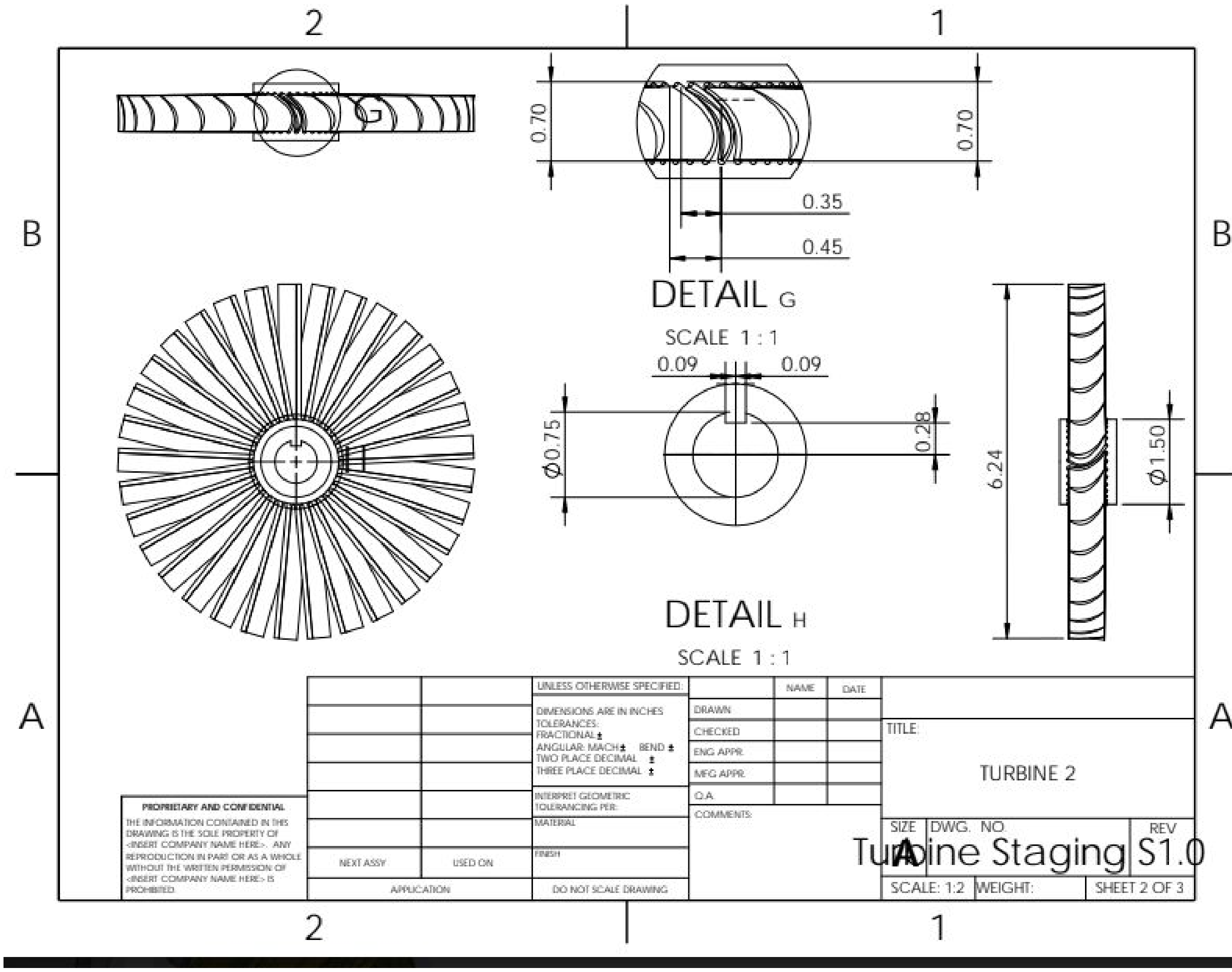

Figure A11.6.12: Turbine 2 Drawing

