Conceptual Design Report for Thermodynamic Demonstration Unit Group 1A

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EGR 476C – Spring 2018
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Disclaimer

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1 Background

1.1 Introduction

A hands-on classroom experience can be vital for a college student's understanding of course material. This project's main goal is to help bridge the gap between figures and equations on paper to a functioning model that a student can interact with. The team aims to create a Brayton Cycle demonstration unit for a Thermodynamics II class. The model will be a based on a Turbojet engine to provide a real-world application of the Brayton Cycle. This will benefit students by showing how a cycle is applied in a real-world situation. The sponsor and client for the project is David Willy, an instructor at Northern Arizona University. Once completed, this model will elevate his lectures and give students a better understanding of the Brayton Cycle.

1.2 Project Description

Thermodynamics II (ME392) classes are in need of in-class demonstration equipment to help teach specific topics. This project will aide in the understanding of a specific cycle that will be determined by the client and team. For this project, one or more working benchtop examples are required to help with instruction. An example of a system within the design space that the client has in mind can be found here: https://www.youtube.com/watch?v=6rX4xv5-NvE&feature=youtu.be. Note that this is just an example and should NOT be directly copied.

Client Requirements

- Must be able to operate in a safe manner for classroom demonstration
- Must not function from combustion (compressed air or electrical source is acceptable)
- Must be able to demonstrate at least one application (turbofan, etc)
- Must be mounted onto a cart for ease of transport in and out of the classroom
- Must be powered from typical wall outlet sources or be self powered
- Should be able to collect data to analyze performance
- The system does not have to work exactly as in the real world, but a user should be able to convert the testing results so it can be compared to a real world system
- Should be able easy to identify subsystems and functions of those subsystems within the demo unit

Client Based Deliverables

- At least one functioning system with data collection
- User's manual for operation
- Supporting Literature for system and subsystem functionality
- Short video demonstration in support of the User's Manual

2 Requirements

2.1 Customer Requirements (CRs)

As noted previously, the customer for this project is David Willy, an Instructor at NAU, who intends to use this model as an in-class teaching tool. After meeting several times with Mr. Willy, reviewing the project description, and discussing the problem, the team came up with the following list of Customer Requirements (CRs), presented in Table 1 for easy reference.

Table 1: Customer Requirements

Scaled
Portable
Interactive
Educational
Usable in a lecture
Safe
Wall outlet or self-powered
Instructions for use
Durable

The client's biggest priority is for the model to be interactive. To accomplish this, he had several specific requests: the model must take temperature and pressure measurements at every state in the cycle, and it must be transparent to allow students to see its inner-workings. Our team generated several more customer requirements based on this request: educational and usable in a lecture. For this model to be beneficial it must add a teaching element that a lecture alone cannot accomplish. Furthermore, the model must operate within the timeframe of a lecture, so its operation time cannot be exceedingly long. It must also be scaled, portable, and fit on a cart for transport into and out of a classroom. The model must also include instructions so that any instructor or student is easily able to operate it. Additionally, it must be reliable, so that it operates the same way every time, and durable, so that it lasts for many semesters of instruction. A model that only works intermittently or breaks after just a few uses would not be a worthwhile investment. Finally, the model needs to be safe for both the instructor and the students. To ensure safety and compatibility in the classroom, the model must receive power from a standard wall outlet or be self-powered.

2.2 Engineering Requirements (ERs)

With the list of Customer Requirements established the team sought to create measurable Engineering Requirements (ERs) to meet all customer needs. Table 2 provides a summary of these requirements.

Table 2: Engineering Requirements

Fits inside 2’x3’ perimeter
Total weight ≤100 lbs.
Measure pressure and temperature at every stage
Demonstration time ≤ 15 minutes
Clear outer casing
Use 120v AC, 60 Hz, and/or compressed air tank
Minimize exposure to dangerous or moving parts
Must last ≥ 10 semesters

In order to make the model scaled and portable, the team decided that the model should fit within a two-foot by three-foot perimeter and should weigh less than 100 pounds. This was a rough estimate based on the average cart size and may be adjusted based on the final cart purchased. The weight is likely a large overestimate but will ensure the model is movable by a single person when placed on a cart. The ER describing the ability to measure temperature and pressure at every state came directly from a customer request. This will make the model more interactive and to add to its educational value. When analyzing Brayton Cycle problems, pressure and temperature are the first pieces of information needed, so these measurements are crucial to the effectiveness of this model.

To further enhance the educational aspect of the design, the team decided that the outer casing must be constructed from clear material. This will allow students to visualize how the model runs and how the cycle operates. In order to ensure the model is usable within a lecture, the team limited the total operation time to 15 minutes. The model must also be powered by 120v, 60Hz, AC electrical power and/or compressed air, so that it can be easily and safely powered in the classroom. To further enhance safety, the team decided that there should be minimal exposure to any dangerous or moving parts.

To address reliability and durability, the team specified that the model must last 10 semesters minimum. Ideally the model would last much longer, but the team feels that a five-year period will allow the model to fulfill its purpose and provide sufficient time for the investment costs to be recuperated.

2.3 House of Quality

After generating a list of Engineering Requirements, a Quality Functional Deployment (QFD) or “House of Quality” was used to determine which were most important. To begin, the team rated each Customer Requirement on its level of importance on a scale from one to five. Next, each Engineering Requirement was rated based on its effect in meeting the customer needs. A score of 1 indicates a weak relationship, 3 indicates a moderate relationship, 9 indicates a strong relationship, and a blank indicates no relationship. These relative scores were multiplied by the respective weights for each customer need and summed to calculate the Absolute Technical Importance. The Relative Technical Importance is simply an ordinal ranking of the engineering requirements based on their absolute technical importance. Figure 1 displays the completed QFD.

Customer Requirement	**Weight**	**Engineering Requirement**	Size constraint	Weight	Measure inputs/outputs	Operation time	Outer casing	Power source	Minimize exposure to moving parts	Lifespan
1. Scaled	3		9	3				1		
2. Portable	4		9	9		1				
3. Interactive	2		1		9	1	9			
4. Eductational	5				9	3	9			1
5. Safe	5							1	9	
6. Usable in a Lecture	5		3	1	3	9	3	1		3
7. Wall outlet or self-powered	4							9		
8. Instructions for use	3									1
9. Durable/Reliable	3							1		9
Absolute Technical Importance (ATI)			80	50	78	62	78	52	45	50
Relative Technical Importance (RTI)			1	5	2	3	2	4	6	5
Target ER values			2' x 3'	<100 lb	>2	≤15 min	clear	AC/air	n/a	≥5 yr

Figure 1: Completed QFD

The QFD revealed that the most important Engineering Requirements were the size constraint, temperature and pressure measurements, and clear outer casing. This is to be expected, as all these engineering requirements ensure the educational aspects of the final design.

3 Existing Designs

3.1 Design Research

Given the nature of this project, there were several possible areas of research. The team needed to research the Brayton Cycle, commercial applications of the Brayton Cycle, and current small-scale benchtop-type demonstration units, similar to what we intend to build. The team began research by investigating real-world applications of the Brayton Cycle. While there are countless variations of Brayton Cycle engines, they can be categorized into four main types: turbojets, turboprops, turbofans, and turboshafts. All four of these engines share the same core element: a gas generator consisting of a compressor, combustion chamber, and turbine section [1]. The turbojet is the simplest of the four types and is essentially just the gas generator described above with an inlet and exhaust nozzle added. The compressor, driven by the turbine, compresses air into the combustion chamber, where combustion adds a large amount of heat to the flow.

The heat and pressure are converted into rotation to power the compressor, and the remaining energy is then used to create thrust in the exhaust section. A turboprop operates on the same principle, except the excess energy remaining after powering the compressor is used to power another turbine section, attached to a propeller through a gearbox [1]. In a turboprop, the propeller generates the majority of the thrust rather than the exhaust nozzle. A turboshaft engine is nearly identical to a turboprop engine, except that its output shaft is instead used to power the rotor blades of a helicopter, or connected to a generator such as in a power plant [1].

The turbofan engine is the most widely used type of engine for aircraft propulsion [1]. In a turbofan, excess shaft power is used to drive a fan ahead of the main compressor. The air from this fan passes around the gas generator through a separate nozzle, which provides the majority of the thrust [1].

Our client initially requested that our group avoid building a turbofan model, so we debated between the other three types. Initially we intended to design a turboprop style model. However, given the small size of our design team, we ultimately decided it would be best to focus on the simplest type: the turbojet, which would provide a model of the Brayton Cycle without the added complexities of an additional gearbox and propeller.

3.2 System Level

3.2.1 Real-World Applications

Most modern-day aircraft have abandoned the turbojet engine in favor of the quieter and more efficient turbofan. However, one application where turbojets are still frequently used is small unmanned aerial vehicles, like drones and cruise missiles. The compact size and relative simplicity of a turbojet engine makes it useful in these applications. Today, one of the leading manufacturers of turbojet engines is Safran, who produces the Microjet engine line. There are several different variations in this engine range, so the team decided to focus one type, the Microturbo TRI 60, to get an idea of turbojet engine specifications. The Microturbo TRI 60 is shown in Figure 2 [2].

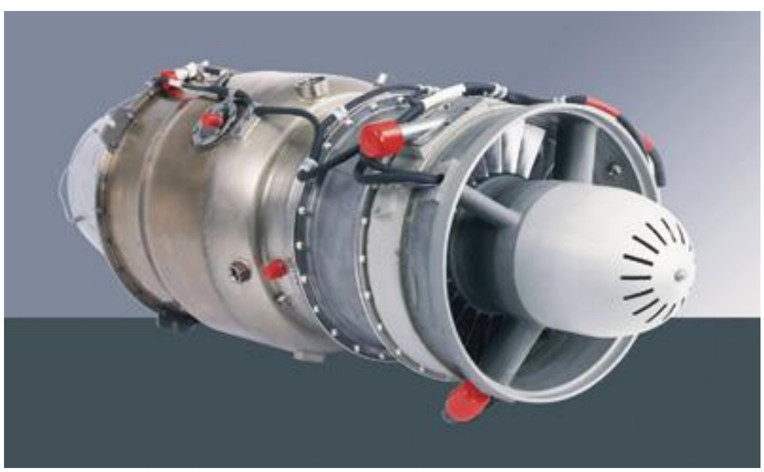


Figure 2: Microturbo TRI 60 Turbojet Engine [2]

There are also several variations within the TRI-60 product line, but all variants share similar specifications. This turbojet engine is approximately 26 inches long, 13 inches in diameter, and weighs between 108 and 135 pounds. It makes use of a three-stage, axial turbine, with a compressor pressure ratio ranging from

3.83:1 to 5.58:1. The combustor is an annular smokeless type, with 12 nozzles and a single spark igniter housed in a stainless-steel casing. The turbine is a single stage, axial design, and mates directly to the compressor through a single shaft. The turbine inlet temperature is approximately 1,850 °F [2]. These design specifications yield between 787 and 1,200 pounds of static thrust (lbst) depending on the model variation [2]. The Microturbo TRI 60 engine has been used in many applications, from Anti-ship missiles to Drones [2].

This research was very surprising to the team. The TRI 60 turbojet is small enough to meet the target size specified by our Engineering Requirements and can still generate over 1000 lbst! While this engine is far more complex than anything our team can produce, it is valuable in determining some design criteria for our model. It also reveals how compactly turbojet engines can be manufactured.

