NORTHERN ARIZONA UNIVERSITY

Thermodynamics Demonstration Unit 1B
High Bypass Turbofan

EGR 476C-02

Erich Gemballa: Manager, Data Collection Lead
Gavin Geiger: Treasurer, Compressor Lead
Brendan Savelli: Web-Admin, Heat Exchanger Lead
Hamad Almutairi: Secretary, Materials Lead
Abdullah Abdulghafour: Editor, Turbine Lead

Client: David Willy

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Tables

Figures

1.0 Background

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. 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. The easiest way to visualize the Brayton cycle is through a jet engine. A jet engine compresses incoming air, heats it up through combusting fuel, and expands out with a higher velocity than the incoming air all within a relatively compact system. An educational model for use in a classroom would not need to have the same pressures or temperatures achieved with combustion of a fully functioning jet engine. Therefore, the team decided that recreating a turbofan jet engine that is a fraction of the size and without combustion is the ideal aid to help teach students how a Brayton cycle works.

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. The team decided that using a turbofan jet engine is ideal in showing the compression and expansion of the working fluid while also displaying data to validate principles taught in the classroom.

2.0 Requirements

Through the process of client meetings and customer interviews, the team was able to relate the project problem statement to customer needs. By determining customer needs, the team assembled engineering requirements to demonstrate the critical components of the project.

2.1 Customer Requirements

Upon discussing with the client, it was determined to extend customer research to practicing thermodynamic professors at Northern Arizona University. Professors that were questioned were Dr. Wade, Dr. Nelson, and Dr. Mazumdar. After proceeding with customer interviews, it was determined to set the customer requirement as mentioned 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 synthesized the information required from the client and customer interviews to associate each customer requirement to an engineering requirements. This information is presented in Table [2].

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 House of Quality

Correlating the customer needs acquired through interviews with the engineering requirements is done through the House of Quality, displayed in Table [3]. The purpose of correlating the two requirements will help the team determine the most critical components that benefit educating the most. Upon completing the house of quality, it was determined that the thermal capacity of the system is most important aspect to properly teach the fundamentals of thermodynamics.

Table [3]: 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**

3.0 Existing Design

An existing design that the team has based designs around is the Rolls-Royce Trent 556 [1]. Modeling the existing Rolls-Royce engine to a working 3D printed model has been done through ratios to simulate an operational high bypass turbofan. This comparison is shown in table 4.

Table [4]: Modeling Ratios

	Rolls-Royce Trent 556	**1:10 ABS model 30% fill**
Length [m]	3.9	.39
Diameter [m]	2.47	.247
Weight [m]	4840	17.59
Bypass ratio	7.61:1	7.6:1
Air Flow rate [kg/s]	879	87.9
Thrust to weight ratio	5.25:1	5.25:1
Pressure ratio	36.3:1	3.6:1

Components will be tested by blowing air, as the working fluid, through the model at different velocities and measuring velocities temperatures and pressures the overall goal of maximizing the overall efficiency and maximizing the combustion chambers temperature (Kelvin) without exceeding the 378 K glass transition temperature of ABS. Individual components will be tested and compared to the benchmark throughout the design process. The exit velocity of the low bypass will be measured with a pitot tube. The team will compare the compressors by measuring the pressure in the combustion chamber with a manometer. The turbine will be tested through means of measuring velocity of the fluid flow and rotational rotational speed of the shaft. The team will improve on existing models by instrumenting the turbofan with pitot tubes, manometers, and thermocouples at the inlet, exit, and combustion chamber.

3.1 Design Research

Existing models that simulate the Brayton Cycle process through Turbofans have been researched to find optimal solutions to the subsystem levels [3]. Utilizing the existing model designs as benchmarking our designs.

Further research was performed to create the top level systems. Each top level system: Rotor blade design, data acquisition, and casing design was broken down into further subsystems to create unique designs for specific sections of the project.

3.2 System Level

To design an operational high bypass turbofan that is educational, the team has allocated research into the rotor blade design, data acquisition, and casing design. The purpose of these systems is to finalize design options through the means of a pugh chart. Each of the top level systems have been analyzed provide background along with related associations to the project.

3.2.1 Rotor Blade Design

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.

3.2.2 Data Acquisition

From the problem statement set by the client, educating future engineering students on the principles of thermodynamics, data acquisition is the top level system responsible for educational purposes. Current technology used in acquiring pressure is pitot-static tubes in flying aircraft, and manometers in wind tunnels. For temperature data acquisition, thermocouples are used in many applications to evaluate exact locations of temperature.

3.2.3 Casing Design

Current designs for a High Bypass Turbofan include a volume reduction for the combustion chamber to increase pressure and temperature. Applying current design applications of a high bypass turbofan is unrealistic in the project, due to the high precision of manufacturing and high temperatures. Due to the constraints of material selection and maximum temperatures, reducing volume in the heat exchanger section does not yield better results.

3.3 Functional Decomposition

3.3.1 Black Box Model

The black box model for the educational high bypass turbofan is important to identify all the materials, energies, and signals that are critical for the unit to produce power. Implementation of each of the customer requirements in the black box model illustrates the importance of how the team plans to incorporate data acquisition to achieve an educational model. Figure [1] shows the team's black box model.

