Upgrading the SR-30 Miniature Turbojet For Adaptable Exhaust

Final Design Review

Report prepared for:

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Statement of Disclaimer

Executive Summary

The California Polytechnic State University, San Luis Obispo (Cal Poly, SLO) Aerospace Department is requesting a variable nozzle adaptation for their SR-30 turbojet engine. The nozzle is intended for laboratory use in sophomore and junior level courses to supplement instruction on the effects that exhaust behavior has on the performance of propulsion technologies. Topics covered during a performance study of the SR-30 turbojet engine will include, but are not limited to: Brayton Cycle analysis, turbojet operation in ideal and non-ideal test conditions, instrumentation limitations, and basic nozzle operation.

The SR-30 turbojet engine is similar in design and operation to engines used to power full-size jets, but is scaled down in size for practical use in educational laboratories. Current designs for variable area nozzles in the aeronautics industry are tailored for use on large jet engines, rather than small educational engines such as the SR-30 turbojet. Therefore, this senior project seeks to adapt existing technology designs to an appropriate scale, and manufacture a variable-area nozzle that will allow for controlled exhaust-flow restriction. The solution proposed in this document draws on existing fighter jet variable nozzles J85 and F119-PW-100 for inspiration in nozzle flap layout and uses common methods of robotic motion control, including linear electronic actuators and hydraulic actuators.

Given the scale of the existing turbojet exhaust pipe, this senior project team, “TurboTRIO”, has determined that a circular nozzle would be difficult to actuate in an accurate, flexible, and durable manner. Similarly, design specifications such as thrust-vectoring capabilities and hydraulic control systems present themselves as unnecessarily complicated for the scope of this project. As such, these were likewise discarded. The proposed design is, consequently, a converging-diverging nozzle with a fixed-area converging duct and throat, and a variable-area diverging duct. The diverging duct will have a rectangular cross-section, and will be composed of two stationary flaps and two independently-actuated flaps controlled via mechanical linear actuation. This design will allow for educational demonstrations and performance analyses of a sonic converging nozzle, supersonic converging-diverging nozzle, and potentially engine thrust vectoring.

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1 Introduction

The senior project team, TurboTRIO, is designing a variable area nozzle for the Aerospace Department at California Polytechnic State University, San Luis Obispo. The completed design should allow students to compare the effects that exhaust-flow restriction has on engine performance characteristics, such as thrust and efficiency.

This proposal presents an assessment of existing designs and solutions available, a summary of objectives for the proposed project, an outline of the timeline and tasks to be accomplished within the next year, and a preliminary variable area nozzle design for the Cal Poly Aerospace Department, as represented by Professor Graham Doig. Due to funding and time constraints, what follows is a description of a set of activities that the aforementioned parties believe can be accomplished within the desired time frame and budget to meet the needs of the Cal Poly Aerospace Department.

2 Background

The SR-30 engine is designed for student learning purposes and not to mimic a full-size turbojet, therefore puts constraints on the design. A major design parameter is that the nozzle design must be directly integrated to the turbojet system. This is because the system measures thrust through a Futek Load Button Load Cell in the vertical direction. To accomplish this the turbojet is mounted on pivots and cannot be attached to any other points within the system boundaries. Integrating the nozzle directly to the turbojet will allow it to still rotate on these pivots and read thrust through the same load cell. The main purpose of this project is to allow students to see the effects a varying exit area has on the thrust of the engine and will take these design parameters into careful considerations.

2.1 Turbojet Engine Components

The main design of a turbojet engine consists of an inlet, compressor, combustor, turbine, and exhaust nozzle. A cutaway diagram of the SR-30 turbojet engine being used in the Cal Poly Aerospace Department's Propulsion Laboratory can be seen in Figure 2.1.1 on the following page.

The inlet nozzle of a gas turbine engine is used to isentropically slow the free stream entering the engine to a velocity that the compressor can handle. This is an especially important component in turbojet engines being used in high-speed flights, because it ensures that the compressor stage is not overworked.

The compressor stage is used to increase the pressure of inflow air to provide for efficient combustion. A typical configuration of a compressor will consist of multiple, alternating rows or rotating and stationary sets of vanes, which are used to increase the flow velocity and then convert the flow's dynamic pressure to static pressure. Although each stage of blades can be modeled as isentropically compressing the flow, it is desirable to provide the highest compressor ratio possible across the compressor assembly, thus providing a high pressure flow to the combustor stage.

The combustor stage injects fuel into the high-pressure intake air flow at a controlled Air Fuel Ratio (AFR), and ignites the mixture. Upon combustion, the chemical energy of the fuel is released in the form of heat, and this energy can be harnessed as a change in momentum, propelling the engine forward.

The turbine stage is designed similar to the compressor stage in that it uses rotating blades to isentropically change the pressure-velocity relationship of the flow. However, the turbine stage seeks to expand the combustion products and extract energy from the flow in order to drive the compressor stage. The two are connected by an insulated shaft, and thus the turbojet engine acts as a fully throttleable closed-loop control system.

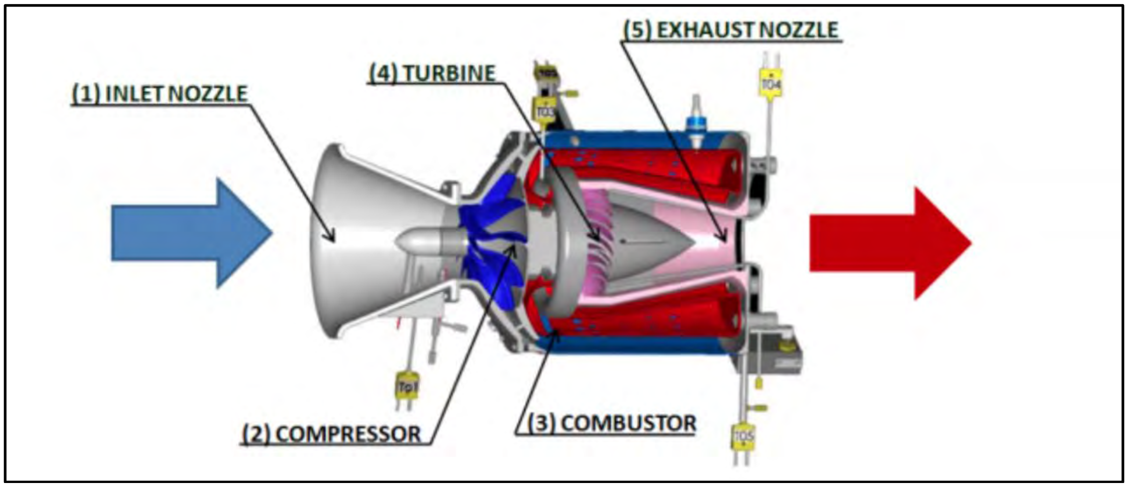


Figure 2.1.1 SR-30 Gas Turbine Cutaway (Source: Turbine Technologies LTD)

2.2 SR-30 Gas Turbine Engine

The SR-30 engine, designed by Turbine Technologies, is depicted in Figure 2.1.1 in the previous section. It is a miniaturized turbojet engine with an inlet bell nozzle, single stage centrifugal compressor, combustion chamber, single stage axial-flow turbine, and small exhaust nozzle stage. Table 2.2.1 tabulates the instrumentation at each stage of the SR-30 cycle.

Table 2.2.1 **SR-30 Engine Instrumentation Specifications**

		Temperature Instrumentation	Pressure Instrumentation
Ambient Conditions		-	-
Compressor Inlet	Station 1	Stagnation, T_{01}	Differential, P_{d1}
Compressor Exit	Station 2	Stagnation, T_{02}	Static, P_2
Combustion Chamber	Station 3	Stagnation, T_{03}	Stagnation, P_{03}
Nozzle Entrance	Station 5	Stagnation, T_{05}	Stagnation, P_{05}

The SR-30 engine has a compression ratio of 3.4, engine pressure ratio of 30, and specific fuel consumption of 1.2. At a maximum design speed of 87,000 rpm, it is designed to produce 178 N of thrust, with a maximum exhaust gas temperature of 720 ºC and mass flow of 0.5 kg/s. It is designed to run on a number of fuels, including Kerosene, Diesel, Jet A, A-1, and B, as well as JP-4, 5, and 8.

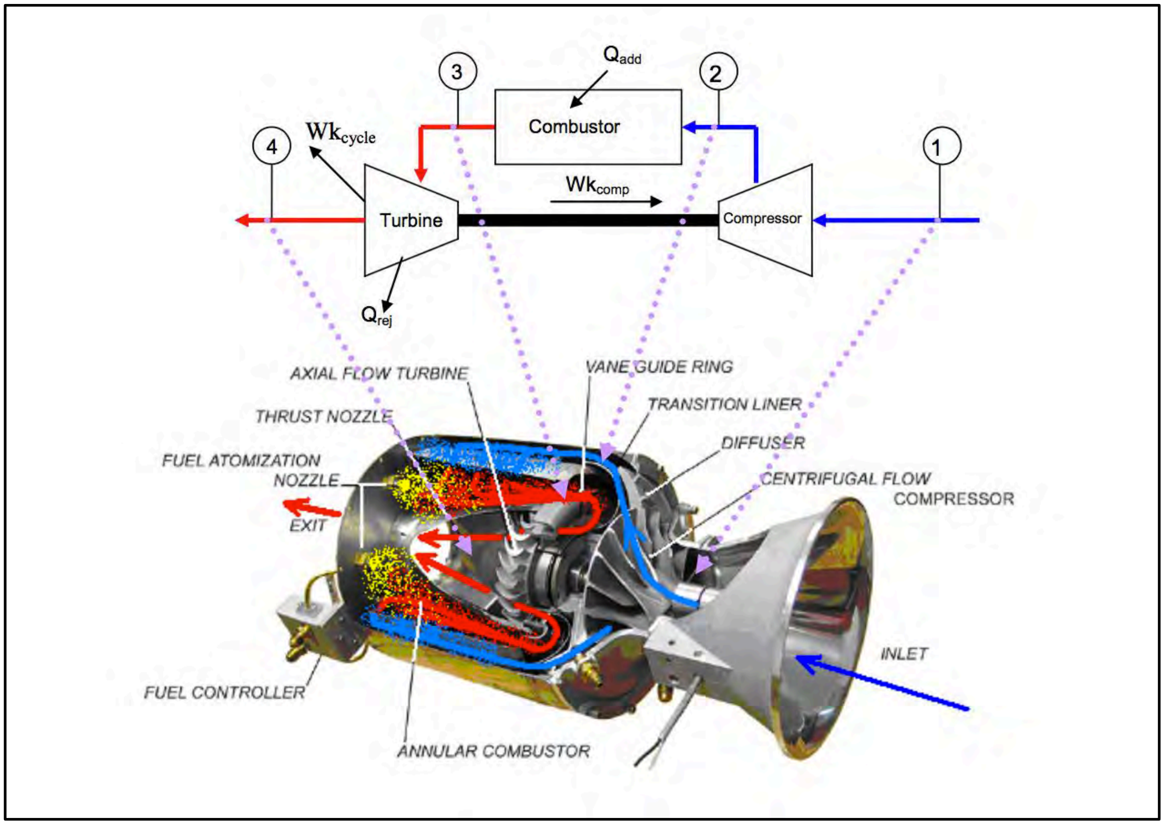


Figure 2.2.1 Schematic of Brayton Cycle for Gas Turbine and Cut Away of SR-30 Engine. (Source: Turbine Technologies)

For the purposes of the design presented in this report, it is assumed that the engine operates according to the ideal Brayton Cycle, depicted in Figure 2.2.1, as well as operating with ideal gas turbine performance characteristics. The design is based on the specific MiniLab setup acquired by the Cal Poly Aerospace Department and its maximum operating parameters, which are slightly lower than the specified maximum design conditions. The Cal Poly engine is powered by a 120V single-phase, 60 Hz power outlet, is spin-started by compressed shop air at 110 psi, and runs on Jet A fuel.

The SR-30 engine poses several design challenges. The most significant issue is that the high temperatures at the exhaust and the manufacturing processes available to us limit the minimum size per part, while the engine's small scale demands an equally small maximum size. This results in a very narrow band for possible nozzle thickness and flap length and width, which limits our design choices (see section 4, Concept Design Development). The size of the nozzle likewise impacts the flow through the nozzle. Because the cross-sectional area is fairly small, the friction losses from the wall surface finish will provide substantial flow losses. Additionally, the flaps that allow the nozzle to vary exhaust area require flat segments to attach, resulting in a shift from the circular exhaust pipe of the engine to transition to a polygon. The scale also provides a challenge for the actuation system; the nozzle walls are relatively thin and the actuation must be attached not far from the nozzle exhaust, making it difficult to isolate the actuation system from the high temperatures.

2.3 Exhaust Nozzle Theory

An exhaust nozzle can be used after the turbine stage of a turbojet engine to isentropically expand the exhaust gas, thus extracting excess energy from the flow. Ideally, the high-pressure, high-temperature exhaust gas at the inlet of the nozzle is accelerated through the nozzle profile so that the potential and thermal energy is converted into high kinetic energy at the nozzle exit. As this high energy flow at the nozzle exit undergoes a change in momentum, a thrust force will be imparted on the engine body, propelling it forward.

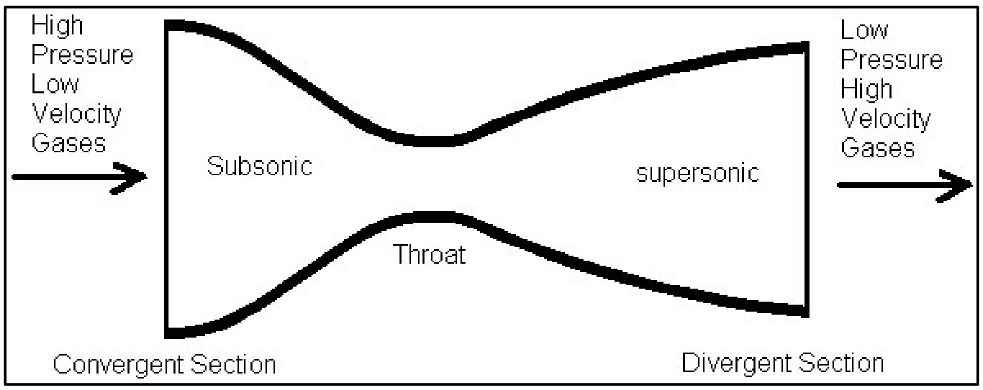


Figure 2.3.1 Example of a convergent-divergent nozzle. (Source: Andrew Carter)

The most common nozzle design for supersonic flow has a converging-diverging geometry. In this type of nozzle, exhaust gases enter the nozzle body at high temperatures and pressures, but at relatively low speeds. The nozzle geometry converges to a minimum-area throat section, which is ideally designed to accelerate the flow to the local speed of sound in the working fluid. This behavior as known as a sonic throat condition. The compressible flow can then be further accelerated through the diverging portion of the nozzle to reach speeds greater than the speed of sound, known as supersonic flow. However, if the flow pressure at the sonic throat is not high enough, the flow will decelerate through the diverging nozzle geometry back to speeds below sonic, and is referred to as subsonic flow. Although subsonic flow through the nozzle will still impart a thrust force to the engine, the thrust produced will be significantly less than that produced by supersonic speeds.

2.4 Common Uses of Variable Nozzles

Variable area nozzles are primarily utilized on military jets for turbojet engines with an afterburner system. Afterburners reheat the combustion exhaust after expansion through the engine's turbine stages, thus adding more thermal energy to the exhaust flow. Ideally, the exhaust nozzle on such an engine works for many operating points of the system, at many altitudes of flight. To operate ideally across a broad range of operating conditions, the nozzle dimensions can be altered to vary the exhaust flow expansion conditions. Commonly, the cross-sectional exit area of a turbojet engine nozzle is constricted so that the exhaust exit pressure matches atmospheric back pressure at altitude, thus providing maximum thrust to the aircraft.

Variable area nozzles are designed with one of two primary exit geometries: conical, or rectangular. The performance of conical variable area nozzles surpasses their rectangular counterparts in nearly every regard, excluding stealth capabilities. Conical nozzles geometrically lack corners, leading to fewer supersonic shock waves, lower turbulence, less boundary layer flow separation, and fewer vibrations. Additionally, conical nozzles are light in weight and allow for thrust vectoring in every direction. In contrast, rectangular nozzles can only vector in two directions: pitch (diving and climbing), and roll (corkscrewing around the axis of travel); they do not allow for vectoring in a yaw (spinning about the perpendicular axis) direction. Below, Figure 2.4.1 depicts a representation of these three axes. Rectangular nozzles are primarily utilized for stealth purposes to reflect radar away in a singular direction, whereas conical nozzles would diffuse radar in a multitude of directions. The use of rectangular nozzles on stealth aircraft allows for flight missions that are undetectable to radar operators on the ground. However, for non-stealth flight vehicles conical variable nozzles are most commonly utilized, due to their exceptional performance characteristics. Rectangular nozzles are used only if stealth is of the utmost priority, and they are thus found exclusively on fighter jets.

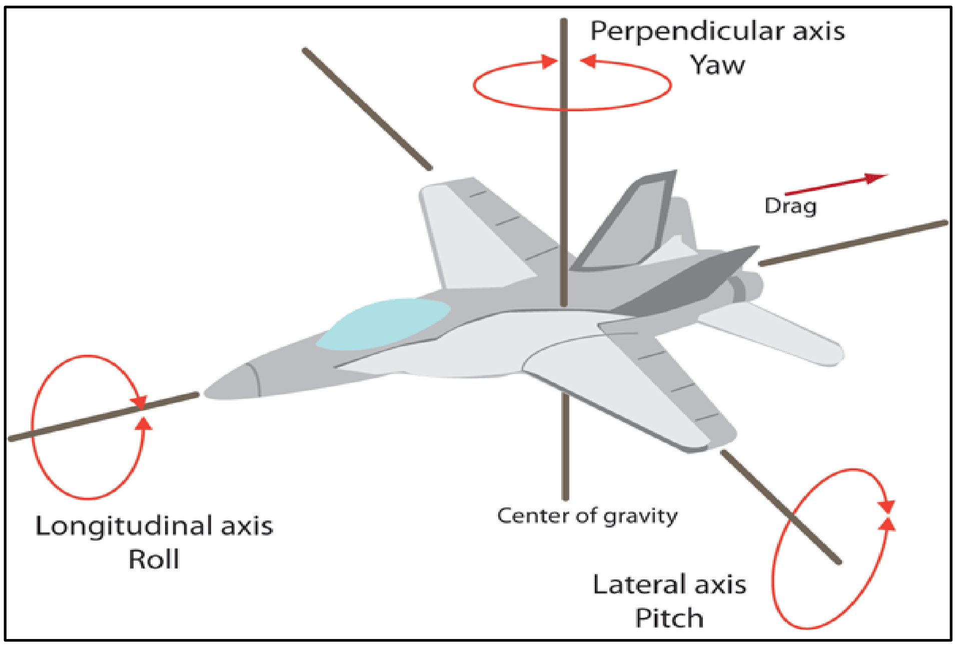


Figure 2.4.1 Diagram depicting the three axis of rotation. (Source: Stephan Mraz).

The nature of a square, two-dimensional model similarly allows for greater thrust vectoring (as much as 20 degrees) than a circular nozzle would permit. However, this also restricts the vectoring and requires consideration for the transition of flow from a circular to a rectangular cross-sectional area, adding a distortion of flow and some frictional losses.

2.5 Benchmarking: Converging-Diverging Nozzle (F119-PW-100)

Converging-diverging variable nozzles, such as the F119-PW-100 seen below, are used to accelerate air flow to supersonic speeds. This design technique is primarily used with supersonic aircraft, namely fighter jets, to provide additional thrust to engines not utilizing afterburner systems – thus providing the jet with greater flexibility in speed and fuel consumption ranges than an equivalent system utilizing afterburning (Gamble). The high fuel consumption of afterburning makes it impractical for commercial jets, leaving the usage almost exclusively reserved for military aircraft.

Figure 2.5.1 The F119-PW-100 engine and nozzle. Both sides are flat fixed flaps, while the top and bottom sides are curved plates that are independently actuated, allowing vectoring as well as converging and diverging. (Source: John Pike)

Utilizing a converging-diverging nozzle to achieve supersonic flow with the SR-30 turbojet engine would allow students to explore the performance characteristics of an engine operating at supersonic speeds without an exhaust afterburning system.

2.6 Benchmarking: Ejector Nozzle (J58)

The ejector nozzle is a classification of the variable converging-diverging nozzle family, the most common of which is used on Pratt & Whitney's J58 engine. However, rather than repositioning the divergent flap of the nozzle cone, the effective nozzle exit area is changed by directing a secondary stream of high pressure air to fill the over-expanded portion of the divergent nozzle. This effectively reduces the nozzle expansion ratio (the ratio of the nozzle exit area over the nozzle throat area) without introducing excess complexity that comes with a fully actuated variable exit nozzle.

The primary exhaust stream of an ejector nozzle exits the combustor and enters the ducted converging section, flows through the throat at sonic conditions, and enters the diverging portion of the nozzle. The secondary air stream pressure controls the mass flow through the diverging section of the nozzle, which in turn controls the exit area and expansion ratio of the primary stream. When this nozzle fails to operate at ideal conditions, it will perform similarly to the converging-diverging nozzle as the exhaust flow becomes over or under-expanded.

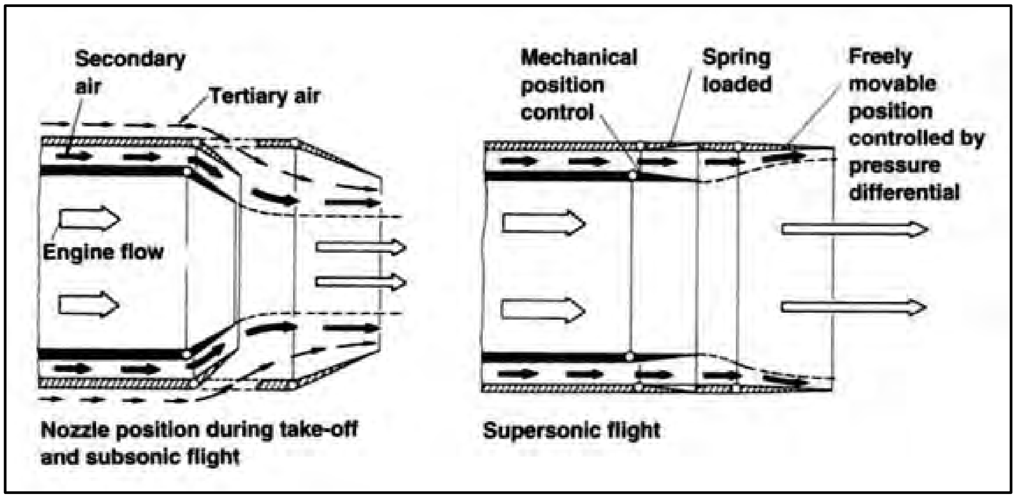


Figure 2.6.1 An ejector nozzle converging (left) and diverging (right). The converging of the nozzle allows the exhaust flow to reach a sonic velocity and the diverging section allows it to reach supersonic velocities. (Source: Turbine Technology)

2.7 Remote-Controlled Nozzle Actuation Systems

Variable nozzles are controlled by linear actuators. There are two applications of such actuators. The first is to position the actuators perpendicular to the nozzle flow (along the circumference), causing a chain reaction with a series of levers to pull back the flaps or push them together. While the inherently large numbers of flaps (especially when overlapped similar to a vegetable strainer) allows for variable flow without creating large gaps between the panels, the control format makes vectoring challenging and is difficult to manufacture at the scale needed. The more common type has actuators parallel to the long rectangular panels that form the nozzle walls. These actuators extend or contract, causing the panels to fold closer together or expand outward, respectively, to vary the exit cross-sectional area. Likewise, these actuators can be extended to differing lengths to cause vectoring (S&S Turbines). This two styles can be seen in the following figures.

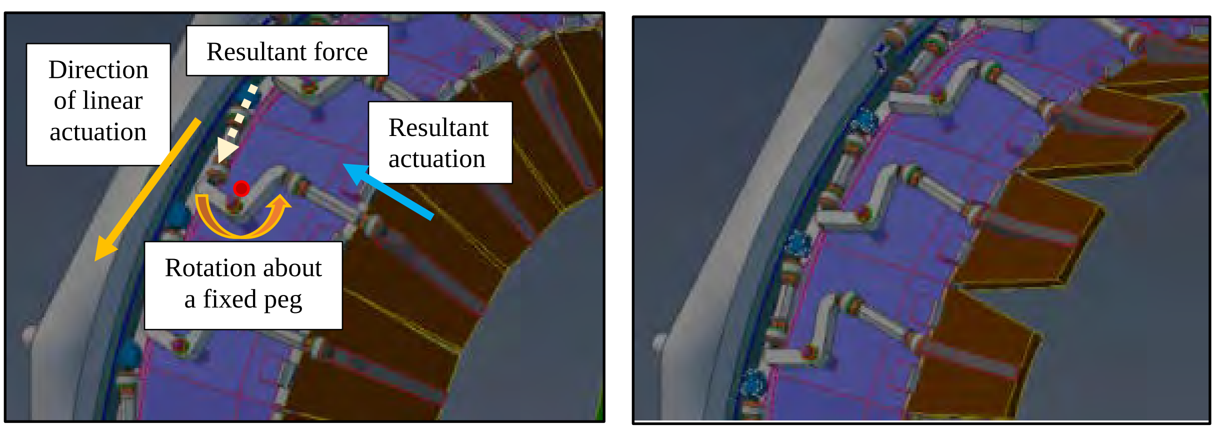


Figure 2.7.1 A linear actuation system along the circumference of the nozzle. The linear actuators rotate a piece of metal around the circumference, pushing curved pieces set tangentially to the circular metal rods, pulling a second rod connected to a flap. (Source: RocketNut).

Figure 2.7.2 Linear actuators placed parallel to flow on the F-15 Eagle Fighter. The actuators tug directly along the nozzle. (Source: UAV News)

Both of the above applications involve linear actuators controlled by motors that are spurred to motion by an applied voltage. An alternative would be to drive the linear actuator using a hydraulic piston. In such actuation, a subsystem pumps fluid about at a designated compressed pressure. Extra fluid is forced into the space on either side of the piston in order to move it along its path. Because liquids can be reasonably modeled as incompressible, it's easy to achieve the precise location of the piston, and thus consistently achieve the desired exit area. However, this introduces a second system for the fluid requiring its own power, maintenance, controls, and actuation. This would effectively double the scope of this project and as such is ruled out as a reasonable design solution.

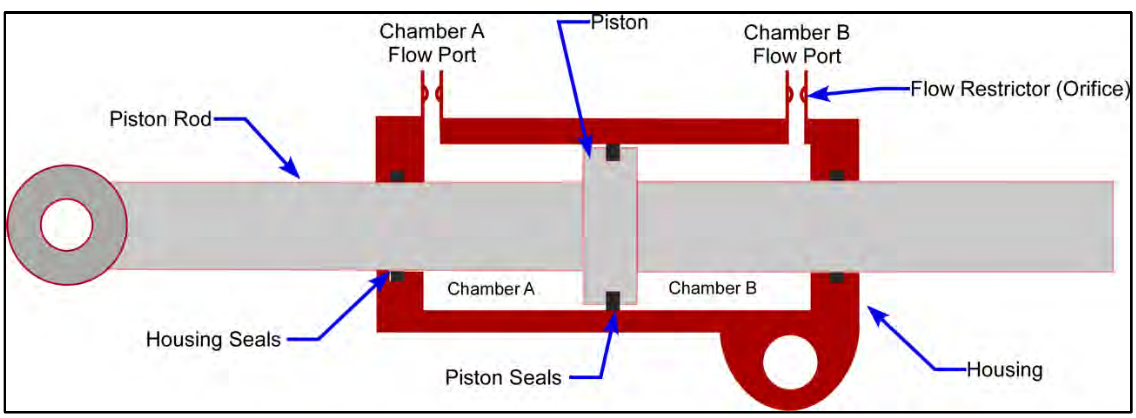


Figure 2.7.3 Schematic of a hydraulic linear actuation system. Fluid forced through Flow Port A moves the piston to the right; fluid forced into Flow Port B forces it to the left. The pressure of the fluid system and the position of the valves for Ports A and B determine the location of the piston, and thus the head of the shaft. (Source: Michele Ferlauto).

2.8 Interviews with the Propulsion Laboratory Supervisors

As our primary design concept (detailed in a further selection) is similar to the existing aerospace nozzle, we interviewed Amelia Grieg, Daniel Johnson, and Tyler Croteau – the people who supervise and run the propulsion laboratories -- to better understand their uses of the existing variable nozzle and its elements they liked and disliked. We also asked them what experiments they might run with their ideal variable nozzle. From those conversations, we determined that the biggest issue with the current system is that the pressure sensors are inaccurate so the data is often not useful. Another common theme is that the control system for the current nozzle – a hand-pumped pneumatic piston system – is frustratingly imprecise and the ruler used visually determining the width of the nozzle exit (to calculate area) is difficult to read.

The lab instructors' biggest desire for a new nozzle is the ability to explore supersonic flow and to show the effects of a converging nozzle. They had low interest in thrust vectoring, although they liked the concept. As such, we now consider supersonic capabilities a key criteria and have revised our scope such that thrust vectoring is a stretch goal rather than a primary target. They also suggested the possibility of using a pressure rake (a series of pitot tubes that could move in sync to create a cross-sectional experimental view of the pressure) which could help the computational fluid dynamics students compare their models to the reality. While we agree this would be a neat addition, further research concluded that most pitot tubes can't handle the temperatures at the current exhaust – something that will only be exacerbated by adding a nozzle – so we consider this a stretch goal.

They also suggested adding fluid thrust vectoring as a comparison to mechanical thrust vectoring. Fluid thrust vectoring requires creating a pocket of fluid within the nozzle that pushes against the main flow, redirecting it. This process can be seen in the figure below. Mechanical vectoring, in contrast, relies on the shape and location of the physical nozzle walls to alter the direction of the flow. This would drastically complicate our nozzle system and is consequently another unlikely stretch goal given the time restrictions on our project.

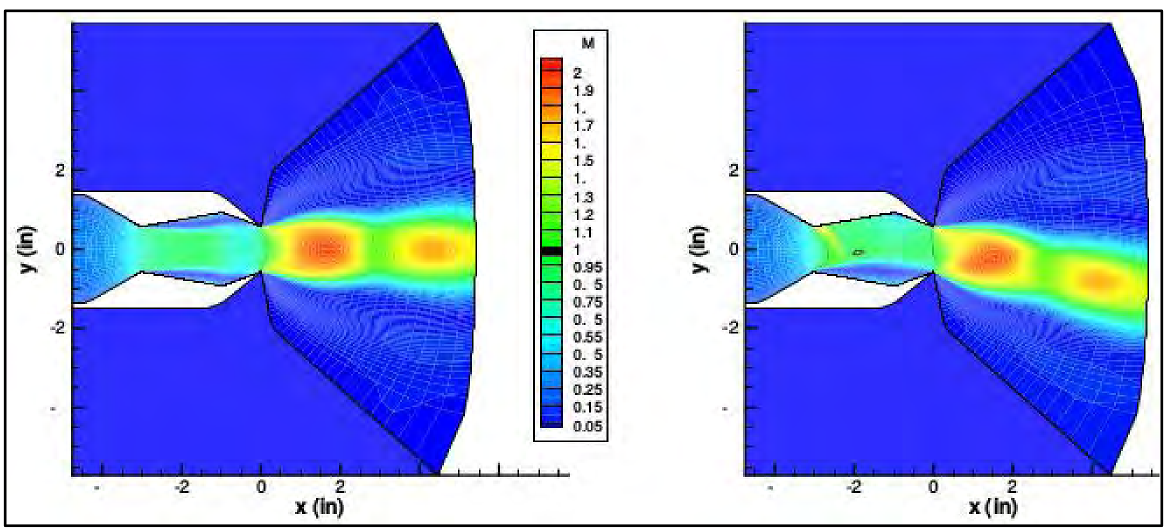


Figure 2.8.1 Fluid thrust vectoring simulation for a supersonic converging-diverging nozzle. (Source: Michele Ferlauto.)

2.9 Interviews with Professors with Relevant Technical Specializations

We interviewed Russell Westphal and Patrick Lemieux who specialize, respectively, in compressible flow and engine design to confirm the results of our calculations and to do a feasibility check on several of our concepts. From these conversations we gleaned that while students would probably appreciate an engine which looked like the majority of variable nozzles in use (i.e. circular nozzles), we should not prioritize that element of realism because the miniature turbojet – by virtue of its size and educational purpose – already has several elements that distinguish it from engines in the field. For instance, our flightless engine has no concern of weight in its structural design. Similarly it has a relatively low combustion temperature, indicating shortcuts in manufacturing that are unlikely to be implemented in a fighter jet engine; Lemieux speculated that the temperature was lowered to reduce the stress on the turbine blades which would lower efficiency and engine performance. The two professors agreed that a pressure rake is unreasonable given the temperatures, but we might be able to include a gas sniffer for combustion product analysis, particularly regarding the air-fuel ratio in the exhaust. As sniffers are commonly used in industry to determine combustion products and ration, most sniffers could handle our temperature range. We consider this a likely stretch goal at this time.

2.10 Difficulties with the SR-30 Engine

One problem with the documentation is the inconsistent notation; the manufacturer's original design of the engine contained instrumentation for pressure and temperature readings at five different locations. The location just past the turbine blades (location 4) was giving almost identical readings to the exhaust instrumentation (location 5 at the time) because the fuel was still combusting through the engine's nozzle. This impacts the efficiency of the engine and the composition of the exhaust, which reduces consistency in engine operation and varies the exhaust measurements at different throttle levels. Consequently, Turbine Technologies decided to remove the instrumentation for location 4 and relabel location 5 as 4. Unfortunately, not all documentation reflected this change, and consequently there remains significant confusion when documents refer to the temperature or pressure at location 4, especially since the two locations used different types of instrumentation conditions (stagnation vs static vs dynamic). For consistency and clarity, the team has decided to stick with the original notation of 1, 2, 3, and 5 for the current instrumentation.

Another significant challenge with working with this engine is the documentation conflicts with itself regarding the measurement conditions (static vs stagnation vs dynamic) for temperature and pressure at each location; each of the documents provided by the manufacturer had contradictory indications for which conditions each sensor was reading. Although TurboTRIO tried contacting the manufacturer for clarification, the engineers' responses likewise conflicted with the existing documentation. Furthermore, some of the conditions indicated are highly improbable; for instance, it's nearly impossible to measure static temperature in the middle of a flow because the probe would have to move with the flow, calling into question several of the callouts' potential veracity. Similarly, the pressure readings at locations 2 and 5 are, by inspection, a pitot tube parallel to the middle of the flow (oriented downstream) to approximate – at best guess -- a static reading, rather than using a truly-static pressure tap at the wall.

Likewise confusion, the pressure probe at the inlet is visually dissimilar to all recognizable styles of pitot and pitot-static probes, making it difficult to determine its function. Professor Russell Westphal speculated that the most likely condition for the inlet pressure probe is a differential pressure, but given the location of the holes on the probe, he also said that the probe would need to be calibrated and suggested the Data Acquisition System (DAQ) display might have a built in calibration not listed in the manuals. However *if* present, the calibration is a predetermined value, rather than based on actual local external operating conditions, introducing further error.

The last main issue currently is that the cam of the thrust lever is offset, meaning the thrust lever stops depressing the throttle when only about halfway to “full throttle” position. This has led to several issues in engine operation including the minimum idle shaft speed being too low (triggering an automatic engine shut down), the thrust lever not providing as nuanced control over the operation range available, and the engine not achieving its maximum thrust levels; Turbine Technologies claims the idle position should result in 47,000 rpm (current output is 42,000 rpm) and maximum should achieve 87,000 rpm (currently 73,000 rpm). The latter is particularly problematic when trying to determine design conditions, material choices, and safety factors for operation at the engine’s maximum output.

Additionally, the Cal Poly SR-30 engine only outputs a maximum of 80 N thrust at maximum shaft speed. This gives us Mach 0.5 at the exit of the turbine, indicating that it would be difficult, if not impossible, for our nozzle to reach choked flow (Mach 1.0, “sonic flow”), which limits the types of flow conditions we can demonstrate with our nozzle, even without the flow losses mentioned above. Ideally our nozzle would show boundary layer separation (where the air starts to separate from the walls of the nozzle), sonic and super-sonic flow (where the airflow after the throat of the nozzle, respectively, meets or exceeds the speed of sound), and over-, under-, and perfectly expanded flow (where the air after the throat has expanded too much, too little, or just the right amount to provide maximum thrust). However the engine’s relatively low speeds mean not all of these may be possible. These potentials are explored further in section 4, Concept Design Development, and section 5, Final Design Development.

3 Objectives

This section takes the customers wants and needs to develop a list of engineering specifications. Each specification is put through a Quality Function Deployment analysis needs to measure whether or not it is achieved in the final design. The final design is visualized in the boundary diagram to show all key components.

3.1 Describing the Problem

The California Polytechnic State University at San Luis Obispo (Cal Poly SLO) Aerospace Engineering Department is requesting a variable nozzle attachment to their existing SR-30 miniature turbojet engine. The completed design will be used to enhance student laboratories. Consequently, the nozzle needs to be remotely operated, allowing students to safely constrict, diffuse, and redirect the airflow to measure the impact on engine thrust and cycle efficiency. Additionally, students must be able to measure the position, cross-sectional area, temperature, and pressure at the existing turbojet exhaust outlet, and at the end of the new nozzle. A more detailed list of the Aerospace Department’s needs and wants can be found in Appendix A.

3.2 Engineering Specifications

With these wants and needs in mind, TurboTRIO has performed a Quality Function Deployment (QFD) analysis for the proposed nozzle to identify key elements to develop engineering specifications for the final design. The QFD analysis consists of customer interviews, benchmarking tests, and supporting analysis to determine and weight the customers' needs in the development of the design and how important certain features are if forced to choose which elements to pursue. The full QFD "House of Quality" can be found in Appendix B. See section 2 "Background" for information on competitive technology and designs. See Table 3.2.1 below for details on each element.

Table 3.2.1 **Engineering Specifications for a Variable Nozzle Attachment**

Engineering Specification	**Method of Measuring Successful Achievement**
Variable Exit Area of Single, Attached Nozzle: The nozzle is attached to the existing turbine such that it translates the produced thrust to the engine and relevant instrumentation. The nozzle can be adjusted to have at least two distinct exit diameters.	Inspection; attempt to vary the exit area using controls both while the engine is off and while engine is in operation.
Fully Instrumented Apparatus: The nozzle contains instrumentation (such as thermocouples, pitot-static tubes, and pressure transducers) that allows for sufficient data acquisition as is required for post-lab analysis. This includes pressure and temperature at the entrance and exit of the nozzle, as well as the cross-sectional area of the exit and – if relevant – the degree of flow vectoring.	Inspection for physical components; inspection of DAQ readings with confirmation by calculation that the values displayed are appropriate.
Integrated Data Acquisition System: The data is integrated into the turbine's DAQ display such that students can easily access, read, and record the data relevant to the nozzle.	Inspection; nozzle data displays on the DAQ system without interfering with existing DAQ data.
Operational with Minimal Directions: Students have little or no difficulty completing the procedures with the directions provided; few directions are necessary for students to understand how to operate the system.	Study; bring in a sample of students to conduct the intended procedures with our written instructions under our observation and complete a survey on the ease of completing the tasks and understanding what was asked of them.
Consistently Operational: The design operates with few or no failures over the duration it takes to complete all laboratory data collection.	Trial; run the engine for 10 trials with no more than 1 failure.