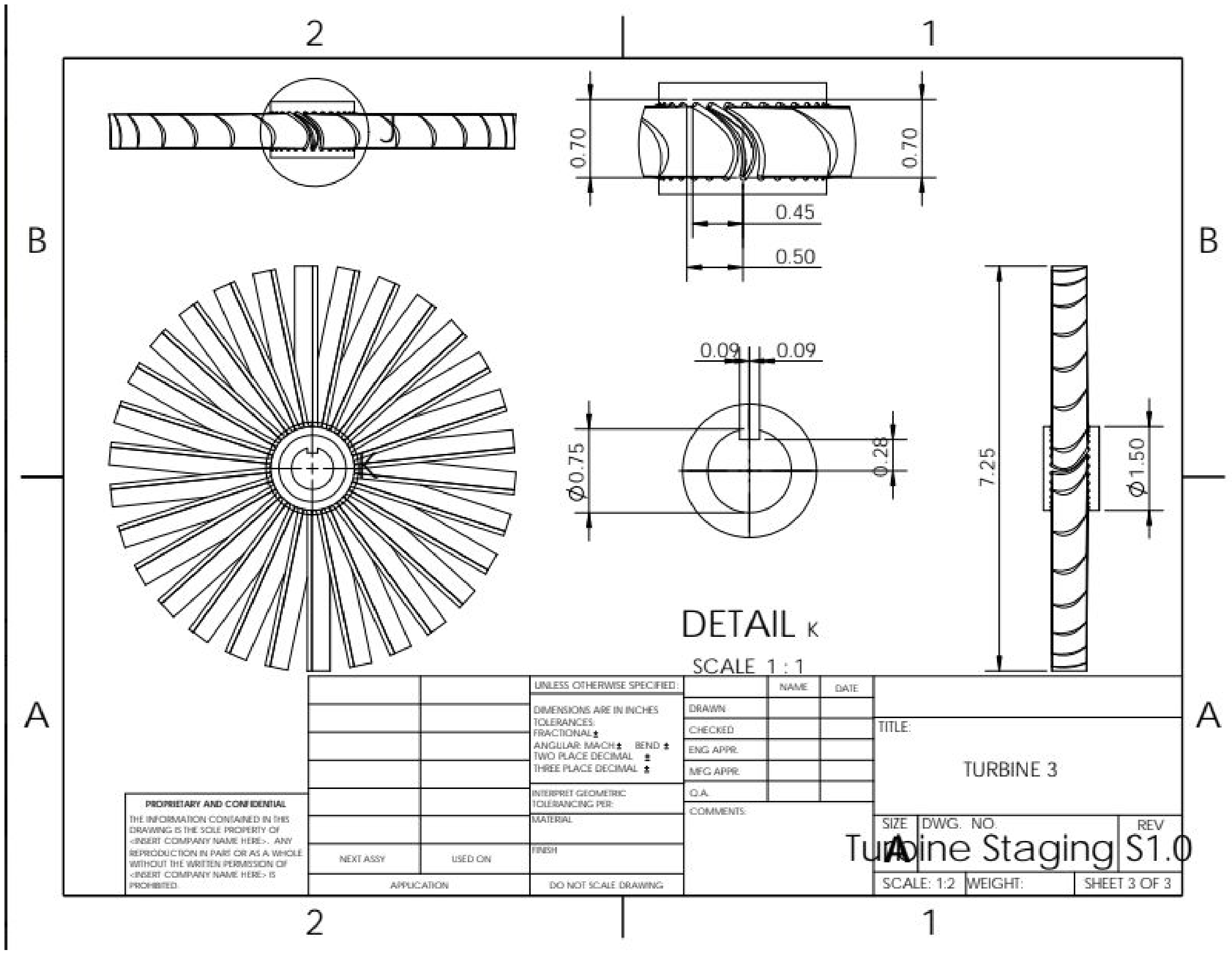

Figure A11.6.13: Turbine 3 Drawing