3.2.2 Existing Demonstration Units

One of the most interesting products discovered during our research is the MiniLab Gas Turbine Lab made by Turbine Technologies [3]. This is a self-contained turbojet engine demonstration unit, which is essentially the end goal for this design project. As shown in Figure 3, the MiniLab Gas Turbine Lab consists of a small-scale SR30 Turbojet engine, mounted inside of an enclosed workbench. The apparatus is mounted on wheels to allow for easy transportation and is shielded to protect users from heat and moving parts.

Figure 3: MiniLab Gas Turbine Lab [3]

This product measures temperature and pressure at every state, which is an essential customer need for our design. It also includes its own software program, which can be used to display these pressure and temperature readings, as well as fuel flow, thrust, and engine speed, shown below in Figure 4. Additionally, the software allows users to plot any of the measurable parameters to learn how the performance reacts to the operating conditions.

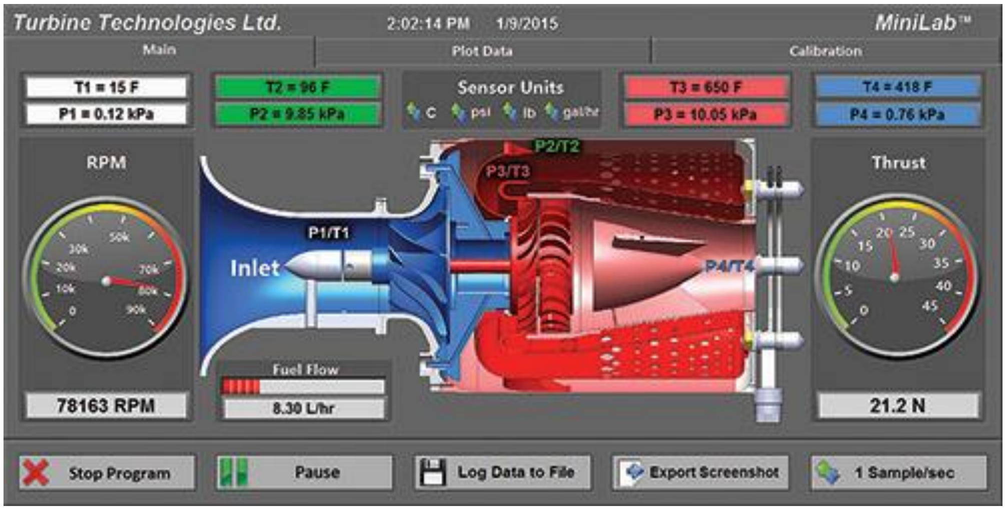


Figure 4: MiniLab Interactive Virtual Instrument Panel [3]

This product is essentially the ideal version of a Brayton Cycle demonstration unit and meets or exceeds all customer needs given to our design team. Unfortunately, this is far more complex than any design our team can produce and is also far too expensive. However, it provides a valuable benchmark which demonstrates how a model like this might operate. Additionally, the team also feels that there are several ways this design can be improved upon. For example, given that the MiniLab uses a real turbine engine, the user cannot see any of the moving parts inside of the engine. While our design will not be able provide the realism of this model, we feel that it can offer an advantage by allowing students to visualize what is actually happening during the operation of the Brayton Cycle.

3.2.3 Other Applications

During research our team found that there are fully-functional scale models of turbine engines used for model airplanes. These small replicas function as real engines and use actual fuel and combustion. At the time of this research, the team was still planning on building a turboprop engine, and thus focused on this type of engine. One example of a model turboprop is the Wren Power Systems Model 54 turboprop engine, which is shown in Figure 5.

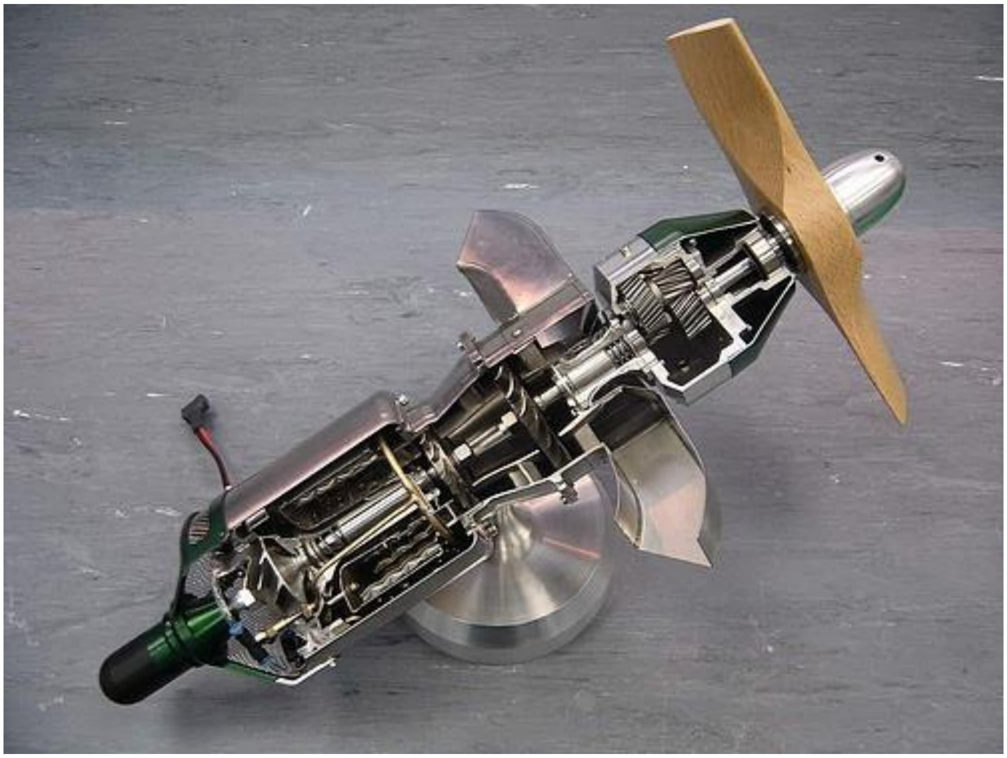


Figure 5: Wren 54 Turboprop Cutaway [4]

This engine utilizes a single compressor and two turbine stages. The first turbine is used only to power the compressor. There is a second, separate shaft with a single turbine that drives the gearbox for the propeller. This design is called a two-stage engine because of the separated turbine stages, which can be seen in Figure 5 above. In this model, the intake is on the opposite end of the propeller, which is a less common design. Real turboprop engines usually have the intake behind the propeller to help force more air in the compressor. Because of this engine's size it is extremely sensitive to foreign particles and the reversed design is preferable, as the intake will be inside the cab of the model plane and will allow cleaner air to enter the compressor. This two-stage design is less efficient than a single-stage design where the output shaft of the turbine is directly connected to the gearbox. This is because the second turbine is an impulse turbine relying on the air being exhausted to spin the shaft causing greater losses than if the shaft was directly connected to the gearbox [5]. Another peculiarity of this design is the use of a radial compressor rather than a typical axial compressor. In this application, the radial compressor is advantageous, as it can be implemented using a single stage. This parameter is discussed in more detail in the Compressor section.

These model turbines are visually impressive and the cutaway shown above would make an excellent teaching tool. Unfortunately, however, they are very expensive; Wren Power Systems website lists the model shown above costs around $4,000, which is far outside of our team's budget [5]. Still, it was beneficial to find this model, as it showed an example of a Brayton Cycle model very different from the typical design. This showed our team that we can alter the standard design to better suit our application.

3.3 Functional Decomposition

3.3.1 Black Box Model

With more background research into how a Turbojet engine works, the team was able to synthesize a Black Box Model deconstructing the functions of the engine, shown in Figure 6 below.

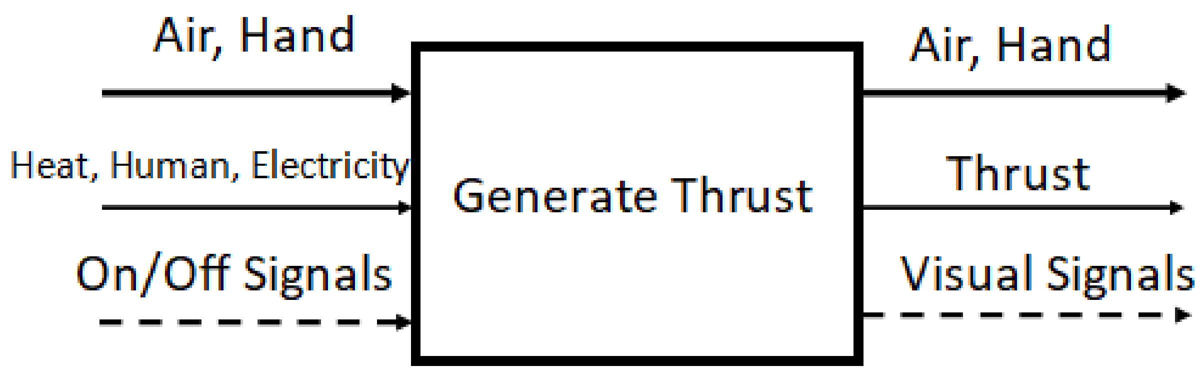


Figure 6: Black Box Model

The purpose of a Black Box Model is to define the main function of the design and the inputs and outputs to the system. The overall function of generating thrust is in the center of the Black Box, while the different inputs and outputs are labeled on the arrows surrounding the box. The solid, thick arrow at the top of the model represents the materials entering and leaving the system. For this design, the materials are air and a human hand. The air is the working fluid for the system and will generate thrust, and the hand will be operating the system. The thinner, solid arrow at the center represents the energies flowing into and out of the system. Several types of energy combine to create the sole output energy: thrust. Heat will help to stretch the maximum amount of power output. Human energy switches the system on and off, and electricity is used to power the heating system and compressed air tank. The dashed arrow on the bottom of the Black Box Model represents the signals going in and out of the system. For this project there are on and off signals entering the system and visual signals exiting for temperature and pressure.

3.3.2 Functional Model

After creating the Black Box Model, our team next moved to a Functional Model to illustrate the specific tasks that must be accomplished by the device. To do this, the team deconstructed a gas turbine engine into its basic components, creating a function chain linking them together. In principle, a turbine's operation is very simple: air is drawn in, compressed, expanded, and exhausted. Each of these four main functions are illustrated in the bottom chain of the Functional Model, shown in Figure 7. However, these elements alone would not allow our model to operate correctly. As will be discussed later, an outside energy source is required to replace the combustion process for this demonstration unit. Thus, a function chain was added for electricity. Finally, human energy was required to regulate the process, added at the top of the Functional Model.