Table 3.2.2 **Engineering Specifications for a Variable Nozzle Attachment**

Engineering Specification	**Method of Measuring Successful Achievement**
Nozzle Operates Within Design Parameters: The nozzle operates as intended, not exceeding the designed safety factors no causing the existing engine to exceed its designed parameters.	Measurements and calculations; using the data from the DAQ, confirm the nozzle is operating within design parameters.
Direct User Control of System: User has complete control of adjusting the nozzle from the control interface of the system.	Pass/fail test; attempt to use the provided controls to adjust the nozzle cross-sectional area and collect data.
System Operates at Safe Decibel Levels: The actuators and other mechanisms in the nozzle design operate within the laboratory regulations for noise.	Pass/fail test; using a decibel meter, compare the maximum output volume measured to the maximum safe with the existing ear protection.
Exit Nozzle Can Change Angle: The nozzle can change the angle of the output area to show vectoring of the thrust.	Pass/fail test; attempt to change the nozzle area using the provided controls.

It should be noted that we cannot measure the reliability (i.e. consistency of operation) of the nozzle over its lifetime, therefore we have proposed a test that shows an immediate reliability from which we can extrapolate continued satisfactory performance.

Below is a table containing the specific design specifications we are aiming to meet with our final product. The satisfactory compliance with these targets will be measured through tests (T), inspection (I), analysis (A), or a combination thereof.

Table 3.2.3 **Nozzle Design Specifications Table**

Spec #	**Parameter Description**	**Requirement or Target**	**Tolerance**	**Risk**	**Compliance**
1	Weight	2 kg	Max	L	T
2	Volumetric size in space	80mm x 80mm x 200mm	Max	L	T, I
3	Production cost	$300	Max	M	I
4	Thrust	150 N	Max	M	A, T
5	Exhaust Temperature	720°C	Max	L	T, I
6	Mach at inlet	0.3	Min	L	A, T
7	Mach at throat at 50% throttle	0.4	Min	M	T, A
8	Mach at exit at 80% throttle	0.5	Min	M	T, A
9	Exit width at max extension	55 mm	+/- 2 mm	M	T, I
10	Exit width at min extension	45 cm	+/- 2 mm	M	T, I

3.3 Conceptualizing the Project

A visual representation of the scope we are exploring is in Figure 3.3.1 below. We are attempting to address student knowledge and interaction with the nozzle, the data integration into the existing DAQ system, and the nozzle itself.

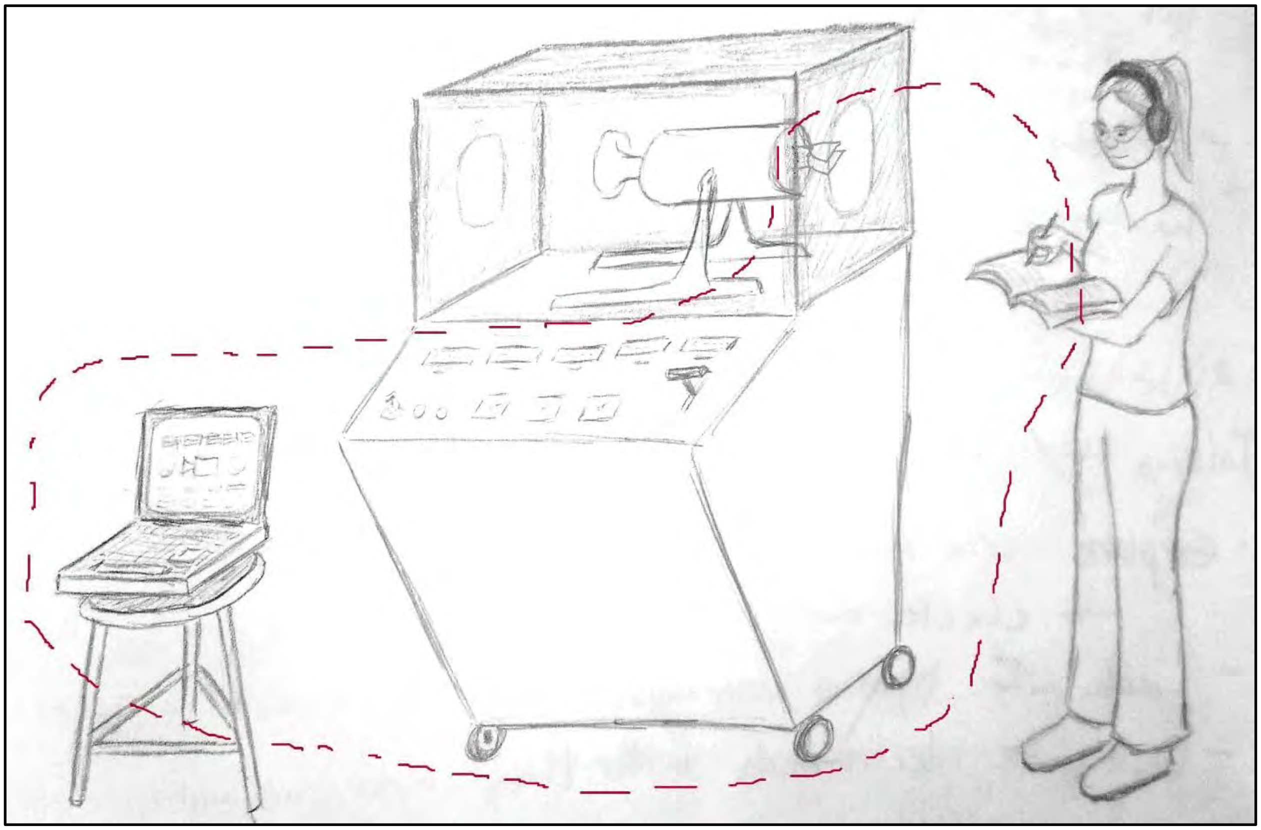


Figure 3.3.1 Boundary diagram of propulsion lab 41B-144.

4 Concept Design Development

Many factors -- including the desires of the Aerospace Department, the limitations of our manufacturing capabilities, and the feasibility of our ideas – lead to the development of our current design. This section discusses the process our team went through and why we made the decisions we did.

4.1 Design Parameters

The SR-30 engine is intended for student learning purposes and not to mimic a full size turbojet, and therefore imposes constraints on the design. A major design parameter is that the nozzle must be directly integrated to the turbojet system. This is because the system measures thrust through a Futek Load Button Load Cell in the vertical direction. To accomplish this the turbojet is mounted on pivots, specified in the figure below, and cannot be attached to any other points within the system boundaries. Integrating the nozzle directly to the turbojet allows it to still rotate on these pivots and read thrust through the same load cell. There is a weighted balance that can be adjusted to counteract the additional weight of the nozzle. This same load cell has a capacity of 100 lbf that needs to be considered for the range of thrust expected. Another critical design parameter is the fuel lines on the rear face of the turbojet that are seen in second figure below. These need to be avoided and cannot support loads, creating difficulty in actuating the flaps.

Additionally, as mentioned in the background, the exhaust pipe of the nozzle is a mere 55mm in diameter, while under 10mm away from that lip is the pressure transducer for P3, and not far beyond that, the fuel lines. These features place constraints on our design on the possible outside radius of the flange and the location of the actuation system. Taking these stated design parameters into consideration, TurboTRIO began the concept development process.

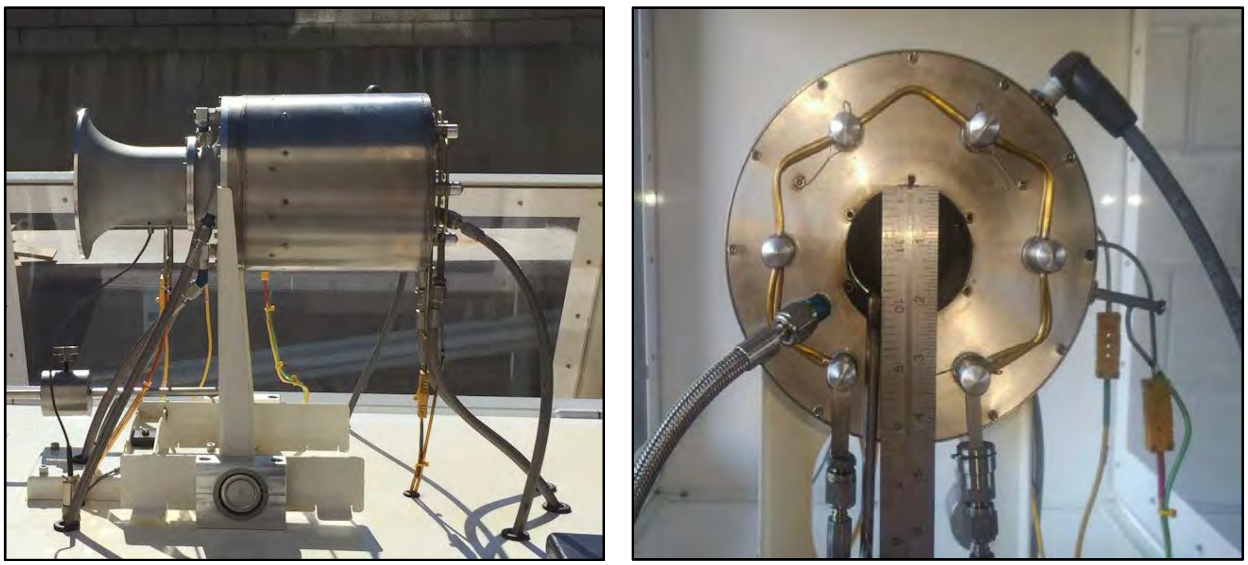


Figure 4.1.1 Side view (left) and back view (right) of the SR-30 engine.

4.2 Concept Development Process and Results

The concept development process started with various ideation sessions (for pictures of the sketches done in these sessions, see Appendix J). It was important to keep an open and creative mind for these sessions in order to develop as many ideas as possible. This method helps to keep from fixating on specific details and look at things from alternative perspectives.

The first ideation session had a focus on mechanical fixtures for the nozzle and how to integrate the nozzle to the turbojet system. This session consisted of a ten-minute time limit in which the team would write and draw as many ideas as possible on a whiteboard. From this session ideas on materials, instrumentation, manufacturing processes, and structural mobility were generated. Refer to Appendix I for a full list of the ideas. This ideation session determined that welding, fasteners, and an external support structure appeared to be the most achievable given the limitations of the turbojet casing. It also revealed possible nozzle designs, specifically rectangular and conical, and various methods to actuate the flaps. With the nozzle being the main focus of the project, the team decided to further brainstorm nozzle designs.

The next ideation session was conducted with a focus specifically on the nozzle design and how to vary the exit area. This session used the technique of brain-writing, where the first person writes a list of ideas down before passing it the next person. This person then builds off of these ideas and continues onto the next. The session generated similar concepts to the first ideation session however looked at each idea more closely. Overlapping flaps, sliding flaps and contracting flaps were the three best concepts for a feasible flap design. Pivot points, tracks and rollers, and linear actuators proved to be the best methods for actuating the flaps. Lastly, the focus on manufacturing the designs narrowed the processes down to machining, casting and 3-D printing. With a good starting point for the nozzle and flap designs, the next focus was on attaching the nozzle to the turbojet system.

Of the several dozen ideas generated in these sessions, most of these designs were physically impossible or exceeded our manufacturing capabilities. Likewise, the Aerospace Department maintained strong preference for a singular nozzle that was reminiscent of existing nozzles used in industry, ruling out the majority of the remaining designs. What remained were the three options discussed in the next section.

Additionally we did a third ideation session dedicated specifically to actuation, focusing on how to move the more feasible systems remaining from our first ideation sessions. While most of our designs featured a hinge of some sort, our ideas ranged from pullies and gears to pneumatic systems. Unlike our ideation for the nozzle itself, most of these designs were technically feasible. We rapidly ruled most of them out for having too many small inter-related parts (a high risk for failure, even if they could handle the existing pressures and temperatures). We also ruled out the pneumatic and hydraulic systems on the basis of requiring too much extra energy and an extra system to handle the fluid. These restrictions left us with the options of using linear actuators, in-line stepper motors on the hinges, or a stepper motor connected by a short gear chain.

The next step was to take these ideas and build them as basic models. This helped to visualize the ideas and find what works and what doesn't. Specifically, these models showed what elements of the project would be mechanically feasible and helped influence the concept model. The concept model is a more in depth representation of the ideas that can show the basic functions, shape, and size of the concept nozzle. From here concept CAD models were developed to check the functionality of each.

4.3 Nozzle Concept Selection Process and Results

To find the optimal design the TurboTRIO team considered several possible designs for creating the desired nozzle shape. The first possibility is a conical nozzle with overlapping flaps, shown in the figure below. This option was appealing because it is more effective than a rectangular nozzle – there are no concerns of significant turbulence at any of the edges -- and it is circular such as many nozzles found in industry. However, the biggest challenge of this design is the scale of the SR-30 engine. This design relies on a large number of nearly-flat flaps that are narrow enough to allow for conical approximation; the small size of the turbojet's exhaust nozzle makes attaching and actuating the necessary number of flaps difficult, which ultimately ruled out this design.

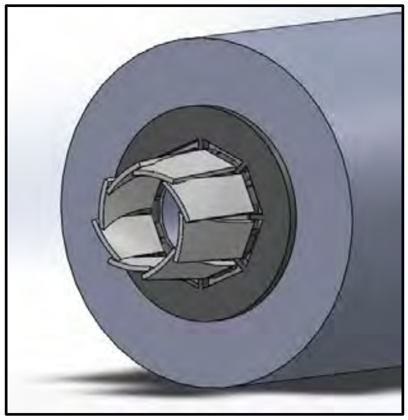


Figure 4.3.1 Standard nozzle flap placement of a conical nozzle. Flaps overlap, allowing them to fold much like a vegetable steamer.

A second design option, shown below, eliminates the imperfections of using nozzle flaps by having multiple nozzles that are perfectly shaped to their function. These nozzles could be actuated into position a number of ways, such as a series of robotic arms, but the simplest solution would be a wheel. While this would allow for the most efficient nozzles and opens the possibility to an infinite number of nozzles that could be attached and swapped out a handful at a time, it raises the issue of rotating the nozzles into place – most notably avoiding the fuel lines (not shown in the figure below; see section 4.5 ‘Detailed Description of Chosen Concept’). Another significant issue would be the torque of the airflow through the nozzle on the hub of the wheel and, related, how to translate the thrust produced by the nozzle to the engine’s sensors (or directly to the DAQ display). Because of the difficulty of positioning the nozzle snuggly enough against the turbine to avoid flow losses, the difficulty of translating the thrust from the wheel to the engine’s thrust sensors, and the challenges of actuating around the fuel lines, this design was also eliminated.

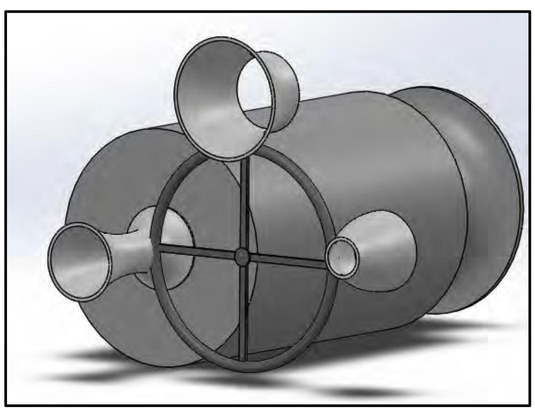


Figure 4.3.2 A system where a wheel rotates different fixed nozzles into position. Nozzle options shown are converging-diverging (left), pure-diverging (top), and pure-converging (right).

Focusing on a rectangular nozzle with two fixed sides and two variable-position sides (the most feasible option given the design criterion and manufacturability constraints), TurboTRIO developed an alternative to the industry standard of flat flaps: have the two sides be curved to the ideal converging-diverging curve to achieve supersonic flow. Both the start and end of each flap is flat, allowing the nozzles to be positioned to achieve pure-diverging (the inlet sides of the flaps are parallel), pure-converging (the outlet sides of the flaps are parallel), or converging-diverging. While in a pure-diverging position, the flow would theoretically show boundary layer separation at higher flows. When in a pure-converging position, the flow would reach sonic "choked" flow at a lower mid-range shaft speeds. While in a diverging position, the flow would be choked at mid-range speeds, allowing students to see choked-to-subsonic flow initially, and potentially transitioning to choked-to-supersonic flow at higher shaft speeds. These three nozzle and the three crucial positions of the flaps are shown in the figures below. The two drawbacks to this option are the losses inherent in transitioning from a circular to a rectangular cross-sectional area, and the unique, specialized shape needed by the movable flaps; this would primarily raise issues in nozzle repair down the line, an inconvenience mostly mitigated by creating several spare flaps.

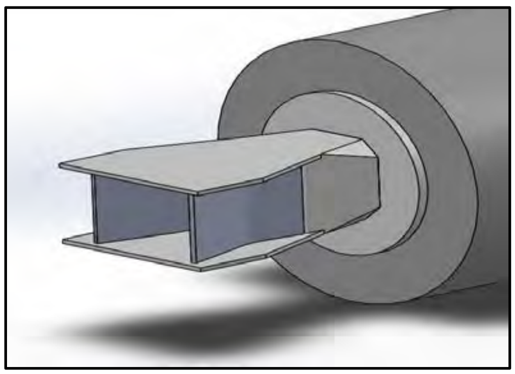


Figure 4.3.3 A rectangular nozzle with two fixed top plates and two side flaps that can be independently actuated. The movable flaps are flat on either end, with a curve in the middle.

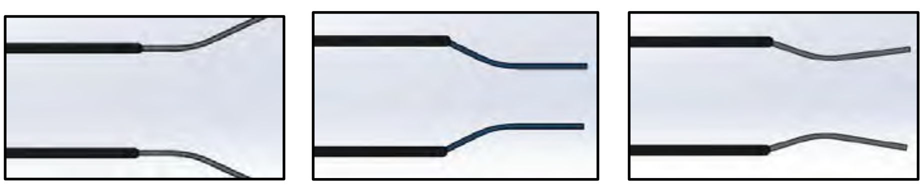


Figure 4.3.4 The three positions of the curved-flap rectangular nozzle allows for pure-diverging (left), pure converging (middle), or converging-diverging (right) nozzle shapes.

While we liked this design, the challenges of getting the precision of the curves on the side flaps and the unlikeliness of achieving choked flow given our engine's capabilities lead us to focus more on using this concept, but with flat side flaps.

4.4 Actuation Concept Selection and Results

When considering how to actuate the system, the first option we considered was having linear actuators attach to the side flaps, as shown in the figure below. Simple and straight forward, the design was appealing for its ability to independently actuate the sides, leaving thrust vectoring an option if we chose to pursue it. The downside, however, was the actuators attaching directly to the side flaps, which would mean requiring actuators capable of handling the high temperatures. These actuators were difficult to acquire, which lead us to pursue other options.

The second idea, inspired by the nozzle on the larger Aerospace engine, was to use a linear actuator attached to the arms coming off the posts the flaps pivoted on. This idea rapidly morphed to having two actuators – one per flap, independently moving – to retain the potential of thrust vectoring and, hopefully, be able to more accurately center the nozzle's output direction; with the singular actuator squeezing both flaps, we could potentially have the flow unintentionally force the nozzle to one side or another, while retaining our desired area. That unintentional vectoring would have been problematic if not designed for, because the engine's load cell only measures axially, and its supports are not intended to withstand torsion. This system had the downside of having to calibrate the actuators to align with one another and leaves them within the troublesome heat zone, but seemed to be our best option.

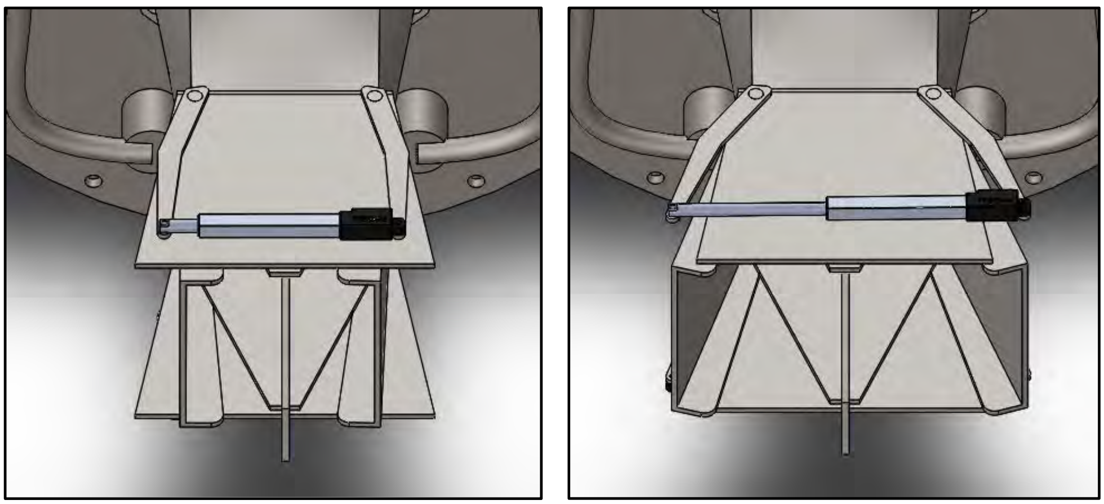


Figure 4.4.1 Linear actuation in parallel from the arms of the hinges.

As actuation wasn't as large a priority as a functional nozzle and we were confident that we could find ways to thermally isolate the actuators, we decided to consider that our actuation system for the time being and figure out the specifics of handling the heat issues later.

4.5 Preliminary Analysis

A preliminary design analysis was conducted for the rectangular nozzle extension concept. Using data collected from the SR-30 turbojet engine at a maximum throttle setting of 73,300 rpm, a basic Brayton Cycle analysis was first performed to determine flow conditions at the turbojet exhaust exit, referred to as Station 5. This evaluation of exhaust flow behavior was then used to construct a preliminary set of nozzle designs and area ratio dimensions, with the goal of generating the maximum thrust possible while running the engine at its maximum speed. These preliminary dimensions provided a basis upon which the TurboTRIO team could design the remaining subsystems of our nozzle extension.

Table 4.5.1 **SR-30 Cycle Measurements and Analysis**

		Stagnation Temperature, T_0	Stagnation Pressure, P_0	Static Pressure, P	Mach Number
		[K]	[Pa]	[Pa]	[-]
Ambient Conditions		295	1.02E+05	-	-
Compressor Inlet	Station 1	295	**1.02E+05**	**9.73E+04**	**0.246**
Compressor Exit	Station 2	413	-	2.47E+05	-
Combustion Chamber	Station 3	959	2.48E+05	-	-
Nozzle Entrance	Station 5	730	1.14E+05	**1.15E+05**	**0.402**

*Note: Values in **bold** represent values calculated in the Brayton Cycle analysis. All other values are direct measurements recorded during engine operation at a speed of 73,000 rpm.

As stated in section 2.2 of this report, SR-30 Gas Turbine Engine Background, the Turbine Technologies SR-30 MiniLab system directly measures and outputs a set of data monitoring engine operating parameters. The engine instrumentation measures stagnation temperatures at Stations 1, 2, 3, and 5, differential pressure at Station 1, static pressure at Station 2, and stagnation pressures at Stations 3 and 5. Additionally, engine thrust, speed, and fuel volumetric flow rate are each monitored.

Using the flow parameters recorded at the engine's maximum operating point, as indexed in the table above, a basic Brayton Cycle analysis was performed to determine the remaining flow conditions of the turbojet exhaust at Station 5. The details of this analysis can be found in Appendix D, both as a published Matlab code, and hand calculations. The engine was assumed to operate under the ideal Brayton Cycle model, which assumes a closed system with a working fluid that can be modeled by air as an ideal gas, isentropic compressor and turbine stages, and constant pressure heat addition and rejection from the system.

Additionally, the engine was assumed to operate as an ideal gas turbine system, which provided the following simplifications: approximately stagnant flow after the compressor stage, negligible fuel flow rate in comparison with the air mass flow rate, no losses through the mechanical shaft system between the compressor and turbine stages, and approximately axial flow through the exit of the turbine/exhaust nozzle sections. Other assumptions made in this analysis were that both the stagnation pressure at the engine intake, and the static pressure at the engine exhaust exit were equal to absolute ambient pressure. The results from this Brayton Cycle analysis are indexed in Table 4.5.1 above as bolded values.

Using the results from this ideal engine analysis, a preliminary nozzle design was developed for the maximum-throttle operating condition at 73,000 rpm, assuming a constant-area throat and a range of exit areas. Although the results of this preliminary design did not account for nozzle wall geometry, they did indicate a prediction of nozzle exit flow velocities and ideal thrust, as functions of the nozzle exit area position. Most notably, Figure 4.5.1 depicts the nozzle exit (indicated as Station 6) flow Mach number as a function of the nozzle exit area. These results indicated that the exit flow from the nozzle would be capable of reaching supersonic speeds as the nozzle area increased from a critical choked flow area - assuming that the pressure differential was high enough between the throat pressure and ambient back pressure. If this pressure differential did not reach high enough values, the flow would become sonic at the nozzle throat area, and then decelerate back to subsonic speeds as it expanded through the diverging nozzle section.

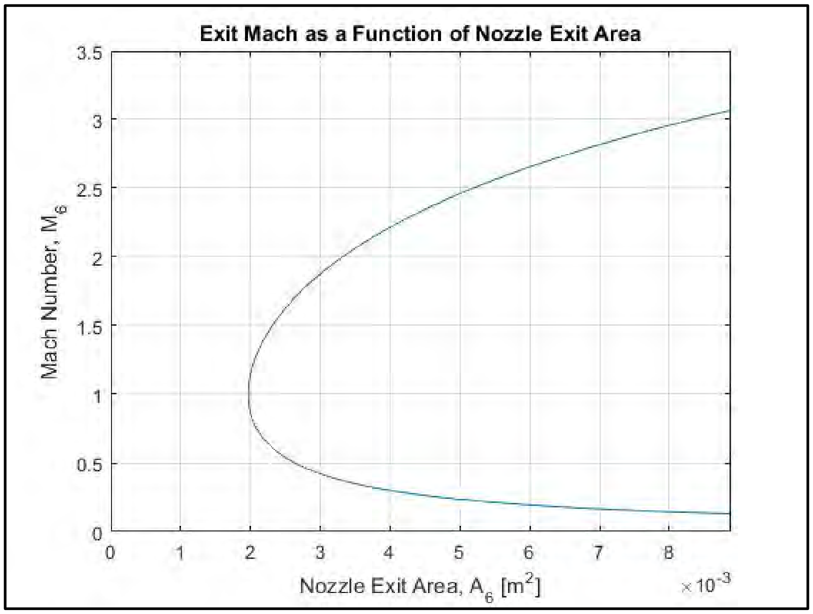


Figure 4.5.1 Exit Mach as a Function of Nozzle Exit Area

Additionally, Figure 4.5.2 depicts the expansion ratio between the variable nozzle exit area and the nozzle throat area, at each exit width controlled by the actuating side flaps.

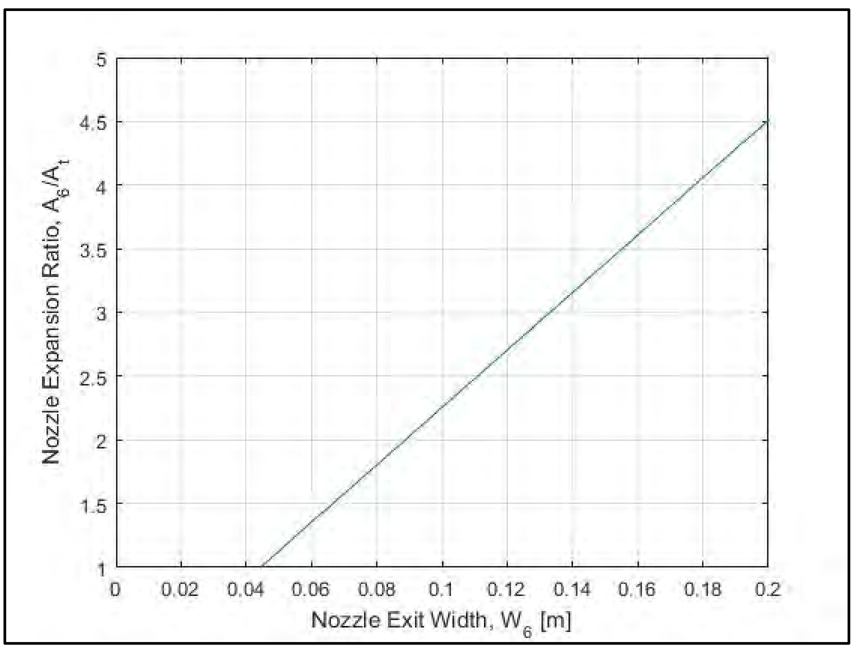


Figure 4.5.2 Relationship between Nozzle Expansion Ratio and Nozzle Width.

The expansion ratio is a frequently referenced parameter in nozzle design and analysis – however, the nozzle exit width is a more intuitive dimension to reference while describing the fluid's behavior as the nozzle area is varied. Therefore, the remainder of the nozzle dimensional analysis presented in this report refers to the nozzle exit flow parameters as functions of the nozzle exit width. Additionally, it was later determined that the flow pressure at the engine's turbine exit cannot reach high enough values to achieve sonic conditions at a converged throat, and all further nozzle designs were therefore produced under the assumption that the exhaust flow would remain subsonic.

4.6 Detailed Description of Selected Concept

Analyzing the concepts, from section 4.3, and implementing them to the turbojet system helped show the flaws and benefits of each design. These were then put into a decision matrix, found in Appendix F, that narrowed the possible designs to a rectangular nozzle. Given the small scale of the turbojet, manufacturing proved to be a major concern for the overlapping flap conical nozzle concept. Specifically, actuating the flaps would require a very obscure design to avoid the fuel lines and would create complications in attaching the nozzle to the turbojet system. For these reasons the overlapping flap conical nozzle design was ruled out. Next the rotating fixed nozzle design was analyzed and found to be too large to fit within the boundaries of the turbojet casing and therefore ruled out. This left the rectangular nozzle design.

Table 4.6.1 **Nozzle Decision Matrix**

Nozzle Decision Matrix	**Weight Factor**	**Conical Nozzle**	**Rectangular Nozzle - Flat Flaps**	**Multiple Attachments**	**Rectangular Nozzle - Converging Diverging Flaps**
Area Change	0.25	4	4	5	4
Vectoring	0.05	-4	3	4	-2
Accuracy	0.1	3	5	5	1
Manufacturability	0.2	-4	2	2	-1
Compatibility	0.1	5	3	-5	3
Size	0.05	2	3	-5	3
Reliability	0.1	-3	4	2	3
Cost	0.15	-1	3	-3	0
Sum of +		1.9	3.35	2.55	1.85
Sum of -		-1.45	0	-1.2	-0.3
Total		0.45	3.35	1.35	1.55

Table 4.6.2 **Actuation Decision Matrix**

Actuation Decision Matrix	Weight Factor	Ratchet Lever and Gear Train	Pulley System	Step Motor	Bendable Flaps with Rollers	Hydraulic Slide
Size	.05	0	0	1	3	-2
Toggling	.1	-3	-5	4	3	4
Low power draw	.1	5	5	-2	-2	-5
Reliability	.15	5	5	4	3	1
Precision	.05	2	5	2	4	4
Accuracy	.3	5	2	5	3	3
Cost	.1	2	-2	0	-2	-4
Manufacturability	.15	-2	-4	3	-4	-5
Sum of +		3.05	2.1	3.1	2	1.65
Sum of -		-0.6	-1.3	-0.2	-1	-1.75
Total		2.45	0.8	2.9	1	-0.1

The rectangular nozzle does not conflict with the fuel lines, can be directly integrated to the turbojet, can feasibly incorporate the linear actuators to the flaps, and vary the exit area. To work around the fuel lines an exhaust extension will be used to extend past the lines while transitioning from the existing circular exhaust to the rectangular shape of the nozzle. This extension will act as a throat that will converge to help establish choked flow (Mach # of 1) in the exhaust flow. To integrate this to the turbojet, the exhaust extension will have a flange around the circular end that can be bolted to the turbojet through the present threads on the rear face of the turbojet. Longer bolts will need to be purchased for this. The rectangular end will be welded to the nozzle configuration. The configuration consists of a stationary upper and lower triangular flap and boundary flaps to minimize losses. Two pivoting flaps will be on either side of the configuration and pivot at the interface between the exhaust extension and nozzle. Linear actuators will be attached at these pivot points, one above and one below the nozzle. With the boundary flaps restricting access to the pivoting flaps, this is the best way to actuate the flaps and vary the exit area. Lastly, for the design the nozzle height is assumed to be constant through the diverging section. With the critical parameters met the material and further specifications were taken into account.

The exhaust nozzle will need to maintain its strength in high temperatures, which limits the material to nickel and stainless steel alloys. Nickel alloy Inconel is a nickel based super alloy that is well suited for applications requiring high strength in temperatures up to 1600 K and AISI type 304 stainless steel is a ferrous, heat resisting alloy that is well suited for temperatures up to 1700 K. These materials are used in industry for full size turbojet nozzles. Both materials are MIG welded and can even be welded to each other. Nickel Inconel is more difficult to weld and the welds often crack if done poorly. Further analysis of the manufacturing plan will need to be carried out to select a final material.

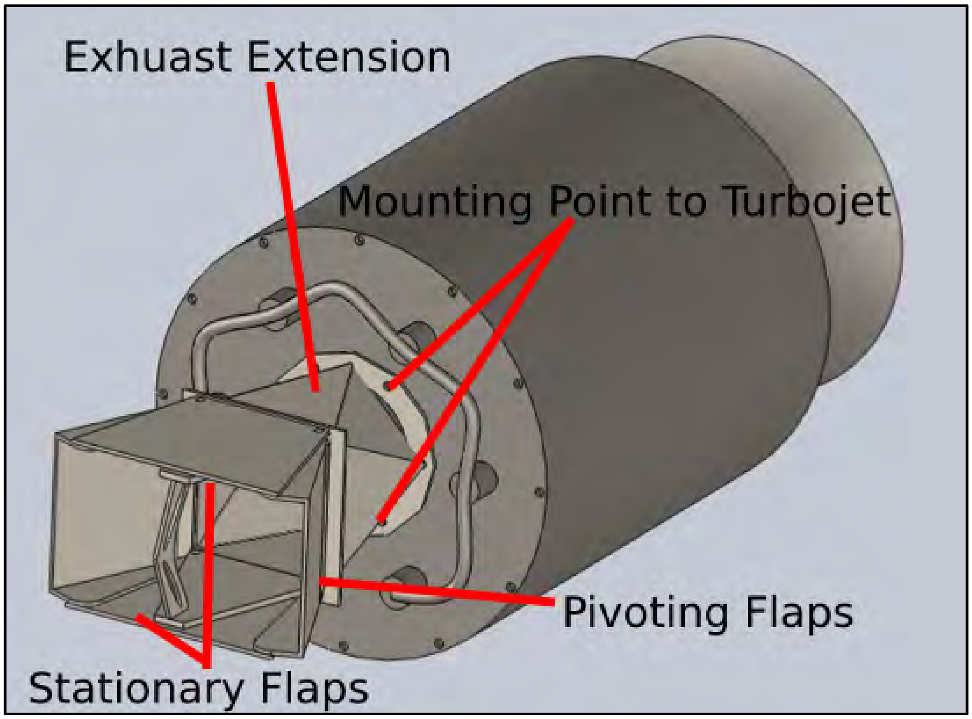


Figure 4.6.1 Assembly of the SR-30 Engine and nozzle.

A detailed set of manufacturing drawings for this preliminary design can be found in Appendix K, Original Concept Drawings.

5 Proposed (CDR) Design

This section discusses the design we settled on pursuing, as well as refinements this selected design underwent to reach our initial proposed design. This design has since undergone further changes as we grappled with the realities of manufacturing our prototypes. Discussion of those modifications and our finalized design can be found in section 6, Final Design.

5.1 Development of the Proposed Nozzle Design

In our initial concept development, we had focused primarily on the nozzle shape and how it would vary. As we progressed into design refinement, we began to add other structures we had neglected in our conceptual development: how the hinges would be positioned to minimize flow losses and how to avoid the instrumentation at station 5.

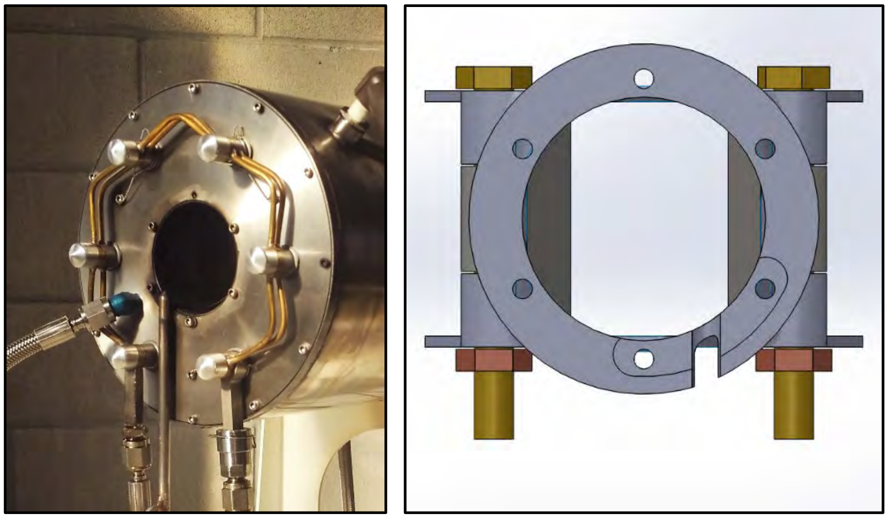


Figure 5.1.1 The back of the engine, with the pitot tube visible (left) and the flange designed to accommodate it at the point the nozzle attaches (right).

As seen in the figures below, the concept we selected at the end of PDR had several features we had to consider. The first main issue was the transitional section between the exhaust of the engine and the throat of the nozzle. The corners of the design, depicted more clearly below, created far too many losses, prompting us to look for a way to make the transitions corner-less.

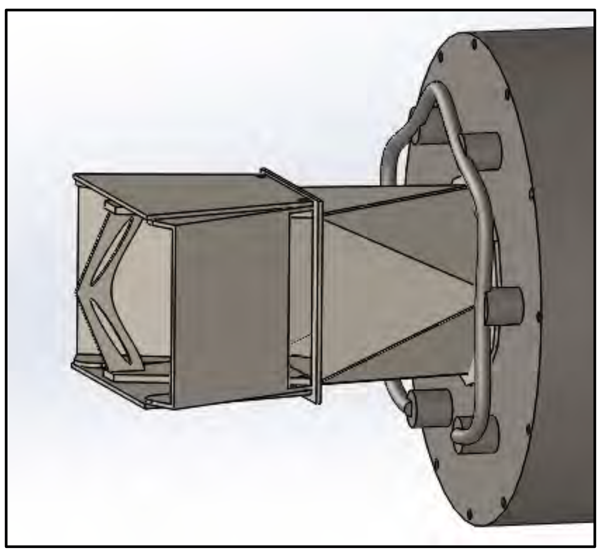


Figure 5.1.2 The side view of the transitional section of the nozzle.