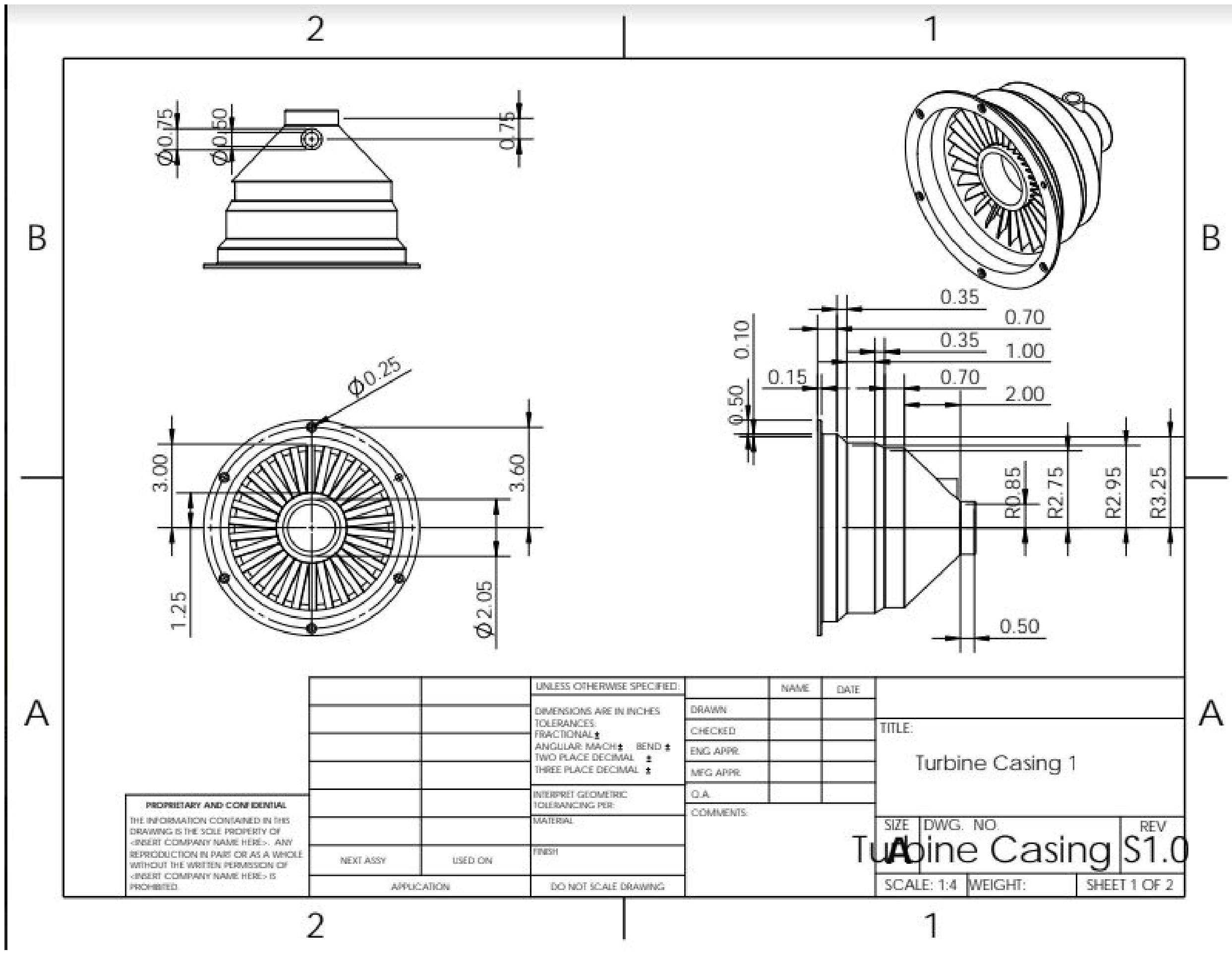

Figure A11.6.14: Turbine Casing 1 Drawing