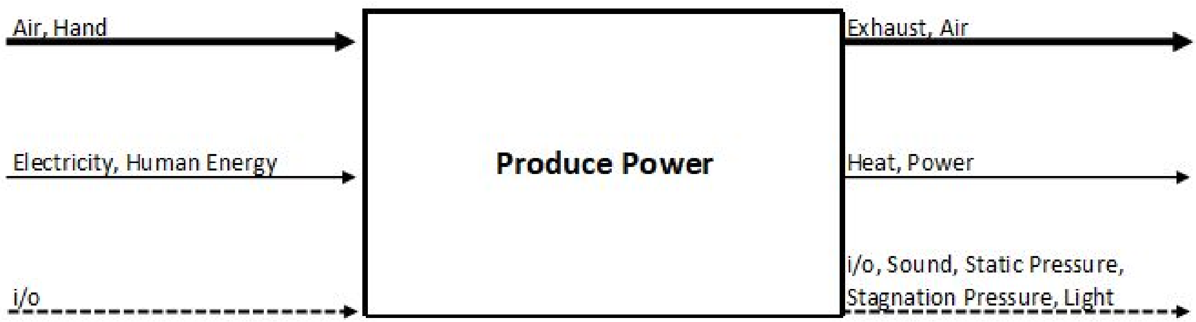


Figure [1]: Black Box Model

3.3.2 Project Decomposition

A turbofan process was created using a functional flowchart to illustrate the processes involved throughout the model in order to generate a visual demonstration of P-v diagrams as well as temperature locations. Figure [2] shows all the work and heat flows along the entire turbofan process. Figure [3] illustrates the locations for data acquisition for each of processes which is used in the educational portion.