As our original thought with the nozzle was to weld triangular slabs of sheet metal together, it was a natural extension to consider bending a single piece of sheet metal to the right shape. However, in further research, we rapidly discovered sheet metal is a challenge to bend into the irregularly-shaped transition we were hoping for. Furthermore, with the thickness of sheet metal we would need in order to withstand the heat loads, the small relatively sharp bends we were needing (especially in other areas like the flaps, seen in the figure below) would be difficult if not impossible, and would create tremendous stresses in those corners.

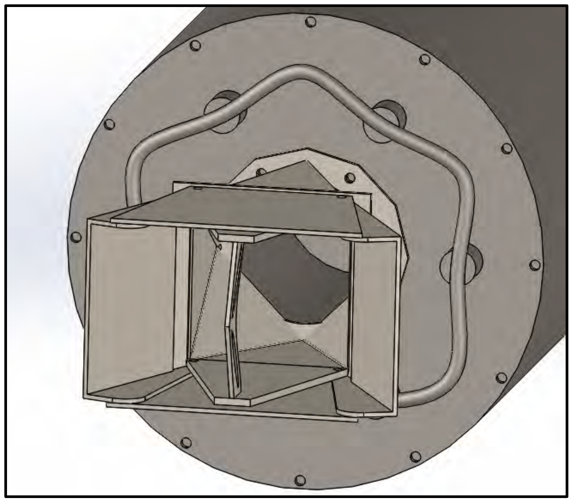


Figure 5.1.3 A frontal view of the nozzle, illustrating the variable side flaps.

With that consideration in mind, we turned to casting. While casting could provide an idyllic transitional shape, we found that the surface finish on casting was much more rough than we were hoping and would require a tremendous amount of post-processing (likely by hand, given the unusual shape) in order to achieve the surface finish we needed for smooth flow. Additionally, Professor Martin Koch was also somewhat skeptical of the ability to cast our parts given the scale and wall thickness we were considering.

Putting that aside, we were tipped off that Cal Poly has a metal 3D printer available and that the aerospace industry has been transitioning to 3D printing more of their parts. Enthusiastically, we talked more to Professor Koch and Professor Xuan Wang about the capabilities, pros, and cons of 3D printing. Determining that it would make an ideal process for us, we decide to 3D print a redesigned version of our nozzle out of plastic – our first structural prototype – as a proof of concept that this process would work for the scale, shape, and details we needed. Below is the model we used for 3D printing, and the successful prototype, which we put on the engine to test the fit of our estimates for the sizes of the bolts. (We'd measured the values, but the elements had limited accessibility, making us cautious of trusting their accuracy.)

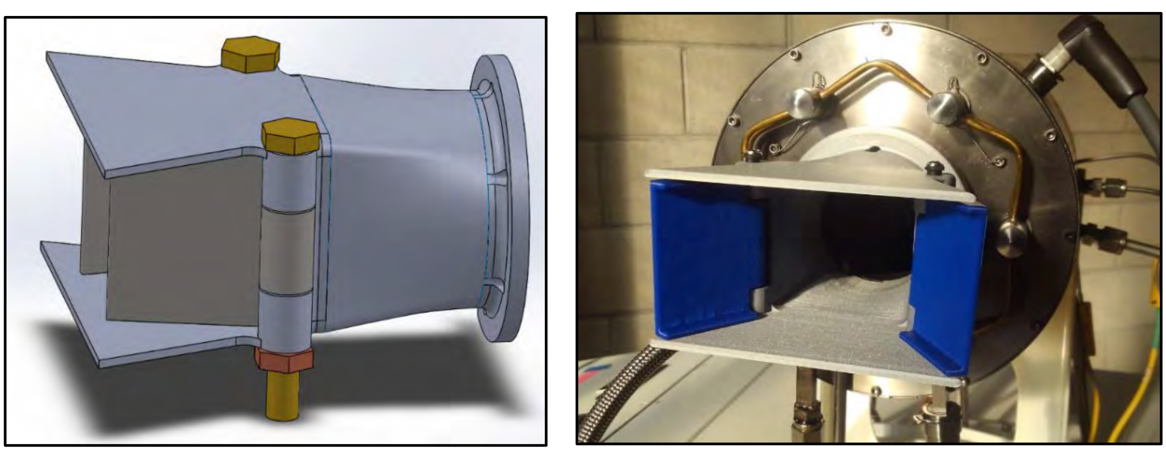


Figure 5.1.4 The CAD model of the structural prototype (left) and its printed counterpart (right).

In the printing process, we realized a few limitations that worked alright with plastic, but wouldn't be feasible with metal printing. The first, most obvious issue was that in printing the nozzle with the exit pointed up, the hinges didn't have enough support and would likely collapse mid-print. Secondly, the holes on the flange -- meant to allow us to put in the bolts that would connect the nozzle o the engine – were difficult to access. These features are shown in the figure below. While the hinges would be simple fix by adding more supporting material behind them, the bolt holes couldn't be solved so easily; the bolts needed to go into the existing bolt holes of the turbine which were located immediately against the rim of the exhaust pipe. At that location, extending the bolt holes further for better access (or widening the through-holes to make the bolts more accessible at an angle) cut through the sides of our nozzle, leaving us with holes in the wall.

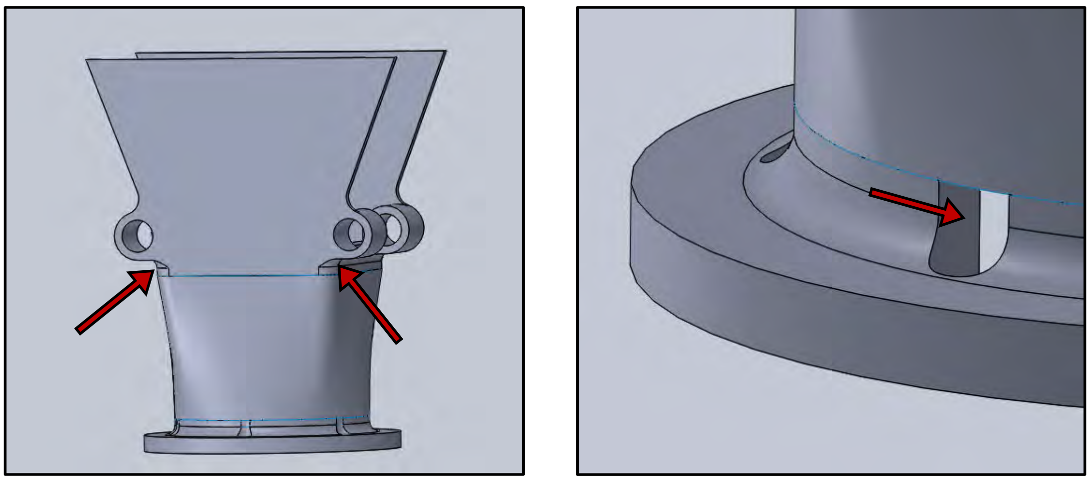


Figure 5.1.5 A nozzle showing the hinges lacking supporting material beneath them in the orientation we intended to print (left) and a close-up of the rim of the nozzle with the bolt holes widened by 5mm to allow for better ability to insert and remove the bolts, thus cutting into the sides of the nozzle (right).

Also by inspection we decided the stationary flaps on the top and bottom of the nozzle were too thin, the side flaps should similarly be thicker, and the length of the diverging section should be longer. Tackling these problems, the team determined the best way to allow for the bolt holes was to create two separate flanges – one to attach to the engine and one to attach the nozzle to that connective flange. As 3D printing only allowed a maximum of 100mm vertical height, the separation of the main nozzle into sub-sections encouraged us to separate more pieces, including separating the diverging section such that we could elongate the flaps. However, with that elongation came the need for more support against thermal deformation, not only through thickening, but also by including a centralized brace for stability. The result of these changes was the nozzle depicted below:

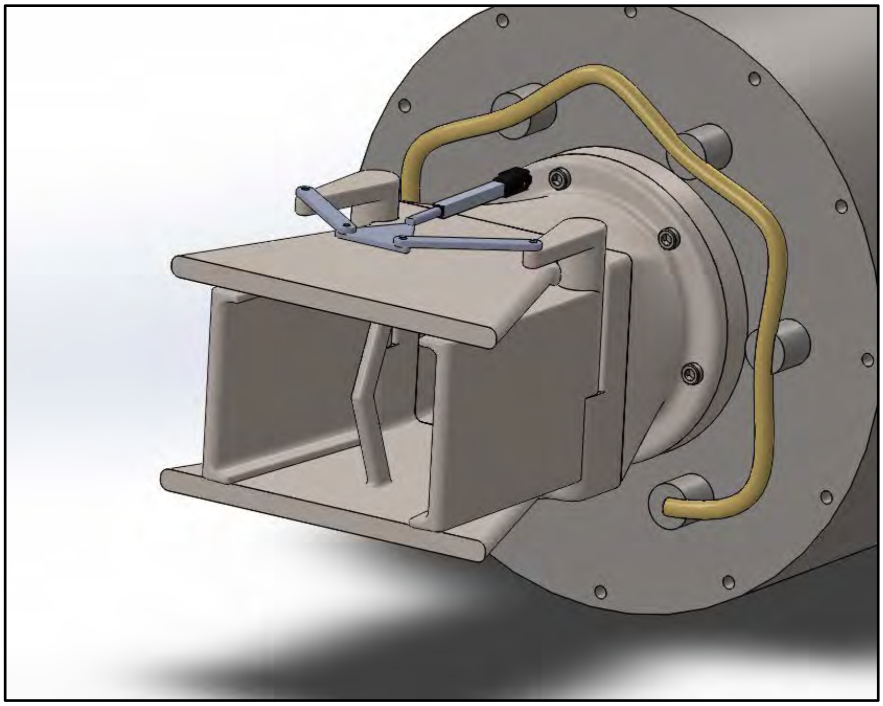


Figure 5.1.6 An isometric view of the current nozzle design.

Considering the nozzle we selected, we looked into manufacturing. With our nozzle design firmed up, we returned our focus to the actuation system.

5.2 Refinement of the Proposed Actuation System.

As mentioned before, the heat loads seen by the actuators will be fairly high – in the ball park of 450°C at maximum throttle – and the actuators we'd found handled heat best were only rated for 320°C. While isolation of the system was a possibility, we decided to more seriously explore a suggestion we gained from our PDR feedback: using a stepper motor in line with the hinges. This was appealing because it eliminated excessive connections and the motor would likely be able to handle more heat than the actuators. We could even simplify this design to include a gear chain between the two hinged posts, thereby having the actuators inherently align the flaps to be angled equally. Around this same time, we also revised our assessment of how feasible it would be to re-design the engine supports for thrust vectoring, determining it was a stretch goal we didn't want to aim for anymore (especially since the aerospace department didn't have a significant preference on having that capability). While two stepper motors, each controlling a hinge, had the same alignment challenges as two linear actuators, the geared chain with a singular motor did not.

While the simplicity and build-in alignment was desirable, we also were aware that motors are not meant to act as positioners; while the motor would be excellent for actuating the flaps to the correct angles, the strain of providing a steady, stationary counter-torque to the pressure of the fluid in the nozzle would be too much for the engine to handle. This would lead to early failure of the engine and potential wear making it less accurate or allowing the flaps to flutter, introducing flow disturbances and an inconsistent area – something significant with the small scale we were looking at.

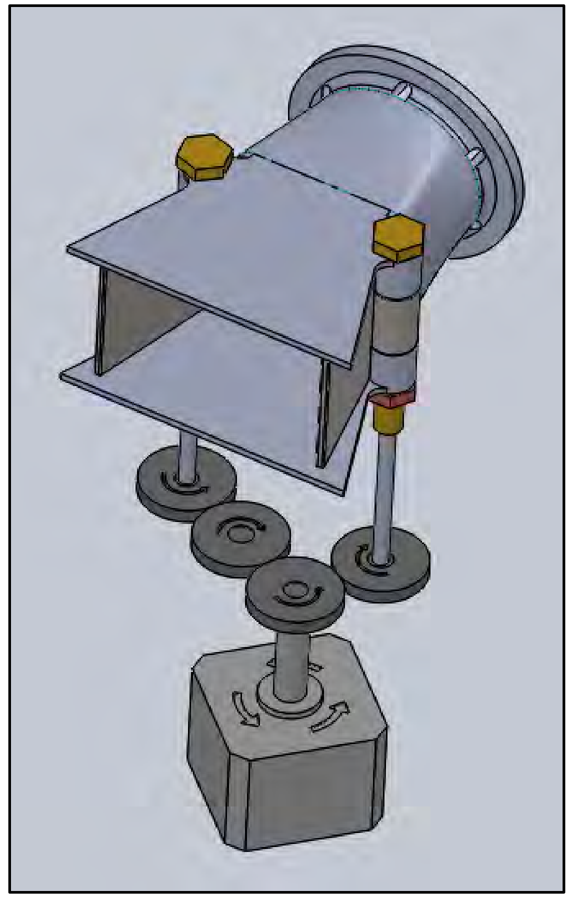


Figure 5.2.1 A sample gear-based actuation system driven by a stepper motor.

With that as a consideration, we returned to the linear actuators as our most likely option, an interest reinforced when we discovered some actuators came with a built-in control system, which reduced the amount of systems we'd need to design and manufacture. We decided to talk to Professor John Fabijanic about our concerns. He agreed that the actuators we had accessible couldn't handle the heat loads and the positioning of the actuators that we'd been considering would be inadvisable. However, he gave us several ideas that we incorporated into our design, resulting in the actuation system presented in the next section.

5.3 Description of the Proposed Design

The nozzle, as we've designed so far, is comprised of a flange attached to the back plate of the engine through the existing bolt holes. As the warranty on the engine only applies if the engine is still intact in its original form, it was high priority for us to attach the nozzle as a removable part through existing structures. However, these bolt holes are thin and very close to the exhaust exit, making it impossible to construct a nozzle with a thick enough wall that still allowed for a slot to insert the bolts; the hole placement requires the inner wall of the section is removed to accommodate the bolt heads. While this is troublesome-but-workable for idealized flow in a straight section, our CAD models rapidly indicated that it would cut large holes through the diverging section's outward-expanding sides. Separating these two segments by adding a second flange – one where the bolts into the engine can be inserted without navigating around the nozzle itself -- avoids this issue and provides a broader surface area to more firmly attach the nozzle. At the point of connection between the two flanges, guiding pegs help center the nozzle while thicker bolts connect the two surfaces together. The redesign is also easier replacement of the first flange, should it break due to stresses or should instrumentation that we designed around – such as the pitot tube at location P5 – need replacing with a different-sized part. The ability to replace individual segments of the nozzle was another large priority of ours.

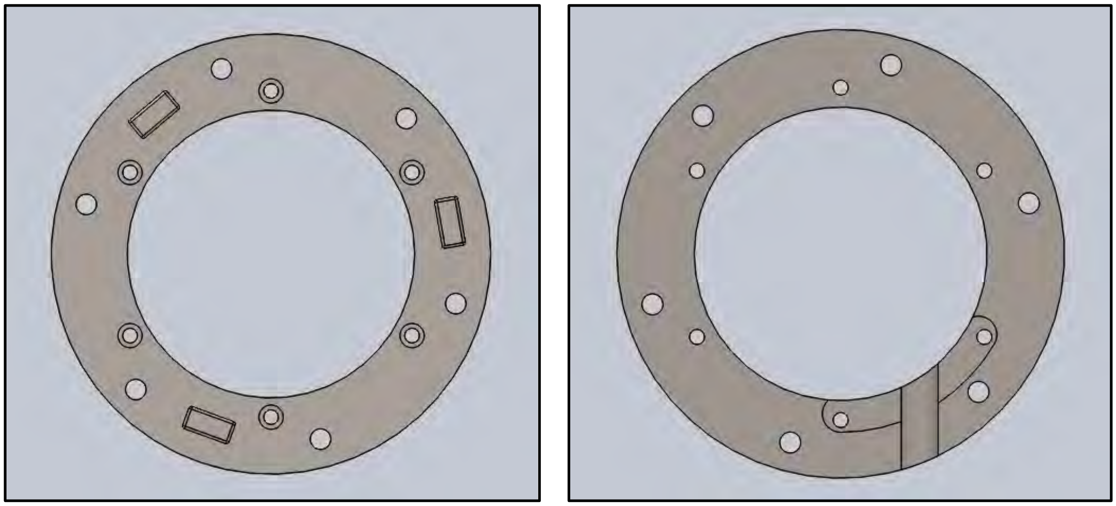


Figure 5.3.1 The mounting flange viewed from the side attaching to the throat (left) and the side flush to the engine's back plate (right).

The second flange extends into the converging section, a constant-area change of the inner shape of the nozzle from circular at the flange to a more rectangular cross-section just behind the hinges, where the shape stabilizes into a square throat with slightly filleted corners. The more rectangular shape allows for the straight hinges, permitting the flaps to be attached, while the length of the transition and the rounded corners provide the smoothest change possible to minimize flow losses.

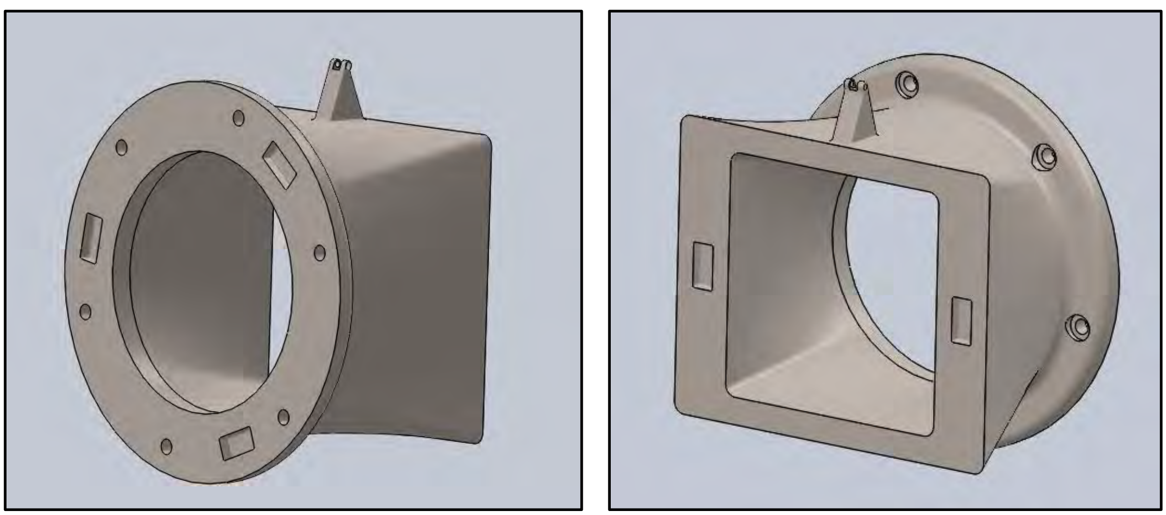


Figure 5.3.2 The converging section as seen from the side that attaches to the mounting flange (left) and the side that connects to the diverging section (right).

The third segment of the nozzle is comprised of the hinges and the stationary top and bottom plates of the nozzle. The increasing width of these plates along the direction of flow allows the mobile side flaps – the fourth major component – to be placed into diverging positions, as well as parallel, and converging (relative to the throat), without leaving gaps where the plates and flaps intersect. The top plates are supported by brace towards the front to help reduce bending of those flaps due to thermal deformation. The brace is filleted on all edges and is a V shape to help minimize flow disturbance.

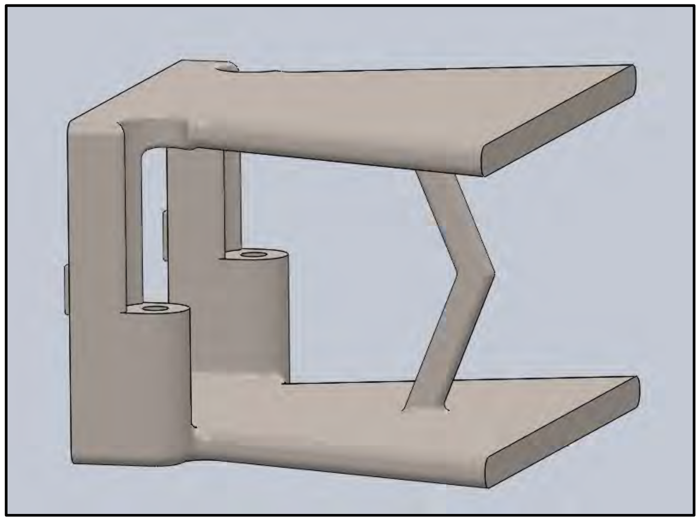


Figure 5.3.3 The diverging component of the nozzle. On the left, the tabs that center this section to the throat can be seen. Also visible is the bottom half of the hinge used to support the flap.

The side flaps likewise contain a portion of the hinge, allowing a guiding bolt to pass through both the flaps and the nozzle hinges. This bolt, being separate, allows the nozzle and the flaps to be separated, should one need replacing. The section of the hinge on the nozzle will support the hinge's weight and the bolt through both stabilizes the hinge in position and vertical alignment. On the sides facing inward towards the nozzle flow, the sides are curved to help minimize flow losses at the intersections of the side flaps and the top and bottom plates of the diverging section. They also provide some structural support to the flaps that reduces deformation from thermal and pressure loads.

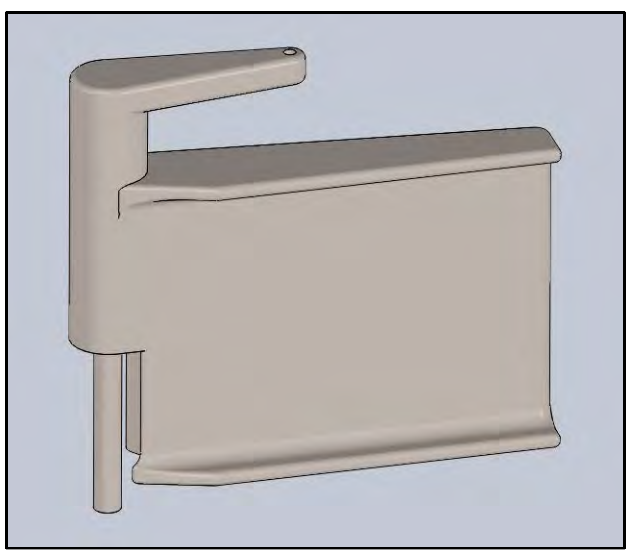


Figure 5.3.4 The left-hand side flap.

At the top of each flap, above the nozzle, are short arms. When a torque is applied, these features turn the hinge of the side flaps, and thus control the flap position. Attached to these arms are two rigid rods (one per flap), which connect them to a centralized linear actuator. Visible in the figure below, as the actuator lengthens, it pushes the flaps outward, resulting in a diverging position. As the actuator contracts, it draws the flaps inward into a converging position. The distance from the hinges and the exhaust helps thermally isolate the actuator somewhat to handle the high heat loads. Additionally, the points of connection or the rigid rods themselves will be made from a material with low conductivity to help minimize the heat transfer through the metal of the actuation system, further isolating it from heat loads. Identifying what that heat load might be is something we will need to run tests on to determine. (See section 7.5 for more details.)

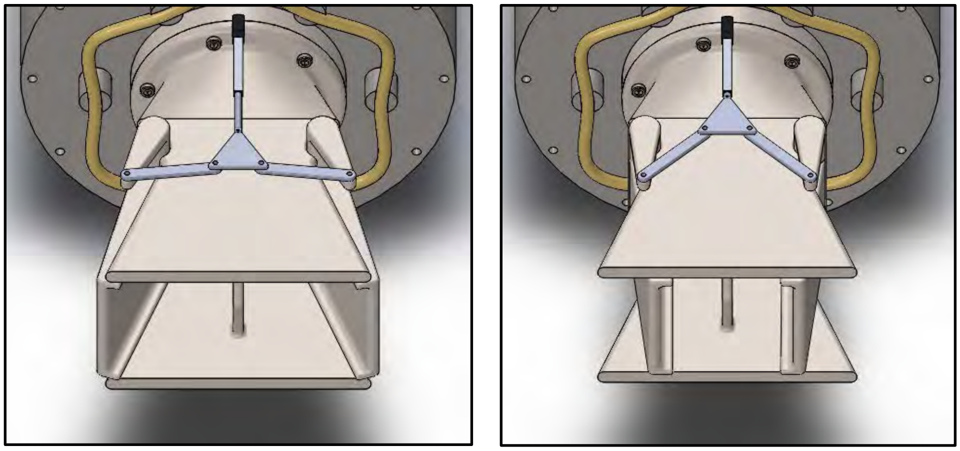


Figure 5.3.5 A demonstration of the actuation system at maximum divergence (left) and maximum convergence (right).

All together the assembly will come together as shown below:

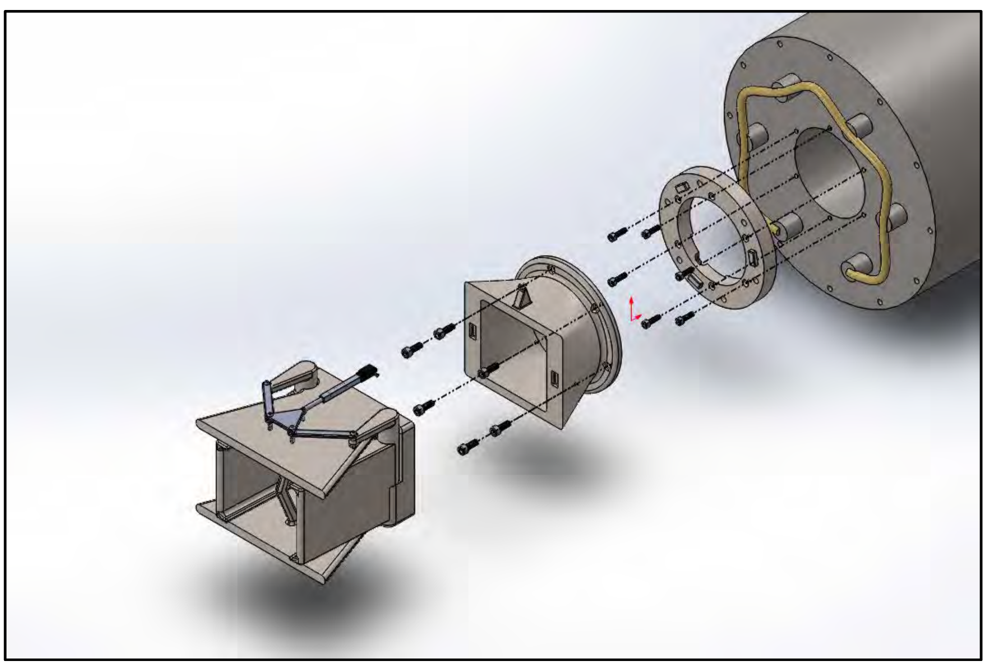


Figure 5.3.6 Depiction of the mounting flange, throat, and diverging section as they would be assembled in their attachment to the engine.

For the complete set of manufacturing drawings for the nozzle and actuation components, see Appendix L.

5.4 Detailed Analysis

Further analysis of the SR-30 cycle and exhaust flow parameters focused on designing a nozzle extension with more concrete cross-sectional area and width dimensions. Although a majority of the preliminary analysis focused on flow parameters while the engine runs at a full throttle condition of 73,000 rpm, it was decided to design the variable area nozzle extension for an engine throttle position of 65,000 rpm, to allow for a larger range of operating conditions for the nozzle areas in conjunction with the engine throttle position.

A *ConvergingDesign* function was developed to dimension a nozzle "throat" with a square cross-sectional area. In earlier versions of our design, this throat actually converged in area from the cross-sectional area at Station 5. However, once it was decided that sonic and supersonic flow speeds were unrealistic given the SR-30 engine's output flow pressures, the design was altered to have a constant-area duct between Station 5 and the "throat". Therefore the "converging duct" was adapted to be a constant-area shape change from a circular cross-sectional area at Station 5 to a square cross-sectional area at the throat. To minimize flow losses at this square throat, and for manufacturing purposes, fillets were added to the corners of the square cross-section. The *ConvergingDesign* function takes these design specifications into account, and with a fillet radius input it calculates the cross-sectional geometry of the throat section, with a cross-sectional area equal to that of Station 5. These calculations can all be referenced in Appendices D and E.

Next, the diverging geometry was determined for this nozzle design. The inside duct height of the diverging section was assumed to remain constant from the inside throat height, with the side flaps remaining capable of swiveling in or out, allowing the cross-sectional area at Station 6 to change. An array of desired cross-sectional area ratios was defined for this exit area with respect to the square throat cross-sectional area. For the design presented, the Station 6 cross sectional area was defined to include stations of 80, 90, 100, 110, and 120 percent of the throat area. The *DivergingDesign* function then took these cross-sectional area inputs and calculated the exit width required at Station 6 to meet the defined area. At these 5 nozzle positions, a prediction was made for the various flow parameters, i.e. static and stagnation pressures, static and stagnation temperatures, local speed of sound, velocity, Mach number, and flow density, as well as the predicted ideal thrust produced by the engine. These results can be seen in Figures 5.4.1, 5.4.2, and 5.4.3, as well as in Appendices D and E.

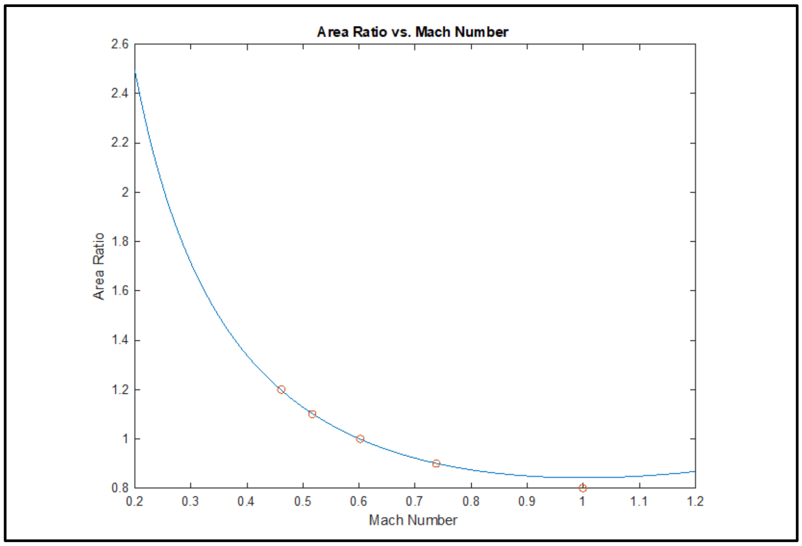


Figure 5.4.1 Station 6 Mach Number as a function of Area Ratio.

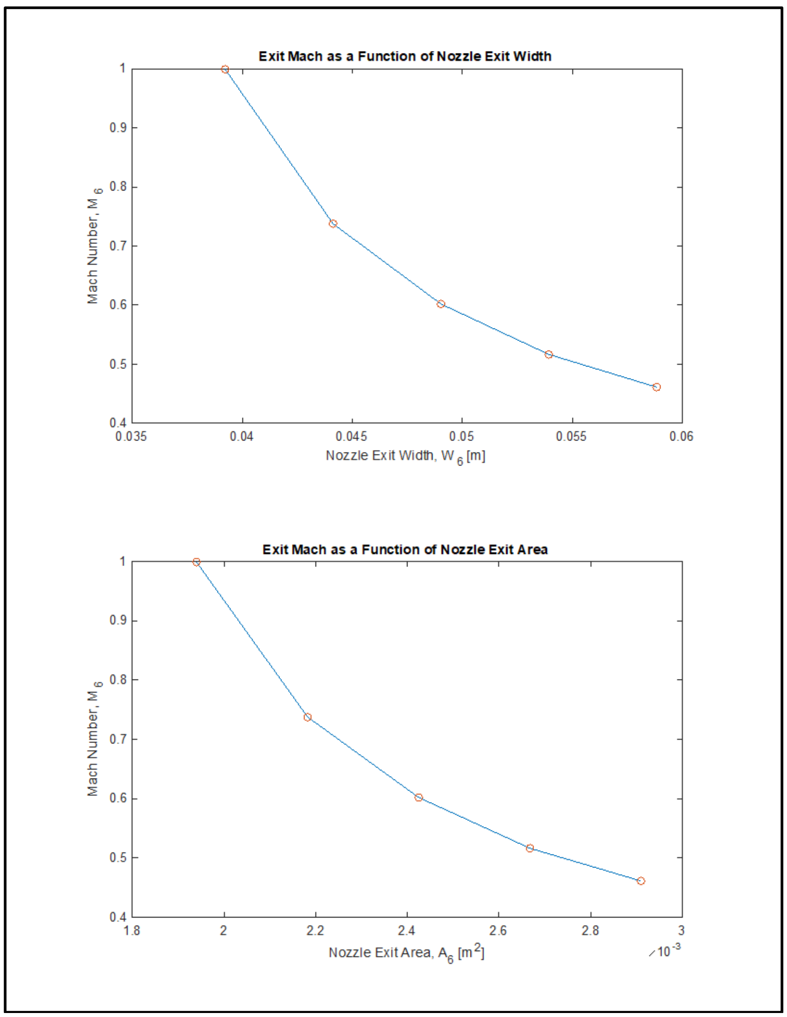


Figure 5.4.2 Station 6 Mach Number as a function of Exit Area and Exit Width.

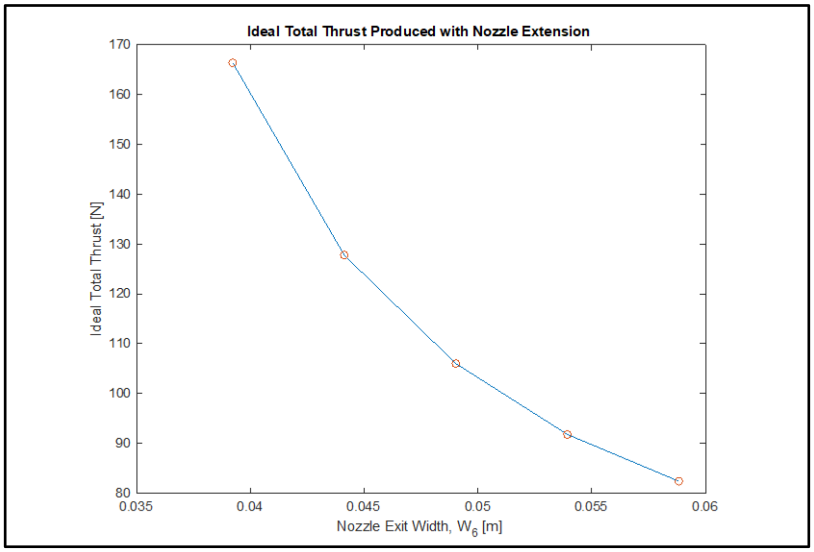


Figure 5.4.3 Engine Ideal Total Thrust as a function of Station 6 Exit Width.

Preliminary analysis of the SR-30 system, as presented in Section 4.4 of this report, primarily focused on analyzing the system's ideal Brayton Cycle flow parameters. It also made a rough prediction of the flow behavior that could be expected when adding a nozzle extension to the engine's exhaust system. However, a key theory was missed in this preliminary analysis: if a nozzle extension was added to Station 5 of the SR-30 Turbojet, then the static pressure at this point could no longer be equal to ambient pressure, and instead the ambient-static pressure condition would apply to the exit of the nozzle extension, designated as Station 6. With this taken into consideration, the cycle analysis was adjusted to account for flow parameters at Station 5 with a nozzle, and separately for flow parameters without a nozzle. Details of this analysis can be seen in the *SR-30_Cycle_Analysis* Function presented in Appendix E of this report. Table 5.4.1 below tabulates the predicted difference in flow parameters between Station 5 with and without a nozzle extension - however, as shown in the figures above, the resulting flow velocities and pressures predicted at Station 6 were much higher than those predicted in earlier analysis.

Table 5.4.1 Calculated Flow Parameters at Station 5 With and Without a Nozzle Extension.

			Station 5 Without Nozzle Extension	Station 5 With Nozzle Extension
Static Pressure	P_5	Pa	101,830	85,951
Static Temperature	T_5	K	690	658
Local Speed of Sound	a_5	m/s	526	514
Velocity	V_5	m/s	178	312
Mach Number	M_5	-	0.3390	0.6073
Density	ρ_5	kg/m^3	0.5143	0.4556

*All values are calculated for engine throttle position of 65,000 rpm.

Based on the results from this analysis, it has been concluded that the physical effects of adding a nozzle extension to the exhaust plane of the SR-30 engine cannot accurately predict the exhaust flow properties through our nozzle design. While the previously discussed analysis of Station 5 with a nozzle extension predicts that the velocity, and subsequently the Mach Number, of the exhaust flow will significantly increase, the true flow behavior cannot be determined without reference to the engine's performance curves. The analysis of exhaust flow with a nozzle extension seems to indicate that the pressure upstream of the exhaust flow, at the turbine exit, will significantly increase when the static pressure at that plane is no longer equal to ambient pressure. Theoretically if the engine remains at the same operating speed, this significant of a pressure increase would not be physically possible. Through consulting literature and Dr. Westphal of Cal Poly's Mechanical Engineering Department, it has been concluded that instead of a significant pressure increase occurring with the nozzle addition, the mass flow rate through the engine will decrease as the nozzle width converges. This means that the predicted flow velocities and Mach Numbers are much higher than those that will actually be seen with the nozzle extension.

An alternative approach to predicting the flow's behavior has been proposed for further analysis on this nozzle design. Rather than analyzing the flow at Station 5 from a flow parameter perspective using available data, we will analyze it from an engine work perspective. If the engine is assumed to run at the same speed, then the work input/output between the compressor and turbine sections will remain closely correlated with and without a nozzle extension. We will therefore analyze the SR-30's work behavior without a nozzle extension, and use the resulting predicted flow parameters at the exit of the turbine to predict flow behaviors with a nozzle addition.

5.5 Safety, Maintenance and Repair Considerations

While it is certainly possible for students to misuse the nozzle system in ways that constitute a danger to the engine or themselves, TurboTRIO has very little to do in terms of adding safety measures; all the elements we would include as safety features are already built into Turbine Technology's engine set up. The engine itself has several automatic stops in its coding to ensure the engine operation stays within the parameters the metals and components are rated to handle. If the pressure or temperature exceeds that capacity at any point in the engine, it will automatically turn itself off. This is especially important for us as we move forward into testing our nozzle, as analysis can't fully accurately predict how adding the nozzle will impact the engine upstream. Another key safety feature is the protective casing around the engine. This casing is to protect the operator from any parts flying off and, more likely, anyone who mistakenly thinks they can safely touch the outside of the engine while it's running. A detailed analysis of the potential hazards and the associated precautions can be found in Appendix H, the Safety Hazard Checklist, and Appendix G, the Failure Modes and Effects Analysis chart.