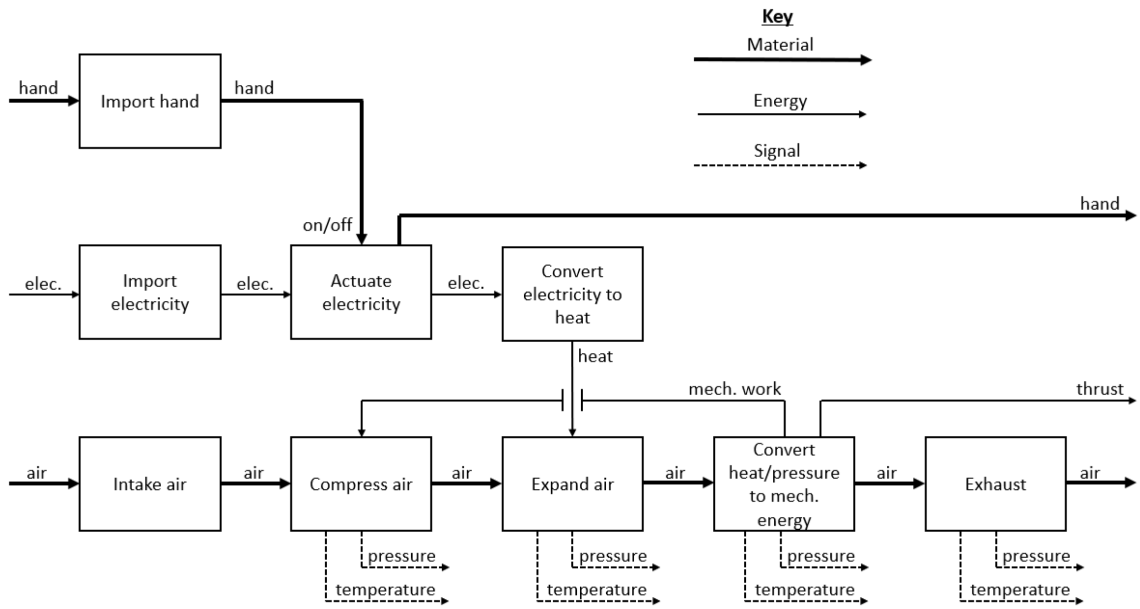


Figure 7: Functional Model

The Functional Model also helps to reinforce some of the customer needs. As discussed previously, one of the customer's most important requests was to be able to use this device as an education tool. Thus, the related Engineering Requirement was to measure temperature and pressure at every state. This can be seen in the pressure and temperature signals exiting from the bottom function chain.

3.4 Subsystem Level

As mentioned previously, all Brayton Cycle engines, including turbojets, turbofans, turboprops, and turboshafts, share a similar core element known as the gas generator, which consists of a compressor, combustion chamber, and turbine section. Thus, in performing subsystem design research, the team decided to focus on these three elements.

3.4.1 The Compressor

The compressor is the first component in a Brayton Cycle engine. It connects through a shaft to the turbine, from which it receives its power. The purpose of the compressor is to compress the air and raise its pressure before combustion to stretch the pressure vs. volume (P-V) diagram as well as the Temperature vs. Entropy (T-s) diagram, increasing work output.

There are several ways to compress air in a Brayton Cycle engine. The standard type utilized in most jet engines today is the axial compressor. This configuration is composed of radial vanes (or blades) that are mounted like discs on a central hub, which directs the flow through the compressor parallel to the shaft [6,7]. Figure 8 shows a simple diagram of an axial flow compressor with stator vanes.

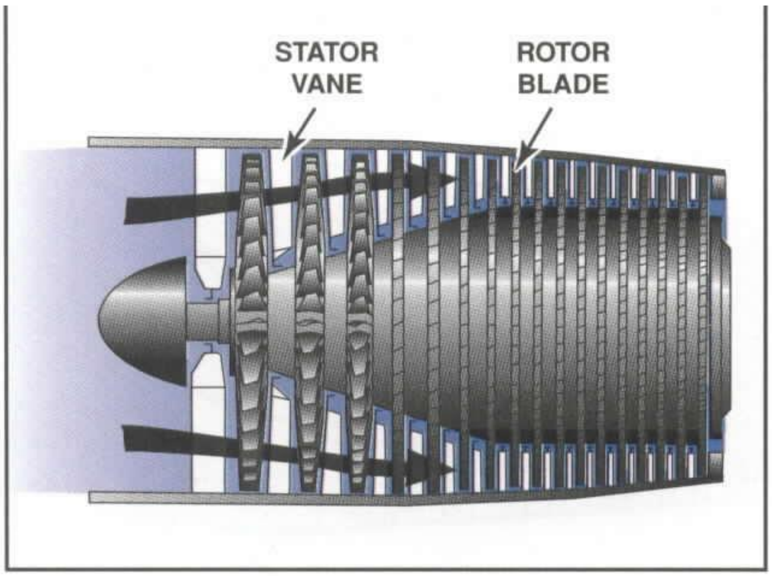


Figure 8: Cross section of an Axial Compressor [7]

As shown above, the rotor blades rotate and are similar to a fan blade, drawing air into the engine. As the flow moves further into the engine, the area between the rotor hub and outer case decreases, which further compresses the air. This compressed air flow is then directed to the combustion chamber.

The stators do not rotate with the rest of the blades, and while a functioning compressor can be made without them, stators increase the efficiency and effectiveness of each stage. A single compressor stage is defined to have one set of rotors and one set of stators [8]. The rotating blades will cause the flow to swirl in the direction of rotation, which causes the compressor to be less efficient as air can escape to the previous compressor stage [9]. A simple diagram a rotor and flow swirl can be seen in Figure 9 below.

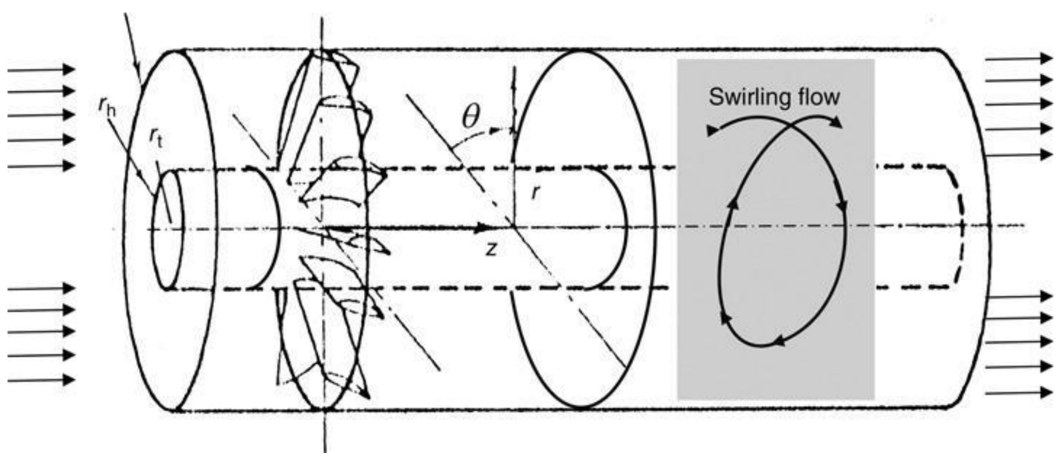


Figure 9: Flow swirl due to rotor [9]

Adding stator blades redirects the flow parallel to the axis of rotation. This decreases turbulence in the flow, increases the static pressure of each stage, and directs the flow perpendicular to the blades of the next stage.

The decrease of area between the inner hub and outer casing is an essential part to effectively compressing flow in an axial compressor. To achieve this area decrease, the diameter of the hub can change, the outer diameter of the casing can change, or both may change. The design shown in Figure 8 uses a combination of both to accomplish the area decrease. The first section, closest to the inlet on the left, has a constant outer casing diameter while the hub has a converging cross section. Next, the center section has a combination of a changing outer casing and inner hub radii. Lastly, the far right section has a constant hub radius with a converging outer casing. A more in-depth look at the relationship between the hub and outer casing can be seen in the turbine section.

Another compressor configuration is the radial, or centrifugal, compressor. Unlike the axial compressor, this configuration relies on the swirling of air to function; it forces the air away from the rotor and down to the combustion chamber. This configuration is primarily used in turbochargers in the automotive industry, though it can be used in a Brayton Cycle engine as seen in the model turboprop shown in Figure 5. It was also implemented in early jet engines [6]. Figure 10 below shows the rotor and housing of a radial compressor.

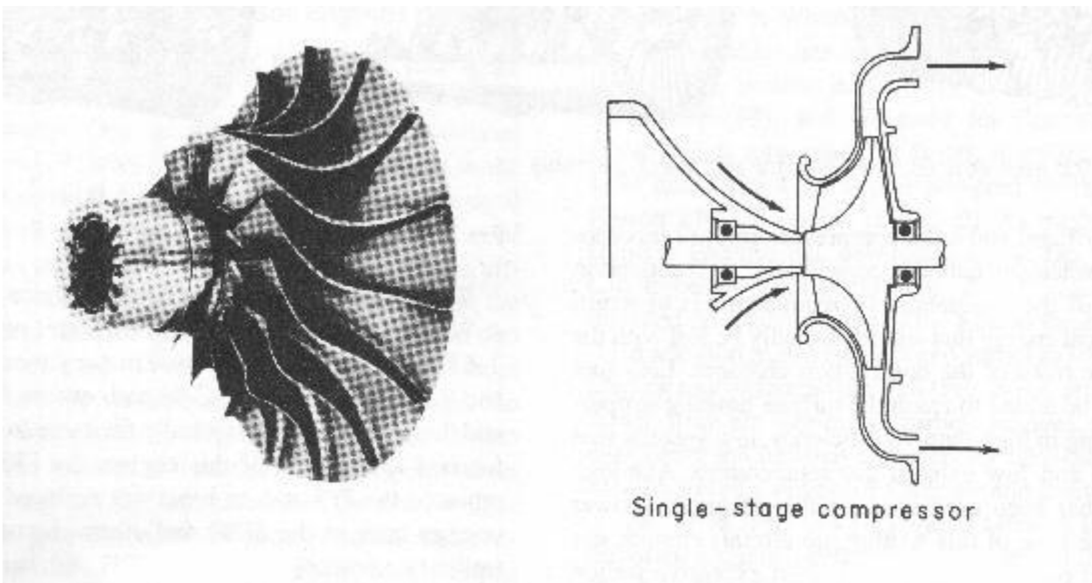


Figure 10: Cross section of Radial Compressor

As Figure 10 demonstrates, the vanes of a radial rotor direct the air from the center of the rotor to the outer edges. This configuration is ideal when using only one compressor stage as one radial stage is much more effective at compression than a single axial stage [6]. One NASA article states that an average axial compressor stage can increase the pressure by about 1.2 times, where a similar single-stage radial compressor stage can compress the air by a factor of 4 [6]. Though they are simpler and more efficient, radial compressors cannot be placed in series the same way as axial compressor stages. To place radial compressor stages in series, the flow must be redirected to the center of the next stage for the rotor to be effective.

Our team decided an axial compressor would likely be the best option for our design. This is detailed in the design selection stage later in the report. Because our design is to be used as an educational tool, and is supposed to represent how an actual Brayton Cycle engine works, we decided against the radial compressor, as they are rarely used in actual jet engine applications.

3.4.4 The Combustion Chamber

The main purpose of the combustion chamber is to add heat to the system before the working fluid enters the turbine. This increased temperature gradient increases the potential work output from the turbine. In a typical design, air is mixed with a fuel source and ignited in the chamber. There are typically three different geometric shapes for combustion chambers [10]. The Can Combustor, Figure 11, is made of several different chambers through which air flows [10]. Each chamber has outer and inner tubes; the inner tube is used for combustion, where the air flows through louvers in the inner liner [10]. The outer tube is used to regulate air flow [10].

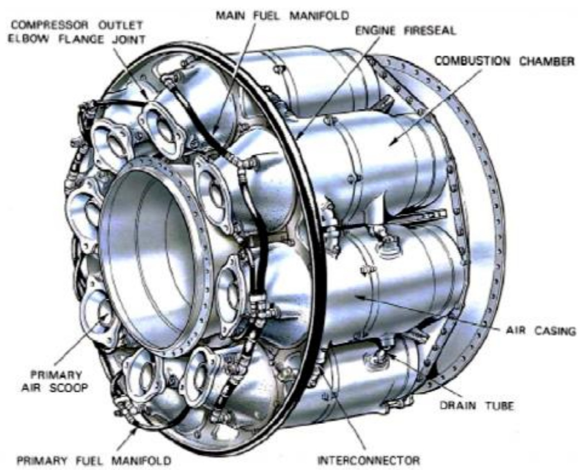


Figure 11: Can Combustor [10]

An annular combustor, Figure 12, has a single chamber with walls inside to control the air flow into the combustion zone [10]. There are two areas where the compressed air is mixed with the fuel. The primary air supply is fed into the combustion chamber to mix with the fuel source and combusted [10]. The secondary air is used to cool the air-fuel mixture before entering the turbine to prevent damage to the turbine blades [11].