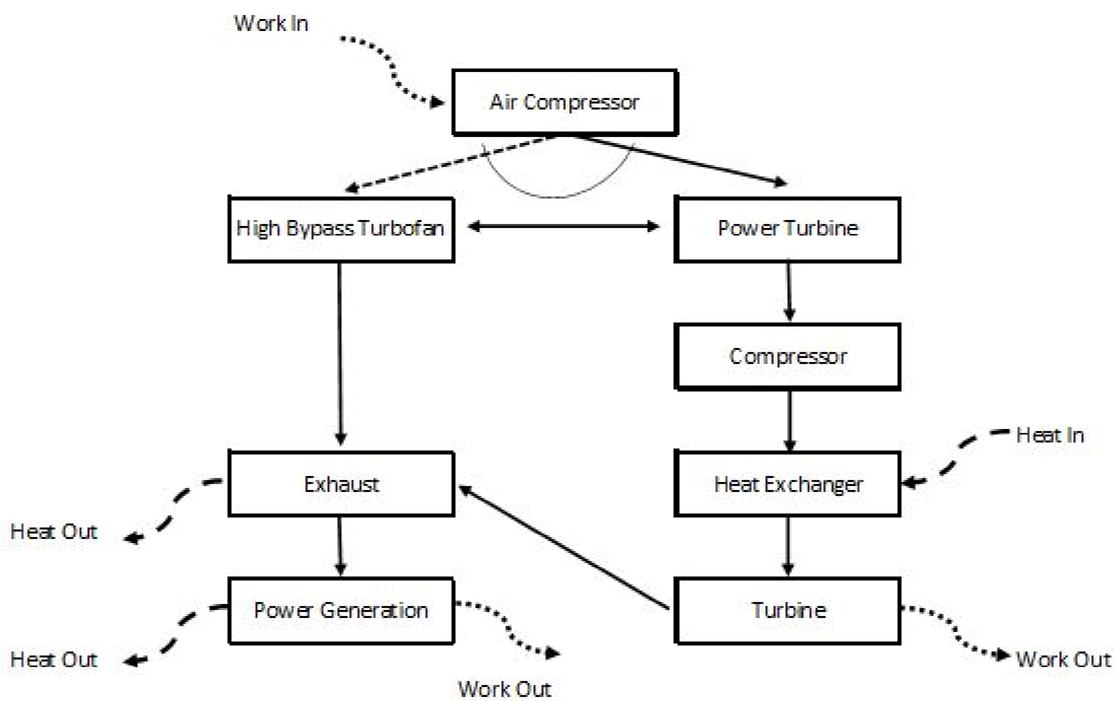


Figure [2]: Turbofan Functional Flowchart

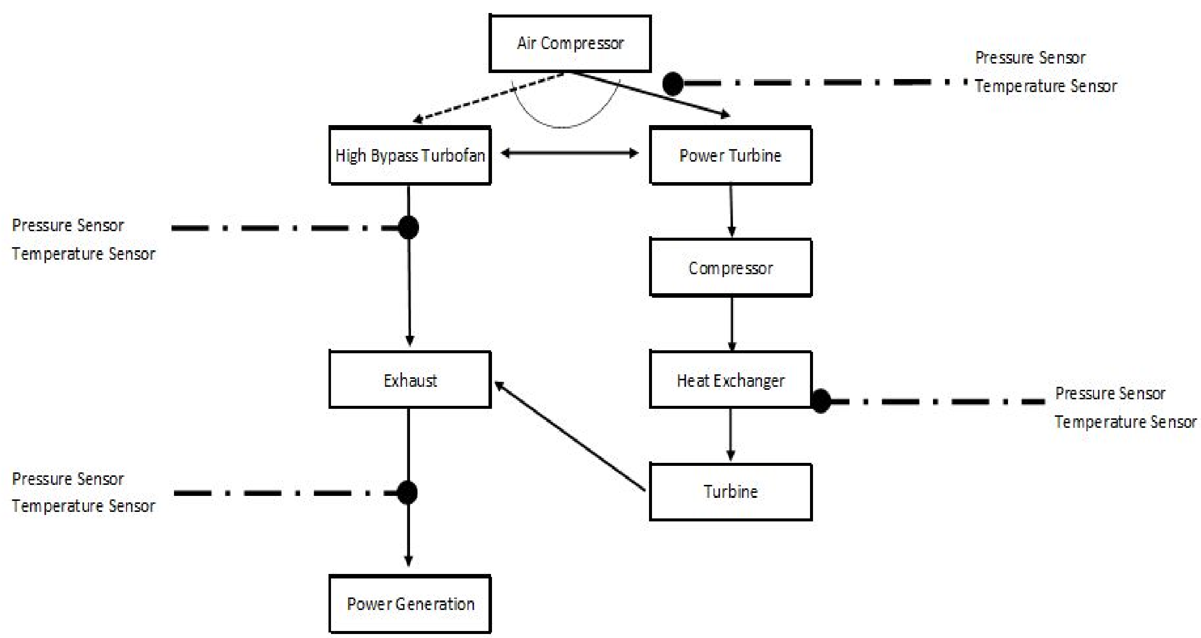


Figure [3]: Pressure and Temperature Locations for Flowchart

3.4 Subsystem Level

3.4.1 Rotor Blade Design

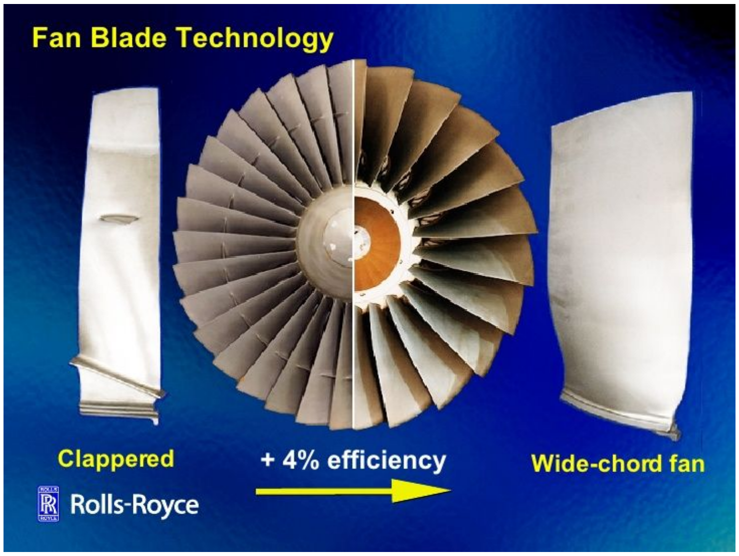


Figure [4]: Fan Blade Technologies [3]

3.4.1.1 Chord width-

The chord of the fan blade has and impact on the efficiency, weight and cost of the engine. Figure [4] shows the difference between clappered blades and a wide-chord blade. Long thin blades are lighter but require a clappered in the middle of the blade to prevent blade deformation. Shock waves form around the clappers causing a reduction in efficiency. Wide chord fan blades are more efficient but heavier and more expensive. The added weight of bigger blade requires more expensive hollow titanium blades. Figure [5] and [6] show another viewpoint of the blades. For the model engine, the wider blade design won't require any cost increase beyond a small amount of ABS filament, so it makes sense to incorporate this feature into the model.

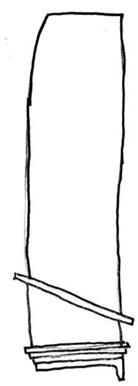


Figure [5]: Clappered Blade

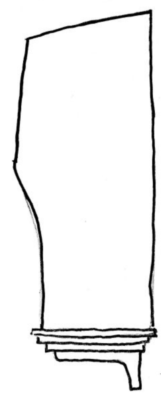


Figure [6]: Wide-Chord Blade

3.4.1.2 Angle of attack-

The angle of attack is defined as the angle between the chord line and the direction the flow is moving. Figure [7] shows the visualization of the topic.

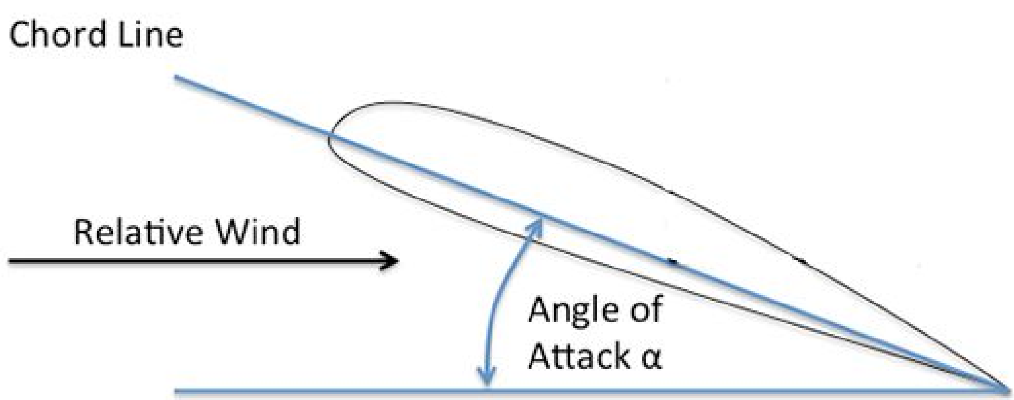


Figure [7]: Angle of Attack for Rotor Blade Design [4]

The angle of attack is used in rotor blades to direct the fluid flow to either the next blade or to the next section of the engine. For the compressor blades, the angle of attack of the first blade is relatively large in order to slow down the fluid flow and direct it to the next blade. The following blade will not have as extreme of an angle of attack, but will have the same function of the first blade: to continually slow down the fluid in order to increase the pressure. Depending on the desired compression ratio, the number of compressor blades will be variable to reach the ratio. Following the heat exchanger, the turbine blades serve a similar purpose as the compressor blades. The turbine blades are designed with relatively small angle of attack, but instead with a large blade curvature. How curvature of the blade affects the fluid flow is discussed further in the following curvature section.

3.4.1.3 Normal force relative to fluid speed-

The normal force created from the resulting fluid flow is considered to be the lift. Lift is usually related to airfoils with designing airplanes, but lift correlates with the angular velocity for rotor blades. Figure [6] Without the rotor spinning, the fluid will not be moving as designed, therefore not being compressed properly. With the rotors spinning, the fluid is transitioning from linear movements to spinning around the shaft, which further compresses the fluid as desired.