Lastly, our team and future student operators are required to abide by standard aerospace lab procedures of working with a partner at all times, wearing hearing protection rated to handle 90+ dB and shatter-proof safety glasses. Furthermore existing warnings for lab students operating the engine include that students not remove the casing and that they not stand behind the engine while it is in operation, which TurboTRIO will reiterate in all our sample lab procedures.

Our design should require minimal maintenance. It is recommended the bolts are checked for tightness annually and that the actuation system is similarly tested for accuracy with the engine off periodically. We recommend, given how important this is to student measurement success, that this is checked at the beginning of every lab as part of the lab procedure, but could be checked as infrequently as once every quarter.

With the design proposed, there should be very little need for repair – we've designed every component to last at least 15 years (the likely life of this engine). However, should something fail and replacement be necessary, each component (as is detailed above) is able to be individually separated from the nozzle and the engine and 3D printed again; the Aerospace department will retain the CAD files for each part and can print them with the IME's metal printer, the same as we did. All bolts are standard sizes and can be purchased online, and the nozzle can be removed such that Turbine Technologies will still repair the engine as being under warranty. The actuator would be the hardest to repair, but any actuator capable of handling high heat loads would suffice and an adaptor to our actuator system would be very easy to design.

5.6 Material Selection and Part Sizing

The material selection process for the proposed design was based upon material properties, cost and availability, processing, and environment. Section 4.5 of this documents discusses the possible use of Nickel Inconel and Stainless Steel alloys based on their heat resistant properties. This provided a bases for the final material selection process.

The process began by considering our primary concern for the design, the environment the nozzle would be exposed to. As stated in Table 5.4.1, the exhaust flow exit temperature is roughly 700K. With these high temperatures we needed to then focus on material properties, specifically thermal properties. Both the Nickel Inconel and Stainless Steel can withstand temperatures nearly three times that of our expected exhaust flow, seen in Table 5.4.1. The cost and availability of materials became the next focus.

Various Stainless Steel and Nickel Inconel alloys were in stock from various suppliers, alleviating availability as a concern. However, pricewise Nickel Inconel costs nearly five times as much as Stainless Steel alloys. A comparison of price was determined by selecting a 10"x10", 0.12" thick sheet of each material on McMaster-Carr, see Table 5.4.1 below. Knowing the relative price of each material brought processing into consideration.

Processing refers to how the part will be manufactured. Given the unusual contours and dimensions of our design, specifically the shape transition of the throat, machining was not possible and we had to look at other manufacturing processes. We found that casting and 3-D printing were options that would allow this transition. The casting professor, Martin Koch, reviewed our design and informed us that it is possible to cast the part out of AISI Type 304 Stainless Steel, however it could not be done in house at Cal Poly. We would be able to create the molds using campus facilities and then outsource it to his contact in Los Angeles to be cast. Another viable option was brought about by talking to Industrial Manufacturing professor, Xuan Wang. Professor Wang informed us of the Industrial Manufacturing Department's Selective Laser Melting (SLM) machine that can 3-D print parts from AISI Type 316L Stainless Steel. Lastly, a materials comparison table was generated to compare the properties of these metals.

Table 5.6.1 Material Selection Table

		Units	AISI TYPE 304 STAINLESS STEEL	AISI TYPE 316L STAINLESS STEEL	NICKEL ALLOY INCONEL 718
Mechanical Properties	Hardness, Rockwell	[-]	B, 70	B, 80	C, 43
	Tensile Strength, Ultimate	[MPa]	505	515	1375
	Tensile Strength, Yield	[MPa]	215	205	1100
	Modulus of Elasticity	[GPa]	196	193	202
	Shear Modulus	[GPa]	86	82	80
Thermal Properties	Specific Heat Capacity	[J/g°C]	0.5	0.5	0.44
	Thermal Conductivity	[W/mK]	16.2	16.3	11.4
	Melting Point	[°C]	1400-1455	1375-1400	1370-1430
Cost	10”x10”, 0.12” Thick Sheet (McMaster-Carr)	[$]	24.84	64.03	216.24

Table 5.6.2 Material Decision Matrix

Material Decision Matrix	**Weight Factor**	**AISI TYPE 304 STAINLESS STEEL**	**AISI TYPE 316L STAINLESS STEEL**	**NICKEL ALLOY INCONEL 718**
Mechanical Properties	0.10	4	4	5
Thermal Properties	0.20	5	5	5
Cost	0.10	4	2	-3
Availability	0.05	4	4	3
Manufacturability	0.30	-1	3	-2
Environment	0.25	4	4	4
Sum of +		3	3.70	2.65
Sum of -		-0.30	0	-0.90
Total		2.70	3.70	1.75

All factors of each material were reviewed in a decision matrix, Table 5.6.2 above. Cost and manufacturability eliminated Nickel Inconel 718. Manufacturing alone eliminated Type 304 Stainless Steel because of the difficulties casting it would bring about. Being able to 3-D print in house, proved to be the best manufacturing process, therefore Type 316L Stainless Steel would be the material used in our final design.

5.7 Cost Analysis

The following is a breakdown of the cost of the proposed design. It is noted that we do not currently have a price for manufacturing or material on the SLM process used to manufacture the mounting flange, throat, diverging section, and side flaps. The Industrial Manufacturing Department will discuss pricing with the Aerospace Engineering Department.

Table 5.7.1 Proposed Design Cost Analysis

SUPPLIER	PART NUMBER	DESCRIPTION	UNITS	DIMENSIONS	QUANTITY	UNIT PRICE
McMaster-Carr	3368T347	316 Stainless Steel Sheet	[in]	6"x6"	1	$39.96
McMaster-Carr	SCS0003	Socket Head Cap Screw-Stainless (50)	[in]	0-80 Thread, 3/16" Length	1	$8.20
McMaster-Carr	91251A108	Black-Oxide Alloy Steel Socket Head Screw (Pack of 100)	[in]	#4-40 Thread , 3/8" Length	1	$8.07
McMaster-Carr	91251A408	Black-Oxide Alloy Steel Socket Head Screw (Pack of 100)	[in]	#6-40 Thread , 3/8" Length	1	$8.76
McMaster-Carr	91828A004	18-8 Stainless Steel Hex Nut	[mm]	M1.2 x 0.25	1	$9.38
McMaster-Carr	94150A305	316 Stainless Steel Hex Nut	[mm]	M2 x 0.4	1	$2.66
McMaster-Carr	91292A833	18-8 Stainless Steel Socket Head Screw	[mm]	M2 x 0.4 Thread, 10 mm Length	1	$7.16
$McMaster-Carr	91292A832	18-8 Stainless Steel Socket Head Screw	[mm]	M2 x 0.4 Thread, 8 mm Long	1	$6.00
McMaster-Carr	91800A085	18-8 Stainless Steel Narrow Cheese Head Slotted Screws	[mm]	M1.2 x 0.25 Thread, 8 mm Long	1	$13.97
Firgelli	FA-150-S-12-XX	Firgelli Classic Linear Actuator	[-]	-	1	$109.99
Firgelli	2CH-REM	2 Channel Remote Control System	[-]	-	1	$55.00
					Total Cost	**$269.15**

6 Final Design

While the proposed concept was feasible, the design ultimately required a few changes due to the limitations of our manufacturing processes and the tools available within the required time frame. This section discusses those alterations and describes the finalized design, as embodied by the manufactured prototype.

The complete drawing package for this final design can be found in Appendix S.

6.1 Development of the Final Design

One of the most crucial changes came when considering the diverging section. While we liked the concept, we learned that on our scale, 3D printing would not be viable because the top and bottom flaps were too thin for their height; they would not have the support needed to print without deflection. Like the throat, casting was also impossible due to the scale, and machining wouldn't be able to access all the angles necessary as a singular block. Additionally, even if machining were possible as a singular piece, it would be a tremendous waste of steel and money. We decided to split up the diverging section into three sections – the connecting flange, the top flap, and the bottom flap – that could each be cut from a thin steel plate and welded together.

Due to these changes, the side flaps likewise could no longer be supported in the way that we originally envisioned, resulting in necessary modifications to their design. Instead of being formed from a single piece as we'd hoped, we reverted to the design of the Boeing engine's nozzle; the side flaps are situated into position, the rod is slid into place through the top and bottom flaps, and the flaps are welded to the rod. The assembly can be seen in Figure 6.1.1 below.

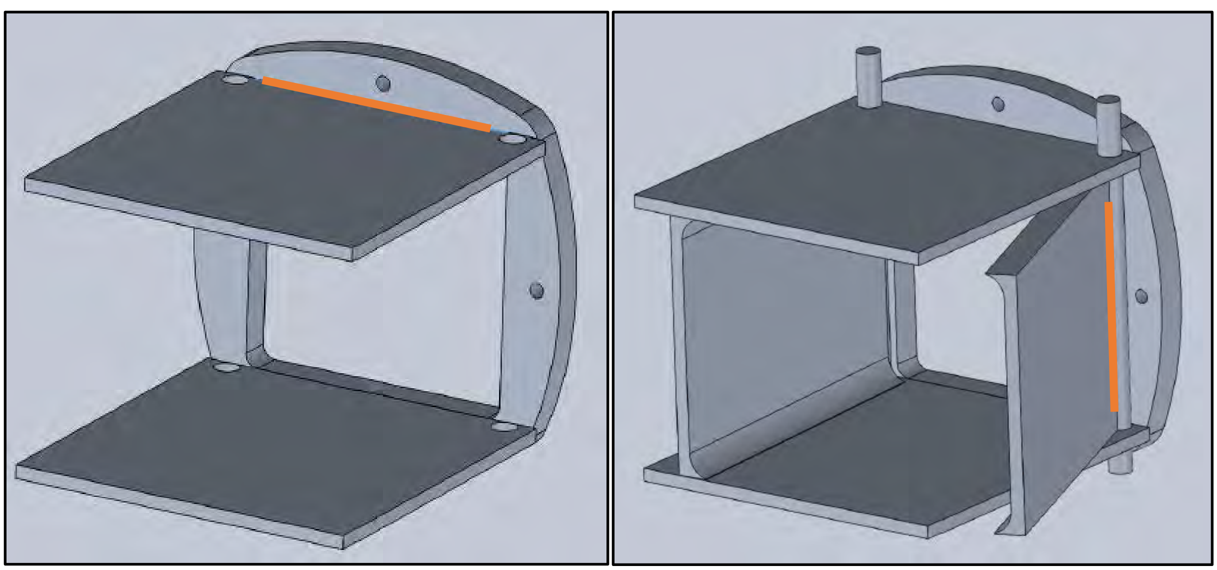


Figure 6.1.1. The assembly of the diverging section, showing the welding required for the top flaps (left) and for the side flaps (right).

Because of the challenges in accurately measuring the dimensions on the engine's back plate, our first step in realizing our proposed design was to make test models to confirm our measurements. We also needed to confirm that our manufacturing processes would work, given the unusual scale and shapes that our design relied on. We started by water jetting a plate of aluminum to have the right outline and the through-holes. This was a test of the water jetting process itself for cutting metal. It also gave us insight into the process' precision. While we found water jetting to be incredibly useful for the outline – not only for the flange, but also for the broken-up sections of the diverging section – the bolt holes were noticeably wider on the far side of the plate than the near side, leading us to decide to drill all holes in our final version.

From there, we machined all of the other cuts needed, and threaded the holes. We then attached the test flange to the turbine. It fit perfectly, indicating all measurements were indeed correct.

We also practiced 3D printing our throat – first out of plastic to confirm the dimensions, and second out of metal to affirm the feasibility of 3D printing on the scale we desired. While we had planned to weld the diverging section to the throat, Professor Xuan Wang of the Manufacturing Department informed us that welding to steel was challenging and a bad weld would require remaking the parts. Determining not to 3D print more times than necessary, due to the slow manufacturing time, we decided to add a flange instead, with the intent to bolt on the diverging section. Consequently, we decided to use this first test print to see if the metal 3D printer could handle having the overhanging flange if we supported it with a fillet underneath it – both were successes. The plastic model confirmed our design had good sizing; the metal model had a few cracks, but the technicians reassured us that these were anticipated design issues that were easily remedied. From this process, we learned that our walls needed to be thinner, and the fillets on the flanges needed to be thicker. We decided the best way to accommodate that was to replace them with chamfers.

Using what we learned, we moved on to manufacturing the final versions of the parts. This is detailed more in section 7, Manufacturing. The final designs, with the above changes, are described below.

6.2 Description of the Final Design

The while the inner ring of bolt holes was constrained by the bolts on the back plate of the engine, we decided six bolts was excessive and the throat would be better served with only four slightly-larger bolts, thereby reducing the stress on the flange and the throat. These bolts were offset an arbitrary 10 degrees off from strictly vertical/horizontal to reduce the stress concentrations near the bottom bolt. We also decided the bolt holes themselves did plenty to align the throat to the flange and decided the centering tabs were likewise unnecessary. The flange can be seen from the front and back below in Figure 6.2.1.

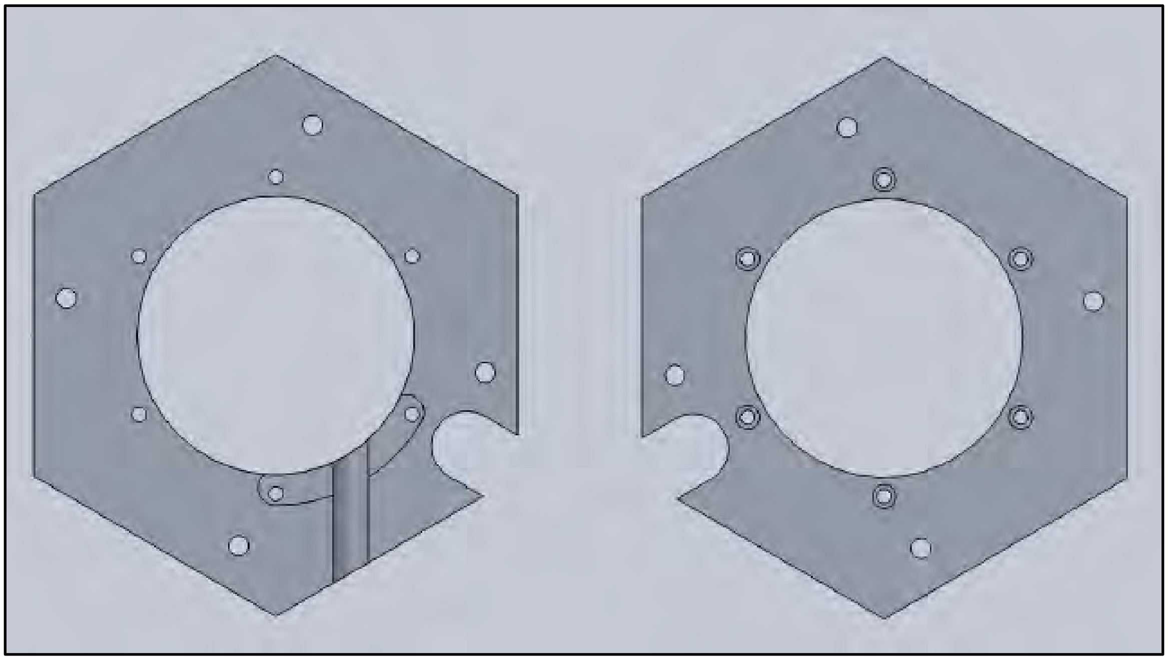


Figure 6.2.1 The mounting flange as seen from the back that will sit against the engine (left) and the front that will go against the throat (right).

Next is the throat itself, shown in figure 6.2.2 below. The design changed very little from earlier renditions, aside from the removal of the tabs and the addition of the top flange. The top flange is thin to put as little strain on the 3D printing process as possible. As shown, both flanges have thick chamfers to reduce cracking. The throat also no longer has the little actuation mount on top, as 3D printing would not support that.

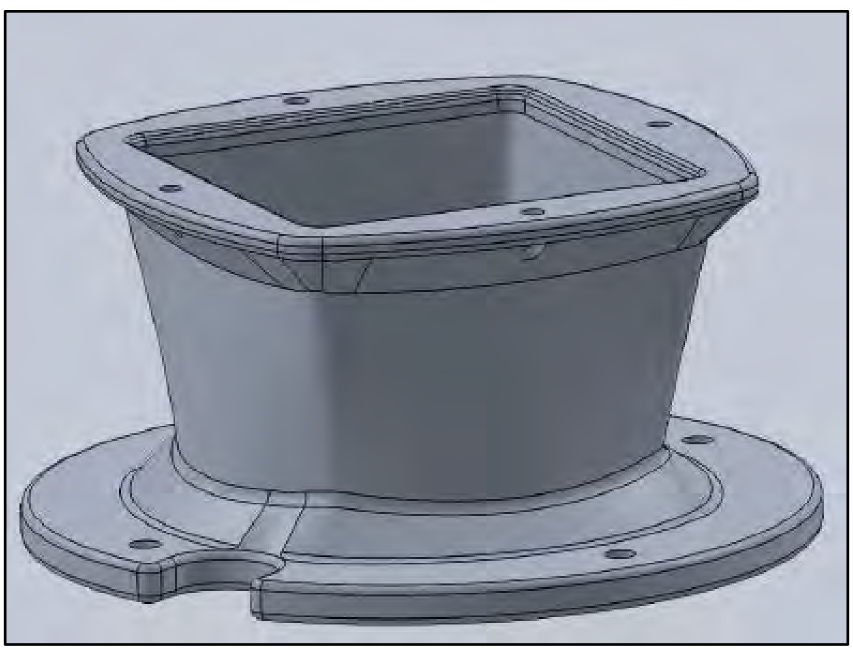


Figure 6.2.2. The throat of the nozzle.

Shown below in Figure 6.2.3 and 6.2.4, respectively, are the components of the diverging section and a depiction of how the diverging section assembles together.

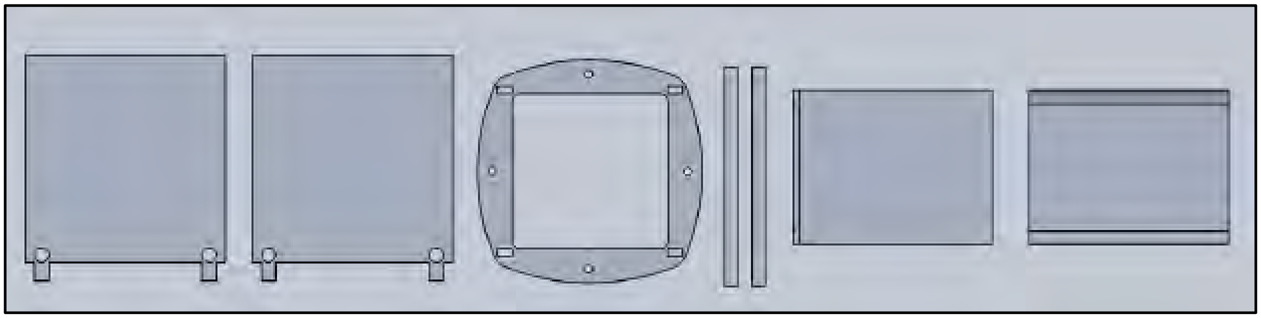


Figure 6.2.3 The diverging section components. From left to right: the top and bottom flaps, the diverging section's mounting flange, the rods, and the two side flaps (on left, with the interior face downward and on right, with it upward).

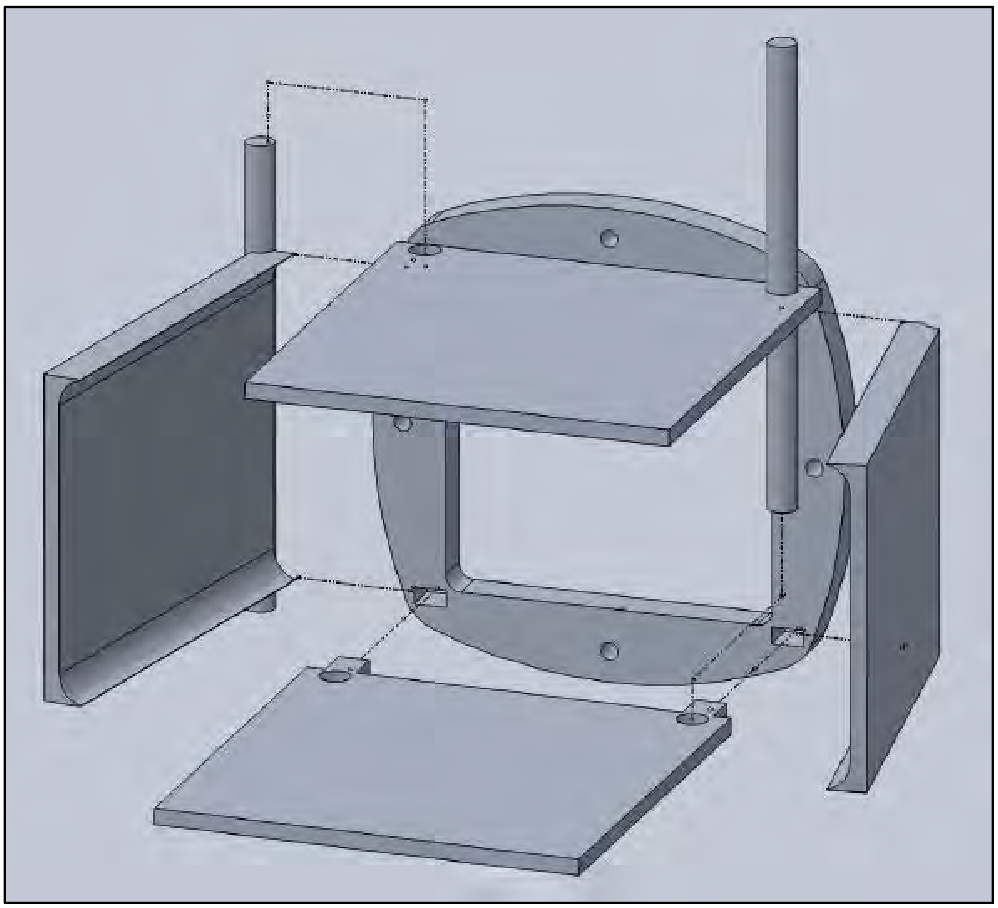


Figure 6.2.4 The assembly of the diverging section.

In the left-hand side of the figure, above, the rod can be seen when attached to the flap. On the right-hand side, the flap and rod are separated and shown ready to be inserted into their correct positions for the welds. The top flap is in place, while the bottom has yet to be inserted, allowing a view of how the two pieces are merged together.

Below is a close-up view of the side flaps, where their form is more clearly visible. On the left, it's easy to see the lips at the top and bottom of the interior-facing side, which help reduce the turbulence in the flow and on the right, the slot that nestles the rod is closest to the viewer.

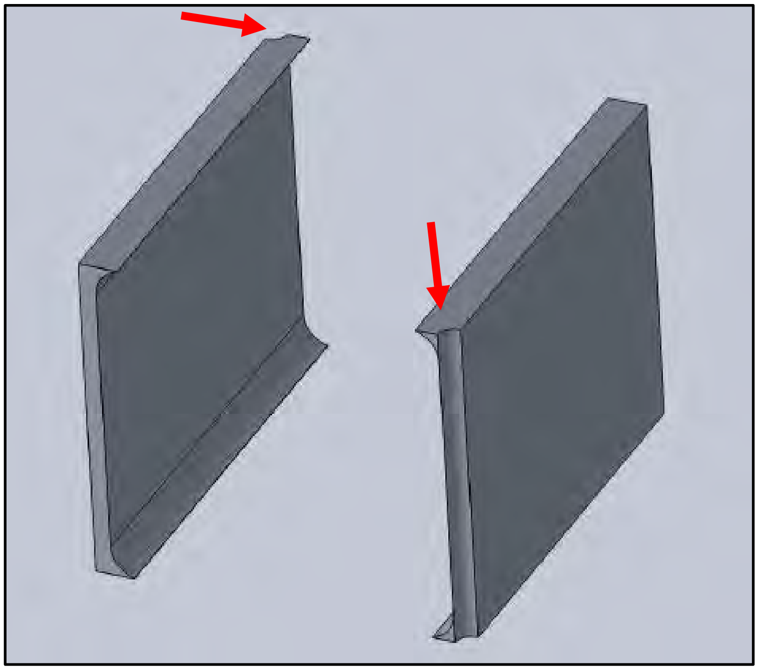


Figure 6.2.5 The side flaps, with the interior face (left) and the exterior face (right) shown. The location for the rod to nest is indicated on both by arrows.

As seen in the completed diverging assembly in Figure 6.1.1, the rods extend substantially above the top plate. While the scope of this project was revised to not include the actuation system, this is a feature remaining from our original actuation design. Should the Aerospace Department choose to use our actuation concept from the proposed design seen in Section 5, these longer rods provide enough room that arms could be attached to them, allowing for the configuration illustrated in Figure 5.3.5.

The above components come together as shown in Figure 6.2.6, below.

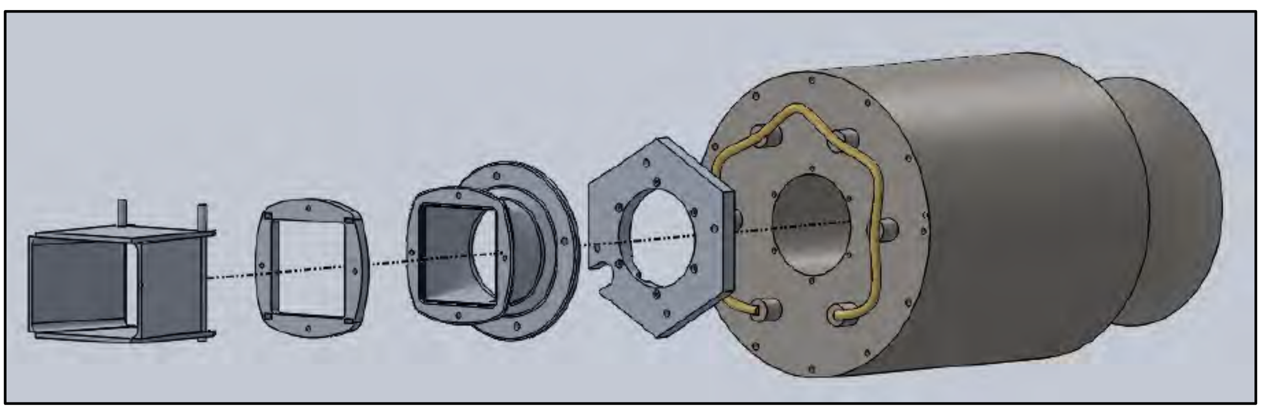


Figure 6.2.6. Assembly of all nozzle components, and attachment to the engine.

If assembled correctly, the nozzle should be able to provide converging, diverging, and a constant area, as demonstrated in Figure 6.2.7 below.

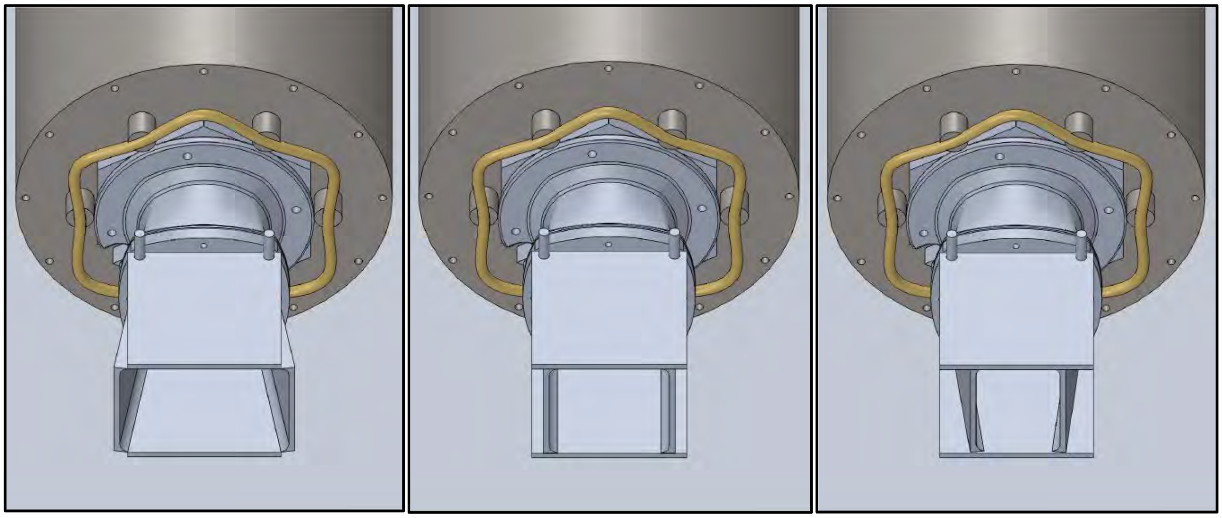


Figure 6.2.7. The nozzle positioned for diverging (left), constant area (middle), and converging (right).

6.3 Detailed Analysis

While the team intended to test our nozzle, challenges – elaborated on in later sections – prevented most of the testing of the nozzle itself. As such, most of our testing revolved around determining the usefulness and limitations of manufacturing processes (detailed in 6.1 above and in Section 7, Manufacturing below). Appendix Q lays out the procedures for the performance validation testing that the nozzle still needs, and the safety precautions recommended during such testing. This will be pursued by the Aerospace Department at the time the engine has been repaired. Appendix R provides a similar operations manual for students' testing in labs.

The data collected includes measurements of the bolt torque, the vibrations on the tip of the nozzle, the volume throughout testing, the back plate temperature, and various points of pressure and temperature. The bolt torque allows testers to determine if any bolts loosened; the vibrometer allows calculation of the dynamic load on the bolts and nozzle; the decibel meter ensures the additional strain on the engine – undoubtedly causing an increase in the volume, especially when converged and running at maximum throttle – doesn't cause the volume to exceed the capacity of the ear protection provided by the lab; monitoring the back plate temperature allows an early warning if the internal engine temperatures at T3 exceed safety limitations without tripping the safety shut downs, as well as the time it takes to cool down where the nozzle is safe to handle and remove manually; the temperature and pressure readings at stations 5 (existing), 6, and 7 allow the calculation of the engine cycle to confirm the engine is not experiencing undue strain. Furthermore, these points allow for calculations of the expansion through the nozzle and the heat transfer through the nozzle walls, which can later be used to predict how much heat the actuation system would need to handle.

6.4 Safety, Maintenance, and Repair

Based on the analysis laid out in section 5 and the testing that shall be conducted, we believe the nozzle to be safe for student use. Any relevant safety issues are due to the engine itself rather than the nozzle.

Maintenance is the same as is indicated in section 5 with our proposed design, relying on occasional oil at the joints as needed, and a check of the bolts every month or two of use to ensure the nozzle is still properly secured.

Repair is the only area substantially impacted by the modifications. While our revised design still emphasizes the separation of components for individual replacement, the final diverging section is a singular unit. Should it need repair and replacement, the components shall have to be machined and welded together again. Aside from that, repair should be the same as indicated in our proposed design.

6.5 Material Selection

While the processes resulted in different stock materials for certain pieces, such as plates rather than 3D printed metal, the metal has remained the same as originally planned: 316 stainless steel.

6.6 Final Cost

The following is a breakdown of the cost of the final design. It is noted that we do not currently have a price for manufacturing or material on the SLM process used to manufacture the mounting flange, throat, diverging section, and side flaps. The Industrial Manufacturing Department will discuss pricing with the Aerospace Engineering Department.

Table 6.7.1 Final Design Cost Analysis

SUPPLIER	PART NUMBER	DESCRIPTION	UNITS	DIMENSIONS	QTY.	UNIT PRICE
Mcmaster-Carr	9246K523	6061 Aluminum	[in]	6 x 6 x 5/8	1	$21.20
Mcmaster-Carr	4816T54	316 Stainless Steel Sheet	[in]	6 x 6 x 1/2	1	$143.83
Mcmaster-Carr	92185A108	316 Stainless Steel Socket Head Screw (Pack of 50)	[in]	4-40 Thread, 3/8 Long	1	$6.52
Mcmaster-Carr	92290A318	316 Stainless Steel Socket Head Screw (Pack of 25)	[in]	10-32 Thread, 3/4 Long	1	$5.43
Mcmaster-Carr	88885K78	316 Stainless Steel Sheet	[in]	6 x 6 x .105	1	$20.61
Mcmaster-Carr	4816T53	316 Stainless Steel Sheet	[in]	6 x 6 x 3/8	1	$96.23
Mcmaster-Carr	89325K89	316 Stainless Steel Rod	[in]	6 x D 3/16	1	$1.86

Table 6.7.2 Final Design Cost Analysis

SUPPLIER	PART NUMBER	DESCRIPTION	UNITS	DIMENSIONS	QTY.	UNIT PRICE
DrillsandCutters.com	MMO3/16-2FSE-BN	3/16" 2 Flute Carbide Uncoated Ball End Mill	[in]	D 3/16	1	$13.44
DrillsandCutters.com	DWTT4-40	4-40 Carbon Steel Taper Hand Tap	[in]	#4-40	1	$1.26
DrillsandCutters.com	DWTT10-32	10-32 Carbon Steel Taper Hand Tap	[in]	#10-32	1	$1.16
DrillsandCutters.com	MMO9/32-4FS	9/32" Carbide 4 Flute Uncoated Flat End Mill	[in]	9/32	1	$19.34
DrillsandCutters.com	MMO5/16-2FSE-BN	5/16" 2 Flute Carbide Uncoated Ball End Mill	[in]	5/16	1	$22.40
DrillsandCutters.com	DWDCO33	#33 Solid Carbide Drill Bit	[in]	0.113	3	$2.67
DrillsandCutters.com	DWDCO21	#21 Solid Carbide Drill Bit	[in]	0.159	3	$3.72
DrillsandCutters.com	DWDCO11	#11 Solid Carbide Drill Bit	[in]	0.191	3	$4.83
					Total Cost	**$364.50**

A complete list of the parts and budget can be found under Appendix N.

7 Manufacturing

The manufacturing of the design was done in-house using Cal Poly's manufacturing equipment and facilities. Manufacturing began on March 1, 2018 and extended into the very end of spring quarter. Due to safety issues with manufacturing equipment, manufacturing was not completed. However, a plan to finish the manufacturing of all components was created and set to be finished within the Aerospace Department. The detailed manufacturing plan for each component of the final assembly is explained in the following sections along with the plan for future manufacturing.

7.1 Manufacturing Overview

The primary manufacturing process of the throat was a Selective Laser Melting (SLM) process and the secondary process was milling. Selective Laser Melting is a form of additive manufacturing where a high power-density laser is used to melt and fuse metallic powders together. We used the SLM machine located in the Casting Lab of Cal Poly's IME Department. This machine used our selected material of Type 316L Stainless Steel, which determined the type of steel for the rest of our components, so as not to worry about differences in shrinkage rates. Milling was done in Cal Poly's Bonderson Project Center and the Aero Hangar. Table 7.1.1 outlines the parts to be manufactured as well as the process that will be used. Please refer to Appendix M for fastener data sheets.

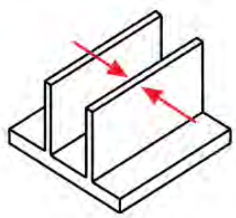
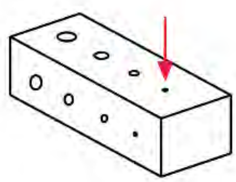
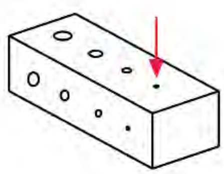
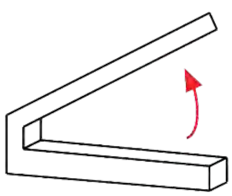
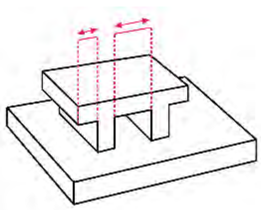
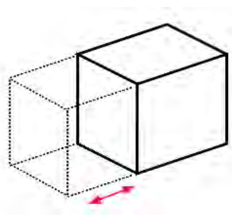
Table 7.1.1 Parts Manufactured

Part Number	Description	Process
11000	Mounting Flange	Water Jet, Mill
12000	Throat	SLM
13001	Diverging Flange	Water Jet
13002	Right Flap	Mill
13003	Left Flap	Mill
13102	Top Flap	Water Jet
13103	Bottom Flap	Water Jet
13104	Rods	Abrasive Saw
Total Parts	**8**	

7.2 Designing for an SLM Process

The primary manufacturing concern for SLM processes' is designing the parts correctly. Though 3-D printing allows difficult contours and geometries to be manufactured, it is pertinent that the CAD models are created with this process in mind. Table 7.2.1 outlines the general guidelines for designing for metal 3-D printed parts, as described by 3D Hubs.

Table 7.2.1 3-D Printing Design Guidelines

Feature	Description
	**Wall thickness** - The minimum wall thickness to ensure a successful 3D print with most materials is 0.4mm. Finer structures are possible, but are dependent on material, orientation, and printer parameters.
	**Pin diameter** - The minimum reliable pin diameter is 1mm. Smaller diameters are possible, but will have reduced contour sharpness
	**Hole size** - Holes diameters between 0.5mm and 6mm can be printed reliably without supports. Support free building of hole diameters between 6mm and 10mm is orientation dependent. Horizontal holes with a diameter greater than 10mm require support structures.
	**Overhanging Surfaces** - The minimum angle where support material is not required on an overhanging surface is 45º relative to the horizontal in most cases. It is possible to reduce this angle further by optimizing the laser parameters.
	**Unsupported Edges** - The maximum length of a cantilever-style overhanging surface is 0.5 mm. An overhanging horizontal surface supported on both ends can be 1 mm long. These rules will apply to embossed and engraved features with unsupported surfaces as well.
	**Tolerances** - Part tolerance in the print direction is ± 1-layer thickness. In the XY plane, the achievable tolerance is ± 0.127 mm

We therefore had to redesign our CAD model to meet this criterion before beginning the manufacturing process.

7.3 Mounting Flange

Main Body:
The mounting flange outline was cut by the water jet and milled from a 5/8” plate of Type 316L Stainless Steel. Manufacturing took place in the Industrial Technologies Lab the in Mustang ‘60, Building 197.