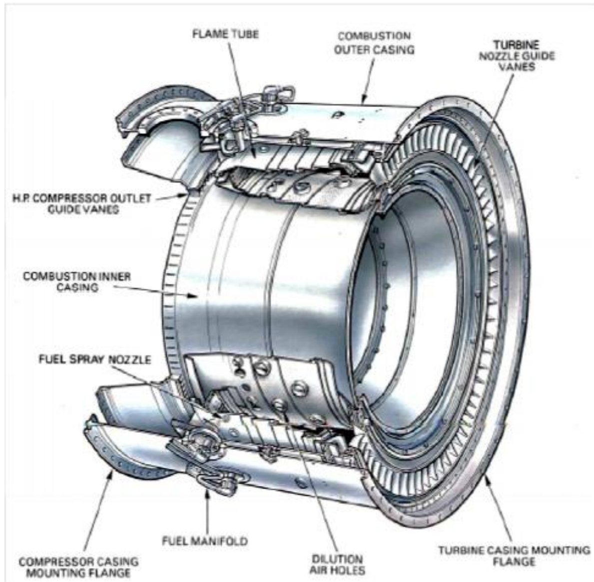


Figure 12: Annular Combustor [10]

The third type of combustion chamber is the Can-Annular combustor, which combines the two previous types as the name suggests [10]. This combustor takes the several chambers of a Can Combustor and incorporates an Annular Combustor in each chamber [10]. This is shown below in Figure 13.

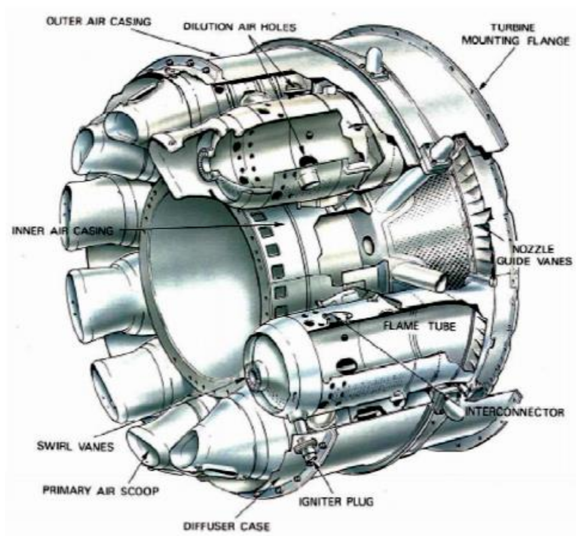


Figure 13: Can-Annular Combustor [10]

For any combustion chamber to work properly, the air velocity entering the chamber must be decelerated with a diffuser to ensure a stable combustion [10]. Too much air in the combustion chamber will cause a lean mixture, preventing the engine from operating at maximum efficiency. The air-fuel ratio that will yield the best efficiency is approximately 1:15 [11].

For safety reasons the team cannot create a model with a functional combustion chamber. The team decided to research outside sources to simulate the effect of an actual combustion chamber. There are several methods of accomplishing the effects of a combustion chamber. One way is to add more compressor stages to increase pressure. Alternatively, compressed air could be added from an outside source. This air could also be heated, either by heating the air before it enters the model or heating a portion of the model. In any of these cases, the engine would still benefit from the use of a diffuser before the simulated combustion chamber to create the most heat transfer into the system.

In both a real or simulated combustion chamber, the design must be such to keep the total pressure loss at a minimum. In any design there will be losses due to friction [11]. Designers should pay close attention to keep the chamber walls smooth and the flow streamlined to minimize pressure drop. For an actual combustion chamber, pressure losses are usually around 2-7 percent [11].

3.4.3 The Turbine

The turbine sits behind the combustion chamber and is mounted on the same shaft as the compressor. Its primary task is to power the compressor, by converting the heat and pressure energy from the combustion chamber into mechanical shaft work [12]. The use of the remaining power depends on the type of application, which heavily influences the final design. However, there are several design options used no matter the application.

Turbine Nozzle

The Turbine stage of a gas generator contains two primary types of components: the turbine nozzle, or stator, and the turbine rotor. The turbine nozzle is a row of stationary blades mounted ahead of the rotating rotor. Because it is stationary, the stator cannot do any work. Instead, it has two main functions. First, it converts the potential energy in the hot, high-pressure gas into kinetic energy by adding swirl to the flow [12,13]. Second, the turbine nozzle changes the direction of the flow, in order to maximize the force it can impart onto the turbine rotor. Generally, a turbine nozzle is placed ahead of each rotor to redirect the flow before each stage. An illustration of this configuration is shown in Figure 14 below.

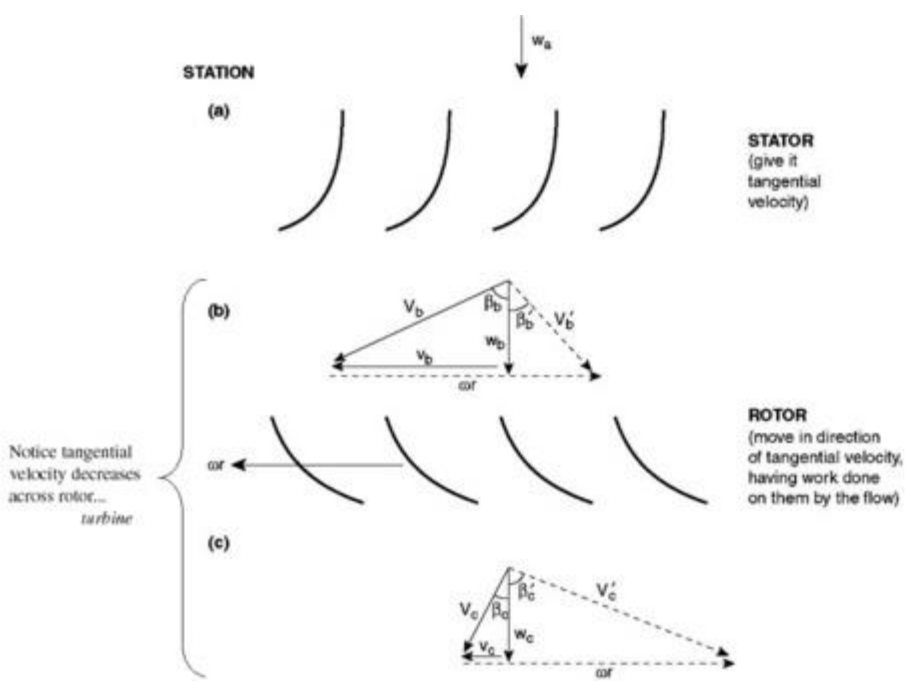


Figure 14: Turbine Stator/Rotor arrangement [13]

However, particularly for our design application, the turbine stator presents a manufacturing challenge. The stator stage must be mounted concentrically between the rotor stages but must be held stationary. In a real gas turbine, the stator can be incorporated into the outer casing of the engine, as shown in Figure 15 [14].

Figure 15: Turbine Stator [14]

However, because our design is intended for use as a demonstration tool, the engineering requirements dictate that the outer casing must be transparent. Most 3D printers can only produce opaque objects even with clear filament. Thus, we will most likely be required to use pre-manufactured tubing, and will have difficulty integrating a stator with this design. However, it is possible to avoid this issue by using a stator-less turbine design. As the name suggests, a stator-less turbine removes the nozzle guide vanes, and the flow exiting one turbine rotor passes directly to the next rotor without the use of a stator in between [15]. While this design simplifies manufacturing, it adds complexity to the rotor blade design.

Impulse vs. Reaction Turbine

There are two major classifications for turbines: Impulse, or constant pressure turbines, and Reaction Turbines [12]. In an Impulse Turbine, gas expansion occurs only in the stator, or turbine nozzle, which converts potential energy in the gas from heat and pressure into kinetic energy. As the gas passes through the nozzle guide vanes, it is accelerated rapidly while its temperature and pressure decreases. The gas then exits the turbine nozzle, impacting the turbine blades, and imparting rotation through momentum exchange [12]. As the gas passes through the rotating stage of the turbine, its pressure remains constant, hence the "constant pressure" name. After each turbine stage, velocity is lower than at the nozzle exit, as energy has been extracted from the flow and converted into shaft work. This process can be observed in the plot on the upper left of Figure 16, which illustrates how pressure, temperature, and velocity change as the flow progresses through the different stages of the turbine [12].

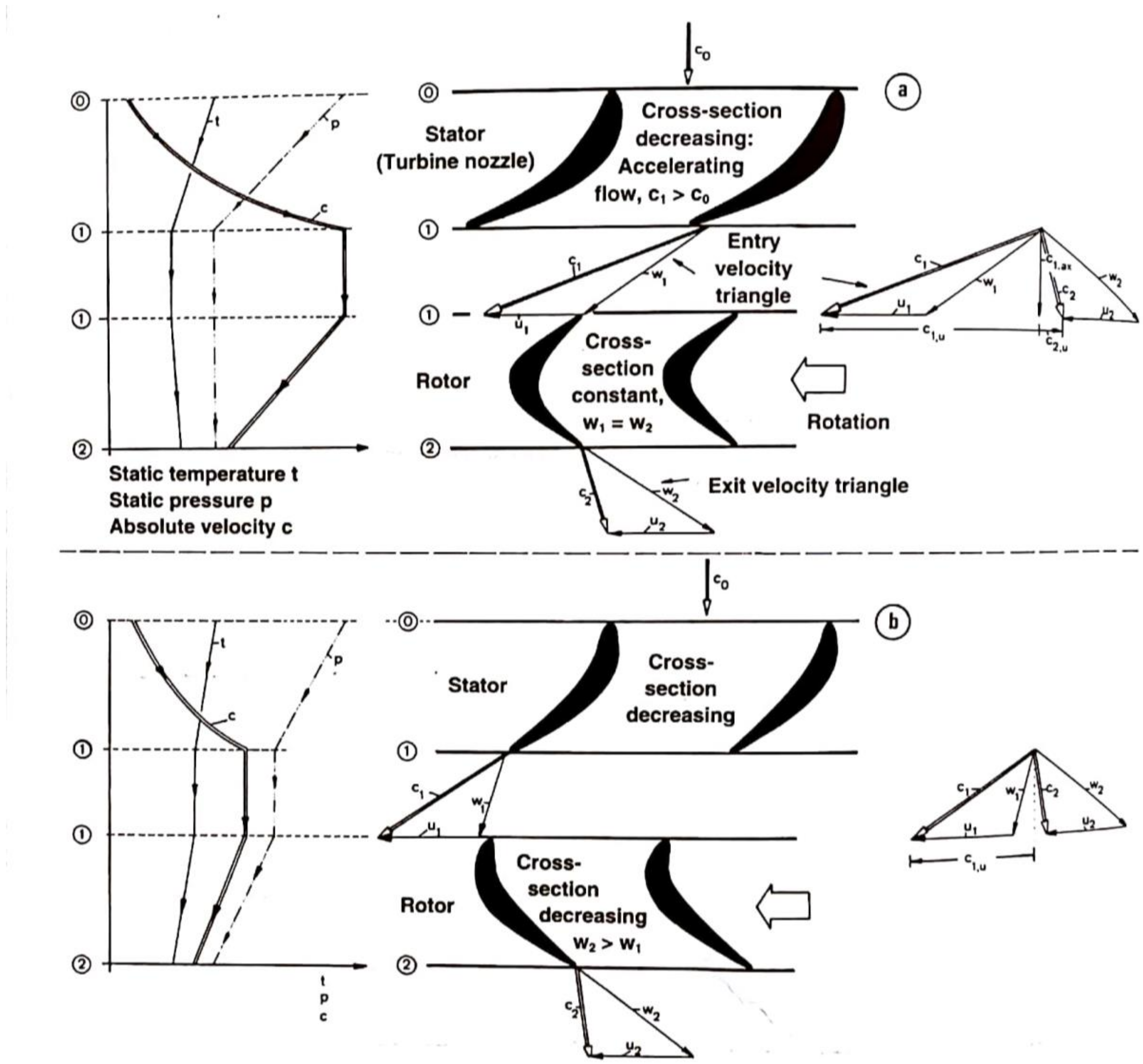


Figure 16: Impulse vs. Reaction Turbine [12].