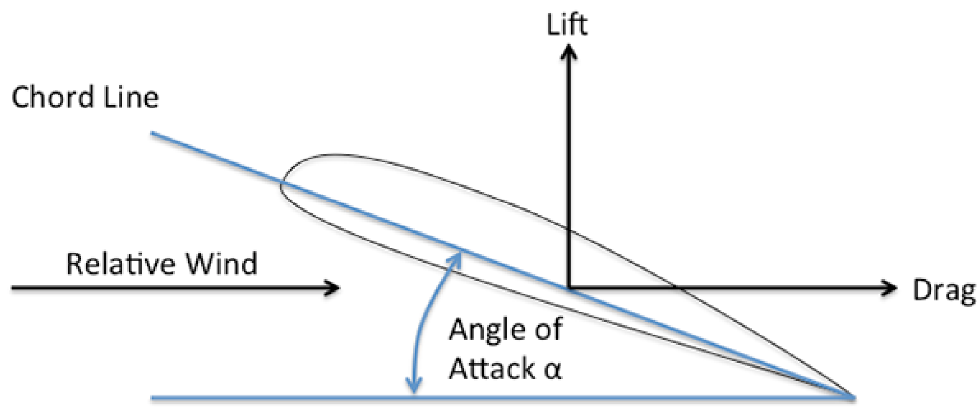


Figure [8]: Lift for Rotor Blade Design [4]

3.4.1.4 Curvature-

The curvature of compressor or turbine blades dictates where the fluid is going to be directed. Similar to the angle of attack, the curvature has a large influence on how well the fluid is compressed in the initial compressor blades and how quickly the fluid exits the turbine. When the fluid comes into contact with the first turbine blade, the highly pressurized fluid will start to convert the stored potential energy and convert it back to kinetic energy. The curvature of the blades will dictate the velocity and direction of the exiting fluid. Ideally, the velocity of the fluid leaving the turbine is the work out of the system. Therefore, the design of curvature for the turbine blades has the largest influence of fluid speed and overall efficiency of the system. The velocity exiting the system must be greater than the velocity of the fluid moving into the system, i.e. work out must be greater than work in. Figure 6 displays the different designs for curvature of turbine rotor blades.

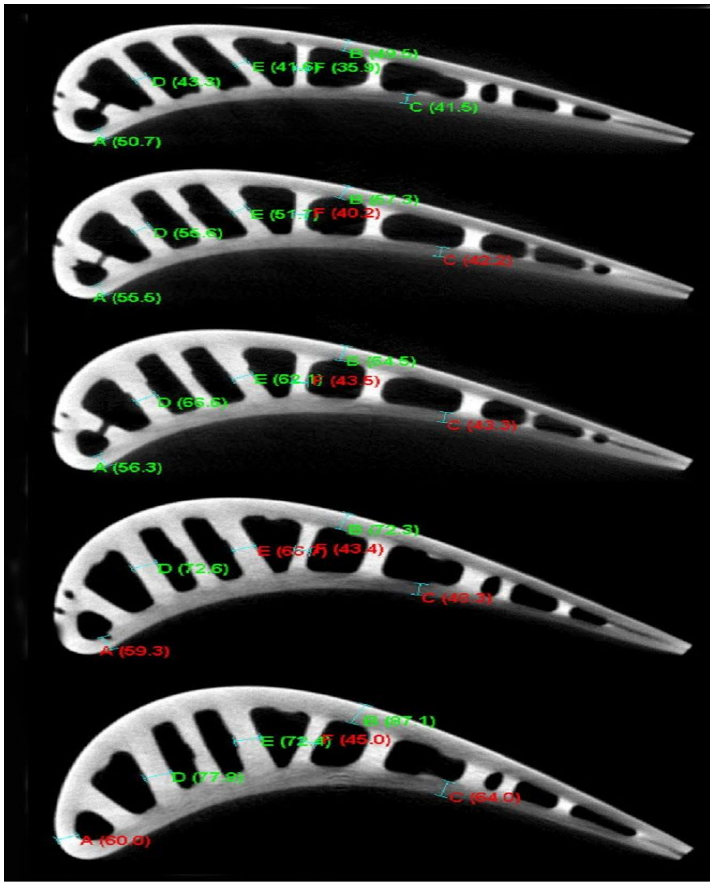


Figure [9]: Curvature for Different Rotor Blade Designs [5]

3.4.2 Data Acquisition

3.4.2.1 Pressure Acquisition-

Pressures must be acquired through four critical stages to generate a P-V diagram. Pitot-static tubes can be used at the inlet and outlet of the turbofan to calculate the static and stagnation pressure to calculate the relative velocity within the high bypass area. Flexible pitot static tubes can be implemented at the desired locations and held in place via rubber gaskets and sealant. Data acquired will be digital for the pitot-static tubes, that is directly connected to the selected data acquisition software.