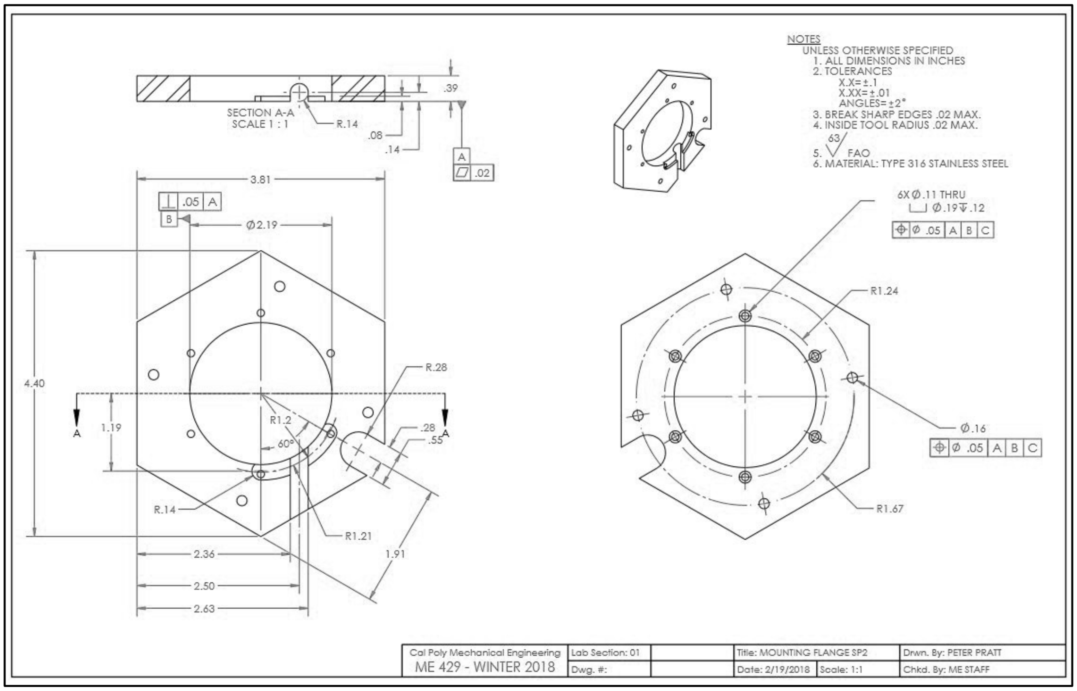


Figure 7.3.1 Detailed Drawing of Mounting Flange

Cutting:
The hexagonal shape and pressure transducer cutout of the mounting flange were cut using the water jet. The water jet cuts with a 3-degree taper from the top surface. In order to maintain flat surfaces each side of the mounting flange was sanded using a belt sander. In cutting the water jet had a mishap and made a small .250” cut into the body of the flange. This cut was filled with a weld and then smoothed out through grinding and sanding.

Milling:
The mounting flange was first face milled down to .400 inches thickness with a 2” carbide face mill. Next, the center pocket of the flange was milled out using a 1” carbide end mill. This process was done by generating a CNC code to ensure circularity. The pitot tube cutout was then milled using a 5/16” carbide ball end mill. Finally, the pitot tube bracket cutout was milled using a rotary table on the mill and a 5/32” carbide flat end mill.

Figure 7.3.2 Face Milling Mounting Flange

Drilling/Boring/Tapping
The mounting flange requires six drilled and bored holes and six tapped holes. The drilling and boring was done using a mill and a rotary table. The rotary table made this process easier because it allowed for one of the holes to be located and then the rest could be found by simply turning the rotary by 60 degrees. The inner holes were drilled with a #33 cobalt jobber drill bit and then counter bored with a #21 cobalt jobber drill bit. The outer holes were drilled with the #21 cobalt jobber drill bit and then tapped with #10-32 carbon steel hand tap.

Integration:
The Mounting Flange will be bolted directly to the rear face of the turbojet with six #4-40 UNF stainless steel socket head screws.

7.4 Throat

Main Body:
The throat was 3-D printed from Type 316L Stainless Steel with the SLM machine in the IME lab. Post machining consisted of face milling and drilling. The IME Department asked that the SLM parts not be machined or sanded for safety reasons. Parts of post machining had taken place but were put on hold until further notice. The manufacturing plan is discussed below and will be carried out by the Aerospace Department technician, Cody Thompson, when approved by the IME Department.

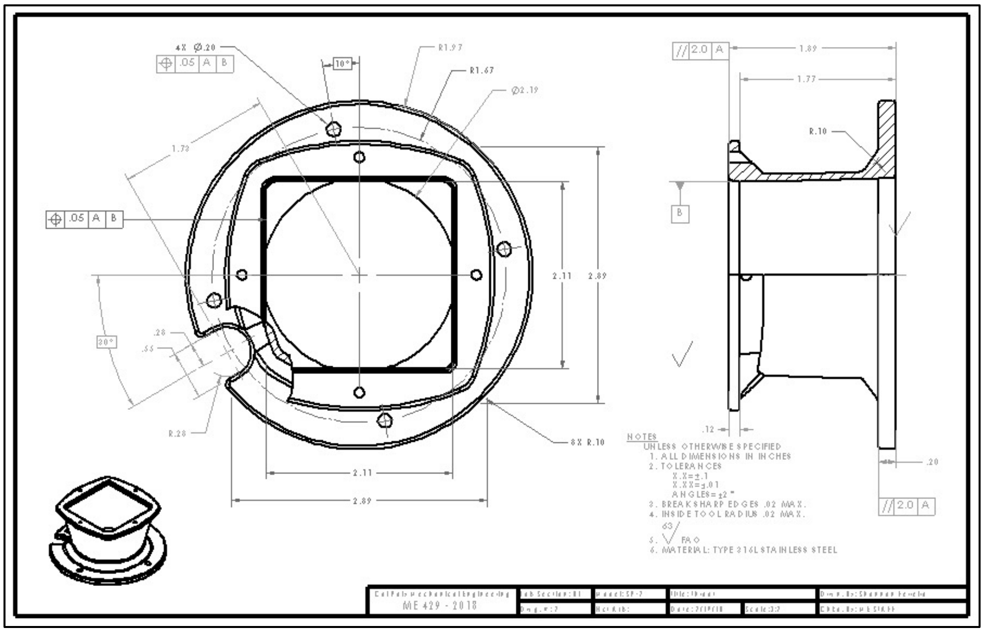


Figure 7.4.1 Detailed Drawing of Throat

SLM:

The SLM process took approximately 36 hours to fully build the throat and had to be cut from the build plate using a band saw. The support material was removed using a grinding wheel and dremel.

Surface Finish:

The surface finish will be refined through hand sanding with 180, 240 and 600 grit sand paper.

Milling:

The top and bottom faces of the throat will need to be face milled with a 1” carbide face mill to meet geometrical tolerances.

Figure 7.2.2 Face Milling Top Surface of Throat

Drilling/Boring/Tapping

The throat requires six drilled holes along the bottom flange. These holes will be drilled with the #11 cobalt drill bit using a rotary table and mill.

Integration:
The throat will be bolted the Mounting Flange using six #10-32 UNF socket head screws.

7.5 Diverging Flange

Main Body:
The diverging flange was manufactured from a 3/8" Type 316L Stainless Steel plate. This process was water jet but not able to be milled due to time.

Cutting:
The flange was cut using the water jet. The sides were belt and hand sanded to even out the 3-degree taper.

Figure 7.5.1 Grinding the Sides of a Stainless-Steel Part

Milling:
The flange will need to be face milled using a 1" carbide face mill down to .250". The outside contour of this flange is difficult to clamp. A four-jaw chuck is recommended as the best alternative to hold the part for milling.

Drilling
The flange will need 4 holes to be drilled with the #33 cobalt jobber drill bit.

Integration:
The diverging flange will be bolted to the Throat with 4 #4-40 UNF stainless steel socket head screws.

7.6 Right and Left Flaps

Main Body:
Both flaps were water jet and milled from a 3/8" plate of Type 316L Stainless Steel plate.

Cutting:
The side flaps were cut using the water jet. The sides were belt and hand sanded to even out the 3-degree taper.

Milling:
The side flaps need to be milled using a 1" carbide face mill and a 3/16" carbide ball end mill.

Integration:
The flaps will be welded to the stainless-steel rods that have been inserted into the top and bottom flaps.

7.7 Top and Bottom Flaps

Main Body:
The top and bottom flaps will be cut using a water jet from a .105" stainless steel plate. They will then be welded to the diverging flange.

Cutting:
The flaps were cut using the water jet. The sides were belt and hand sanded to even out the 3-degree taper.

Welding:
The flaps will be inserted into their respective slots and TIG welded to the diverging flange.

7.8 Assembly of the Diverging Section

Below in Figure 7.7.1, the machined metal components of the diverging section can be seen, without welds, assembled in their appropriate positions. The flap on the right-hand side has been omitted for ease of visibility. The specifications of this assembly can be found in section 6, Final Design.

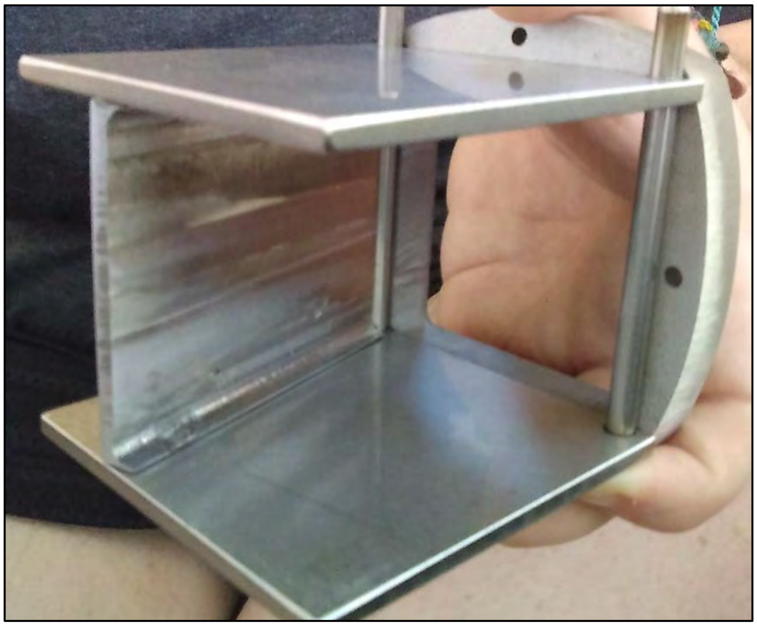


Figure 7.7.1 Diverging Section Without Left Flap

7.8 Future Manufacturing Needed

The previous sections briefly covered what components will need to be manufactured in the future, but this section will go into more detail about the plan. The only fully completed part is the mounting flange. The throat and entirety of the diverging section have been started but not completed.

The throat has been printed, removed from the build plate, the support material has been removed and facing has begun. To finish this part the top and bottom surfaces need to be face milled with the 1” carbide face mill to spec. Next, the four holes need to be drilled using the #11 cobalt jobber drill but on the bottom surface. Lastly, the interior surface needs to be smoothed using a dremel and sand paper. It is important to know that for all processes it is recommended to wear a face or dust mask. The SLM machine produces particles smaller than 5 microns and can be harmful to the lungs if inhaled.

The diverging flange needs to be face milled with the 1” carbide face mill down to spec. One side flap is completed but needs to be sanded on the interior surface. The other side flap needs to be milled and then sanded. The top flaps and rods are cut and complete. Finally, everything needs to be TIG welded for completion. These steps have been explained and outlined to the Aerospace shop technician, Cody Thompson. He has agreed to complete the manufacturing with other aerospace students.

7.9 Manufacturing Recommendations for Remaking Parts

In the instance that a portion of the nozzle becomes damaged and needs to be repaired, we recommend using as much carbide tooling as possible. Several components were machined using non-carbide tooling, which resulted in several drill bits being snapped or otherwise damaged.

8 Design Verification

No design is without its flaws and assumptions. This section elaborates on the analysis we've conducted, along with the tests and other means of verification we have remaining to ensure that the design we have proposed meets the Aerospace Department's wants, needs, and budget, will function as intended, and will be able to withstand the short-term and long-term loads that we expect it to sustain through regular use.

8.1 Testing to Gather Data for Design and Analysis

So far, very few practical tests have been conducted on the engine. The reasons for this are elaborated on in section 9, Project Plan. The plastic 3D printed model known as Structural Prototype 1 was a proof of concept practical test for the feasibility of 3D modeling and a verification that all features of the nozzle had the necessary support and dimensions to print. While much analysis has been done to predict the heat and pressure loads the nozzle and the engine will see, it is impossible to progress into more rigorous and accurate analysis without more data. All of the following tests will be conducted at Cal Poly's Propulsions Laboratory unless otherwise noted. While TurboTRIO was unable to conduct most of them ourselves, these are the tests the Aerospace Department shall carry out:

First, a rough prototype was created out of metal. A test run with just the flange and throat will help determine the engine can handle the presence of a nozzle. Provided the engine's performance doesn't change drastically, the primary testing with the full nozzle can commence, as described under section 6.3 above.

However, should the engine's performance notably change with just the constant-area throat, we recommend additional testing before attaching the assembled diverging section. This would require a 3D printed version of the diverging section fused together into a singular tube. One would be constant area, which would the first one tested with the throat, to see if the extension in the exhaust pipe – without any converging at all – is something the engine can handle, as well as to establish a baseline for that length of nozzle. Next, an identical piece with a 5-10% area convergence would be swapped out, simulating the nozzle when at a slightly converged area ratio. This would confirm the engine could handle limited convergence. It would also allow for models to be created (and verified) to affirm the engine's ability to handle maximum convergence – 20% by design – at maximum throttle. The singular mock diverging sections allow for testing under the best possible conditions, with no losses around the edges of the flaps where the overhangs on the side flaps brush against the top and bottom flaps. They also eliminate the need for an actuation system or anything else holding the flaps in the desired location for testing and generally minimize flow losses. Should issues arise with the intended diverging section, the data comparing these two fixed-area diverging components can provide students an interim solution until such time as a functional variable-area diverging section can be attached.

The Department may also choose to do two other optional tests to prepare for a full-nozzle test: a bolt pull-out test and a test of the engine's capacity to perform normally with the nozzle's weight. These tests are precautionary and would occur before performing the test of the nozzle described above, but analysis indicates a safety facture so large that we believe it is acceptable to not pursue these.

The first of these elective tests is a bolt pull-out test in the materials lab. Simply put, the flange will be secured by its appropriate bolt to the tensile tester in the Materials Engineering lab. The flange will then be tugged until either the bolt or the flange fail, indicating the maximum load the bolt can withstand. The tester will note the failure point for each bolt, then apply a safety factor of at least 2 to the thrust the engine is allowed to produce with the nozzle on. We anticipate that this value will exceed the maximum thrust output of the engine by far.

The other optional test would be attaching weights to the back of the engine, ranging from 0.5 kg to 3 kg. These weights will simulate the load felt by the engine due to the weight of the nozzle. By inspection, the tester can be assured the engine functions normally and sees no deformation in the back plate on account of this weight. The tester can also confirm the load cell still provides accurate measurements of the thrust with the added weight and that the counterbalance weight is sufficient to keep the engine level during testing.

From the test summarized in this section, students can run more accurate cycle analysis on the engine's performance as it is affected by the nozzle and, potentially, determine exactly how the engine would react to different amounts of convergence and divergence. A comparison of the actual cycle analysis to a theoretical one will also determine how useful the nozzle will be for numerical analysis in lab, and allow the Department to tell what accuracy (by percent reduction or increase in exhaust area) is meaningful.

If the nozzle proves effective in demonstrating an alteration to the flow, the Department might also consider doing flow-visualization separate from the turbojet, or create an experimental pressure map of the diverging section's outlet using a pressure rake. This line of consideration would not only provide interesting data for how flow moves through the nozzle but could also provide some interesting demonstrations for other unrelated courses.

8.2 Testing System Performance

Assemblies such as the actuation system will be tested for basic functionality by a room-temperature performance and accuracy test, particularly of any actuation system, or the ability of any temporary figures to hold the side flaps in place while air is moving through the nozzle. Passing that, the assembly will be mounted on the engine and tested for mobility (a confirmation the system was installed correctly), performance as a system, and performance as achieving the parameters we designed to be visible in the engine cycle. These parameters will be confirmed through the engine's DAQ output as well as Prof. Glen Thorncroft and Prof. Graham Doig's thermocouples and pitot tubes.

Should all go well, the system can then be instrumented with permanent instrumentation, have the readouts integration into the computer data collection, and have sample lab procedures created using the test data. This process of data collection will likewise verify the reliability of our nozzle.

A detailed breakdown of all tests to be performed can be found under Appendix O. The risks, concerns, and mitigating efforts is shown in the Risk Assessment, provided in Appendix P.

8.3 Setbacks with Testing and Analysis

This project has faced many roadblocks during its course. The biggest setback to testing was that the engine got shorted out at the beginning of March, not long before our initial testing was supposed to start. The aerospace department's technician often had more pressing priorities, which delayed repairs and consequently the engine remained inoperable for the remainder of this project. This prevented the majority of the testing we'd hoped to do.

However it wasn't the only setback the team faced. Our most useful alternative test would have been to use the supersonic wind tunnel. The tunnel has a small 6" x 6" testing area that would have been easy to create something that funneled the air to go exclusively through our prototype. While the SR-30 has no supersonic potential, this wind tunnel's high pressure capacity would mean the ability to still achieve the same high pressure ratio of the actual engine, except with room-like temperatures. Unfortunately, inspection of the tunnel revealed two crucial flaws: the tunnel's compressor was broken (meaning to test, the Department would have to rent one for approximately $200) and the tunnel lacked instrumentation where we needed it. There were a few thermocouples and pitot tubes, but only one pair (upstream) would have been useful and there was no feasible option to hook up our own instrumentation. Additionally, testing procedure for the tunnel mandated students were not in the room while the compressor was running, meaning that even if we could set up our instrumentation physically, there'd be no way to monitor the outputs. Lastly, the tunnel had been out of use for the better part of a year. While the compressor was a known problem, it'd be hard to determine if any other existing components were in need of repair or replacement.

At this time, as mentioned in the Manufacturing section above, the SLM printer was put under safety review. Without a throat, we had no nozzle; without a nozzle, we had no tests. The team considered doing testing with a plastic 3D printed nozzle (readily available from the Innovation Sandbox), but concluded that at that point there would be too many variables altered to conclude anything usefully referable back to the engine itself. The differences in temperature, the differences in mechanical properties of the plastic (plus safety concerns of the plastic handling the pressure of the air at the appropriate levels, and the weight of the metal diverging section), and the differences in surface finishes would all have to be accounted for. Without any reference to actual engine data, those corrections would be ballpark supposition at best – if the data held meaning at all.

Lastly, issues with manufacturing – including the difficulties reserving the waterjet and lack of carbide tooling on-hand in the machine shops – slowed the manufacturing of the diverging section, meaning that even without the above issues to account for, testing would have been fairly delayed.

9 Project Management

This section discusses the duration of the project and the various deliverables TurboTRIO has committed to completing.

9.1 Deliverables

The design process will span nine months and be completed on June 1, 2018. The steps needed to reach this deadline include; identification of a need, definition of problem, synthesis, analysis and optimization, evaluation, and presentation. Throughout this process key deliverables will be used as checkpoints to ensure the project is on track. These deliverables can be found in Table 9.1.1 below. A Gantt chart timeline of the project can be found in Appendix C.

Table 9.1.1 Key Deliverables for TurboTRIO

Deliverable Name	**Deliverable Description**	**Due**
Scope of Work (SOW)	The start of the formal documentation of the project that grows into the preliminary, interim, and complete design reports. The purpose of the document was to convince the sponsor that we had an understanding of the problem, did background research, and had a plan and the time to complete the project.	10/13/17
Preliminary Design Review (PDR) Presentation	This built off of the SOW and presented the top 5 designs to the class for evaluation and review. This consisted of a report, a presentation and a concept design. This was presented to the sponsor.	11/14/17
Interim Design Review	The interim design review was an informal review which was held in class and reviewed by our peers. At this point all major decisions about the design have been made.	01/16/18
Complete Design Review (CDR) Presentation	This is an extension to the PDR and contained all information needed to complete the design. Detailed drawings, a section describing the design in detail, and associated costs were the main components of the CDR.	02/06/18
Manufacture and Test (M&T) Review	A short presentation to report the status of the manufacturing process. This contained an updated test plan, safety checklist, and an updated schedule focusing on the time needed to complete the project.	03/13/18
Senior Project Expo	This was the final product presentation that showcased the project. The event was open to the public and the poster display was manned by a member of the team at all times.	06/01/18

9.2 The Design Process

The design process outlines the necessary steps to complete each deliverable and complete a final product. As stated in Shigley's Mechanical Engineering Design textbook, the process begins with defining a need (Budynas).

Identification of a Need
The start of the design process began on Thursday September 14, 2017 Professor Graham Doig addressed the Cal Poly Aerospace Department's need for a variable nozzle attachment for their existing SR-30 miniature turbojet. This variable nozzle would be used to demonstrate the effects varying exit area has on the exhaust of the turbojet. Specifically the effects on temperature, pressure and thrust.

Definition of Problem
From September 21 to October 12, 2017 background research was conducted to define the specifications of the problem. To accomplish this, meetings with Professor Doig was held to solidify the Aerospace Department's wants and needs, as well as a proposed budget and timeframe for the project. Background research of nozzle designs, like the ejector nozzle on the J-85-GE-21 engine, induced a feasible basis for a variable nozzle design for the SR-30 turbojet. Test data was recorded on October 6, 2016 in the propulsion lab to obtain critical design specifications for the nozzle. The data is listed in the table below.

Table 9.2.1 Critical Operating Conditions at the current end of the exhaust.

Variable	Minimum Value	Maximum Value
Temperature	310 K	755 K
Pressure	101 kPa	122 kPa
Thrust	13 N	71 N

Synthesis
The synthesis step began with connecting system elements to develop a concept design. This took place from October 13 to November 14, 2017. Ideation took the knowledge gained in defining the problem and compiled it into possible designs. The concept models were evaluated and refined to select the superior concept for the project. This concept was created in CAD for further evaluation and a prototype was constructed for the Preliminary Design Review. At this stage, the design is completed and meets all of the listed design specifications.

Analysis and Optimization
The analysis and optimization began on November 15, 2017 and will end on April 12, 2018. This is a critical and time-consuming stage because it is an iterative process. This means that it may proceed through a number of steps, evaluate the results and go back to an earlier idea to check compatibility. These iterations can take various components back to the synthesis stage to view the effects it has on the system. Through this an optimal design will emerge that is satisfactory for each individual component as well as the complete design of the nozzle. A prototype of the selected nozzle design will be made to be analyzed and further optimized to work out any possible problems.

Evaluation
From April 13 to May 17, 2018 the nozzle was expected to be critically evaluated. The evaluation stage is used as proof of a successful design and includes testing of the prototype in a laboratory. This is where each technical specification of the nozzle would be tested to ensure that Professor Doig's wants and needs were met as well as that the nozzle functions properly. All engineering and non-engineering questions about the nozzle would be answered in this stage. (For reasons expounded upon in 8.3, this evaluation did not occur during this project's timespan.)

Presentation
This stage communicated, on June 1, 2018, the nozzle design to others and proved that the initial problem was solved. Ideally, it would have consisted of delivering the completed final product to Professor Doig and ensuring his satisfaction with the final nozzle design before presenting it to the public in the senior design exposition. This was undoubtedly the most important stage of the design process and was necessary that the team was capable of showcasing the nine-month process in a single product. In practice, the product still had some machining outside our scope of competency, which the Aerospace Department's technician, Cody Thompson, will complete.

9.3 Project Plan for FDR

Between the milestones of CDR and FDR, a set of deadlines and criterion were expected to be met. The primary three categories for these criteria are further system analysis, functional design prototyping, and testing. Table 9.3.1 summarizes the additional steps that were anticipated to be taken before a full system functional prototype would have been be tested, and the timeline for these tasks is reflected in Appendix C.

Table 9.3.1 Project Plan

Detailed Analysis	
System	**Analysis Considerations**
SR-30 - Structures	Load Cell, SR-30 Operation with Nozzle, Housing Thermal Loads, Housing Structural Loads
Nozzle - Fluids	Dimensions, Losses (Rectangular Corners), Material Viscosity
Nozzle - Structures	Nozzle Loads (Structural, Thermal, Vibrational, Weight), Force Translation to Thrust Structure
Actuators	Load Cell, Structural Weight Loads, Thrust Loads, Thermal Loads
Instrumentation	Type (Temperature, Pressure, Stagnation, Static), Operation Range, Position, Calibration, Physical Integration with MiniLab Housing
System Integration	Thrust Structure, Nozzle System Weight, Flange Bolts, DAQ, Instrumentation Limits

Table 9.3.2 Project Plan

Functional Prototyping and Testing	
Functional Prototype	**Test For:**
Stationary Prototype	Structural Loads, Thermal Loads, Thrust Structure, Instrumentation
Variable Area Prototype	Actuator Operation, Thrust Structure, Load Cell, Thrust Produced, Boundary Layer Separation
Instrumentation	Operation Range, Accuracy, Locational Interference, DAQ Integration

9.4 Deviations from FDR Plan

As iterated in other sections, a number of setbacks interfered with the potential for testing. The nozzle's dimensional confirmation and the viability of the manufacturing processes were the only components the team was able to accomplish of our FDR testing goals. Almost all of the tests listed require an operational engine to test on, and will be completed by the Aerospace Department.

10 Conclusions

As was discussed in detail earlier in this document, TurboTRIO has revised and honed the design for our variable area exhaust nozzle to be as accurate as possible without conducting physical tests on the final hardware. These modifications were primarily driven by material limitations and manufacturing constraints, then later affirmed by 3D modeling and analysis. We have completed as much of our metal prototype as safety constraints have allowed – with just a few final post-processing machining procedures remaining for the Aerospace Department to complete. Once the final post-processing has been completed, the completed metal product can be assembled and installed on the SR-30 engine, using the fasteners that we have specified, purchased, and delivered to the Aerospace Department.

We have carefully outlined clear instructions for the Aerospace Department to conduct hot-fire tests of the SR-30 engine with our nozzle attachment, and analyze the resulting data that will be collected. Using these test procedures, our final nozzle design can be validated and further utilized by the department in student laboratory experiments or other research applications.

10.1 Recommendations for Future Development

After conducting a series of tests with our final nozzle hardware as outlined by the TurboTRIO test procedures, further testing and development may be conducted on the nozzle. The initial validation tests that we have outlined for the Aerospace Department to conduct are meant as a proof-of-concept of the nozzle hardware, with the diverging section side flaps held in a series of static positions, so that steady-state analysis can be performed at a series of operating points. Subsequent hardware development should include the addition of an actuation system that will actively change the side flap positions during engine operation. This addition was part of the original scope of our project, and will ultimately prove extremely useful for student lab experiments.

Further augmentation of our nozzle extension should include permanent additional instrumentation, both at the nozzle's exit plane and along the outside walls. Full instrumentation in the exhaust flow-path can be utilized to analyze exhaust exit parameters, such as temperature, pressure, and velocity. These parameters can be compared with the corresponding upstream parameters to assess the effects that the nozzle extension has on changing the exhaust behavior. A MATLAB code has been generated through the course of this project to analyze the SR-30 engine's cycle parameters using the built-in instrumentation, and this code should be adapted to include analysis of any permanent instrumentation that is added to the system. Data measurements from the new instrumentation should also be integrated into the SR-30 Turbojet's Data Acquisition System in LabView, for a fully-operational, user-friendly operating system.

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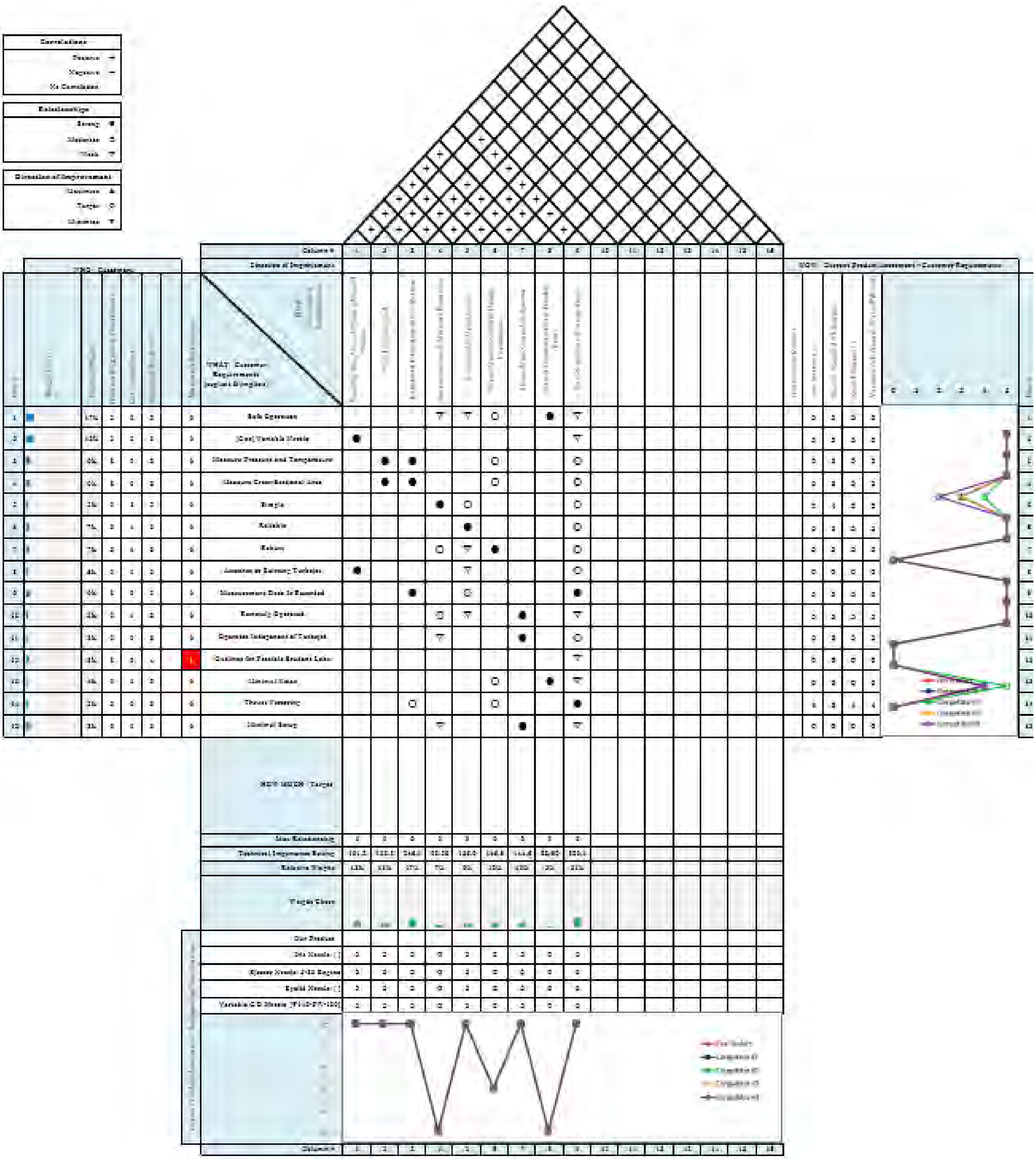
Appendix A: Customer Wants and Needs

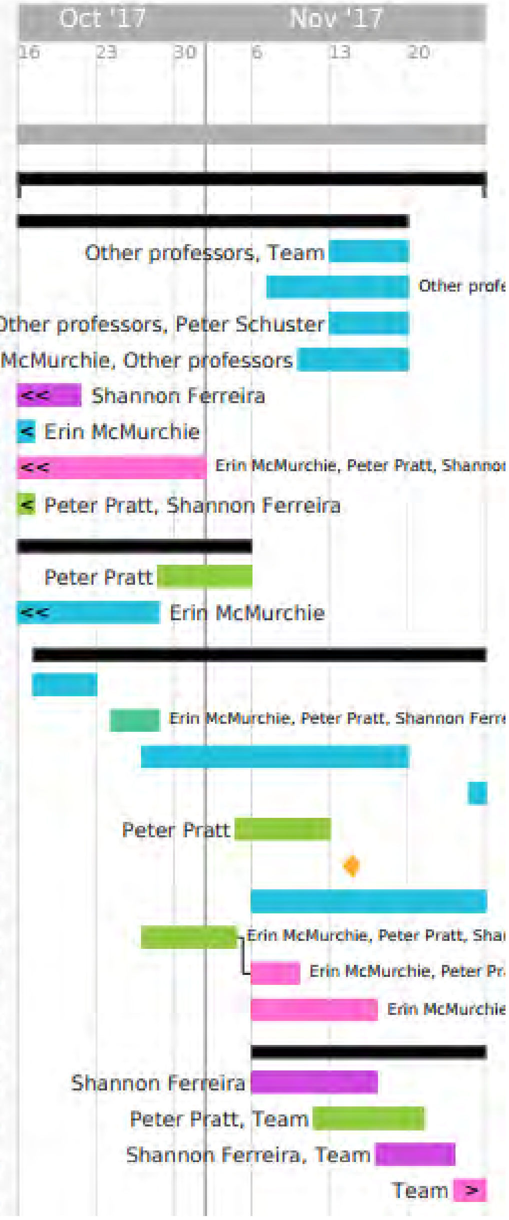
Needs	Wants
• Variable nozzle • Measures pressure and temperature at end of nozzle • Measures pressure and temperature at end of exhaust • Measures cross sectional area at the end of nozzle • Simple, robust, and reliable design • Thermal capability • Attaches to existing system	• Remotely operated • Operates independent of turbojet • Integrate data reading into DAQ interface • Single nozzle • Boundary layer separation visualization • Minimal noise • Thrust vectoring • Minimal setup • Outline for student laboratory exercise

Appendix B: QFD House of Quality

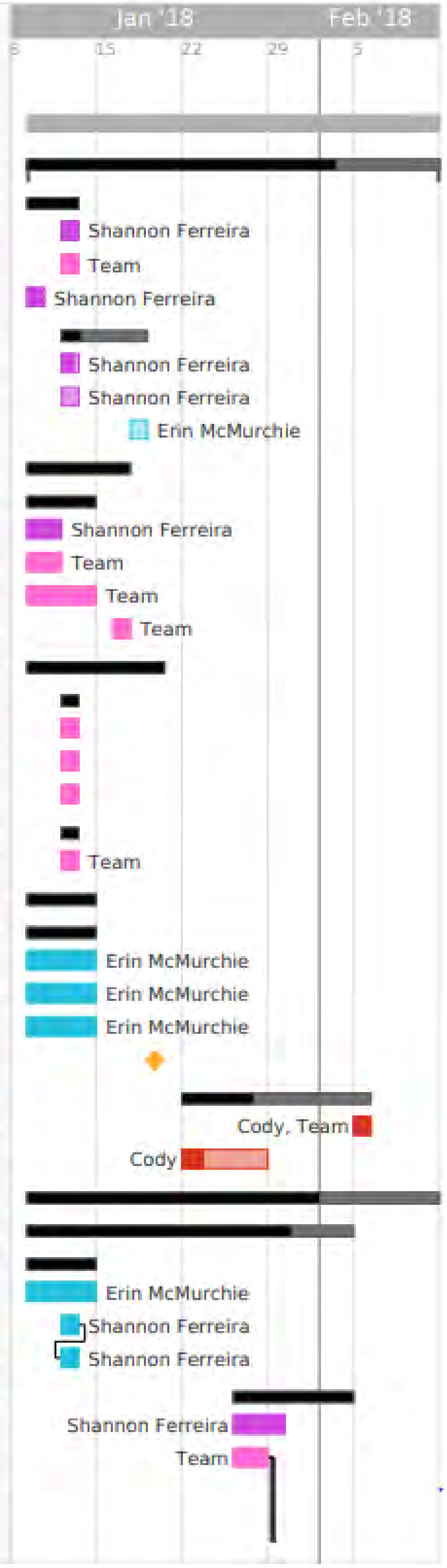


Appendix C: Gantt Chart

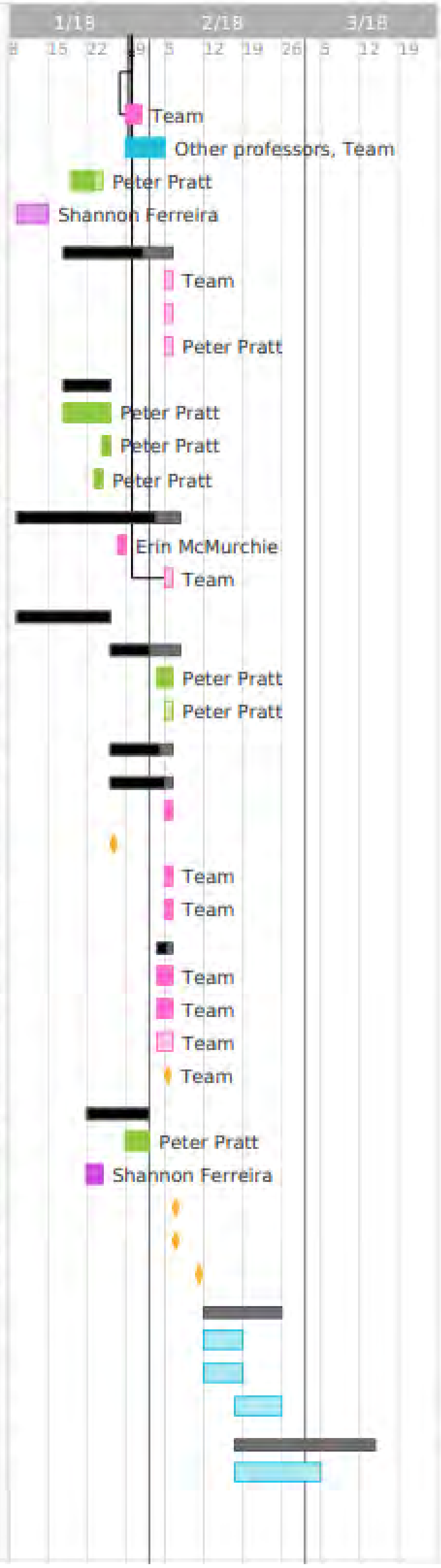
2-3 Mini Turbojet Exhaust (T...	**0h**	**95%**
Fall Quarter 2017	**0h**	**100%**
Background Research	**0h**	**100%**
Talk to Lemieux and Pascual re: eng...	0	100%
Talk with Birdsong/robotics club re: ...	0	100%
Interview IME Professors re: manufa...	0	100%
Interview AERO Professors	0	100%
Converging/Diverging Nozzle Resea...	0	100%
Ejector Nozzle Research	0	100%
Other Variable Nozzle Designs	0	100%
Linear Actuator Research	0	100%
System Requirements	**0h**	**100%**
Create CAD Model	0	100%
Test Run-Data Analysis	0	100%
Initial Design Concept	**0h**	**100%**
Ideation	0	100%
Concept Models	0	100%
Idea Refinement	0	100%
Idea Evaluation and Selection	0	100%
Concept CAD	0	100%
Preliminary Design Review - Class	0	100%
Begin Design Analysis	0	100%
Coordinate Winter Class Schedules	0	100%
Register for classes	0	100%
Ideation, part 2	0	100%
Preliminary Design Review	**0h**	**100%**
Edit SOW - fix comments	0	100%
Expand SOW -- new sections	0	100%
Preliminary Draft	0	100%
Review/edit Draft	0	100%