Alternatively, in a Reaction Turbine, gas expansion takes place in both the stationary nozzle and the rotating turbine [12]. In the rotor section, the gas expands and accelerates similar to the Impulse Turbine, but to a lesser degree. This expansion continues in the turbine section, where the rotating blades share a more similar profile to the guide vanes. Due to the nature of the blade profile design, the air flow creates an aerodynamic force on the turbine blades, much like the lift force on a wing, which causes the turbine to rotate [12]. However, there is still a momentum exchange between the gas and the blades, much like in the Impulse Turbine.

A comparison of these two designs and their respective blade profiles is provided in Figure 15. The plots on the left of the figure compare the differences in pressure, temperature, and velocity through the different sections. Both of these designs have their own benefits. The Reaction Turbine is generally more efficient, but an impulse turbine has a higher power output, which can reduce the number of turbine stages required [12].

Given the benefits of each design, most turbines use a combination of the two. In a turbine, circumferential velocity increases radially outward, from a minimum at the hub to a maximum at the blade tip. However, it is beneficial to have a constant velocity profile across the entire length of the blade. To accomplish this, turbine blades are generally designed as constant-pressure type at the base, gradually changing to the reaction-type at the tip [12].

Hub and Tip Radius

Another consideration of turbine design is the profile of the hub and casing. These choices can affect mass flow rate, power production, and turbine efficiency [16]. Again, there is endless variability in designing these parameters. However, the options can be divided into three main categories: constant tip radius with variable hub radius, constant hub radius with variable tip radius, and variable hub and tip radius [16]. These three designs are presented in Figure 17 for comparison.

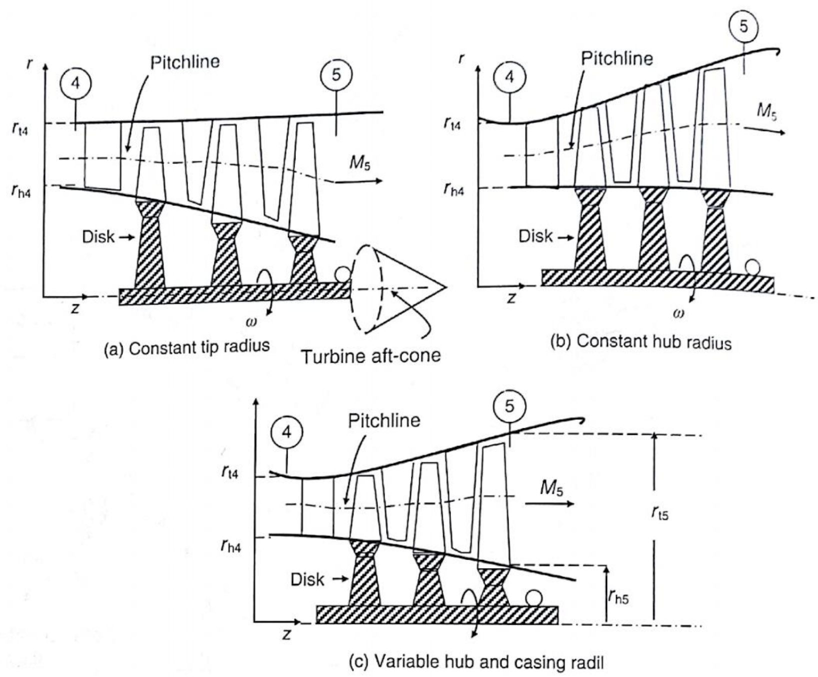


Figure 17: Turbine Hub and Casing Options [16]

Each of these designs offer their own distinct advantages. For instance, a constant tip radius can be beneficial in a turbofan. In a turbofan engine, the hot exhaust is mixed with the "cold" stream from the outer flow. In this scenario, using a constant outer radius can lead to better integration of the cold and hot air streams [16]. A constant outer radius also reduces centrifugal stresses in the rotor blades and can reduce the weight and frontal area of the engine. In aircraft engines, a tapered hub radius can also be advantageous, as the hub can be integrated with the exhaust cone, which is used to direct exhaust flow at the turbine exit [16].

A constant hub radius also has several benefits, particularly in stationary gas turbines used in power plants. This design choice can integrate with an exhaust diffuser, and also reduces manufacturing cost and complexity since all turbine rotor disks share the same inner diameter. Using both a variable hub and tip radius can allow for a constant pitchline. However, it is also the most complex design, the most difficult to manufacture, and generally increases both cost and weight [16].

As mentioned earlier, our design will most likely implement pre-manufactured tubing for the outer casing. Because of this, it will be very difficult to use a variable tip radius design. For this reason, our team believes a constant tip radius will be a better choice, as the hub radius can be more easily changed using 3D printing.

4 Designs Considered

At this point in the project we decided to focus on the main structure of the design. Once we determine how each subsystem will be configured, we can design them accordingly. Though there are just three main subsystems to any Brayton Cycle engine, there are many different ways to build each subsystem. Each team member researched one subsystem and generated a few variations that could be used in our design. The team then worked to create different combinations of these subsystem designs to create a total of 15 different concepts. Most of these designs combined different design elements discussed in the above subsystem research. The design team considered compressor and turbine type, hub and casing geometry, shaft configurations, and different options for combustion chamber substitutes. We sketched each of the 15 concepts, which can be seen in Appendix A. We then compiled these 15 designs into a Pugh Chart and scored each against the engineering requirements and the datum to find the top four designs. The entire Pugh Chart can be seen in appendix B. Below in Figure 18 is small portion of our Pugh chart showing our requirements and how the first 4 designs scored.

		1	2	3	4
Portable		-	s	s	s
Interactive		-	-	-	+
Educational		-	-	+	+
Durable		+	-	-	s
Reliable		-	s	-	-
Fit in 2x3 foot rectangle on cart		s	s	s	s
Total weight under 100lbs		-	s	s	s
Demo shouldn't take more than 15 minutes		s	s	-	-
Visability		-	-	-	s
Use 120v AC, 60Hz, and/or compressed air tank		-	s	s	s
Minimize exposure to dangerous/moving parts		-	s	s	s
Feasibility		-	-	-	-
Efficiency		-	+	+	+
Cost		-	-	-	-
	Total -	11	6	7	4
	Total +	1	1	2	3
	Total s	2	7	5	7
		14	14	14	14

Figure 18: Condensed Pugh Chart Showing Designs 1-4

The red highlighting above the first 3 designs indicates that they were eliminated in the first round of concept selection. The green highlight on the fourth design shows that it scored well enough to proceed to the next step in the process. The descriptions of the designs can be seen in Table 3 below. The yellow row represents the Datum. The Pugh Chart was used to eliminate all but four designs.

Table 3: Design Descriptions

Design description
1. Radial compressor and turbine, no heating
2. constant hub radius, no heating, statorless
3. constant hub radius with preheat, statorless
4. Constant tip radius with preheat, statorless
5. Constant tip radius with heating in chamber, statorless
6. constant tip radius with heating around outside of chamber, statorless
7 .Concentric shaft, 2 separate stages of comp. and turb. with preheat, statorless
8. Front Diffuser, constant tip radius with preheat, statorless
9. Stator compressor and turbine, constant tip radius with preheat
10. Stator compressor turbine, constant tip radius with in chamber heat
11.Statorless, constant hub radius, with heating around outside of chamber
12. Statorless, constant hub radius, with in chamber heating
13. Constant inner and outer radius, stator-less, no heating
14. Stator compressor and turbine, constant hub radius, with preheat
15. Stator compressor and turbine, constant hub radius, with in-chamber heating

The chosen datum was the simplest design possible, which used constant a constant hub and tip radius, stator-less blades, and no added heating in the combustion section. The design sketch for the datum can be seen in Figure 19 below.

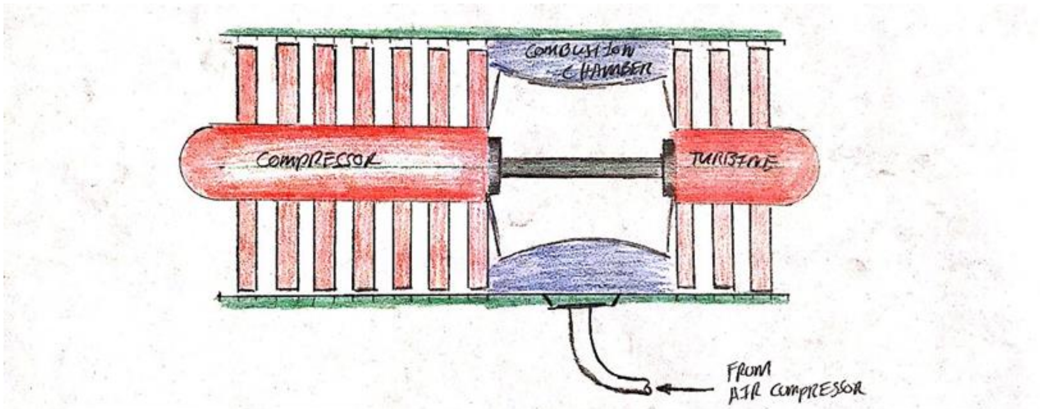
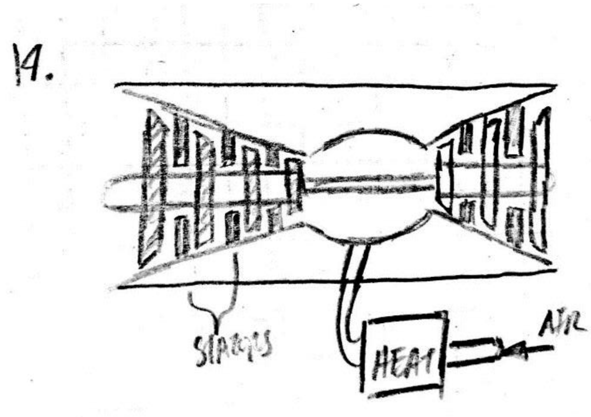


Figure 19: Detailed Sketch of Datum

Each concept utilized a different combination of the subsystem variations. For example, Figure 20 shows a sketch of Design 14, which uses stators on the compressor and turbine. Figure 20 shows a sketch of Design 3 without stators.