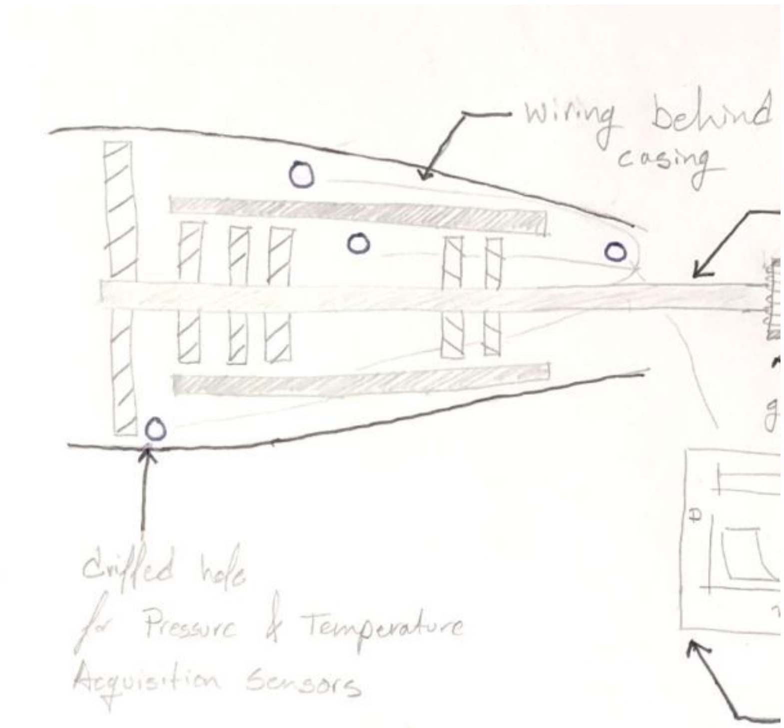


Figure [10]: Data Sensor Location

3.4.2.2 Temperature Acquisition-

Similarly to the pressure, temperature must be measured at critical stages of the turbofan process to generate a T-s diagram. Thermocouples will be placed at the inlet, outlet, heat exchanger, and high bypass area. Each of the temperature locations is identical to pressure locations, therefore the same drilled holes that house the pressure sensors will also house thermocouples.

3.4.2.3 Data acquisition software-

To create a real time P-v and T-s diagram, LabView has been selected to acquire the pressure and temperature data. Alternative software such as Matlab Simulink, and Excel can be used to cost effectively generate plots not in real time. The team proposes to illustrate the power generated through the lightbulb, pressure at each state, temperature at each state, and the volume for each state on a electronic display.

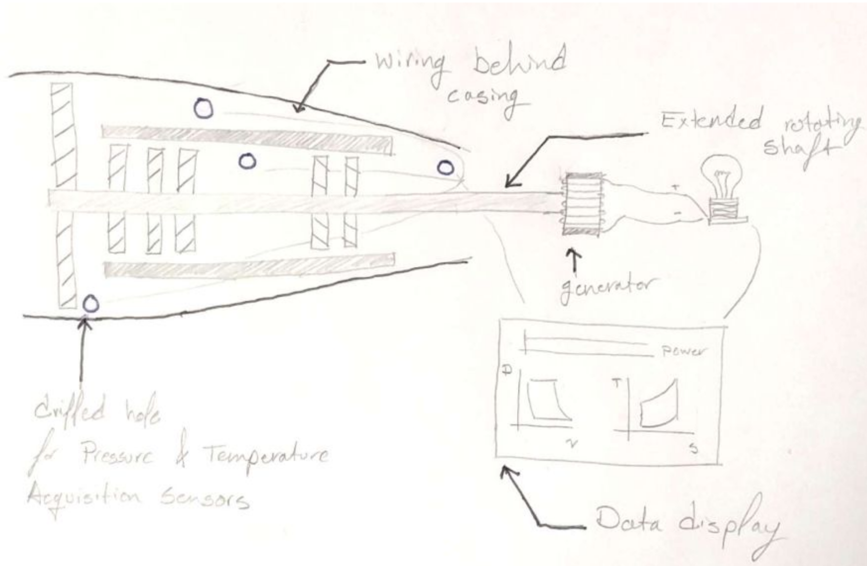


Figure [11]: Data Display and Association

3.4.3 Casing Design

3.4.3.1 Area Reduction Designs-

To accurately demonstrate the inner workings of a high bypass turbofan, the area of the heat exchanger must be reduced to increase pressure while introducing additional heat to the system. Due to material and size constraints, reducing work space is difficult to design and construct to safely introduce a heat source. Designing a reduced heat exchanger area will require additional 3D printed supports that have viewing areas for educational purposes.

3.4.3.2 Straight Area Low Bypass-

By maintaining the same inlet area throughout the entire turbo fan, simplifies the overall design while increasing the difficulty of implementing more heat. Constructing a straight area low bypass simplifies the visibility for the internal workings of a turbo fan.

3.4.3.3 Heating Element Introduction-

By implementing a heating element to the turbofan system, more work will be produced. Although the addition of heat into the system will not produce a higher thrust yield, it will simulate realistic conditions to generate a T-s diagram. Research was done for the implementation of a heating element, and was determined that a hot wire foam cutter is the simplest and more cost effective means to increase temperature.

4.0 Designs Considered

Rotor Blade Design 1-

Using one compressor blade and one turbine blade is ideal in design simplicity, but the resulting efficiency will not be relevant. The air moving into the system will not have slowed down and compressed enough to get relevant compression ratios. The single turbine blade will not be able to convert the potential energy after the compressor into relevant kinetic energy. Essentially the work out will be similar to the work in, not creating ideal efficiencies.

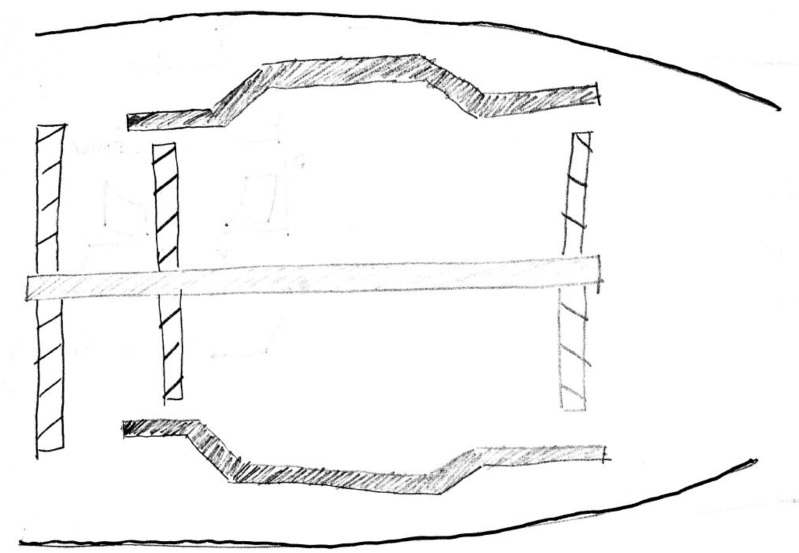


Figure [12]: 1:1 Compressor to Turbine Ratio

Rotor Blade Design 2-

Designing the turbofan to have a total of four compressors and three turbines will yield a higher compression ratio prior to the introduction of heat. Figure [13] illustrates that a higher number of compressor blades will increase pressure. The increased number of turbine blades will convert the potential energy into kinetic energy more efficiently, therefore increasing the efficiency of the overall system.