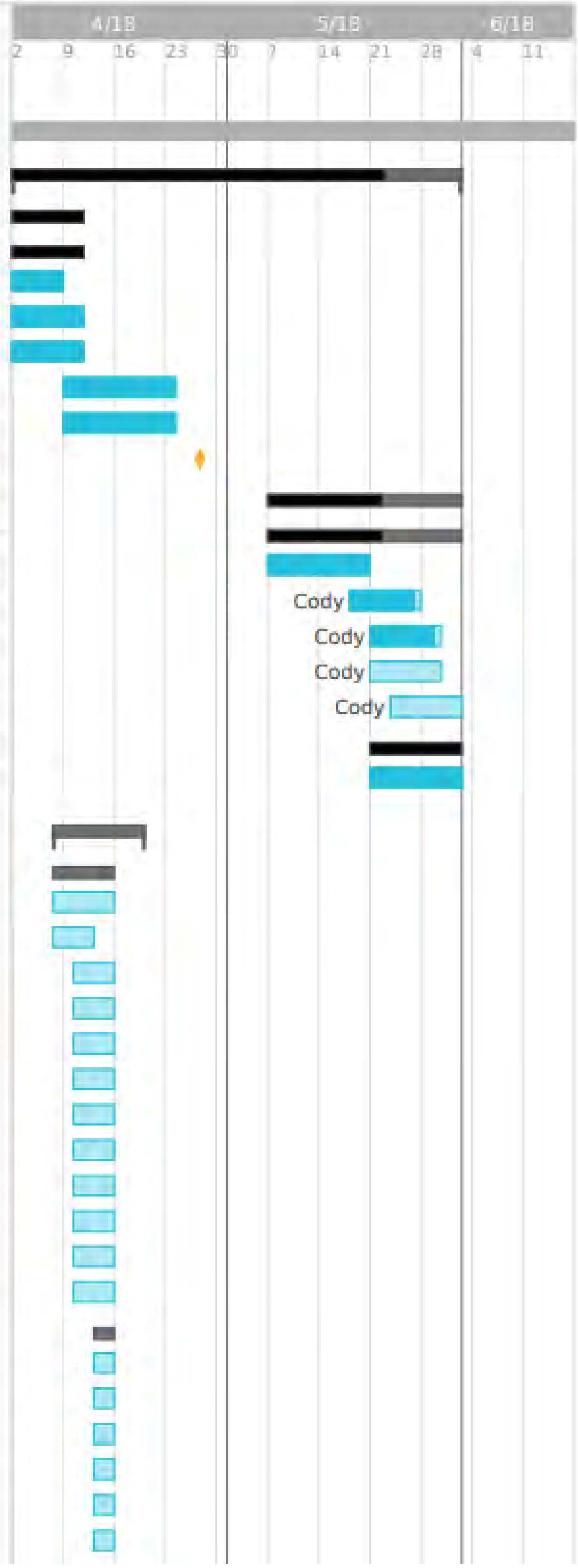
Task	Work	% Complete
2-3 Mini Turbojet Exhaust (T...	0h	75%
Winter Quarter 2018	0h	75%
Start Quarter	0h	100%
New Team Meeting Schedule	0	100%
Edit Team Contract	0	100%
Review PDR Comments	0	100%
Background Research	0h	23%
Changing Shape Ducts	0	70%
Talk to Professors about Changing S...	0	0%
Rectangular Nozzle Articles	0	0%
Gathering Data	0h	100%
Meet Westphal	0h	100%
Research Preliminary Results	0	100%
Check Preliminary Results	0	100%
Westphal Instrumentation	0	100%
Retake Data	0	100%
Interim Design Review (IDR)	0h	100%
Initial Budget	0h	100%
Materials	0	100%
Actuators	0	100%
Fasteners	0	100%
FMEA	0h	100%
FMEA (Failure Modes Effect Analys...	0	100%
Detailed Analysis	0h	100%
Code Calculations	0h	100%
Ideal Engine Performance	0	100%
Efficiencies	0	100%
Variable Area Thrust Difference	0	100%
IDR Presentation	0	100%
SR-30 Engine Work	0h	38%
Back Panel Assembly/Disassembly	0	100%
Cody Throttle CAM	0	25%
Critical Design Review (CDR)	0h	71%
Detailed Analysis	0h	81%
Code Calculations	0h	100%
Work Analysis	0	100%
Data Package Matlab Script	0	100%
Data Plotting	0	100%
Final Data Analysis	0h	100%
Data Trends	0	100%
Hand Calcs	0	100%

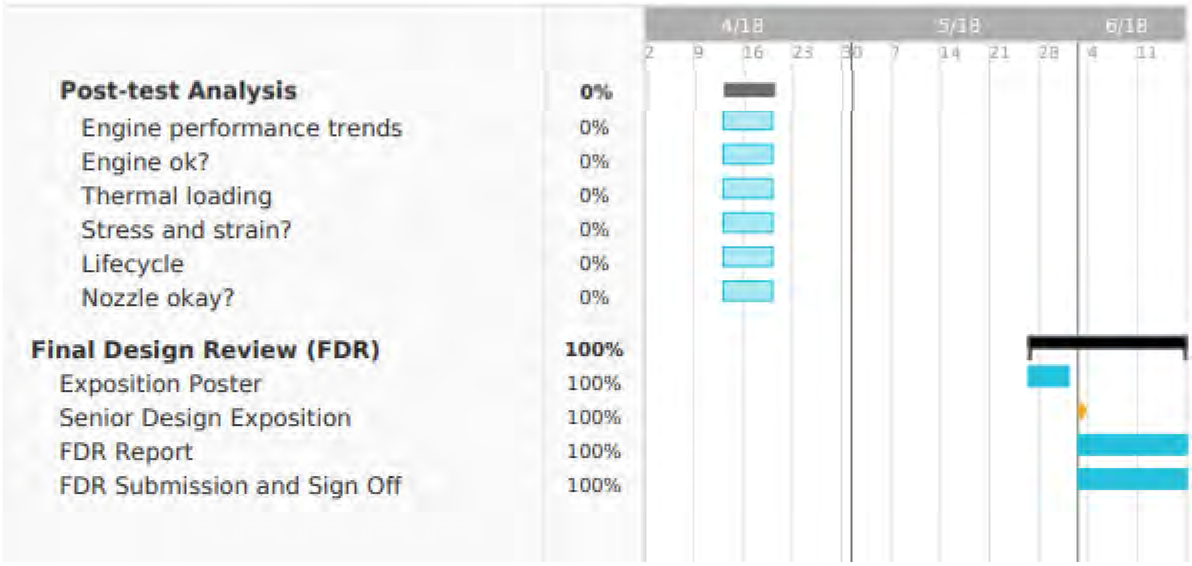


Sanity Check Results Against Lit...	0	100%
Sanity Check Results With Profe...	0	100%
Acuator Selection	0	75%
Instrumentation	0	0%
Manufacturing Processes	**0h**	**73%**
Design for Manufacturing Logbook	0	0%
CAD Model List	0	0%
Bill of Materials	0	0%
Converging Section	**0h**	**100%**
Talk to Martin	0	100%
Talk to Xuan Wang	0	100%
Talk to Trian	0	100%
CAD Refining	**0h**	**85%**
Organize CAD on Drive	0	100%
Add CDR Dimensions to CAD	0	0%
Converging Section Designs	**0h**	**100%**
Diverging Section Design	**0h**	**57%**
Flange Design	0	100%
CAD Assembly	0	0%
Structural Prototype	**0h**	**80%**
Gathering Materials	**0h**	**88%**
Manufacturing Plan	0	75%
Final Part Selection	0	100%
Safety Review	0	100%
Risk Assessment	0	100%
Build Structural Prototype	**0h**	**67%**
Build Converging Section	0	100%
Build Diverging Flaps	0	100%
Build Actuating System	0	0%
Integrate to Turbojet	0	100%
CDR Report	**0h**	**100%**
Changes from PDR	0	100%
Plan New CDR Material	0	100%
CDR Prototype	0	100%
CDR Presentation	0	100%
CDR Report	0	100%
Ordering Parts and Material	**0h**	**0%**
Order bolts, etc.	0	0%
Order Raw Materials, if needed	0	0%
Reserve 3D printer	0	0%
Manufacturing	**0h**	**0%**
3D print	0	0%



Task	Progress
2-3 Mini Turbojet Exhaust (T...	**48%**
Spring Quarter 2018	**83%**
Constant area throat	**100%**
Manufacturing	**100%**
Design tweaks	100%
3D Print throat	100%
Surface finish as needed	100%
Write nozzle safety procedures	100%
Write nozzle use guidelines	100%
Hardware and Safety Demo	100%
Diverging Section	**59%**
Manufacturing	**59%**
Design tweaks	100%
Machine diverging section	90%
Surface finish as needed	90%
Attach diverging section to throat	0%
Confirm sturdiness of connection	0%
Beyond Prototypes	**100%**
Create procedures for full nozzle	100%
Testing and Analysis	**0%**
Testing (measurements)	**0%**
Weight of nozzle	0%
Zeroing and Calibration	0%
Baseline tests/measurements	0%
New engine characteristics	0%
To6, Po6	0%
T @ back plate of engine	0%
Time for engine/nozzle heat to dissi...	0%
T @ outside wall of nozzle	0%
T @ inside wall of nozzle	0%
Decibels (with and without nozzle)	0%
Compression between parts (before...	0%
Vibrational loads	0%
Testing (inspection)	**0%**
Bolts loosen?	0%
Sound increase?	0%
Cracking	0%
Side wall deflection	0%
Top wall deflection (flatness)	0%
Bolts before/after torque	0%




4/18
5/18
6/18
2
9
16
23
30
7
14
21
28
4
11
Post-test Analysis
0%
Engine performance trends
0%
Engine ok?
0%
Thermal loading
0%
Stress and strain?
0%
Lifecycle
0%
Nozzle okay?
0%
Final Design Review (FDR)
100%
Exposition Poster
100%
Senior Design Exposition
100%
FDR Report
100%
FDR Submission and Sign Off
100%

Appendix D: Detailed Analysis Hand Calculations

Cycle Analysis

SR-30 Analysis | 1

Known:

- Run time (t) — t [s]
- Fuel Volumetric Flow Rate — Q_f [gal/hr]
- Engine Shaft Speed — N [rpm]
- Thrust — F [lbf]

- Cycle Parameters:

	static	stagnation	Parameter	units
① Inlet Nozzle		X	$T_1 = T_{01}$	[C]
	*dynamic differential		$P_1 = P_{01}$	[psig]
② Compressor Exit		X	$T_2 = T_{02}$	
	X		P_2	
③ Combustor		X	$T_3 = T_{03}$	
		X	$P_3 = P_{03}$	
④ Turbine Exit	NO DATA		T_4	
			P_4	
⑤ Exhaust "Nozzle" Exit		X	$T_5 = T_{05}$	
		X	$P_5 = P_{05}$	

* Type K Thermocouples

- Fuel = Jet A : LHV = 18,610 BTU/lbf

$\rho = 6.76\ \frac{lbf}{gal}$ @ 15°C (59°F)

→ Jet A : $\rho = 6.84\ \frac{lb}{gal} = 819.6\ \frac{kg}{m^3}$

Jet A-1 : $\rho = 6.71\ \frac{lb}{gal} = 804\ \frac{kg}{m^3}$

$\gamma = ?$

$\eta_1 = ?$

$R = ?$

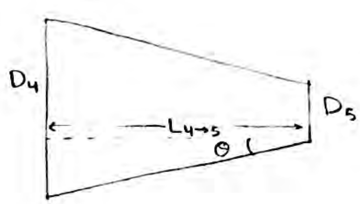
- Engine Dimensions

$D_I = 2.78$ in $= 0.070612$ m

$D_e = 2.1875$ in $= 0.0555625$ m

$D_4 = 3.52$ in $= 0.089408$ m

$L_4 = 11$ cm $= 0.11$ m



SR-30 Data Unit Conversions

Thrust: $[lbf]\left[\frac{4.44822\ N}{1\ lbf}\right] = [N]$

Shaft Speed: $\left[\frac{rev}{min}\right]$

Fuel Flow: $\left[\frac{gal}{hr}\right]\left[\frac{0.00378541\ m^3}{US\ gal}\right]\left[\frac{hr}{3600s}\right] = \left[\frac{m^3}{s}\right]$

$\left[\frac{L}{s}\right]\left[\frac{0.001 m^3}{L}\right] = \left[\frac{m^3}{s}\right]$

Temperature: $[°C] + 273.15 = [K]$

Pressure: $\left([psig] + P_{ambient}\right)\left[\frac{6894.76\ Pa}{psi}\right] = [Pa]$ absolute

OR $\left((kPa(g))\left[\frac{1000\ Pa}{1\ kPa}\right]\right) + P_{ambient}\ [Pa]$

→ $P_{ambient}$: $[mmHg]\left[\frac{101325\ Pa}{760.0\ mmHg}\right]$

→ P_1: $P_1 = P_a - P_{d1}$

$= [Pa] - [kPa]$

$= P_a - [kPa]\left[\frac{1000\ Pa}{1\ kPa}\right]$

Station 5 : Engine Exhaust / Nozzle Inlet

$D_5 = 0.0555625m$

$A_5 = \pi \left(\frac{D_5}{2}\right)^2 = \pi \left(\frac{0.0555625m}{2}\right)^2 \longrightarrow A_5 = 0.00242467 m^2$

$\longrightarrow$ know: Exhaust properties, T_{05}, P_{05}
In data, T_{05} and P_{05} are labled as T_{04} and P_{04}

Station 1: Engine Inlet

$D_1 = 0.070612m$

$A_1 = \pi \left(\frac{D_1}{2}\right)^2 = \pi \left(\frac{0.070612m}{2}\right)^2 \longrightarrow A_1 = 0.0039160 4 m^2$

$\longrightarrow$ know: Air properties, T_1, P_1, $T_{01} = T_{ambient}$, $P_{01} = P_{ambient}$

$0 \rightarrow 1$ Ambient → Inlet (Air) * Treat inlet as incompressible fluid; all other calcs account for compressibility

- known:

T_a T_{01}

$P_a = P_o$ (abs) P_{d1} (dynamic differential)

$V_a = 0$

- $P_{stagnation} = P_{dynamic} + P_{static}$

↳ should be negative gauge value b/c less than stagnation

$\therefore$ P_{static} (abs) $= P_{stagnation}$ (abs) $- P_{dynamic}$ (differential)

$P_1 = P_a - P_{d1}$

→ THEN convert psia to Pa

$P_o = -0.00357$ psig
P_a(abs) $= 14.67$ psia
$P_1 = P_a - P_{d1}$
$= 14.67$ psia $- 0.1823636$ psid
$= 14.4876$ psia $\left[\frac{6894 \text{ Pa}}{\text{psi}}\right]$
$P_1 = 99888.78$ Pa
* Idle Condition

→ Isentropic Flow to Inlet

$$\frac{P_o}{P_1} = \left(1 + \frac{\gamma_A - 1}{2} M^2\right)^{\frac{\gamma_A}{\gamma_A - 1}} \longrightarrow M_1 = \sqrt{\left[\left(\frac{P_{01}}{P_1}\right)^{\frac{\gamma_A - 1}{\gamma_A}} - 1\right]\frac{2}{\gamma_A - 1}}$$

$$\frac{T_{01}}{T_1} = 1 + \frac{\gamma_A - 1}{2} M_1^2 \longrightarrow T_1 = \frac{T_{01}}{1 + \frac{\gamma_A - 1}{2} M_1^2}$$

$$V_1 = M_1 a_1 \longrightarrow V_1 = M_1\sqrt{\gamma_A R_A T_1}$$

→ Ideal Gas Law: $P_1 = \rho_1 R_A T_1 \longrightarrow \rho_1 = \frac{P_1}{R_A T_1}$

→ Mass Flowrate of Air @ Inlet: $\dot{m}_1 = \rho_1 A_1 V_1 = \dot{m}_{Air}$

→ Inlet Diffuser Efficiency: $\eta_d = \frac{T_{01} - T_a}{T_{01} - T_1}$

- assuming isentropic flow for now, $\therefore T_{01} = T_a$

① → ② Compressor (Air)

• known:

T_1	T_{01}	T_{02}
P_1	P_{01}	P_2
M_1		$\dot{m}_2 = \dot{m}_A$
V_1		
ρ_1		
$\dot{m}_1 = \dot{m}_A$		

→ Compressor Work: $\dot{W} = \dot{m}(h_2 - h_1)$

$$\frac{\dot{W}_C}{\dot{m}_A} = C_{pA}(T_{02} - T_{01})$$

→ Compressor Pressure Ratio: (Compression Ratio) $PR = \frac{P_{02}}{P_{01}}$

→ Compressor Efficiency: $\eta_c = \dfrac{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma_A - 1}{\gamma_A}} - 1}{\frac{T_{03}}{T_{02}} - 1}$

→ Ideal Gas Law: $\rho_2 = \frac{P_2}{R_A T_2}$

Need
- P_{02}
- T_2
- ρ_2
- V_2
- M_2

②→③ Combustor (Exhaust)

→ Look up Jet A on CEA

$\dot{Q}_{in}' = \dot{m}_F \, LHV$

$\dot{Q}_{in} = (\dot{m}_A + \dot{m}_F) c_{PE}(T_{04} - T_{03})$

compare values between ideal and actual

- Fuel Volumetric Flow Rate: $Q_F = AV$
- Fuel Mass Flow Rate: $\dot{m}_F = \rho AV = \rho_F Q_F = \dot{m}_F$
- Exhaust Mass Flow Rate: $\dot{m}_E = \dot{m}_A + \dot{m}_F$

Air Fuel Ratio: $AFR = \frac{\dot{m}_A}{\dot{m}_F}$

③→④ Turbine (Exhaust)

→ Turbine Work: $\dot{W} = \dot{m}(h_5 - h_4)$

$$\frac{\dot{W}_T}{\dot{m}_E} = C_{pE}(T_{o5} - T_{o4})$$

→ Turbine Pressure Ratio: $PR = \frac{P_{o4}}{P_{o3}}$
(Expansion Ratio)

→ Turbine Efficiency: $\eta_T = \dfrac{1 - \frac{T_{o4}}{T_{o3}}}{1 - \left(\frac{P_{o4}}{P_{o3}}\right)^{\frac{\gamma_E - 1}{\gamma_E}}}$

* only have P_3, not P_{o3}

Nozzle Design Iteration 1

SR-30 Nozzle Design Iteration 1

→ Design for choked flow condition @ constant area throat

$$\frac{A_5}{A_t} = \sqrt{\frac{1}{M_5^2}\left[\frac{2}{\gamma_E+1}\left(1+\frac{\gamma_E-1}{2}M_5^2\right)\right]^{\frac{\gamma_E+1}{\gamma_E-1}}}$$

$$\longrightarrow A_t = \frac{A_5}{\left\{\frac{1}{M_5^2}\left[\frac{2}{\gamma_E+1}\left(1+\frac{\gamma_E-1}{2}M_5^2\right)\right]^{\frac{\gamma_E+1}{\gamma_E-1}}\right\}^{1/2}}$$

→ Assume square throat; calculate throat dimensions

$$A_t = L_t^2 \longrightarrow L_t = \sqrt{A_t}$$

→ Design Nozzle Exit for Optimal Expansion Condition w/ Square Exit

$P_6 = P_a$ * STATIC Pressure @ 6 must be equal to stagnation back pressure

$P_{o5} = P_{ot} = P_{o6}$ → Assume isentropic flow through nozzle

$$\frac{P_{o6}}{P_6} = \frac{P_{o5}}{P_a} = \left(1+\frac{\gamma_E-1}{2}M_6^2\right)^{\frac{\gamma_E}{\gamma_E-1}} \longrightarrow M_6 = \sqrt{\left[\left(\frac{P_{o6}}{P_6}\right)^{\frac{\gamma_E-1}{\gamma_E}}-1\right]\frac{2}{\gamma_E-1}}$$

$$\frac{A_6}{A_t} = \sqrt{\frac{1}{M_6^2}\left[\frac{2}{\gamma_E+1}\left(1+\frac{\gamma_E-1}{2}M_6^2\right)\right]^{\frac{\gamma_E+1}{\gamma_E-1}}}$$

$$A_6 = \left(\frac{A_6}{A_t}\right)A_t$$

→ Assume Exit is Square @ Optimal Expansion Condition

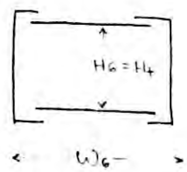
$$A_6 = L_6^2 \longrightarrow L_6 = \sqrt{A_6}$$

Nozzle Design Iteration 2

SR-30 Nozzle Design Iteration 2 — 1

→ Calculate Exit Area and Mach number for a range of exit widths

→ Assume that exit height is equal to nozzle throat height ∴ only diverging geometry is exit width



Looking head-on @ Nozzle Exit

$H_6 = L_t$

$A_6 = H_6 W_6$

$A_6 = \frac{A_6}{A_t} A_t$

→ Plot Mach @ Exit vs. Area @ Exit

→ Plot Mach @ Exit vs. Width @ Exit

→ Calculate flow conditions at Nozzle Exit; Assume isentropic expansion through nozzle

$T_{o6} = T_{o5}$

$P_{o6} = P_{o5}$

$$\frac{P_{o6}}{P_6} = \left(1 + \frac{\gamma_E - 1}{2} M_6^2\right)^{\frac{\gamma_E}{\gamma_E - 1}} \longrightarrow P_6 = \frac{P_{o6}}{\left(1 + \frac{\gamma_E - 1}{2} M_6^2\right)^{\frac{\gamma_E}{\gamma_E - 1}}}$$

$$\frac{T_{o6}}{T_6} = 1 + \frac{\gamma_E - 1}{2} M_6^2 \longrightarrow T_6 = \frac{T_{o6}}{1 + \frac{\gamma_E - 1}{2} M_6^2}$$

$$M_6 = \frac{V_6}{a_6} = \frac{V_6}{\sqrt{\gamma_E R_E T_6}} \longrightarrow V_6 = M_6 \sqrt{\gamma_E R_E T_6}$$

$$F_6 = \underbrace{\dot{m}_E V_6}_{\text{momentum thrust}} + \underbrace{(P_6 - P_a) A_6}_{\text{pressure thrust}}$$

→ Plot Momentum Thrust, Pressure Thrust, and Total Thrust as a function of Nozzle Exit Width

Design 4 Analysis

SR-30 Nozzle Design 4 | Station 5 w/ Nozzle Extension | 1

→ Recalculate flow behavior @ Station 5 w/ nozzle extension attached

• Known: A_5, T_{05}, P_{05}, $\dot{m}_E$, γ_E, R_E

Unknown: T_5, P_5, ρ_5, a_5, V_5, M_5

$$\frac{T_{05}}{T_5} = 1 + \frac{\gamma_E - 1}{2} M_5^2 \longrightarrow T_5 = \frac{T_{05}}{1 + \frac{\gamma_E - 1}{2} M_5^2}$$

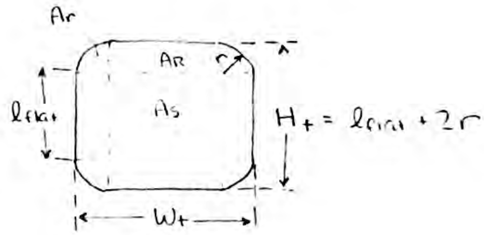
$$\frac{P_{05}}{P_5} = \left(1 + \frac{\gamma_E - 1}{2} M_5^2\right)^{\frac{\gamma_E}{\gamma_E - 1}} \longrightarrow P_5 = \frac{P_{05}}{\left(1 + \frac{\gamma_E - 1}{2} M_5^2\right)^{\frac{\gamma_E}{\gamma_E - 1}}}$$

$$\dot{m}_E = \rho_5 A_5 V_5 \longrightarrow V_5 = \frac{\dot{m}_E}{\rho_5 A_5}$$

$$a_5 = \sqrt{\gamma_E R_E T_5}$$

$$M_5 = \frac{V_5}{a_5}$$

$$\rho_5 = \frac{P_5}{R_E T_5}$$



$A_{Total} = A_{throat} = A_S$

$W_t = H_t$

$A_S = l_{flat}^2$

$A_R = l_{flat}\, r$

$A_r = \frac{1}{4}\pi r^2$

$$\begin{aligned} A_{Total} &= A_S + 4A_R + 4A_r \\ &= (l_{flat}^2) + 4(l_{flat}\, r) + 4\left(\tfrac{1}{4}\pi r^2\right) \\ &= l_{flat}^2 + 4 l_{flat}\, r + \pi r^2 \end{aligned}$$

$H_t = l_{flat} + 2r$

$W_t = H_t$

→ Flow Parameters at Throat

$$\frac{A_t}{A_s} = \frac{M_s}{M_t}\sqrt{\left[\frac{1 + \frac{\gamma_E - 1}{2} M_t^2}{1 + \frac{\gamma_E - 1}{2} M_s^2}\right]^{\frac{\gamma_E + 1}{\gamma_E - 1}}}$$

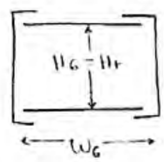
$A_t = A_5$

$A_6 = [\,.60A_t \quad .80A_t \quad 1.0A_t \quad 1.20A_t \quad 1.40A_t\,]$

$A_6 = H_6 W_6 \longrightarrow W_6 = \frac{A_6}{H_6} \quad \therefore \; [W_6] = \frac{[A_6]}{H_6}$

$H_6 = H_t$ → Assume that exit height is equal to the nozzle throat height ∴ only diverging geometry is exit width

$$\frac{A_6}{A_t} = \frac{M_t}{M_6}\left[\frac{1 + \frac{\gamma-1}{2}M_6^2}{1 + \frac{\gamma-1}{2}M_t^2}\right]^{\frac{\gamma+1}{\gamma-1}} \longrightarrow \text{solve for } [M_6]$$



Looking head-on at Nozzle Exit

→ Subsonic flow ∴ P_6 (static) $= P_a$

$$\frac{P_{06}}{P_6} = \left(1 + \frac{\gamma_E - 1}{2}M_6^2\right)^{\frac{\gamma_E}{\gamma_E - 1}} \longrightarrow P_{06} = P_6\left(1 + \frac{\gamma_E - 1}{2}M_6^2\right)^{\frac{\gamma_E}{\gamma_E-1}}$$

→ Assume isentropic expansion (no work, no heat transfer)

∴ $T_{06} = T_{05}$

$$\frac{T_{06}}{T_6} = 1 + \frac{\gamma_E - 1}{2}M_6^2 \longrightarrow T_6 = \frac{T_{06}}{1 + \frac{\gamma_E - 1}{2}M_6^2}$$

$$a_6 = \sqrt{\gamma_E R_E T_6}$$

$$M_6 = \frac{V_6}{a_6} \longrightarrow V_6 = M_6 a_6$$

$$\rho_6 = \frac{P_6}{R_E T_6}$$

Appendix E: Code for Analysis

Design of an Adaptable Exhaust Nozzle for an SR-30 Turbojet Engine
TurboTRIO Senior Project

TurboTRIO Main Script

```
clc
close all
clear
```

Notes

```
% All calculations use SI Units
% Exhaust is modeled as air
% Data collected 1/23/18
% Inputs for the following published script are as follows:
    % What is the FullData file name, including extension?: FullData_1_23_17_Test1.mat
    % What is your ambient temperature [degrees F]?: 71
    % What is your ambient pressure [inHg]?: 30.07
    % What is your desired engine throttle speed [RPM]? : 65000
    % How would you like to dimension the radius of the square throat fillet [m]?: 0.005
```

Nomenclature

```
% Subscripts:
    % 1 = Station 1, Compressor Inlet
    % 2 = Station 2, Compressor Exit/Combustor Inlet
```

```
% 3 = Station 3, Combustor Exit/Turbine Inlet
% 4 = Station 4, Turbine Exit/Rear Cone Entrance
% 5 = Station 5, Rear Cone Exit/Nozzle Inlet
% t = Nozzle Throat
% 6 = Station 6, Nozzle Exit

% a = Ambient Condition
% 0 = Stagnation Value
% d = Differential Value
% A = Air Property
% F = Fuel Property
% E = Air/Fuel Exhaust Mixture Property
```

Load Full Test Data and Input Ambient Parameters

```
prompt1 = 'What is the FullData file name, including extension? ';
FileName = input(prompt1, 's');
load (FileName);

prompt2 = 'What is your ambient temperature [degrees F]? '; % Input Ambient Stagnation Temperature
[F]
Ta = input(prompt2);

prompt3 = 'What is your ambient pressure [inHg]? '; % Input Ambient Stagnation
Pressure [inH]
Pa = input(prompt3);

prompt4 = 'What is your desired engine throttle speed [RPM]? ';
desiredN = input(prompt4); % Desired Engine Speed
for Averaged Data [rpm]
```

Process Full Test Data

Data Averaging Function Zeros, converts units, and averages full data set for all periods of steady state operation.

```
[T01, T02, T03, T05, P1, P2, P03, P05, QF, N, F_actual, Ta, Pa] = InitialProcessing(FullData, Ta,
Pa, desiredN);

% Load Data Outputs from Averaging Function
load ZeroedData.mat
load AveragedData.mat
clear FileName prompt1 prompt2 prompt3 prompt4 % Clear propmt commands from Workspace
```

Load SR-30 Engine Constant Parameters

```
load SR30_Dimensions.mat;                                              % Load SR-30 Dimensions to Workspace
load SR30_Fluid_Properties.mat;                                        % Load SR-30 Fluid Properties to Workspace
```

SR-30 Cycle Analysis

SR-30 Engine Cycle Analysis Function Uses measured data to calculate Brayton Cycle operating parameters.

```
[P01, M1, T1, a1, V1, rho1, m_dot_A, m_dot_F, m_dot_E, AFR, P5_no_nozzle, M5_no_nozzle, T5_no_nozzle, a5_no_nozzle, V5_no_nozzle, rho5_no_nozzle, P5, M5, T5, a5, V5, rho5] = SR30_Cycle_Analysis(Pa, P1, T01, A1, P05, T05, A5, QF, rho_F, gamma_A, R_A, gamma_E, R_E);
```

Design Converging Duct with Shape Change

Nozzle Converging Section Design Function Uses area and flow parameters at Station 5 to design converging duct. Duct has a cross-sectional area change from circular at Station 5 to square at "Throat".

```
prompt5 = 'How would you like to dimension the radius of the square throat fillet [m]? ';
throat_r_fillet = input(prompt5);                                      % Choose radius of square throat corner fillet [m]

[At, throat_l_flat, Ht, Wt, Mt] = ConvergingDesign(A5, M5, throat_r_fillet);
clear prompt5
```

Design Diverging Flap Geometry

Nozzle Diverging Section Design Uses area and flow parameters at Station 5 and throat to design a series of diverging area positions. Calculates the flow parameters for each of these variable exit areas.

```
[Area_Ratio, A6, H6, W6, M6, P6, P06, T6, T06, a6, V6, rho6, adat] = DivergingDesign(At, Ht, Mt, gamma_E, R_E, Pa, T05, m_dot_E);
```

InitialProcessing Function

```
function [T01, T02, T03, T05, P1, P2, P03, P05, QF, N, F_actual, Ta, Pa] = InitialProcessing(FullData, Ta, Pa, desiredN)

DataMatrix = FullData;
% Imported data columns: Time, T1, T2, T3, T5, P1, P2, P3, P5, Fuel flow, RPM, Thrust
variable = DataMatrix(:,11); % rpm
dataLength = length(variable); % number of data points per column
```

Zeroing Data and Converting Units

```
% Ambient Conditions
Ta = (Ta + 459.67)*(5/9); % Ambient Stagnation Temperature [K]
Pa = Pa*3386.389; % Ambient Stagnation Pressure [Pa]

% Zeroes
ZeroLengthStart = 10; % Start index for section to average as a zero
ZeroLengthEnd = 50; % End index for section to average as a zero

clear ZeroTime ZeroT1 ZeroT2 ZeroT3 ZeroT5 ZeroP1 ZeroP2 ZeroP3 ZeroP5 ZeroFuelRate ZeroRPM ZeroThrust
ZeroTime = DataMatrix(1, 1);
ZeroT1 = 0;
ZeroT2 = 0;
ZeroT3 = 0;
ZeroT5 = 0;
ZeroP1 = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 6));
ZeroP2 = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 7));
ZeroP3 = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 8));
ZeroP5 = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 9));
ZeroFuelRate = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 10));
ZeroRPM = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 11));
ZeroThrust = mean(DataMatrix(ZeroLengthStart:ZeroLengthEnd, 12));

clear ZeroedData

% Zeroing and converting to the right units
i = 1;
while i < dataLength + 1

    ZeroedData (i, 1) = DataMatrix(i,1) - ZeroTime; % time [s]

    % Absolute Temperature
    ZeroedData (i, 2) = DataMatrix(i,2) - ZeroT1 + 273.15; % Compressor Inlet Stagnation Temperature [K]
```

```
    ZeroedData (i, 3) = DataMatrix(i,3) - ZeroT2 + 273.15; %    Compressor    Exit    Stagnation
Temperature                                                                                  [K]
    ZeroedData (i, 4) = DataMatrix(i,4) - ZeroT3 + 273.15; % Turbine Inlet Stagnation Temperature
[K]
    ZeroedData (i, 5) = DataMatrix(i,5) - ZeroT5 + 273.15;       %   Exhaust   Gas   Stagnation
Temperature                                                                                  [K]

    %                                  Absolute                                        Pressure
    ZeroedData (i, 6) = Pa - ((DataMatrix(i,6) - ZeroP1)*1000);                  %   Compressor
Inlet                    Static                        Pressure                             [Pa]
    ZeroedData (i, 7) = Pa + ((DataMatrix(i,7) - ZeroP2)*1000);                  %   Compressor
Exit                     Static                        Pressure                             [Pa]
    ZeroedData (i, 8) = Pa + ((DataMatrix(i,8) - ZeroP3)*1000);
      %         Combustion         Chamber          Stagnation         Pressure           [Pa]
    ZeroedData (i, 9) = Pa + ((DataMatrix(i,9) - ZeroP5)*1000);                  % Exhaust  Gas
Stagnation                                     Pressure                                     [Pa]

    %                                  Other                                         Parameters
    ZeroedData (i, 10) = (DataMatrix(i,10) - ZeroFuelRate)*0.00000028;
      %           Fuel           Volumetric          Flow           Rate             [m^3/s]
    ZeroedData (i, 11) = DataMatrix(i,11) - ZeroRPM;              %    Shaft    Speed    [rpm]
    ZeroedData (i, 12) = DataMatrix(i,12) - ZeroThrust;           %  Engine  Thrust  Output  [N]

     i                                       =                                          i+1;
end

save                          ('ZeroedData.mat',                               'ZeroedData');
% display('Data has been successfully zeroed, converted to the right units, and saved as a .mat
file.')
```

Averaging the Data

```
% Define Parameters

settlingLength = 30;                              %  number  of  data  points  to  detect  drift
[settling]
reactionLength = 5;                                      % number of data points to detect an
intentional                                                                               change
allowedChange = 2;                                             %  percent  variation  allowed
within                    an                        averaged                                area
n = 0;                                                                % number of rows of of
saved               averages;                no                 data                  initially
minLength = 20;                                                % each averaged segment must
contain             at              least              20              data              points
```

```
lastStart = dataLength - settlingLength - minLength;% last data index to contain a possibly-valid
data set
```

Desired Data

```
i = 1;
       %                        resets                       data                    index
while variable(i,1) < 20000                                                         % min N
=                   40000                    rpm                    at                 idle
    i = i + 1;
       %            gets            past            'engine            off'            section
end

%     identifying     steady-state     times     and     averaging     the     data     within
while i < lastStart
       % loop averaging code to find all steady-state segments and their averages

% determining first element that is considered the start of a stable section [if less than
settlingLength,        then        not        a        valid        sample;        not        settled]
    while                          i                          <                          lastStart
        x = 1;
       %                        segment                       length                       counter
        firstValue = variable(i);                                                      % first
value                  in                  a                  stable                  section

        while                      x                      <                      settlingLength
            compValue = variable(i+x);                                                     %
comparision                                                                              value
            ratioP = abs((firstValue-compValue)/(firstValue))*100; %   percent   deviation   from
reference

            if                      ratioP                      >                      allowedChange
                break;
            else
                x = x+1;
               % changes index without impacting total index, measures distance past reference
            end
        end

        if x == settlingLength
       %   if   x   has   reached   settling   length,   you   have   a   valid   starting   index
            break;
        else
       % if x has NOT reached settling, you need to try again with the next starting point
            i                                       =                                       i+1;
        end
end

if i == lastStart
       % i has exceeded the last index possible to find SettlingLength number of steady state
values                                         to                                         average
```

```
    return
end
```

Determine Last Element within a Stable Section

```
maxLength = dataLength - i;                           % max number of possible valid samples

while                          x                           <                           maxLength
       compValue = variable(i+x);                                   %       comparision       value
       ratioP = abs((firstValue-compValue)/firstValue)*100;%  percent  variation  from  reference

       if                      ratioP                      >                       allowedChange
              break;
       else
              x = x+1;                                                            % changes index
without                        impacting                        total                        index
    end                                                                                   %  x  is
equal           to            the           length           of           viable           segment
end
```

Accumulate Variable Segment Averages into a Single Array

```
i = i + settlingLength;                                                           %    get    past
spikes
x = x - reactionLength – settlingLength;
       % number of valid data points for averaging, starting past settlingLength
```

Write Averaged, Zeroed Data into an Array

```
if x > minLength - 1
       %   x   contains   enough   data   points   that   the   average   is   a   trustworthy   value
    n = n+1;                                                                             %  index
for        avgTotal;        adds        new        row        for        the        new        data

    % Columns: time, T1, T2, T3, T5, P1, P2, P3, P5, Fuel flow, rpm, thrust, start index, end index
    AvgTotal(n, 1) = mean(ZeroedData(i:(i+x), 1));         %                                  time
    AvgTotal(n, 2) = mean(ZeroedData(i:(i+x), 2));         %                                    T1
    AvgTotal(n, 3) = mean(ZeroedData(i:(i+x), 3));         %                                    T2
    AvgTotal(n, 4) = mean(ZeroedData(i:(i+x), 4));         %                                    T3
    AvgTotal(n, 5) = mean(ZeroedData(i:(i+x), 5));         %                                    T5
    AvgTotal(n, 6) = mean(ZeroedData(i:(i+x), 6));         %                                    P1
    AvgTotal(n, 7) = mean(ZeroedData(i:(i+x), 7));         %                                    P2
    AvgTotal(n, 8) = mean(ZeroedData(i:(i+x), 8));         %                                    P3
    AvgTotal(n, 9) = mean(ZeroedData(i:(i+x), 9));         %                                    P5
    AvgTotal(n, 10) = mean(ZeroedData(i:(i+x), 10));       %              fuel                flow
    AvgTotal(n, 11) = mean(ZeroedData(i:(i+x), 11));       %                                   rpm
    AvgTotal(n, 12) = mean(ZeroedData(i:(i+x), 12));       %                                thrust
```

```
    AvgTotal(n, 13) = i;                                          %    starting    index    of    segment
    AvgTotal(n, 14) = i+x;                                        %    ending    index    of    segment

    i                                   =                                                            i+x;
else
    % display('Not enough data points remaining to constitute a statistically trustworthy
average.')
end

end

save                            ('AveragedData.mat',                              'AvgTotal');
% display('Data successfully averaged and saved as a .mat file.')
```

Isolate Data at the Desired Engine Speed (rpm)

```
desiredN                                  =                                              65000;
desiredRPM_low = desiredN - 1500;
       % accounts for set N drifting during data collection, averaging slightly below the desired
value
desiredRPM_high = desiredN + 1500;    % accounts for set N having potentially been higher than
desired
i                                         =                                                   1;
lengthAverages                         =                              length(AvgTotal(:,11));
while i < (lengthAverages+1)
       %   identifying   the   line   of   averaged   data   closest   to   the   desired   RPM
    if                   (AvgTotal(i,11)                <                    desiredRPM_low)
        i                                    =                                           i+1;
    elseif                 (AvgTotal(i,11)                >                 desiredRPM_high)
        i                                    =                                           i+1;
    else
        break
    end
end

if               i              ==              lengthAverages              +              1
    % display ('Could not find the indicated desired speed. Please check your data or input a
different                                                                              value.')
    return
else
end
```