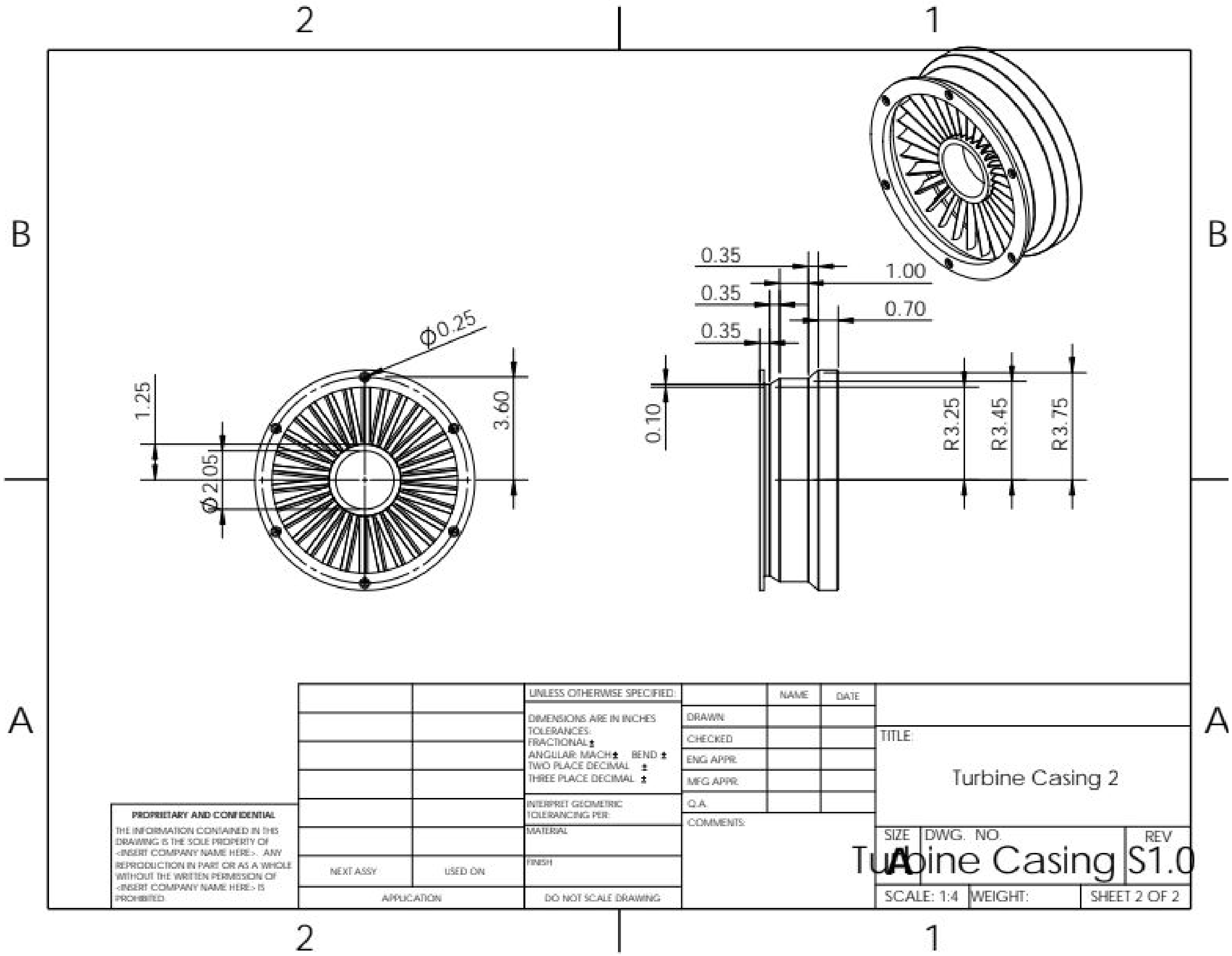

Figure A11.6.15: Turbine Casing 2 Drawing