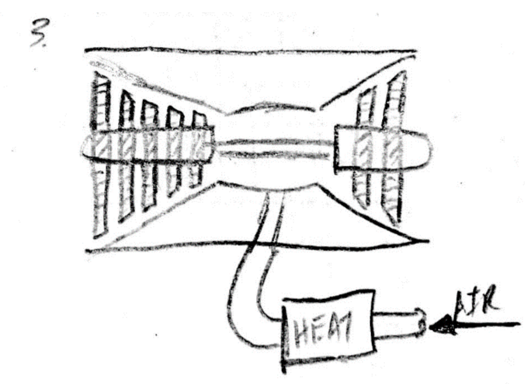
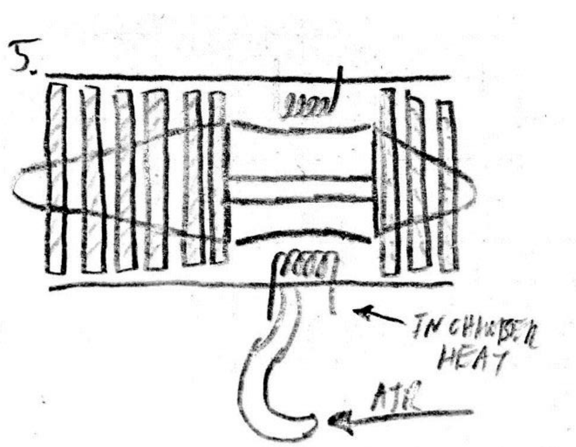


Figure 19: Design 14 Sketch

Figure 20: Design 3 Sketch

In Figures 19 and 20 above, both designs use a "pre-chamber" to heat the incoming air, and both designs utilize the constant hub radius design. To illustrate the different heating designs, Figure 21 depicts Design 5 with the in-chamber heating, and Figure 22 shows Design 11 with the heating around the outside of the chamber.



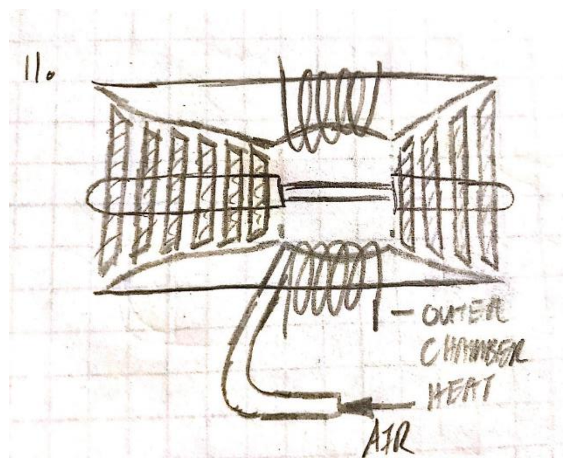


Figure 21: Design 5 Sketch

Figure 22: Design 11 Sketch

In the above figures it can also be seen that Design 5 utilizes the constant tip radius and Design 11 utilizes the constant hub radius.

5 Design Selected

In order to decide on a final design, our team placed the four remaining designs remaining into a Decision Matrix. The Decision Matrix used the same criteria as the Pugh Chart. However, several criteria were rated at “S” or same for all designs, so these were eliminated from the Decision Matrix to streamline the process. After narrowing the criteria, our team assigned a weight to each, based on its importance in meeting the customer needs. The criteria were weighted on a scale from zero to one, with the sum of all criteria weights summing to one. Next, each design was rated on a zero to 100 scale based on its competence for each of the evaluation criteria. Because the designs are highly conceptual at this point, most of these ratings were subjective. We found it most effective to compare the designs against one another when assigning scores. For instance, adding a heating element to the design will increase its educational value and efficiency, but will reduce its reliability and longevity.

After scoring all four designs, these raw scores were multiplied by the weight of each category, and summed to determine the strongest design. The completed Decision Matrix is shown in Figure 23.

	Concept	**9**		**11**		**13**		**15**	
Criteria	**weight**	**raw score**	**wtd score**	**raw score**	**wtd score**	**raw score**	**wtd score**	**raw score**	**wtd score**
Educational	0.2	65	13	80	16	50	10	80	16
Visability	0.18	80	14.4	65	11.7	80	14.4	80	14.4
Minimize exposure	0.13	50	6.5	50	6.5	50	6.5	50	6.5
Cost	0.13	80	10.4	75	9.75	85	11.05	75	9.75
Feasibility	0.1	50	5	70	7	90	9	70	7
Interactivity	0.17	60	10.2	60	10.2	70	11.9	80	13.6
Reliability	0.03	60	1.8	60	1.8	80	2.4	60	1.8
Durability	0.03	60	1.8	60	1.8	80	2.4	60	1.8
Demo time	0.02	80	1.6	80	1.6	90	1.8	80	1.6
Efficiency	0.01	85	0.85	70	0.7	50	0.5	70	0.7
Total	1		65.55		67.05		69.95		73.15

Figure 23: Decision Matrix

As shown above, all four final designs scored very closely, as all had many similarities. However, based on these criteria, Design 15 was the strongest concept. This is illustrated below in Figure 24.

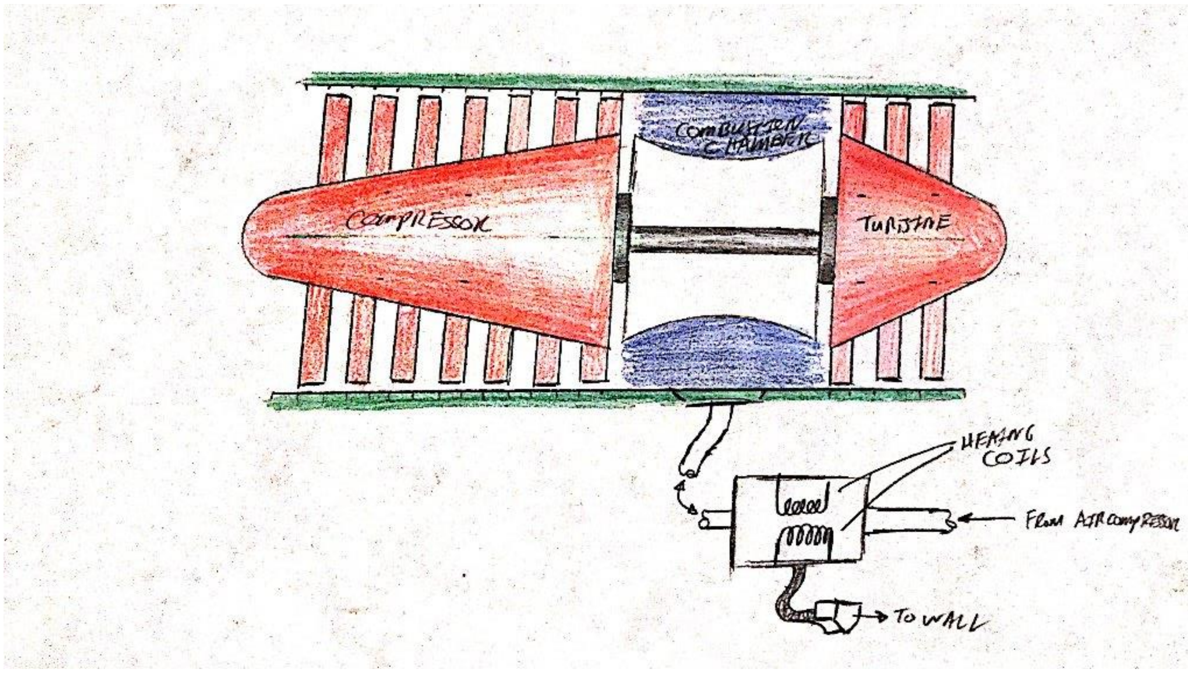


Figure 24: Winning Concept

This design functions without any combustion, as did most others. It features a stator-less compressor and turbine, with a constant blade tip radius and variable hub radius. Compressed air will be used in place of combustion to add energy to the flow in the form of pressure. This design also implements an in-line heater for the compressed air stream to further enhance the energy added during this stage.

5.1 Rationale for Design Selection

Our team sees numerous benefits in this chosen design. First, the elimination of combustion makes this unit much safer to use in a classroom setting. Use of compressed air should be able to sufficiently increase flow energy and adding a heater will help to differentiate further between state measurements. Heating the air before it enters the "combustion chamber" is also beneficial, as it prevents the plastic from being heated directly, theoretically reducing thermal strain and increasing longevity. Finally, the choice of a stator-less compressor and turbine with constant tip radius simplifies manufacturing.

However, the concept generation at this state focused more on large design decisions, so there are still many considerations necessary before finalizing the design. Our team still needs to conduct a large amount of research to effectively design the blade profiles for the turbine and compressor. At this stage, it seems preferable to use the stator-less design for manufacturing feasibility. However, this may need to be revisited based on our aerodynamic research. We also must decide on the ideal plastic type to be used for the 3D printing, and the pressure and temperature sensors that will be used for measurements at each state.

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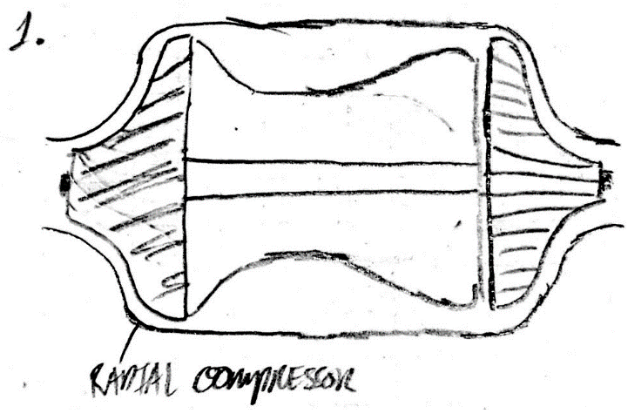
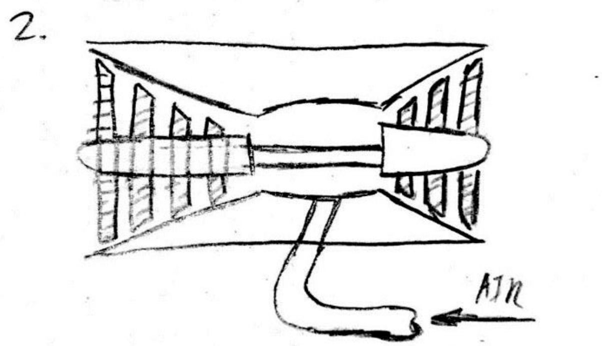
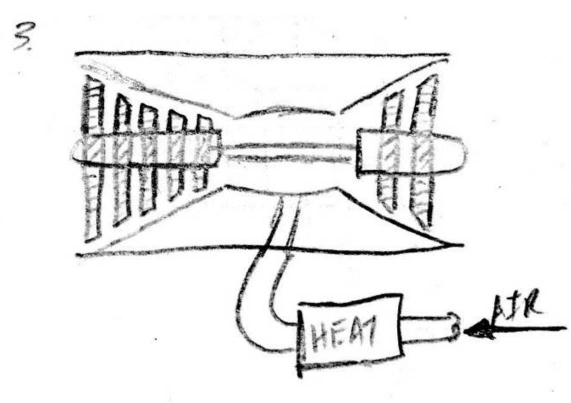
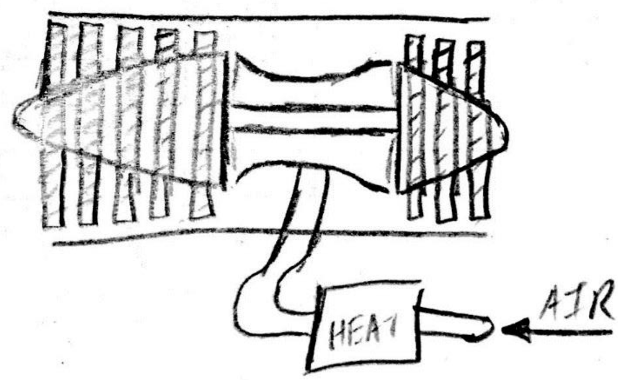
Appendices