Define All Variables as Averages Corresponding to the Desired Engine Speed

```
T01 = AvgTotal(i,2);                                          %    Compressor    Inlet    Stagnation
Temperature                                                                                     [K]
T02 = AvgTotal(i,3);                                          %    Compressor    Exit    Stagnation
Temperature                                                                                     [K]
T03 = AvgTotal(i,4);                                          % Turbine Inlet Stagnation Temperature
[K]
T05 = AvgTotal(i,5);                                          % Exhaust Gas Stagnation Temperature
```

```
[K]

P1 = AvgTotal(i,6);                              % Compressor Inlet Static Pressure
[Pa]
P2 = AvgTotal(i,7);                              % Compressor Exit Static Pressure [Pa]
P03 = AvgTotal(i,8);                             % Combustion Chamber Stagnation
Pressure                                                                        [Pa]
P05 = AvgTotal(i,9);                             % Exhaust Gas Stagnation Pressure [Pa]

QF = AvgTotal(i,10);                             % Fuel Volumetric Flow Rate [m^3/s]
N = AvgTotal(i,11);                              % Engine Speed [rpm]
F_actual = AvgTotal(i,12);                  % Actual Engine Thrust Measured [N]

end
```

SR-30 Engine Dimensions

```
D1 = 0.070612;                                          %    Station    1    Diameter    [m]
D4 = 0.089408;                                          %    Station    4    Diameter    [m]
D5 = 0.0555635;                                         %    Station    5    Diameter    [m]

R1 = D1/2;                                              %     Station     1     Radius     [m]
R4 = D4/2;                                              %     Station     4     Radius     [m]
R5 = D5/2;                                              %     Station     5     Radius     [m]

A1 = pi()*(R1^2);                                       % Station 1 Cross-Sectional Area [m^2]
A4 = pi()*(R4^2);                                       % Station 4 Cross-Sectional Area [m^2]
A5 = pi()*(R5^2);                                       % Station 5 Cross-Sectional Area [m^2]

L_4_5 = 0.11;                                   % Horizontal Length between Stations 4 and 5
[m]
theta_4_5 = atand(((D4-D5)/2)/L_4_5);           % Wall Angle between Stations 4 and 5 [deg]
```

SR-30 Fluid Properties

```
%                    Air                    Properties
gamma_A = 1.4;                    % Specific Heat Ratio
R_A = 286.9;                      % Specific Gas Constant [J/kg*K]

%                    Fuel                   Properties
rho_F = 819.6;                    % Fuel Density [kg/m^3]

%           Exhaust          Mixture        Properties
    %           Model             as               Air
gamma_E = 1.4;                    % Specific Heat Ratio
R_E = 286.9;                      % Specific Gas Constant [J/kg*K]

%        Gravitational         Acceleration   Constant
g = 9.806;                        % Gravity [m/s^2]
```

SR30_Cycle_Analysis Function

```
function [P01, M1, T1, a1, V1, rho1, m_dot_A, m_dot_F, m_dot_E, AFR, P5_no_nozzle, M5_no_nozzle,
T5_no_nozzle, a5_no_nozzle, V5_no_nozzle, rho5_no_nozzle, P5, M5, T5, a5, V5, rho5] =
SR30_Cycle_Analysis(Pa, P1, T01, A1, P05, T05, A5, QF, rho_F, gamma_A, R_A, gamma_E, R_E)
% SR-30 Cycle Analysis
% Runs cycle analysis on SR-30 turbojet engine.
% Solves for exhaust flow parameters needed to design nozzle extension.

% Station 0 to 1 - Compressor Inlet (Air)
P01 = Pa;
       % Inlet Stagnation Pressure [Pa]
M1 = sqrt((((P01/P1)^((gamma_A-1)/gamma_A))-1)*(2/(gamma_A-1)));      % Inlet Mach Number
T1 = T01/((1+(((gamma_A-1)/2)*(M1^2))));                              % Inlet
Static Temperature [K]
a1 = sqrt(gamma_A*R_A*T1);
       % Inlet Local Speed of Sound [m/s]
V1 = M1*a1;
       % Inlet Velocity [m/s]
rho1 = P1/(R_A*T1);
       % Inlet Density [kg/m^3]
m_dot_A = rho1*A1*V1;
       % Air Mass Flow Rate [kg/s]

% Station 2 to 3 - Combustor (Exhaust)
m_dot_F = rho_F*QF;
       % Fuel Mass Flow Rate [kg/s]
m_dot_E = m_dot_A + m_dot_F;                                          %
Exhaust Mass Flow Rate [kg/s]
AFR = m_dot_A/m_dot_F;
       % Air-Fuel Ratio

% Station 5 No Nozzle - Engine Exit (Exhaust)
    % Cycle Analysis before nozzle extension is added to turbojet
P5_no_nozzle = Pa;
       % Station 5 Static Pressure [Pa]
    % Static Pressure at Station 5 is equal to Ambient/Back Pressure b/c exhaust is subsonic
M5_no_nozzle = sqrt((((P05/P5_no_nozzle)^((gamma_E-1)/gamma_E))-1)*(2/(gamma_E-1)));
       % Station 5 Mach Number
T5_no_nozzle = T05/((1+(((gamma_E-1)/2)*(M5_no_nozzle^2))));          % Station 5
Static Temperature [K]
a5_no_nozzle = sqrt(gamma_E*R_E*T5_no_nozzle);
       % Station 5 Local Speed of Sound [m/s]
V5_no_nozzle = M5_no_nozzle*a5_no_nozzle;                             %
Station 5 Velocity [m/s]
rho5_no_nozzle = P5_no_nozzle/(R_E*T5_no_nozzle);                     % Station 5
Density [kg/m^3]



% Station 5 With Nozzle - Nozzle Inlet (Exhaust)
    % Cycle Analysis after nozzle extension is added to turbojet
```

```
syms T5 P5 V5 a5 M5 rho5
eqn1 = T5 == T05/(1+(((gamma_E-1)/2)*(M5^2)));
eqn2 = P5 == P05/((1+(((gamma_E-1)/2)*(M5^2)))^(gamma_E/(gamma_E-1)));
eqn3 = V5 == m_dot_E/(rho5*A5);
eqn4 = a5 == sqrt(gamma_E*R_E*T5);
eqn5 = M5 == V5/a5;
eqn6 = rho5 == P5/(R_E*T5);
sol = vpasolve([eqn1, eqn2, eqn3, eqn4, eqn5, eqn6], [T5, P5, V5, a5, M5, rho5]);
T5 = double(sol.T5);
P5 = double(sol.P5);
V5 = double(sol.V5);
a5 = double(sol.a5);
M5 = double(sol.M5);
rho5 = double(sol.rho5);

end
```

ConvergingDesign Function

```
function [At, throat_l_flat, Ht, Wt, Mt] = ConvergingDesign(A5, M5, throat_r_fillet)

%                 Nozzle                 Converging                  Section                    Design
    %  Uses  area  and  flow  parameters  at  Station  5  to  design  converging  duct.
    %  Duct  has  a  cross-sectional  area  change  from  circular  at  Station  5  to
    % square at "Throat".
```

Determine Throat Dimensions

```
% Design throat outside dimensions
syms                                                                                          l_flat
At = A5;

       %  Throat  cross-sectional  area  is  equal  to  area  at  Station  5  [m^2]
eqn6  =  At  ==  (l_flat^2)  +  (4*l_flat*throat_r_fillet)  +  (pi()*throat_r_fillet^2);
       %   Relationship   between   throat   area   and   throat   dimensions
throat_l_flat = double(solve(eqn6,l_flat));                     % Throat flat section length
[m]

%                 Design                 throat                  outside                 dimensions
Ht = throat_l_flat(2,1) + (2*throat_r_fillet);                         % Throat total height
[m]
Wt = Ht;                                                                                     %
Throat total width [m]
```

Determine Flow Parameters at Throat

Solve for flow parameters at throat.

```
Mt = M5;                                              % Assume no losses in converging duct
shape change

end
```

DivergingDesign Function

```
function [Area_Ratio, A6, H6, W6, M6, P6, P06, T6, T06, a6, V6, rho6, adat] = DivergingDesign(At, Ht, Mt, gamma_E, R_E, Pa, T05, m_dot_E)

%                  Nozzle                  Diverging                  Section                  Design
    %   Uses   area   and   flow   parameters   at   Station   5   and   throat   to   design   a
    %   series   of   diverging   area   positions.   Calculates   the   flow   parameters
    % for each of these variable exit areas.
```

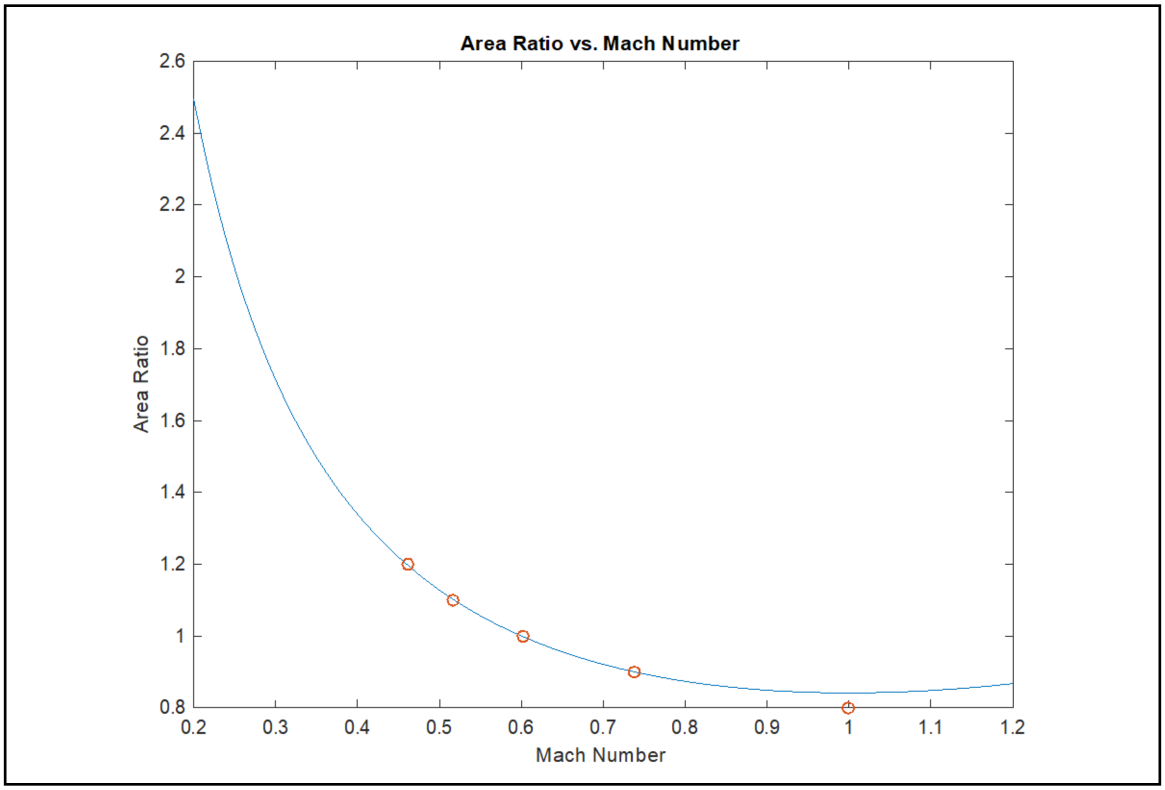
Define Variable Nozzle Exit Area Dimensions

Define 5 positions of Station 6 as percentages of the throat cross-sectional area

```
Area_Ratio = [0.8, 0.9, 1, 1.1, 1.2];                              % A6_sizes = [60%; 80%; 100%;
120%;                                                                                   140%]
A6 = At.*Area_Ratio;                                                           % Define Matrix
of                                            A6                                              values

H6 = Ht;                            % Height between top and bottom flaps will remain constant
with                                         throat                                           hieght
W6 = A6./H6;                                       % Width between side flaps will vary to vary
nozzle exit area
```

Solve for Mach Number at Station 6

```
A6_At                                          =                                          A6/At;
M                                     =                                    linspace(.2,1.2,200);
A6_A          =          (Mt./M).*          sqrt((((1+(((gamma_E-1)/2).*(M.^2)))./(1+(((gamma_E-
1)/2).*(Mt.^2)))).^((gamma_E+1)/(gamma_E-1))));

figure
plot(M,A6_A)
title('Area                Ratio                vs.                Mach                Number')
ylabel('Area                                                                              Ratio')
xlabel('Mach                                                                             Number')
grid                                                                                          on

for                   i                          =                                1:length(A6_At)
    Atemp                                    =                                    A6_A-A6_At(i);
    [~,I]                                   =                                  min(abs(Atemp));
    M6(i)                                         =                                        M(I);
end

hold                                                                                          on
plot(M6,A6_At,'o')
hold off
```



Determine Flow Parameters at Station 6

```
P6 = Pa;                                                    % Station 6 Static Pressure [Pa]
    % Static pressure at nozzle exit is equal to ambient (back) pressure
P06 = P6.*((1+(((gamma_E-1)/2).*(M6.^2))).^(gamma_E/(gamma_E-1)));
    % Station 6 Stagnation Pressure [Pa]
T06 = T05;                                                  % Station 6 Stagnation Temperature [K]
    % Assume Isentropic Expansion between Stations 5 and 6
T6 = T06./((1+(((gamma_E-1)/2).*(M6.^2))));           % Station 6 Static Temperature [K]
a6 = sqrt(gamma_E*R_E.*T6);                                 % Station 6 Local Speed of Sound [m/s]
V6 = M6.*a6;                                                % Station 6 Velocity [m/s]
rho6 = P6./(R_E.*T6);                                       % Station 6 Density [kg/m^3]
```

Ideal Thrust Produced with Nozzle Extension

```
F_ideal_momentum6 = m_dot_E.*V6;                      % Ideal Momentum Thrust Produced [N]
F_ideal_pressure6 = (P6-Pa).*A6;                            % Ideal
```

```
Pressure Thrust Produced [N]
F_ideal6 = F_ideal_momentum6 + F_ideal_pressure6;         % Ideal Total Thrust Produced [N]
```

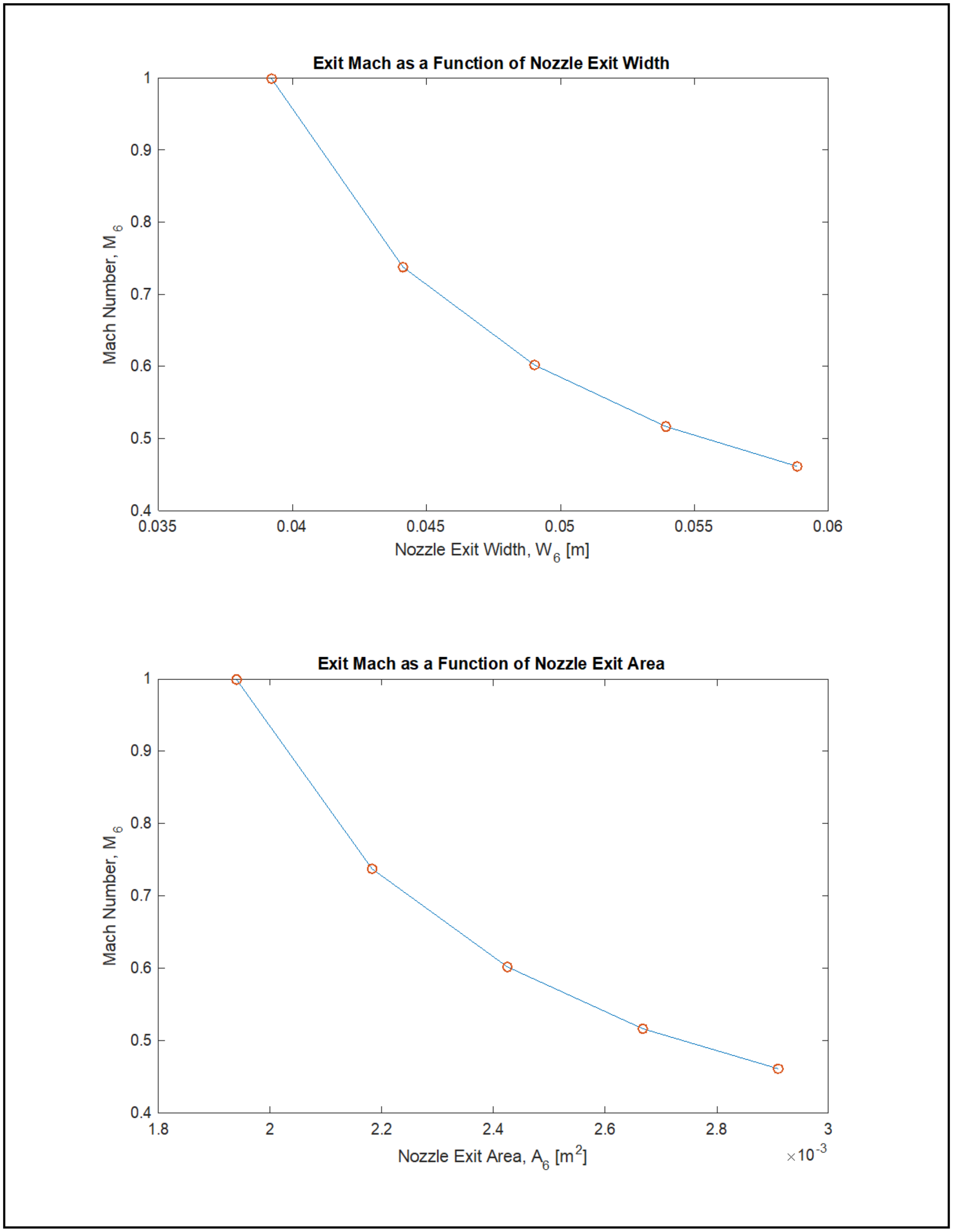
Create Data Structure

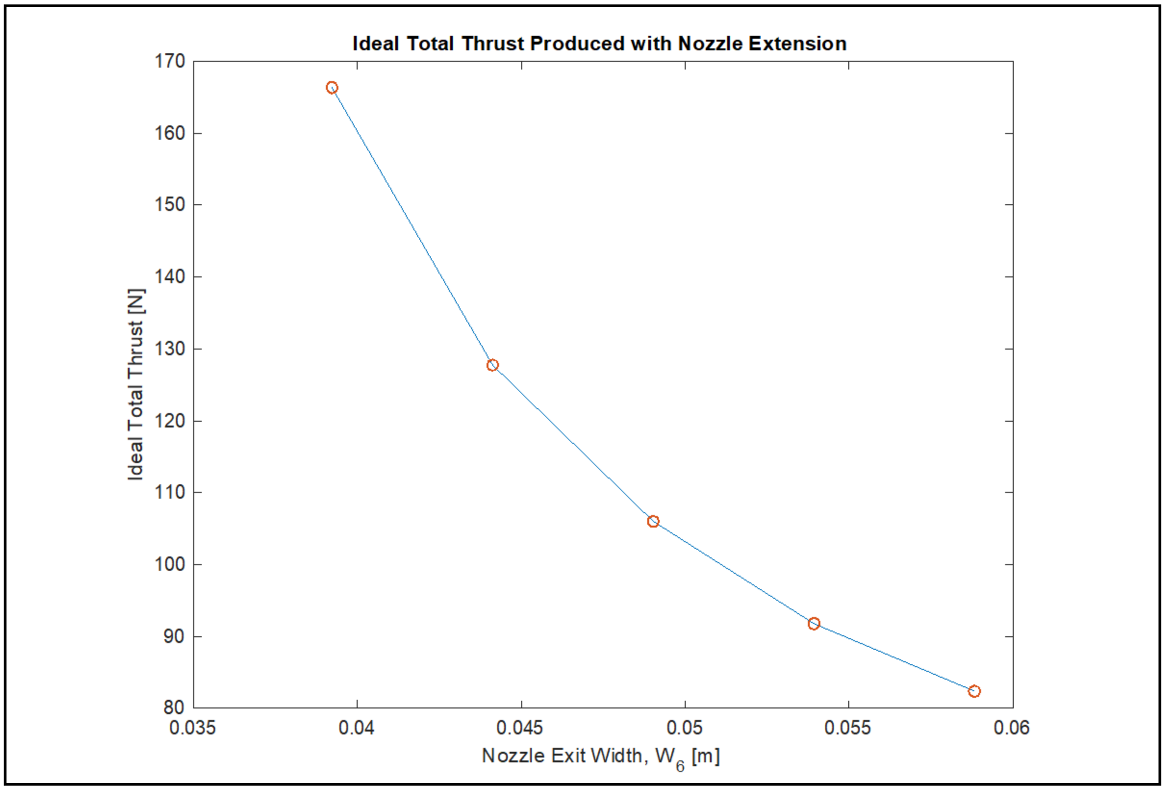
```
 for i = 1:length(A6)
     adat.(['A6' num2str(i)]).AreaRatio6 = Area_Ratio(i);
     adat.(['A6' num2str(i)]).W6 = W6(i);
     adat.(['A6' num2str(i)]).M6 = M6(i);
     adat.(['A6' num2str(i)]).P06 = P06(i);
     adat.(['A6' num2str(i)]).T6 = T6(i);
     adat.(['A6' num2str(i)]).a6 = a6(i);
     adat.(['A6' num2str(i)]).V6 = V6(i);
     adat.(['A6' num2str(i)]).rho6 = rho6(i);
     adat.(['A6' num2str(i)]).F_ideal6 = F_ideal6(i);
 end
save ('adat.mat', 'adat');
```

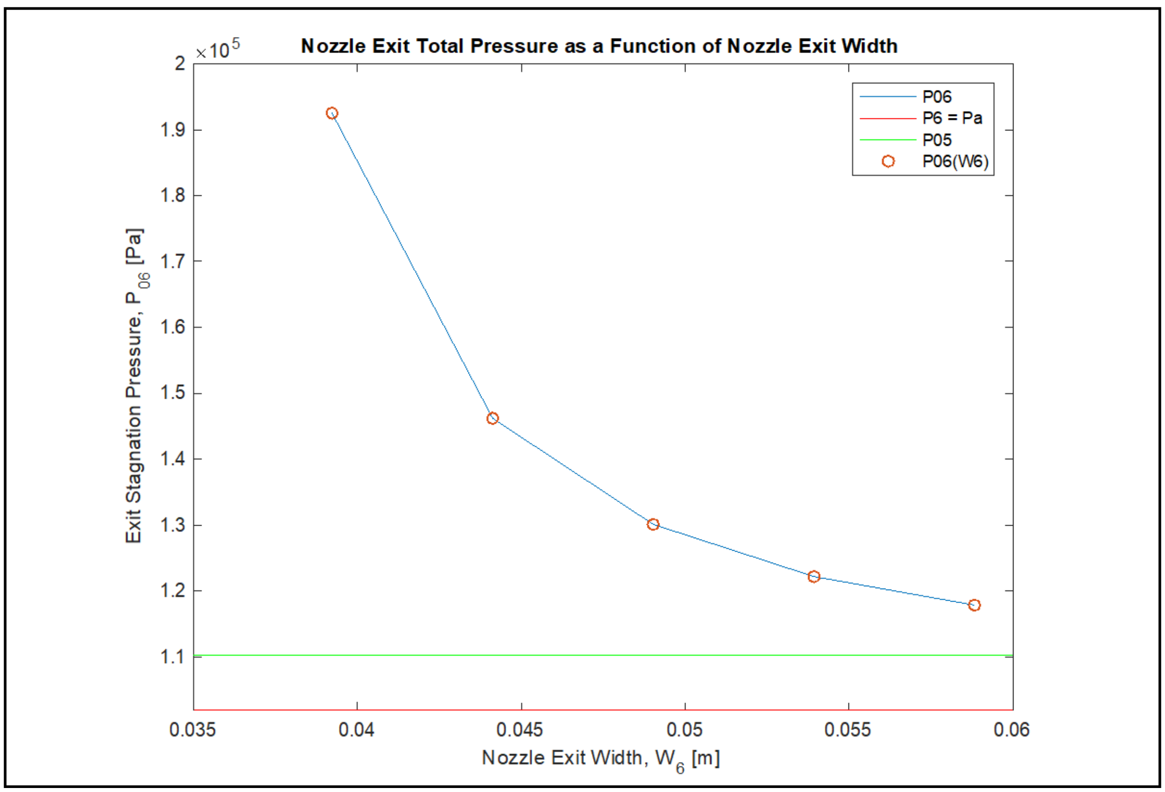
Plot Data

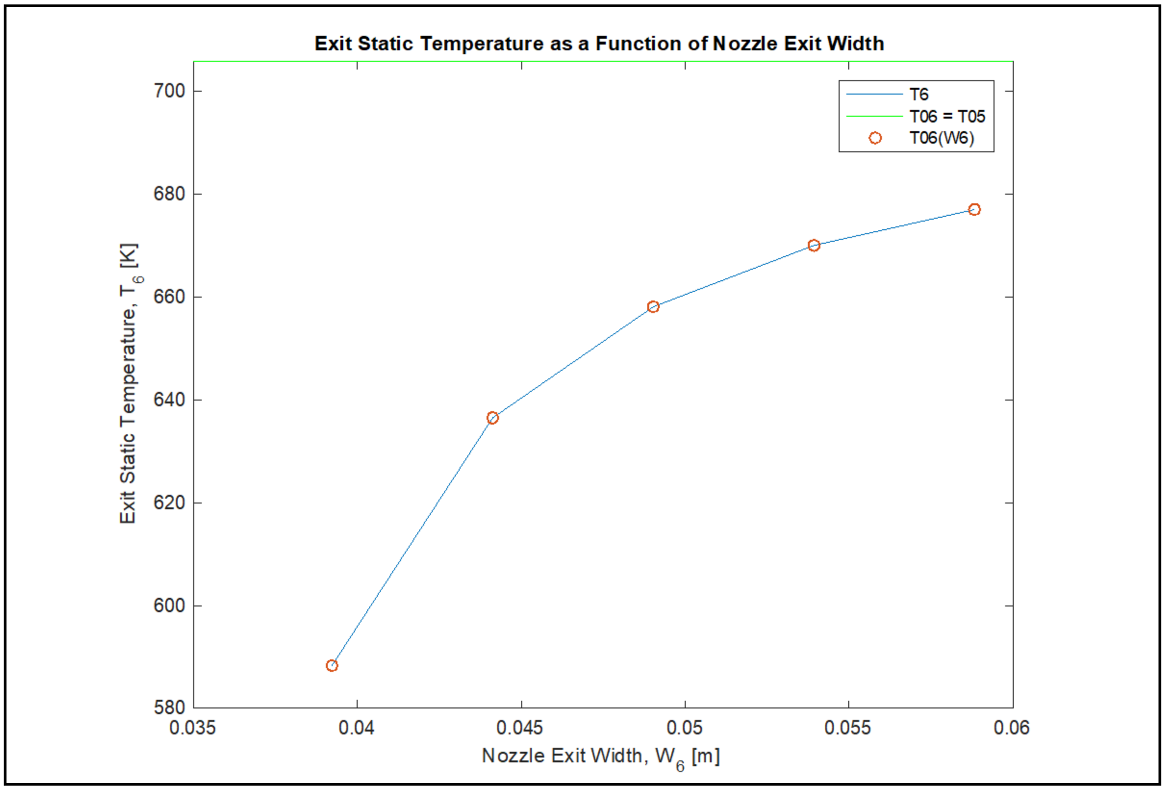
```
% Plot Nozzle Exit Mach Number as a function of Exit Width
figure
subplot(2,1,1)
plot(W6,M6)
title('Exit Mach as a Function of Nozzle Exit Width')
xlabel('Nozzle Exit Width, W_6 [m]')
ylabel('Mach Number, M_6')
grid on
hold on
plot(W6,M6,'o')
hold off



% Plot Nozzle Exit Mach Number as a function of Exit Area
subplot(2,1,2)
plot(A6,M6)
title('Exit Mach as a Function of Nozzle Exit Area')
xlabel('Nozzle Exit Area, A_6 [m^2]')
ylabel('Mach Number, M_6')
grid on
hold on
plot(A6,M6,'o')
hold off

% Plot ideal total thrust produced as a function of nozzle exit width
figure
plot(W6,F_ideal6)
title('Ideal Total Thrust Produced with Nozzle Extension')
xlabel('Nozzle Exit Width, W_6 [m]')
ylabel('Ideal Total Thrust [N]')
```

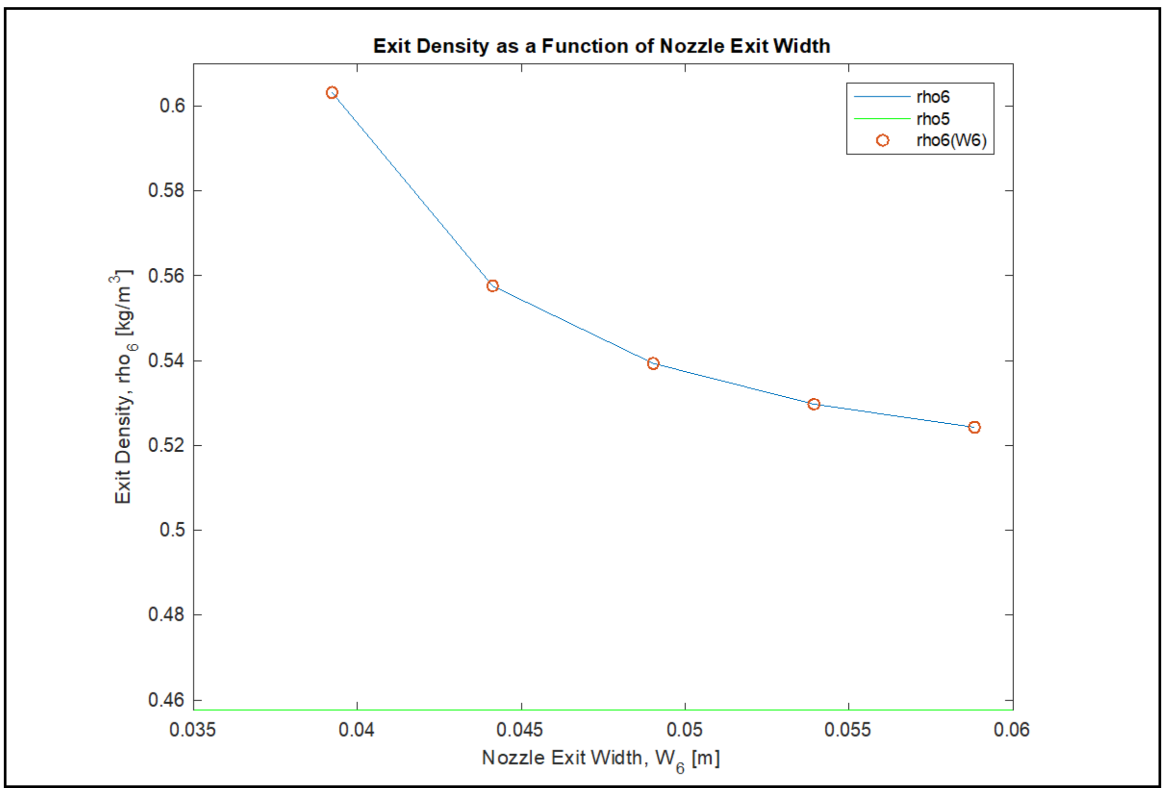
```
grid                                                                                           on
hold                                                                                           on
plot(W6,F_ideal6,'o')
hold off

% Plot Station 6 total pressure as a function of nozzle exit width
figure
plot(W6,P06)
hold on
hline = refline([0 Pa]);
hline.Color = 'r';
hline = refline([0 P05]);
hline.Color = 'g';
plot(W6,P06,'o')
hold off
legend('P06','P6 = Pa', 'P05', 'P06(W6)')
title('Nozzle Exit Total Pressure as a Function of Nozzle Exit Width')
xlabel('Nozzle Exit Width, W_6 [m]')
ylabel('Exit Stagnation Pressure, P_{06} [Pa]')
grid on

% Plot Station 6 static temperature as a function of nozzle exit width
figure
plot(W6,T6)
hold on
hline = refline([0 T05]);
hline.Color = 'g';
plot(W6,T6,'o')
hold off
legend('T6','T06 = T05', 'T06(W6)')
title('Exit Static Temperature as a Function of Nozzle Exit Width')
xlabel('Nozzle Exit Width, W_6 [m]')
ylabel('Exit Static Temperature, T_6 [K]')
grid on

% Plot Station 6 density as a function of nozzle exit width
figure
plot(W6,rho6)
hold on
hline = refline([0 rho5]);
hline.Color = 'g';
plot(W6,rho6,'o')
hold off
legend('rho6', 'rho5', 'rho6(W6)')
title('Exit Density as a Function of Nozzle Exit Width')
xlabel('Nozzle Exit Width, W_6 [m]')
ylabel('Exit Density, rho_6 [kg/m^3]')
grid on



end
```


Exit Mach as a Function of Nozzle Exit Width
Mach Number, M6
Nozzle Exit Width, W6 [m]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.035
0.04
0.045
0.05
0.055
0.06
Exit Mach as a Function of Nozzle Exit Area
Mach Number, M6
Nozzle Exit Area, A6 [m2]
1.8
2
2.2
2.4
2.6
2.8
3
×10-3


Ideal Total Thrust Produced with Nozzle Extension
Ideal Total Thrust [N]
Nozzle Exit Width, W6 [m]
170
160
150
140
130
120
110
100
90
80
0.035
0.04
0.045
0.05
0.055
0.06


Nozzle Exit Total Pressure as a Function of Nozzle Exit Width
×10^5
Exit Stagnation Pressure, P06 [Pa]
Nozzle Exit Width, W6 [m]
P06
P6 = Pa
P05
P06(W6)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
0.035
0.04
0.045
0.05
0.055
0.06


Exit Static Temperature as a Function of Nozzle Exit Width
T6
T06 = T05
T06(W6)
Exit Static Temperature, T6 [K]
700
680
660
640
620
600
580
0.035
0.04
0.045
0.05
0.055
0.06
Nozzle Exit Width, W6 [m]


Exit Density as a Function of Nozzle Exit Width
rho6
rho5
rho6(W6)
Exit Density, rho6 [kg/m3]
0.6
0.58
0.56
0.54
0.52
0.5
0.48
0.46
0.035
0.04
0.045
0.05
0.055
0.06
Nozzle Exit Width, W6 [m]

TurboTRIO Main Script Output Variables

```
A1                                     =                                   0.0039160380814571008;

A4                                     =                                   0.0062783083490096361;

A5                                     =                                   0.0024247617386814416;

A6 = [0.0019398093909451534
      0.0021822855648132976
      0.0024247617386814416
      0.0026672379125495861
      0.00290971408641773];

AFR                                      =                                     96.052687301433323;

Area_Ratio     =     [0.8              0.9              1.0              1.1              1.2];

At                                     =                                   0.0024247617386814416;

D1                                           =                                           0.070612;

D4                                           =                                           0.089408;

D5                                          =                                           0.0555635;

F_actual                                  =                                    53.127927210365854;

H6                                      =                                   0.049459295611054721;

Ht                                      =                                   0.049459295611054721;

L_4_5                                          =                                             0.11;

M1                                      =                                    0.21490016282263791;


M5                                      =                                    0.60049238453497911;

M5_no_nozzle                                 =                                  0.338970398250276;

M6 = [0.99899497487437183
      0.73768844221105523
      0.60201005025125631
      0.51658291457286432
      0.46130653266331662];

Mt                                      =                                    0.60049238453497911;
```

```
N                                     =                     64475.6173887195;

P01                                   =                  101828.71723000001;

P03                                   =                  217937.78697085378;

P05                                   =                  110256.84222999988;

P06 = [192528.745790024
      146186.42515558415
      130087.94221985912
      122153.48568445127
      117821.63924627395];

P1                                    =                   98604.123861097658;

P2                                    =                  217436.73171170749;

P5 = 86408.443215892883;

P5_no_nozzle                               =             101828.71723000001;

P6                                    =                  101828.71723000001;

Pa                                    =                  101828.71723000001;

QF                                  =                 4.3063689481707309E-6;

R1                                         =                       0.035306;

R4                                         =                       0.044704;

R5                                        =                      0.02778175;

R_A                                          =                        286.9;

R_E                                          =                        286.9;

T01                                   =                  295.05464062499993;

T02                                   =                  392.62307812499995;

T03                                    =                  966.5586562499999;

T05                                   =                  705.77159374999962;

T06                                   =                  705.77159374999962;

T1                                    =                  292.35433437441424;
```

```
T5                                       =                                658.29642671175611;

T5_no_nozzle                                  =                           689.91716876440182;


T6 = [588.33999457268283
      636.49724060545623
      658.07238799556012
      670.01199398957544
      676.9596862412028];

Ta                                       =                                294.81666666666672;

V1                                       =                                73.641191211517622;

V5                                       =                                308.77884960421818;

V5_no_nozzle                                  =                           178.43890186440862;

V6 = [485.63142467081479
      372.99287314932252
      309.50656683928514
      267.98508204536296
      240.54719672013772];

W6 = [0.039220319799936329
      0.044122859774928372
      0.049025399749920408
      0.053927939724912451
      0.058830479699904493];

Wt                                      =                               0.049459295611054721;

a1                                       =                                342.67629323433977;

a5                                       =                                514.20943471803776;

a5_no_nozzle                                  =                           526.41440900293526;

a6 = [486.1199874722945
      505.62385392857755
      514.12192655273577
      518.76489617730772
```

```
     521.447626876987];

adat = struct;
```

```
adat.A61 = struct;
adat.A61.AreaRatio6 = 0.8;
adat.A61.W6 = 0.039220319799936329;
adat.A61.M6 = 0.99899497487437183;
adat.A61.P06 = 192528.745790024;
adat.A61.T6 = 588.33999457268283;
adat.A61.a6 = 486.1199874722945;
adat.A61.V6 = 485.63142467081479;
adat.A61.rho6 = 0.603269477175251;
adat.A61.F_ideal6 = 166.35181045975574;
```

```
adat.A62 = struct;
adat.A62.AreaRatio6 = 0.9;
adat.A62.W6 = 0.044122859774928372;
adat.A62.M6 = 0.73768844221105523;
adat.A62.P06 = 146186.42515558415;
adat.A62.T6 = 636.49724060545623;
adat.A62.a6 = 505.62385392857755;
adat.A62.V6 = 372.99287314932252;
adat.A62.rho6 = 0.55762623666606015;
adat.A62.F_ideal6 = 127.76776086727723;
```

```
adat.A63 = struct;
adat.A63.AreaRatio6 = 1;
adat.A63.W6 = 0.049025399749920408;
adat.A63.M6 = 0.60201005025125631;
adat.A63.P06 = 130087.94221985912;
adat.A63.T6 = 658.07238799556012;
adat.A63.a6 = 514.12192655273577;
adat.A63.V6 = 309.50656683928514;
adat.A63.rho6 = 0.53934425361355076;
adat.A63.F_ideal6 = 106.02068796886225;
```

```
adat.A64 = struct;
adat.A64.AreaRatio6 = 1.1;
adat.A64.W6 = 0.053927939724912451;
adat.A64.M6 = 0.51658291457286432;
adat.A64.P06 = 122153.48568445127;
adat.A64.T6 = 670.01199398957544;
adat.A64.a6 = 518.76489617730772;
adat.A64.V6 = 267.98508204536296;
adat.A64.rho6 = 0.5297331452437769;
adat.A64.F_ideal6 = 91.7976088649344;
```

```
adat.A65                          =                              struct;
adat.A65.AreaRatio6                     =                           1.2;
adat.A65.W6                  =              0.058830479699904493;
adat.A65.M6                  =               0.46130653266331662;
adat.A65.P06                 =                117821.63924627395;
adat.A65.T6                  =                 676.9596862412028;
adat.A65.a6                  =                  521.447626876987;
adat.A65.V6                  =                240.54719672013772;
adat.A65.rho6                =               0.52429645094211808;
adat.A65.F_ideal6               =                82.39883097050074;

desiredN                          =                         65000;

g                              =                            9.806;

gamma_A                           =                           1.4;

gamma_E                           =                           1.4;

m_dot_A                   =                   0.33901795886226804;

m_dot_E                   =                   0.34254745885218879;

m_dot_F                  =                 0.0035294999899207311;

rho1                     =                     1.1755875914033258;

rho5                    =                     0.45751373312012494;

rho5_no_nozzle               =               0.51444952669145094;

rho6 = [0.603269477175251

      0.55762623666606015

      0.53934425361355076

      0.5297331452437769

      0.52429645094211808];

rho_F                           =                           819.6;

theta_4_5                    =                 8.7457415009034385;

throat_l_flat                 =              0.039459295611054719;

throat_r_fillet                       =                     0.005;
```