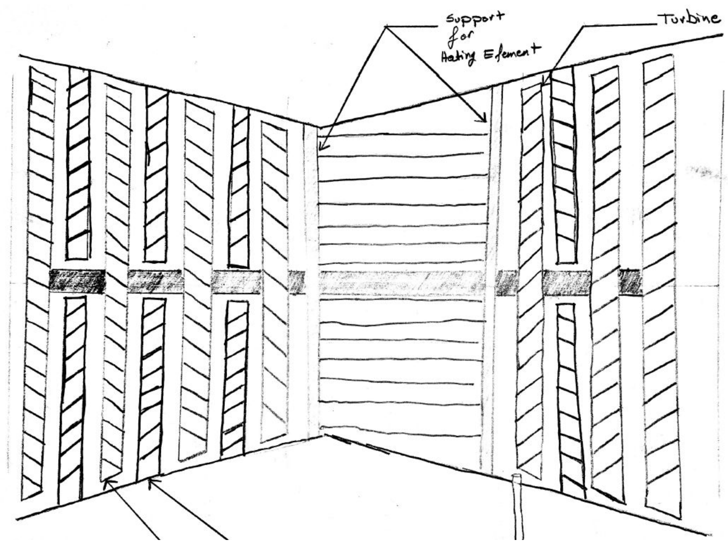


Figure [13]: 4:3 Compressor to Turbine Ratio

Casing Design 1-

Constant area for the heat exchanger is the simplest of the designs for the casing, as seen in Figure [14]. A disadvantage of this design is it's failure to educationally represent the true functions of a working turbo fan. Although the decrease in area for the heat exchanger will not produce better results for the project, it does not accurately represent a working high bypass turbo fan.

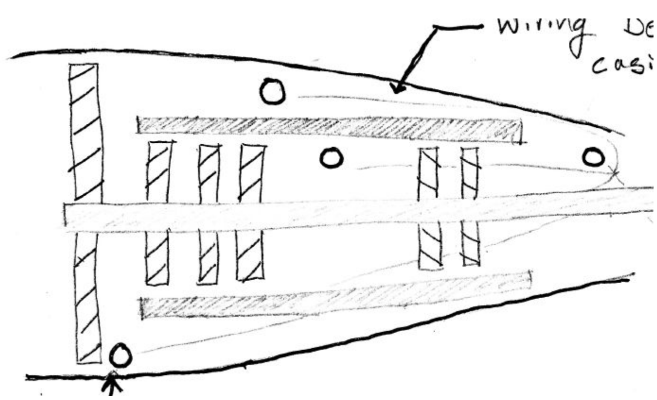


Figure [14]: Constant Area for Heat Exchanger

Casing Design 2-

Increasing the area of the heat exchanger is useful for the simplifying the addition of the heating element, as seen in Figure [15]. Although the increase of area is beneficial for construction simplicity, it does not accurately portray the real inner workings of a combustion chamber. In an operating high bypass turbofan, the decrease of area is useful to increase the pressure and temperatures necessary to produce thrust.

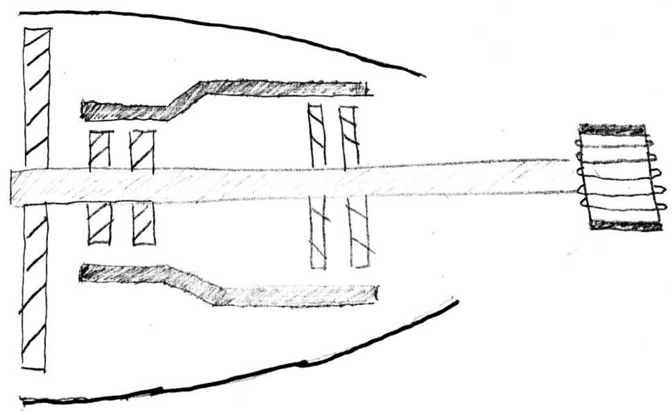


Figure [15]: Increased Area for Heat Exchanger

Casing Design 3-
Decreasing the area for the heat exchanger is the most realistic model for illustrating the increase of pressure and temperature in a high bypass turbofan. Although the area reduction accurately portrays a working turbofan, it makes the installation of the heat exchanger more difficult as well as more difficult to design the casing.

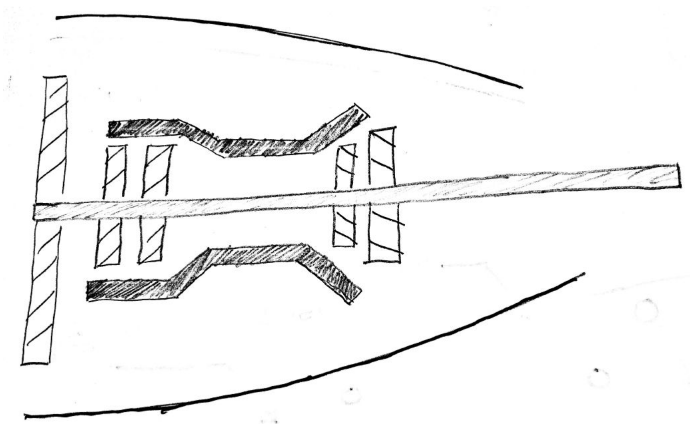


Figure [16]: Decreased Area for Heat Exchanger

Pressure Acquisition 1-
Flexible pitot-static tubes have been researched and found to be simple to implement into the system through planned holes in the casing. Having a system of two pitot static tubes measuring the pressures of the heat exchanger and the high bypass area, data for velocity can be calculated through dynamic pressure.