Appendix A: Concept Sketches









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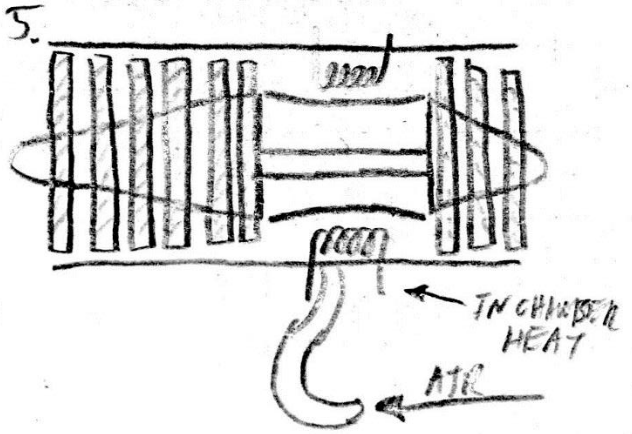

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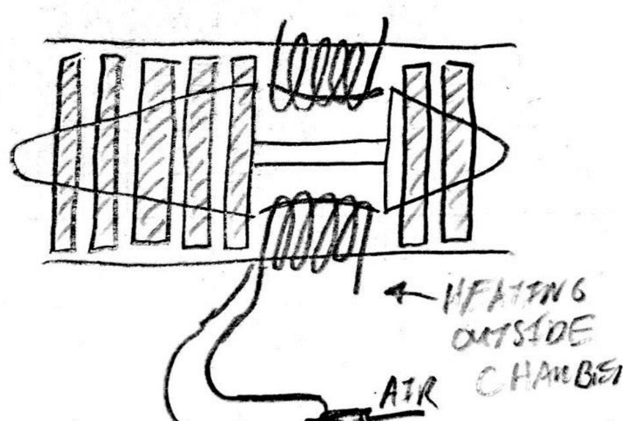
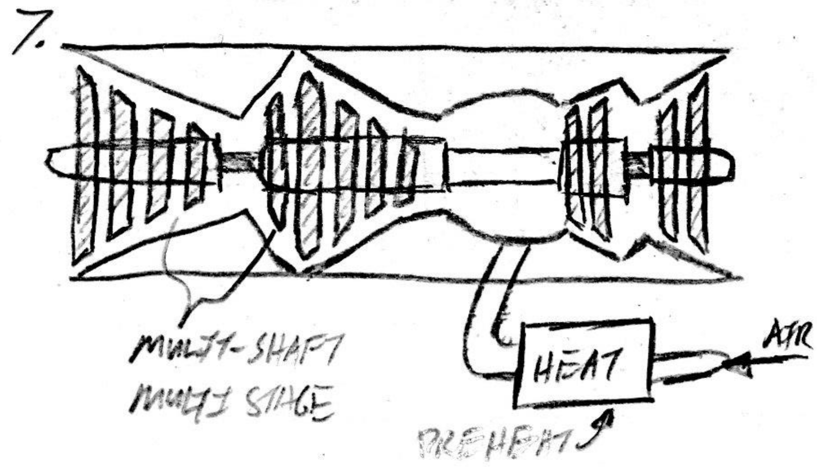
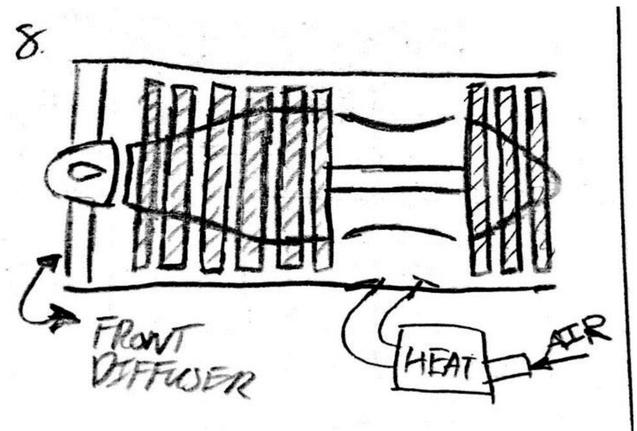
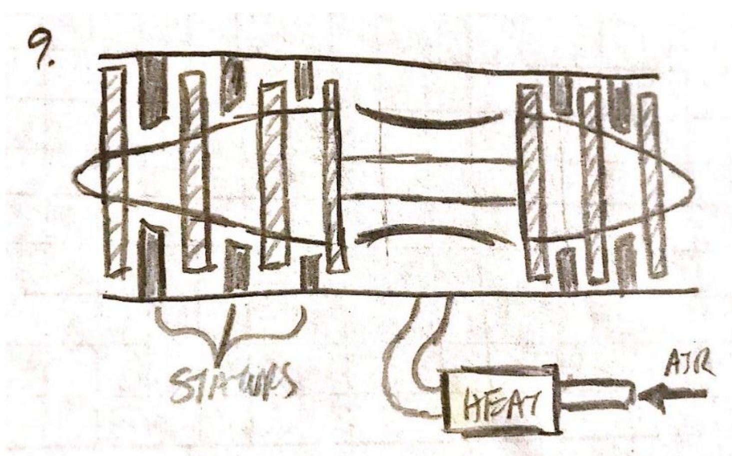
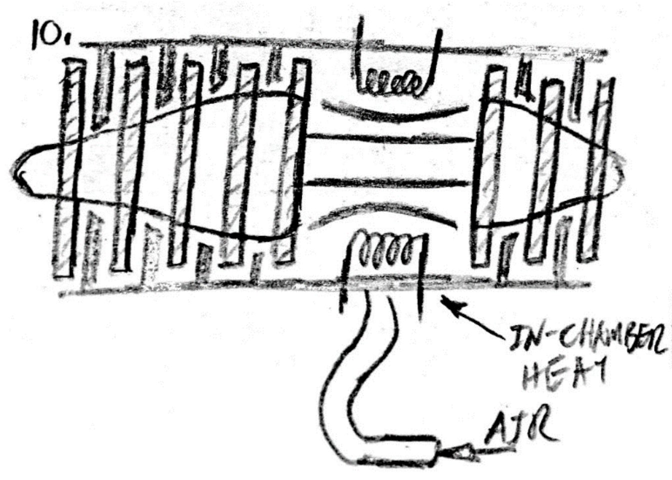
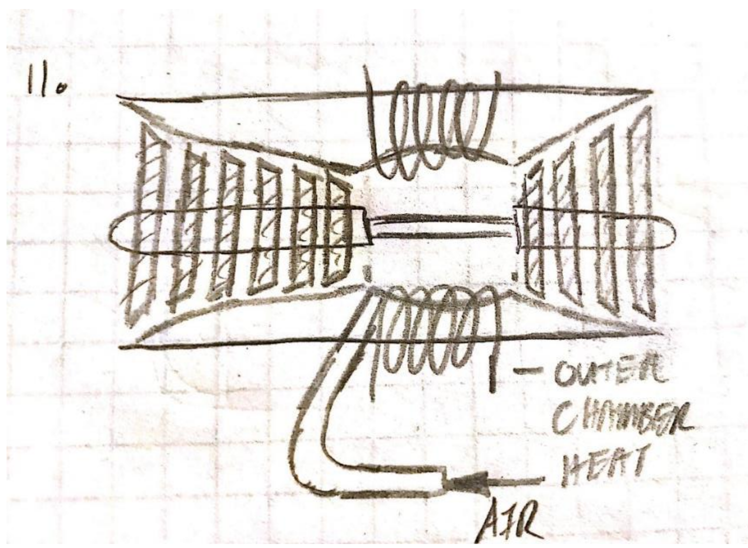


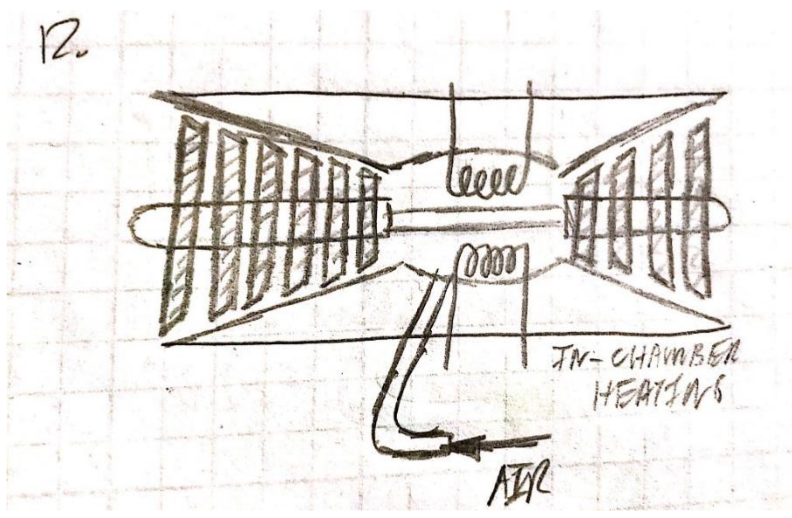

7.
MULTI-SHAFT
MULTI STAGE
HEAT
AIR
PREHEAT


8.
FRONT
DIFFUSER
HEAT
AIR


9.
HEAT
AIR


10.
IN-CHAMBER HEAT
AIR


11.
OUTER CHAMBER HEAT
AIR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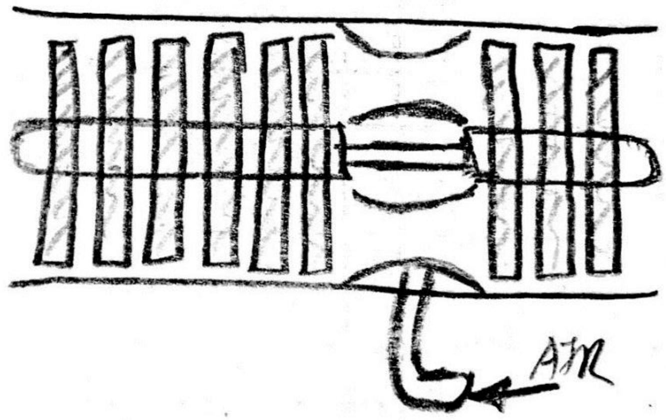
IN-CHAMBER HEATING
AIR

13.