Figure [17]: Pitot-Pal Sensor [6]

Pressure Acquisition 2-

Applying an inclined manometer at the inlet and outlet of the turbofan will simulate stage 1 and 4 of the Brayton cycle. Having a manometer at the inlet and outlet adds to the simplicity of set up for demonstration purposes.

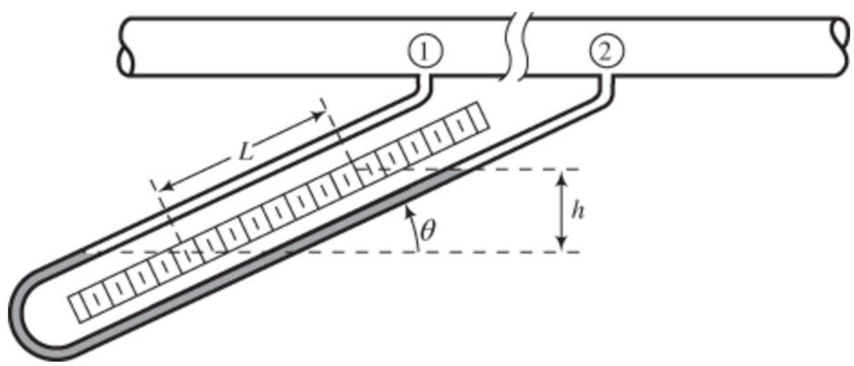


Figure [18]: Inclined Manometer Schematic for Inlet and Outlet Pressures [7]

Heat Exchanger-

Figure [19] shows the location of the heat exchanger in terms of an reduced area heat exchanger. By showing a side view of the implementation of the hot wire cutter, it is easier to visualize how the team plans to locate the apparatus. Figure [20] illustrate the curved supports for the hot wire foam cutter. The cutters are designed with a variable voltage running through piano wire to increase temperature along a horizontal array.

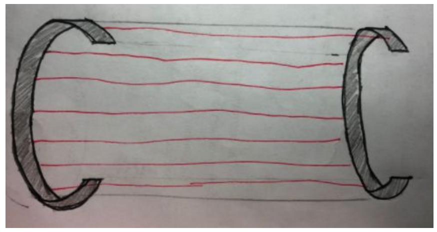


Figure [19]: Hot Wire Foam Cutter Heat Exchanger Iso View

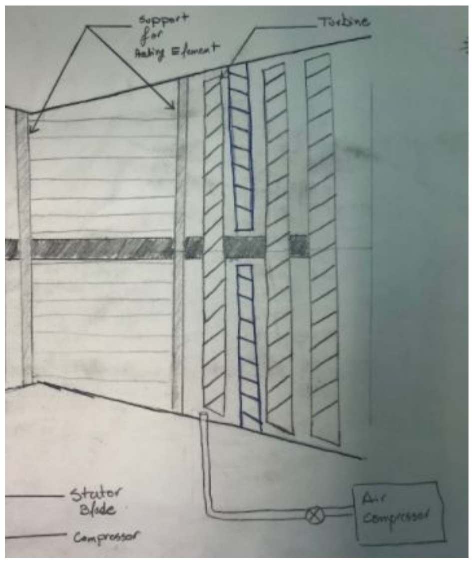


Figure [20]: Location of Heat Exchanger

Temperature Acquisition-

Located at the same places as the pressure sensors, the thermocouples will be at each stage of the Brayton Cycle. Measuring the temperature difference is useful to illustrate the cause and effects of a heat exchanger in the Brayton Cycle process.

Figure [21]: Thermocouple Probe [8]

Data Collection Software-
Through the means of data collection, the team hopes to illustrate the educational principles of thermodynamics through pressure, volume, temperature, and power produced. Power will be displayed on a screen as well as being illustrated through a generator to power a light bulb. Although data collection software research has been limited, the team is focusing on illustrating each pressure and temperature for the stages of a Brayton Cycle.

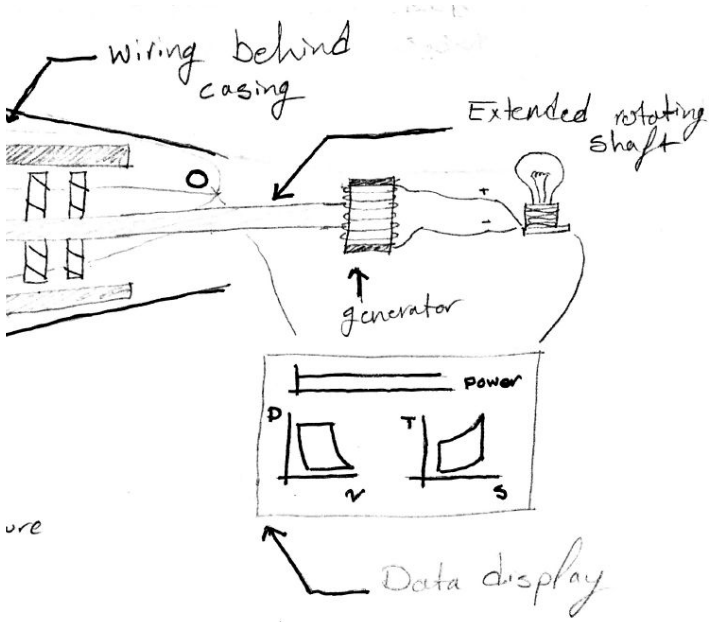


Figure [22]: Proposed Data Display Concepts

5.0 Design Selected

The overall task of the project was to design and construct an educational model of the Brayton cycle. The completed model will demonstrate beginning thermodynamic principles through real time P-v diagrams as well as power generation. The high bypass turbofan shaft is attached to a generator that will convert the rotational energy to voltage and then to power a lightbulb. The lightbulb will also provide a physical representation of the work output from the system. Along with the implementation of power generation, pressure and temperature sensors will be located at critical states to generate P-v diagrams and temperature locations.