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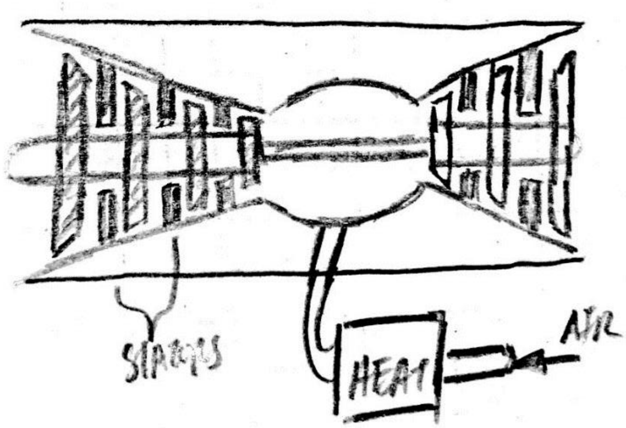

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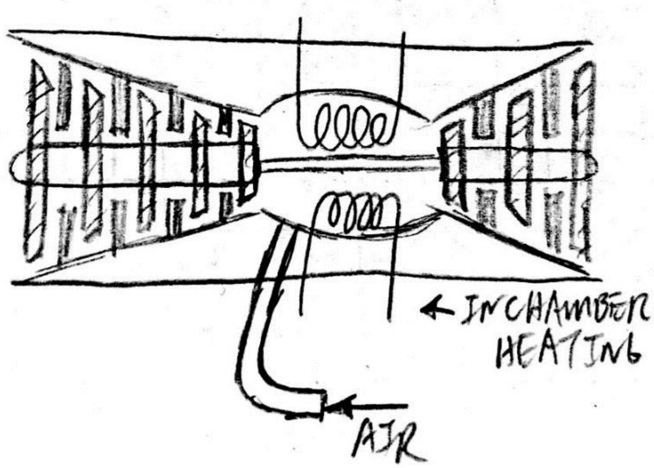
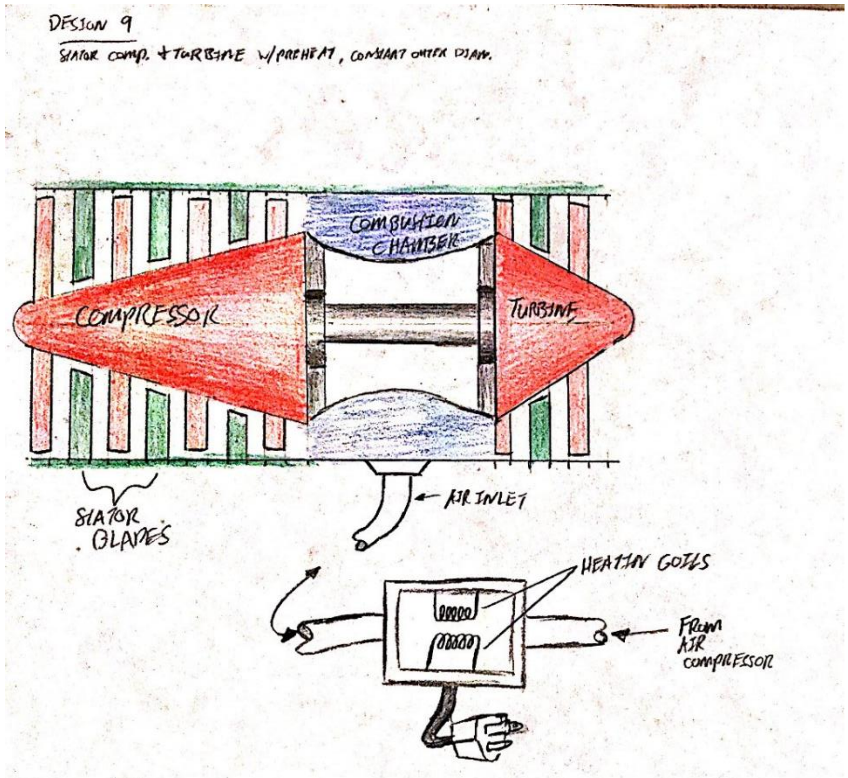
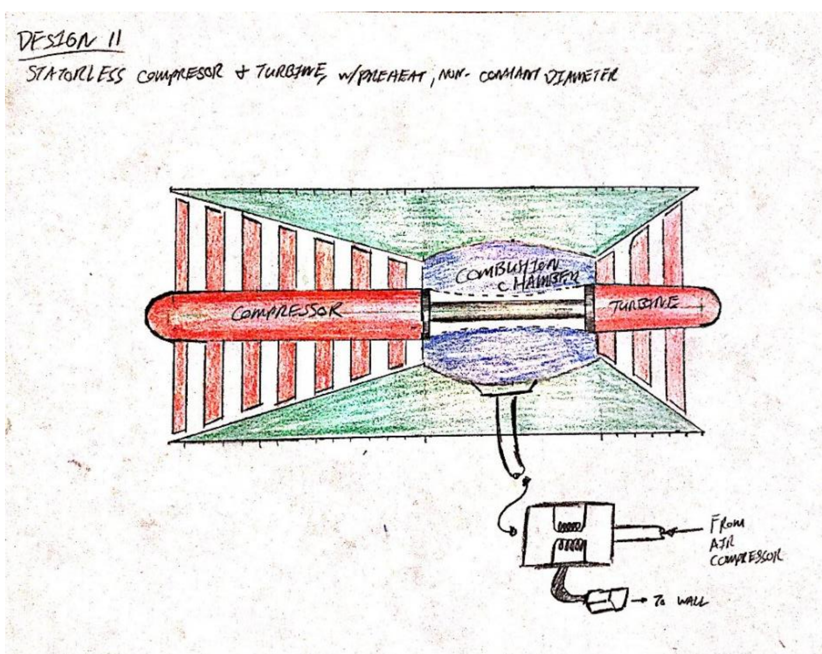
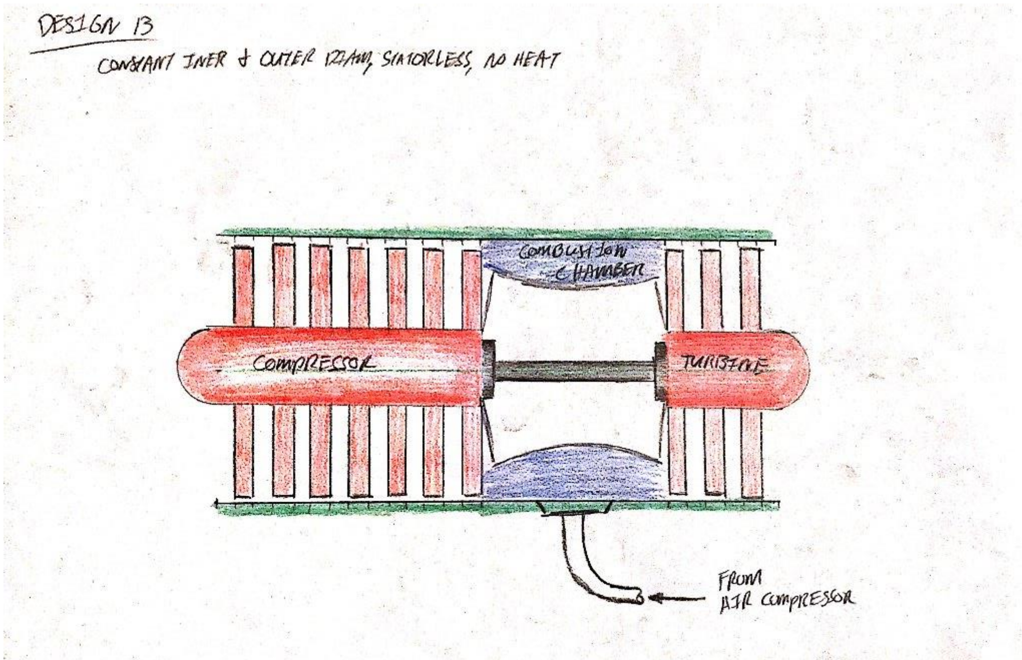
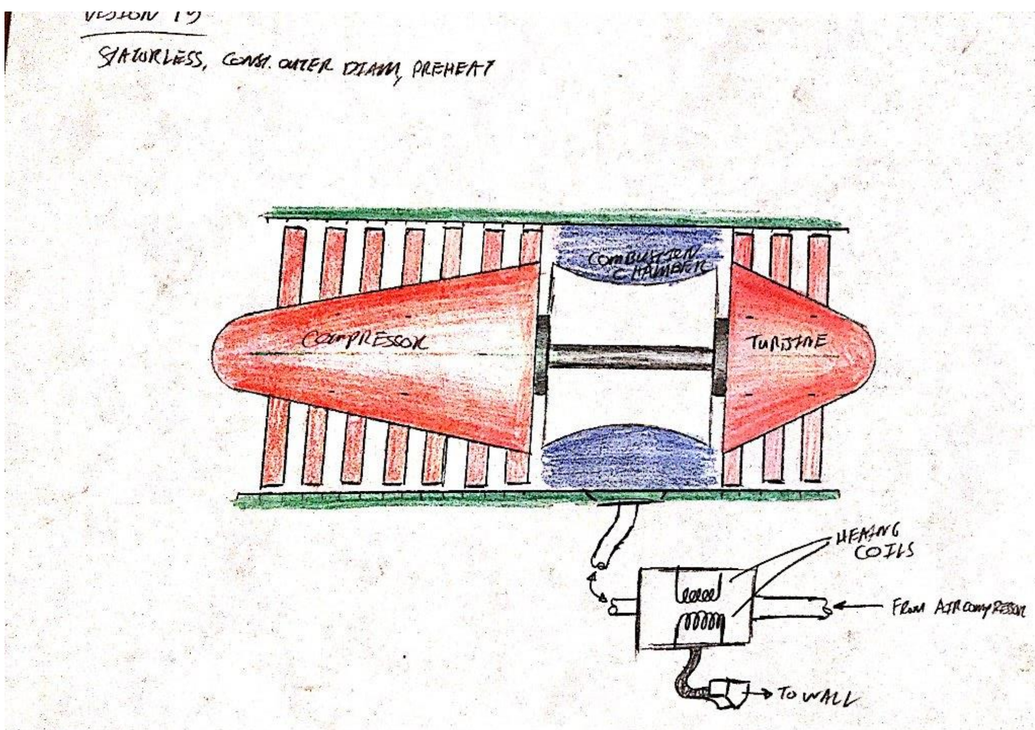



DESIGN 9
STATOR COMP. + TURBINE W/PREHEAT, CONSTANT OUTER DIAM.
COMBUSTION CHAMBER
COMPRESSOR
TURBINE
AIR INLET
STATOR BLADES
HEATIN COILS
FROM AIR COMPRESSOR


DESIGN 11
STATORLESS COMPRESOR + TURBINE, W/PREHEAT, NON-CONSTANT DIAMETER
COMBUSTION CHAMBER
COMPRESSOR
TURBINE
FROM AIR COMPRESSOR
TO WALL


DESIGN 13
CONSTANT INER & OUTER DIAM, STATORLESS, NO HEAT
COMBUSTION CHAMBER
COMPRESSOR
TURBINE
FROM AIR COMPRESSOR


STATORLESS, CONST. OUTER DIAM, PREHEAT
COMBUSTION CHAMBER
COMPRESSOR
TURBINE
HEATING COILS
FROM AIR COMPRESSOR
TO WALL

Appendix B: Pugh Chart

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Portable	-	s	s	s	s	s	s	s	s	s	s	s		-	s
Interactive	-	-	-	+	+	+	-	s	+	-	-	s		s	s
Educational	-	-	+	+	+	+	+	s	+	-	s	s	D	+	s
Durable	+	-	-	s	-	-	-	-	s	-	+	+		s	s
Reliable	-	s	-	-	-	-	-	-	-	-	s	s		-	-
Fit in 2x3 foot perimeter	s	s	s	s	s	s	s	s	s	s	s	s	A	s	s
Total weight < 100lbs	-	s	s	s	s	s	s	s	s	s	s	s		s	s
Demo < 15 minutes	s	s	-	-	-	-	-	-	-	-	-	-		-	-
Visability	-	-	-	s	s	s	-	-	s	-	-	-		-	s
120v AC, 60Hz, and/or compressed air	-	s	s	s	s	s	s	s	s	s	s	s	T	s	s
Minimize exposure	-	s	s	s	s	s	s	s	s	s	s	s		s	s
Feasibility	-	-	-	-	-	-	-	s	-	-	s	-		-	s
Efficiency	-	+	+	+	+	+	+	+	+	+	s	s	U	+	+
Cost	-	-	-	-	-	-	-	-	-	-	-	-		-	-
Total -	11	6	7	4	5	5	7	5	4	8	4	4		6	3
Total +	1	1	2	3	3	3	2	1	3	1	1	1	M	2	1
Total s	2	7	5	7	6	6	5	8	7	5	9	9		6	10

Figure B1: Pugh Chart