Proposed designs that have been selected are determined through the pugh chart at Tables [5-8]. Along with proposed designs for different concepts, specific data acquisition sensors have been selected along with a proposed data display. Area reduction has been selected to simulate the working processes of the combustion chamber. To simulate the combustion chamber, implementation of an array of hot wire cutters to increase the working fluid temperature in hopes of producing additional thrust.

5.1 Rationale for Design Selection

Relating engineering requirements to design alternatives was performed in the Pugh Chart, Tables [5-8] in the appendix. The designs were compared to only their alternatives within their respective top level system designs. The Pugh chart determined that a wide-chord blade type will perform better, a 4:3 compressor turbine ratio will produce more work out, and a decreased area for the heat exchanger helps compress the fluid even further. Utilizing the Pugh chart and the designs it deemed the more efficient, the team has narrowed down the alternatives towards a final design. Narrowing down the design choices is related to educating future engineering students about thermodynamic principles. Education regarding the Brayton Cycle will include the generation of P-v diagrams and the temperatures associated to each state to illustrate the work produced of the system.

The team will use a high bypass ratio to increase efficiency and reduce noise. The team decided to use compressed air as the working fluid for safety and economical reasons. Through the means of a hot wire foam cutter, the team plans to increase temperature within the heat exchanger section to generate more pressure, and to simulate the realities of a turbofan through the means of clear acrylic casing to maximize visibility. A wide-chord fan blade design was chosen for the increased efficiency it provided.

REFERENCES

[1] Rolls-Royce, The Jet Engine, Derby: Rolls-Royce Limited, 1966.

[2] Xena, "Jet Engine," Thingiverse, 7 July 2013. [Online]. Available: https://www.thingiverse.com/thing:114468

[3] Fan Blade Technology, https://www.phase-trans.msm.cam.ac.uk/mphil/Trent1/sld025.htm

[4] Fehrm, Bjorn, “Turbofan engine challenges” Leeham news and comment; November 04, 2016
https://leehamnews.com/2016/11/04/bjorns-corner-turbofan-engine-challenges-part-2/

[5] Nikon, “XRay Inspection of Turbine Blade” [online]. Available: www.nikon.com/products/industrial-metrology/lineup/xray_ct/ct/xth450/

[6] S. A. Supply, "Pitot Pal Tubes," [Online]. Available: http://www.aircraftspruce.eu/airframe-parts/tubing/pitot-pal-tubes.html.

[7] M. Farthing, "Slideplayer," [Online]. Available: http://slideplayer.com/slide/2502477/.

[8] Amazon, "K Type 50x50mm Thermocouple Temperature Sensor Cable," [Online]. Available: https://www.amazon.com/50x5mm-Thermocouple-Temperature-Sensor-Meters/dp/B00C97J5EE.

APPENDICES

Appendix A: Pugh Charts

Table [5]: Pugh Chart, Blade Design

		 Clappered Blade	 Wide-chord blade
Criteria	Weight		
Work Output		-	+
Aerodynamic		-	+
Thermal Capacity		S	S
Isentropic Efficiency		-	+
Volume		S	S
Data Acquisition		S	S
Opacity		S	S

Table [6]: Pugh Chart, Compressor and Turbine Ratios

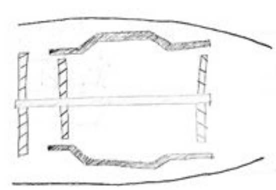
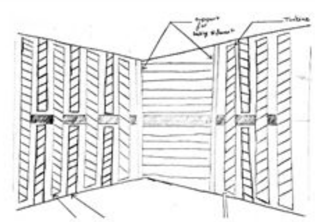
		 1:1 Compressor to Turbine Ratio	 4:3 Compressor to Turbine Ratio
Criteria	Weight		
Work Output		-	+
Aerodynamic		S	+
Thermal Capacity		+	-
Isentropic Efficiency		S	+
Volume		+	-
Data Acquisition		S	S
Opacity		+	-

Table [7]: Pugh Chart, Casing Designs

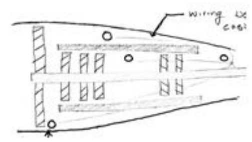
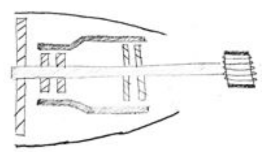
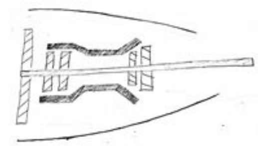
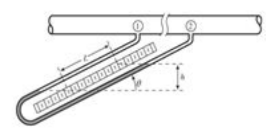
		 Constant Area for Heat Exchanger	 Increased Area for Heat Exchanger	 Decreased Area for Heat Exchanger
Criteria	Weight			
Work Output		S	-	+
Aerodynamic		S	-	+
Thermal Capacity		S	+	-
Isentropic Efficiency		S	-	+
Volume		S	+	-
Data Acquisition		S	S	S
Opacity		S	+	-

Table [8]: Pugh Chart, Data Acquisition

		 Pitot-Pal Sensor	 Inclined Manometer	 Thermocouple Probe
Criteria	Weight			
Work Output		S	S	S
Aerodynamic		-	S	S
Thermal Capacity		S	S	S
Isentropic Efficiency		S	S	S
Volume		-	-	-
Data Acquisition		S	S	S
Opacity		S	S	S