Appendix F: Decision Matrices

Decision Matrix -- Nozzle

Decision Matrix	Weight Factor	Conical Nozzle	Rectangular Nozzle - Flat Flaps	Multiple Attachments	Rectangular Nozzle - Converging Diverging Flaps
Area Change	0.25	4	4	5	4
Vectoring	0.05	-4	3	4	-2
Accuracy	0.1	3	5	5	1
Manufacturability	0.2	-4	2	2	-1
Compatibility	0.1	5	3	-5	3
Size	0.05	2	3	-5	3
Reliability	0.1	-3	4	2	3
Cost	0.15	-1	3	-3	0
Sum of +		1.9	3.35	2.55	1.85
Sum of -		-1.45	0	-1.2	-0.3
Total		0.45	3.35	1.35	1.55

Decision Matrix – Actuation

Decision Matrix	Weight Factor	Ratchet Lever and Gear Train	Pulley System	Step Motor	Bendable Flaps with Rollers	Hydraulic Slide
Size	.05	0	0	1	3	-2
Toggling	.1	-3	-5	4	3	4
Low power draw	.1	5	5	-2	-2	-5
Reliability	.15	5	5	4	3	1
Precision	.05	2	5	2	4	4
Accuracy	.3	5	2	5	3	3
Cost	.1	2	-2	0	-2	-4
Manufacturability	.15	-2	-4	3	-4	-5
Sum of +		3.05	2.1	3.1	2	1.65
Sum of -		-0.6	-1.3	-0.2	-1	-1.75
Total		2.45	0.8	2.9	1	-0.1

Appendix G: Failure Modes & Effects (FMEA)

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Rec'd Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	Action Results: Severity	Action Results: Occurence	Action Results: Criticality
Flow direction / alters flow characteristics such as speed and direction	Does not move enough to impact flow	a) cannot achieve boundary layer separation b) cannot achieve meaningful change in thrust c) does not achieve sonic speed at throat	8	1) doesn't converge enough 2) doesn't diverge enough 3) disrupts flow to be too turbulent	1) smoother edges 2) wide range of actuation 3) CFD analysis	3	CFD Discussion with AERO professors	2	48						
Actuation / controls system to achieve desired flow characteristics	Moves in limited directions	a) can't control nozzle direction accurately b) unintentionally causes thrust vectoring due to uneven actuation c) cannot alter flow enough to achieve desired results	5	1) not enough actuation range 2) actuators are uncalibrated 3) installed improperly 4) not enough actuators present 5) not able to push back on thrust	1) check specs for distance 2) calibrate and test before installing	5	Testing with prototype	4	100						
Actuation / controls system to achieve desired flow characteristics	Doesn't move	a) nozzle doesn't effect flow significantly b) fixed nozzle only shows a few types of flow characteristics	7	1) actuators not powered 2) actuators not powerful enough to fight thrust 3) actuators break	1) check specs for strength 2) test prototype	2	Observe with prototyle	1	14						
Support / holds nozzle in desired location	Nozzle out of place	a) flow is not redirected as intended	9	1) nozzle slips (bolt breaks) 2) nozzle comes away from face of engine 3) nozzle falls off	1) have extra bolts on hand 2) test bolt strength / check specs 3) inspect before use	2	Inspect before use	4	72						
Data Analysis / allows numerical understanding of engine performance	Reasonable data is not acquired	1) data isn't being measured 2) data isn't being recorded	5	1) instrumentation doesn't exist 2) instrumentation needs to be calibrated 3) instrumentation is broken 4) computer program is broken	1) have extra instrumentation on hand 2) include back up "sample" data	2	As part of initial run, check data is being recorded and saved	3	30						

Appendix H: Safety Hazard Checklist

Y	N	
■	□	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
□	■	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
■	□	3. Will any part of the design undergo high accelerations/decelerations?
□	■	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
■	□	5. Could the system produce a projectile?
□	■	6. Could the system fall (due to gravity), creating injury?
□	■	7. Will a user be exposed to overhanging weights as part of the design?
□	■	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
□	■	9. Will any part of the electrical systems not be grounded?
□	■	10. Will there be any large batteries (over 30 V)?
□	■	11. Will there be any exposed electrical connections in the system (over 40 V)?
■	□	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
■	□	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
□	■	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
□	■	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
■	□	16. Could the system generate high levels (>90 dBA) of noise?
■	□	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
■	□	18. Is it possible for the system to be used in an unsafe manner?
■	□	19. For powered systems, is there an emergency stop button?
□	■	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any “Y” responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the next page.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The system will involve hazardous revolution and rotational energy storage in the form of the turbojet compressor and turbine blades. These features accelerate very quickly and if anyone's finger (or any other object) were inside the blades at start up (or inserted while running), the inserted item/body part would snap immediately and likely result in a projectile and possibly an explosion depending on how it harmed the engine. Likewise, if a blade of the turbine were to break off, the high speed of rotation could eject the broken blade as a projectile.	None needed – there is a protective casing around the engine which makes it very hard to touch the engine. Similarly, the high temperatures the engine runs at are a significant deterrent to moving into a position such that one *might* touch the engine or be at risk of being hit by a projectile.	N/A	N/A
The fuel used to power the turbine is highly flammable. As a team, we have also determined that the fuel is still combusting on its way to the exhaust exit of the engine. Additionally, the engine operates at extremely high temperatures, reaching temperatures well over 400°C at the exhaust exit.	None needed – the fuel is stored away from student access (handled only by the lab technicians) and the students are instructed by the lab supervisor to stay away from the exhaust stream. Similarly, there is a protective case that keeps students away from the exit of the turbojet and the location of the DAQ display encourages students to stand to the side of the engine rather than behind it.	N/A	N/A
The system can generate over 90 decibels.	None needed – students are already required to wear ample ear protection when in the lab, regardless of whether the equipment is currently in use or not.	N/A	N/A
It is possible for the system to be used in an unsafe manner for the reasons detailed above. There are undoubtedly an infinite number of other ways the system could be used unsafely – humans are notoriously inventive – but nothing else is *likely*.	Not applicable – all likely hazards have been accounted for by the designers of the engine system itself, so no further action is needed. The only action that could be taken to prevent the system from being used unsafely would be for students to use existing data rather than operate the turbine, which defeats the purpose of having laboratories.	N/A	N/A

Appendix I: Solutions Idea List

Nozzle

Strong options:

- Rectangular nozzle with flat flaps
- Rectangular nozzle with curved flaps for converging-diverging

Less likely options:

- Fixed nozzle shapes in a plug-and-play system
- Circular nozzle comprised of nearly-flat flaps

Controls

Strong options:

- Linear mechanical actuators directly pushing the flap sides
- Rotational mechanical actuators turning the flap hinges
- Linear mechanical actutors pushing a lever that turns the flap hinges

Less likely options:

- Linear hydraulic actuators
- Linear mechanical actuators rotating a series of levers along the circumferance of the nozzle.

Niceties

Likely-included stretch goals:

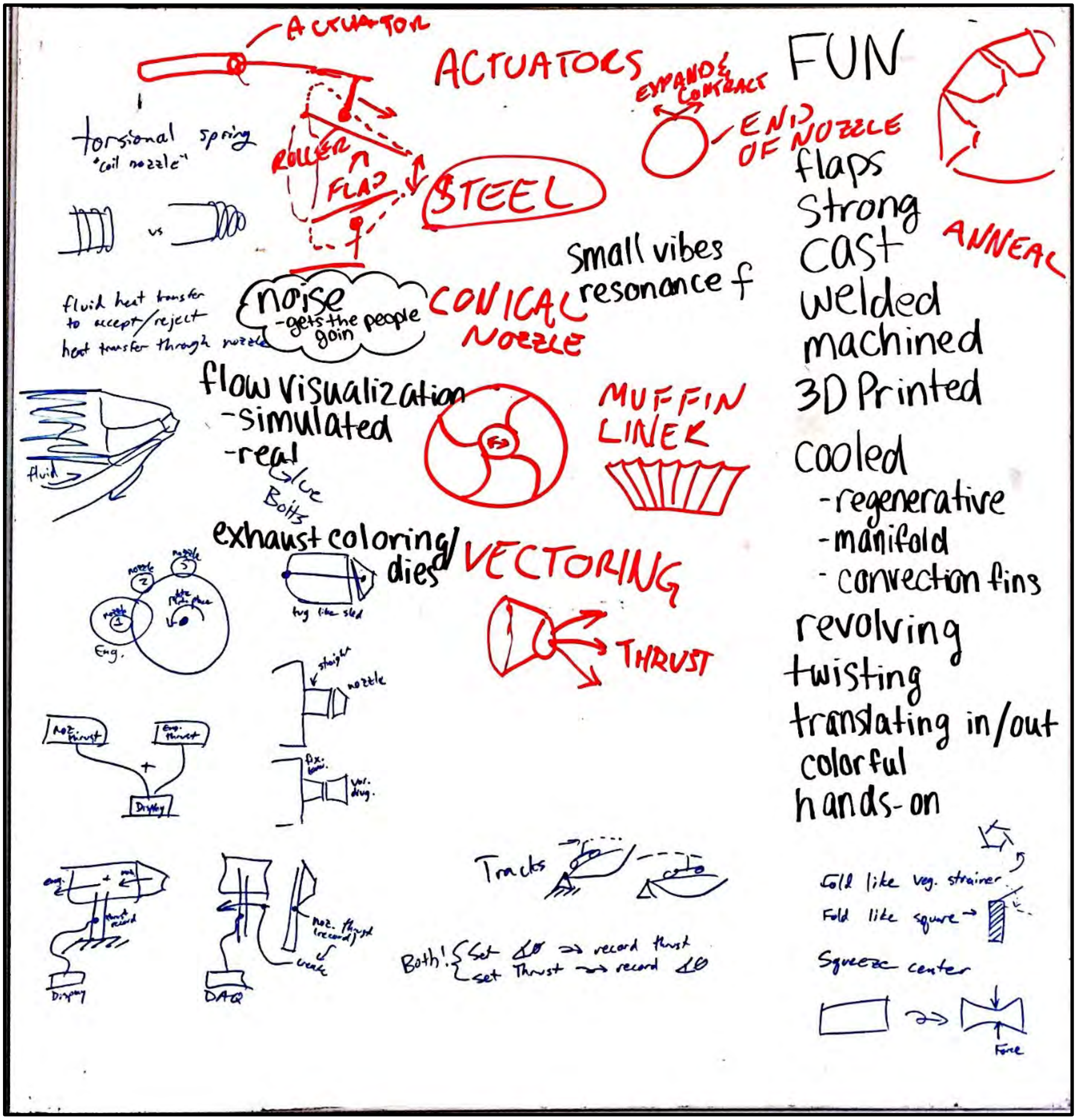
- Suggested labs including procedures and sample calculations

Interesting but unlikely stretch goals:

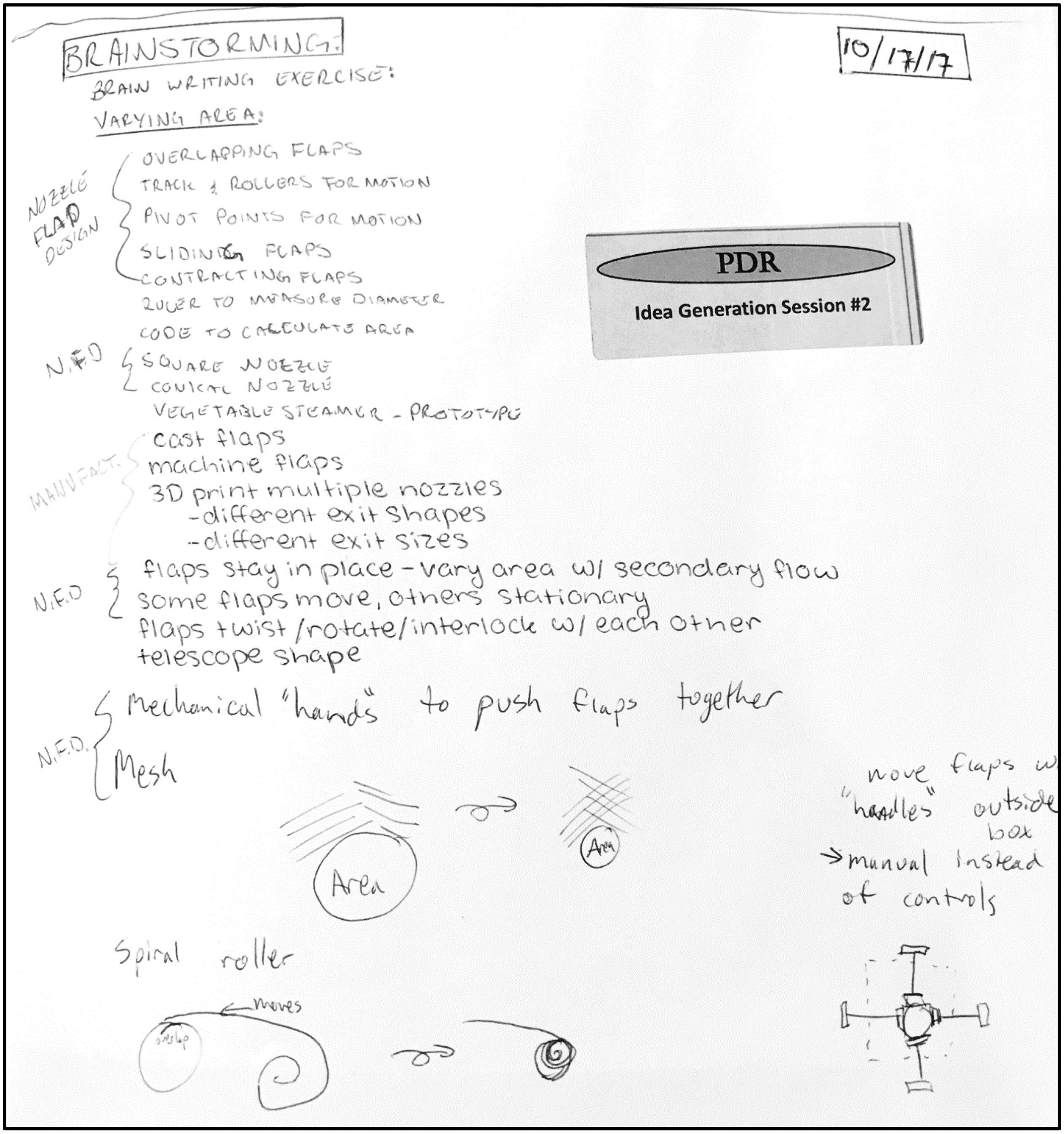
- Incorporation of a fluid thrust vectoring
- Incorporation of a pitot rake

Appendix J: Sample Selection of Ideation

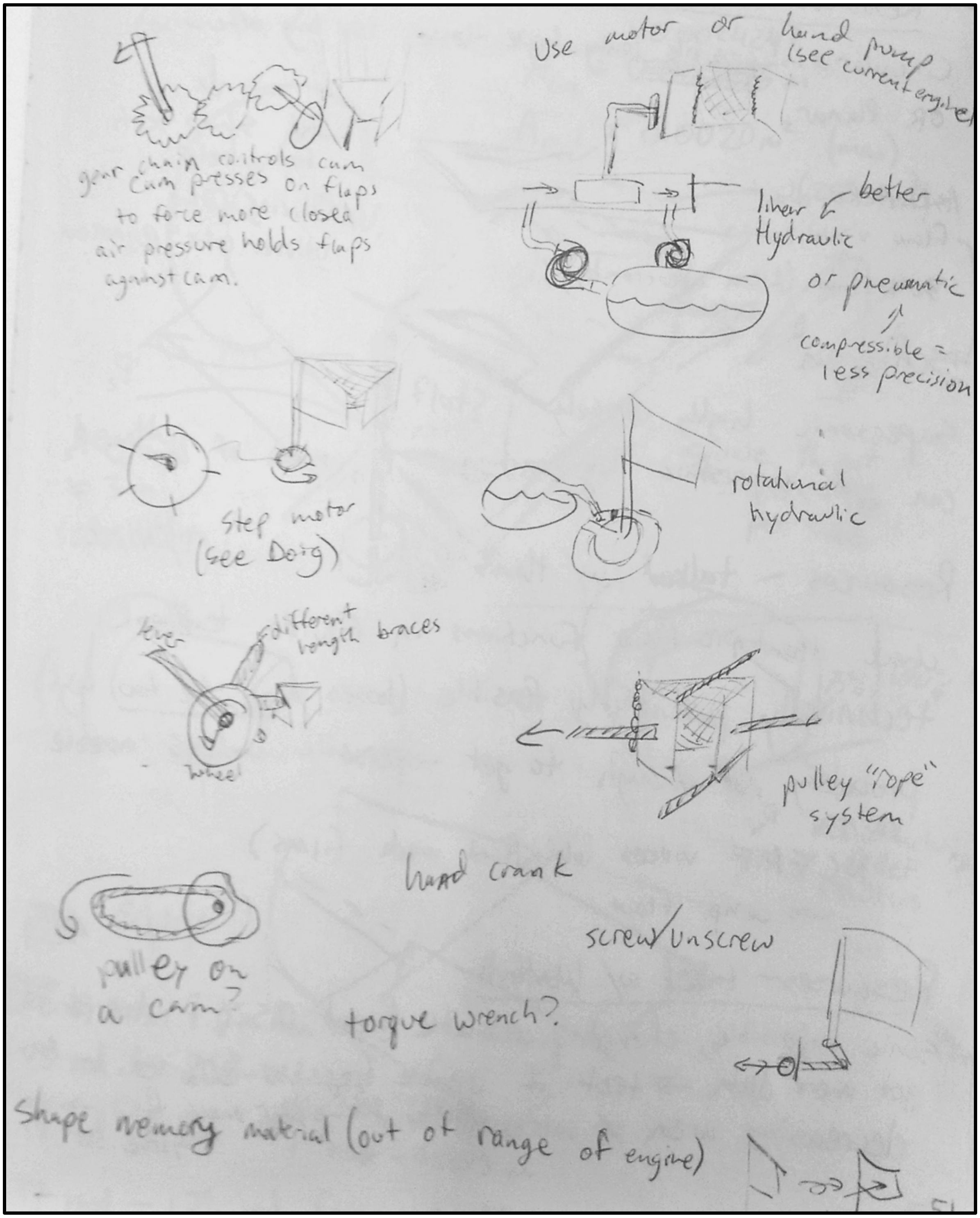
Ideation session #1: Nozzle Shape and Motion



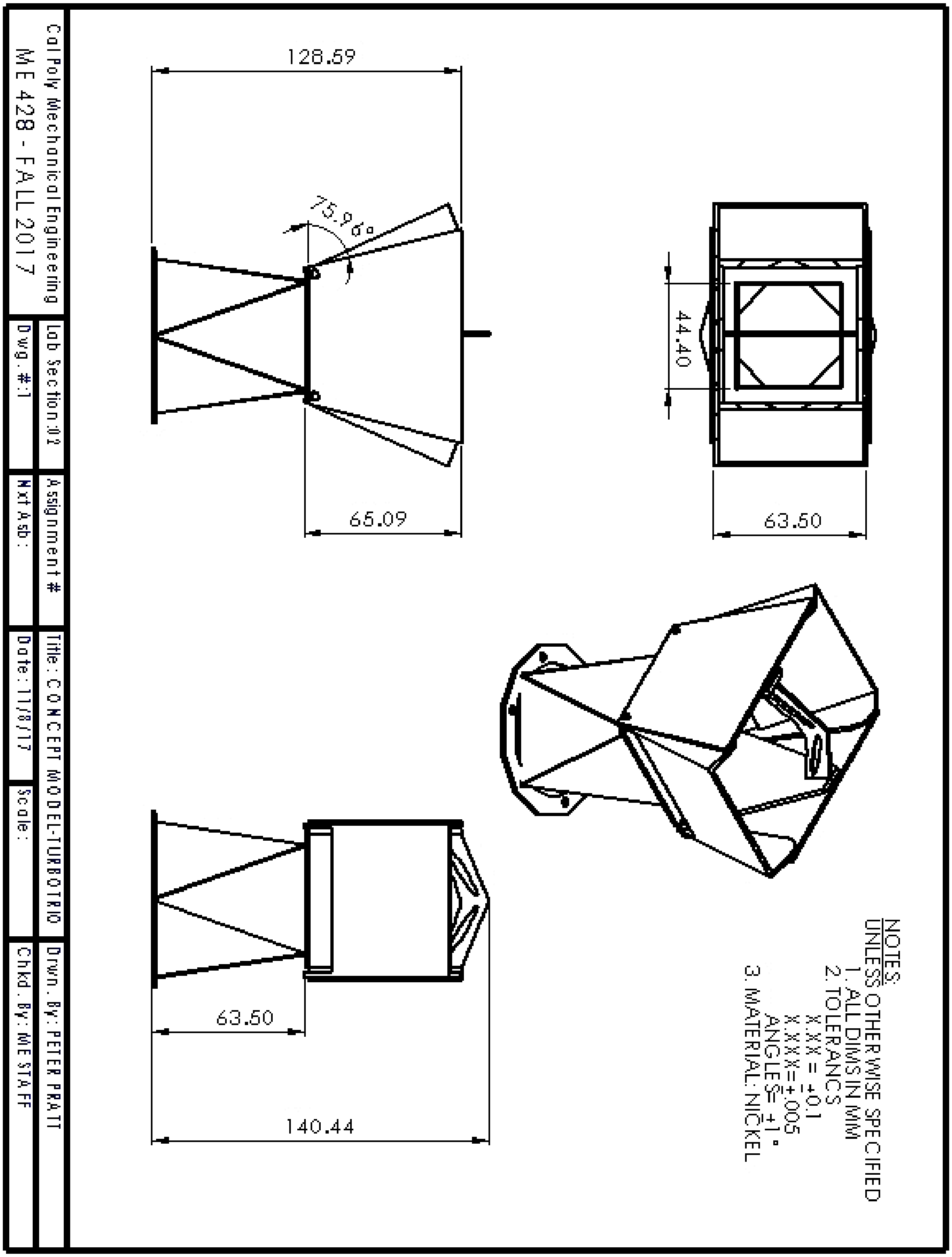
Ideation session #2: How the Nozzle Folds

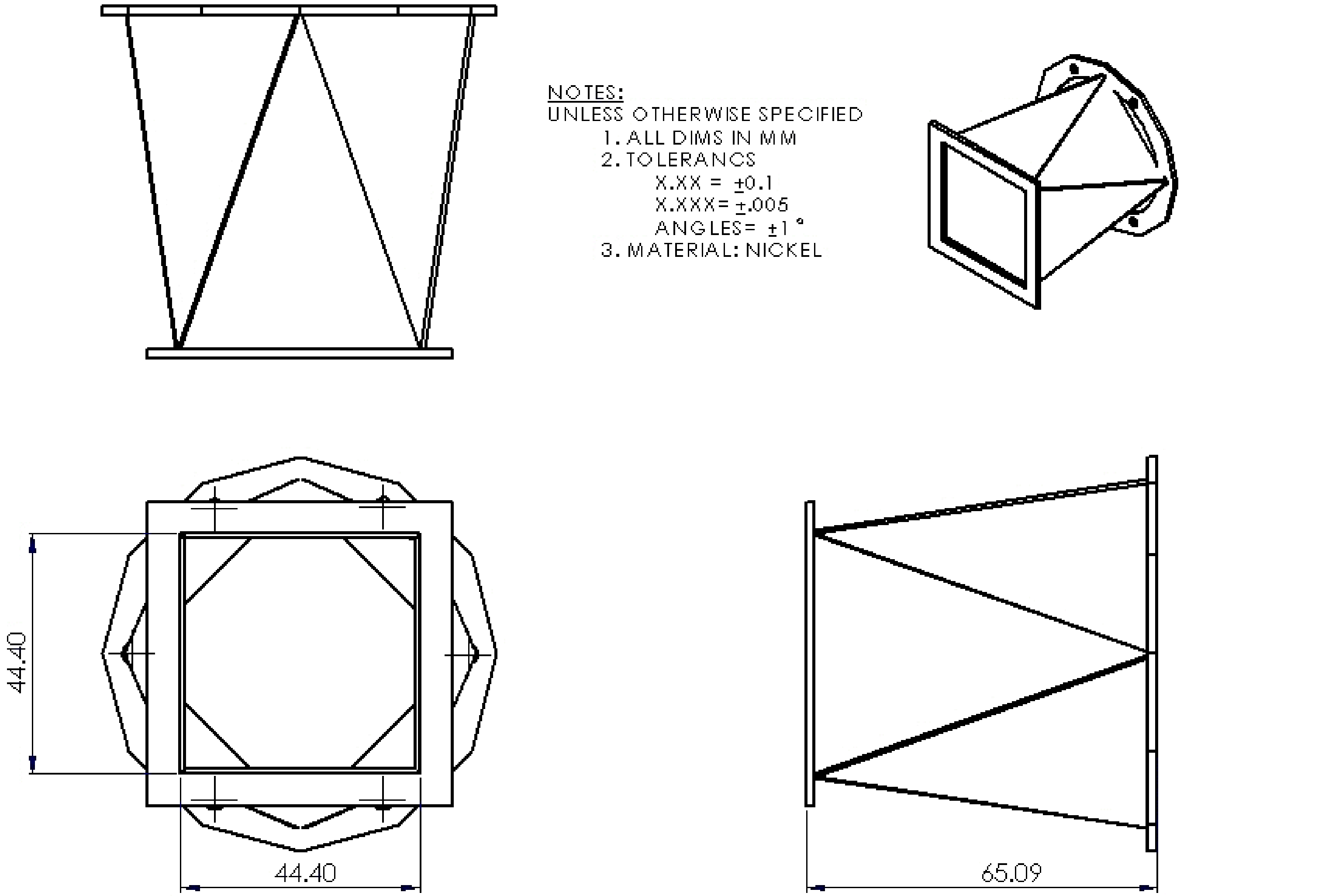


Ideation session #3: Actuation



Appendix K: Original Concept Layout Drawing





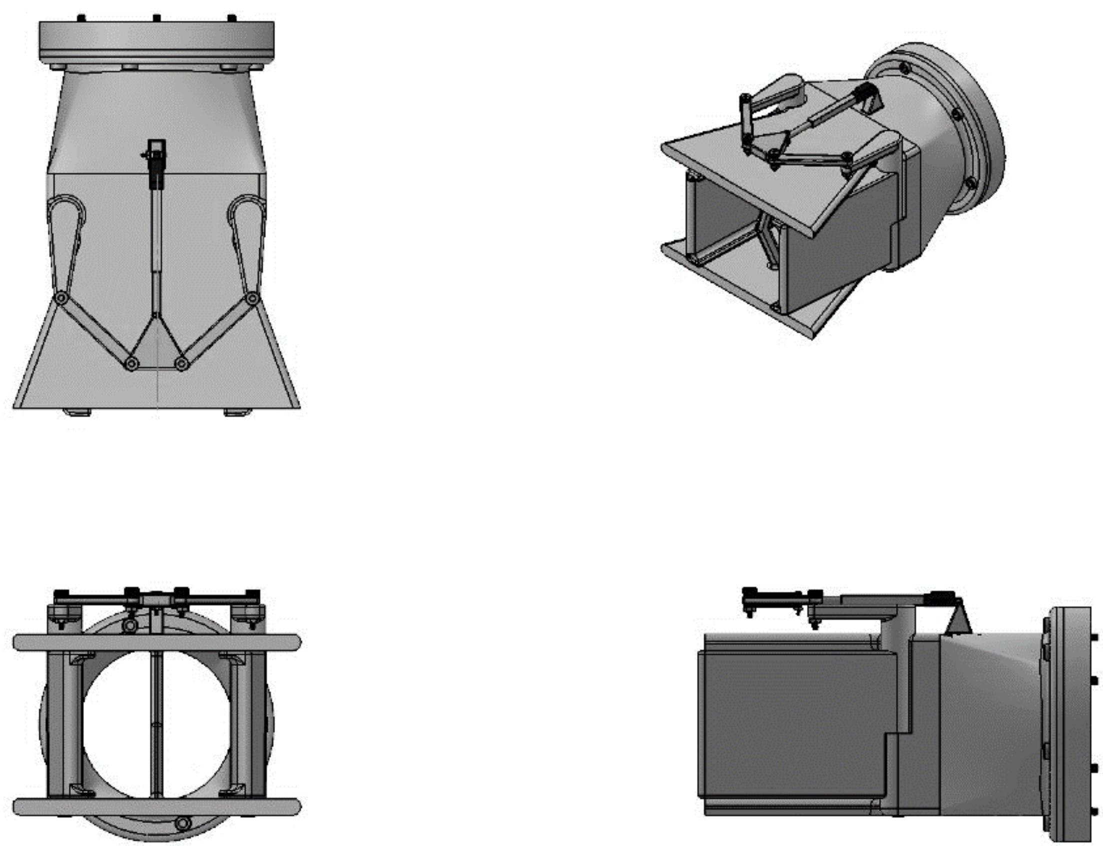
NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS IN MM
2. TOLERANCS
X.XX = ±0.1
X.XXX= ±.005
ANGLES= ±1 °
3. MATERIAL: NICKEL

Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: EXHAUST EXTENSION	Drwn. By: PETER PRATT
ME 428 - FALL 2017	Dwg. #:2	Nxt Asb:	Date: 11/27/17 Scale: 1:1	Chkd. By: ME STAFF

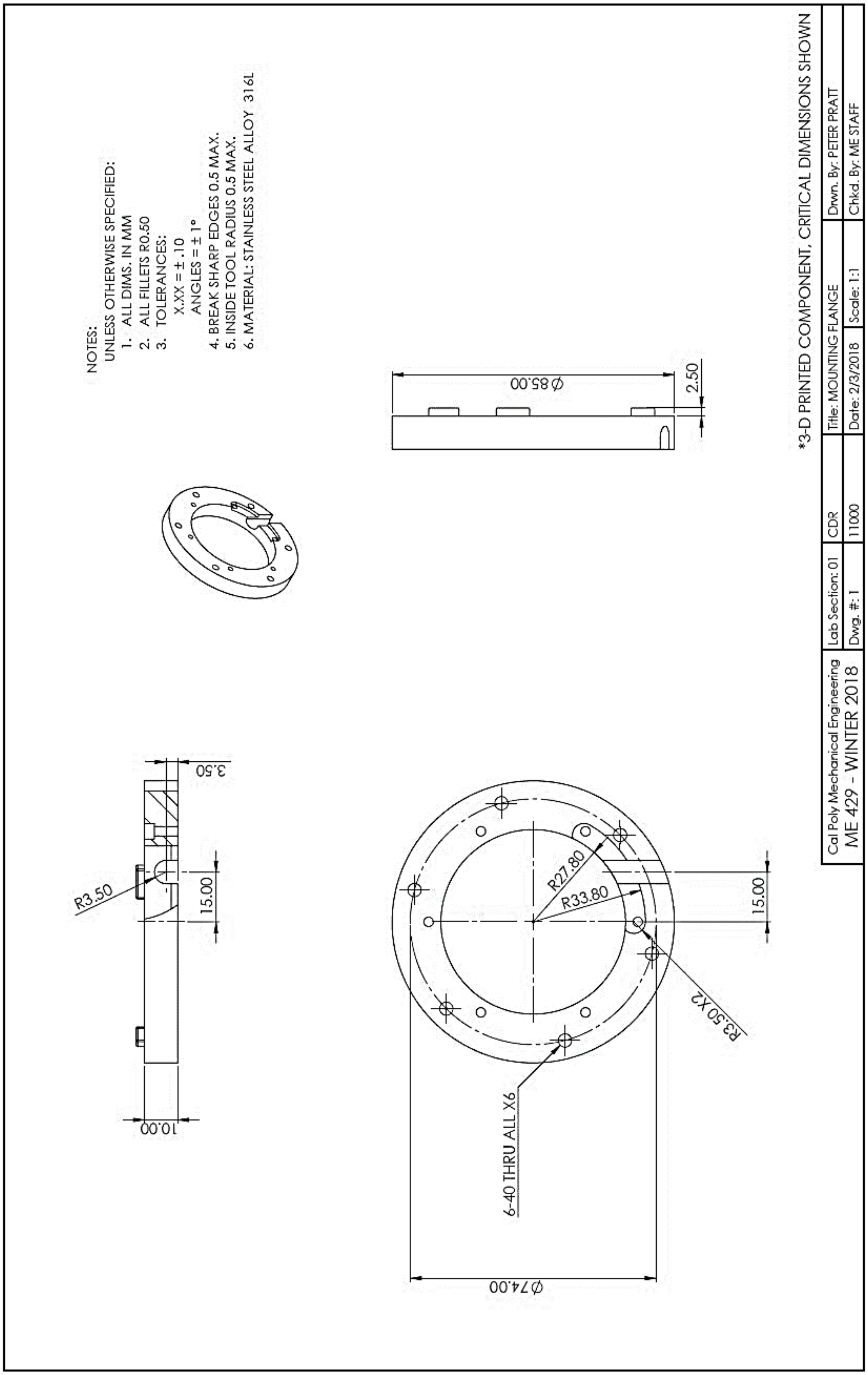
Appendix L: Complete Drawings Package (CDR)

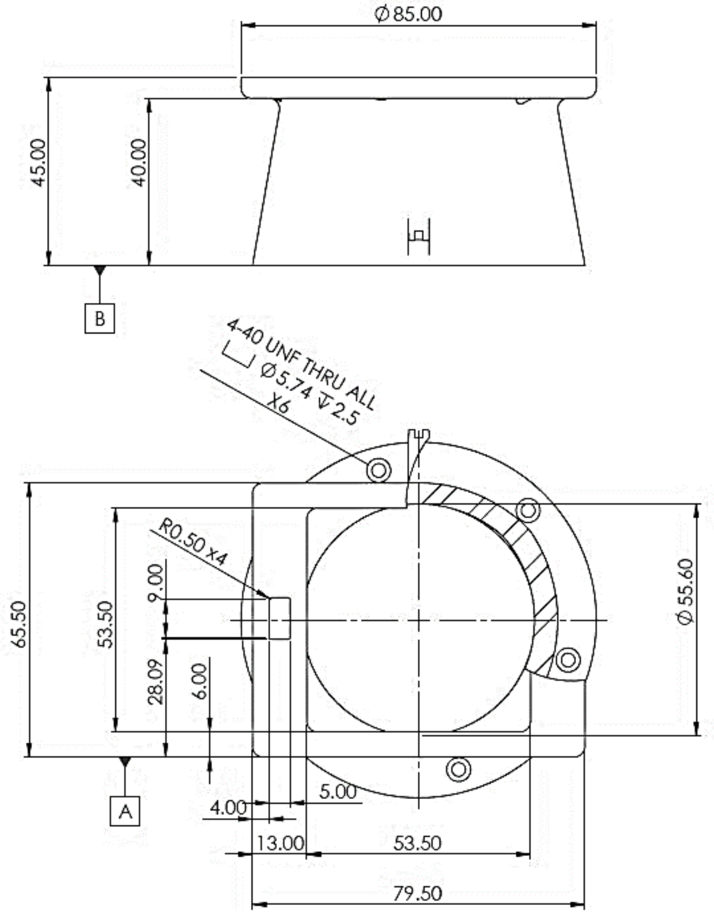
Bill of Materials:

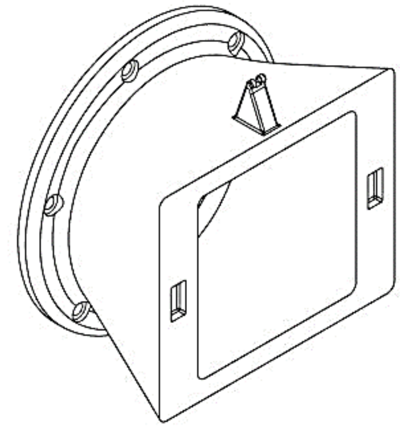
BOM LEVEL	PART NUMBER	PART NAME	UNIT OF MEASURE	DIMENSIONS	QTY	PRICE
1	1301T591	304 Stainless Steel Rod	Feet	2	1	$14.37
2	3368T347	304 Stainless Steel Sheet	Inches	24"x36"	1	$117.87
3	SCS0003	Socket Head Cap Screw- Stainless (50)	Inches	0-80 x 3/16	1	$8.20
4	FA-150-S-12-XX	Firgelli Classic Linear Actuator	-	-	2	$219.98
5	2CH-REM	2 Channel Remote Control System	-	-	2	$110.00
					Total:	**$470.42**



Cal Poly Mechanical Engineering	Lab Section: 01	CDR	Title: CAD MODEL FOR REFERENCE	Drwn. By: TURBOTRIO
ME 429 -WINTER 2018	Dwg. #: 00	N/A	Date: 2/9/2018 / Scale: 1:1.5	Chkd. By: ME STAFF


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS R0.50
3. TOLERANCES:
X.XX = ±.10
ANGLES = ±1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
Ø85.00
2.50
R3.50
15.00
3.50
10.00
R27.80
R33.80
15.00
R3.50 X2
6-40 THRU ALL X6
Ø74.00
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
Cal Poly Mechanical Engineering
ME 429 - WINTER 2018
Lab Section: 01
Dwg. #: 1
CDR
11000
Title: MOUNTING FLANGE
Date: 2/3/2018
Scale: 1:1
Drwn. By: PETER PRATT
Chkd. By: ME STAFF

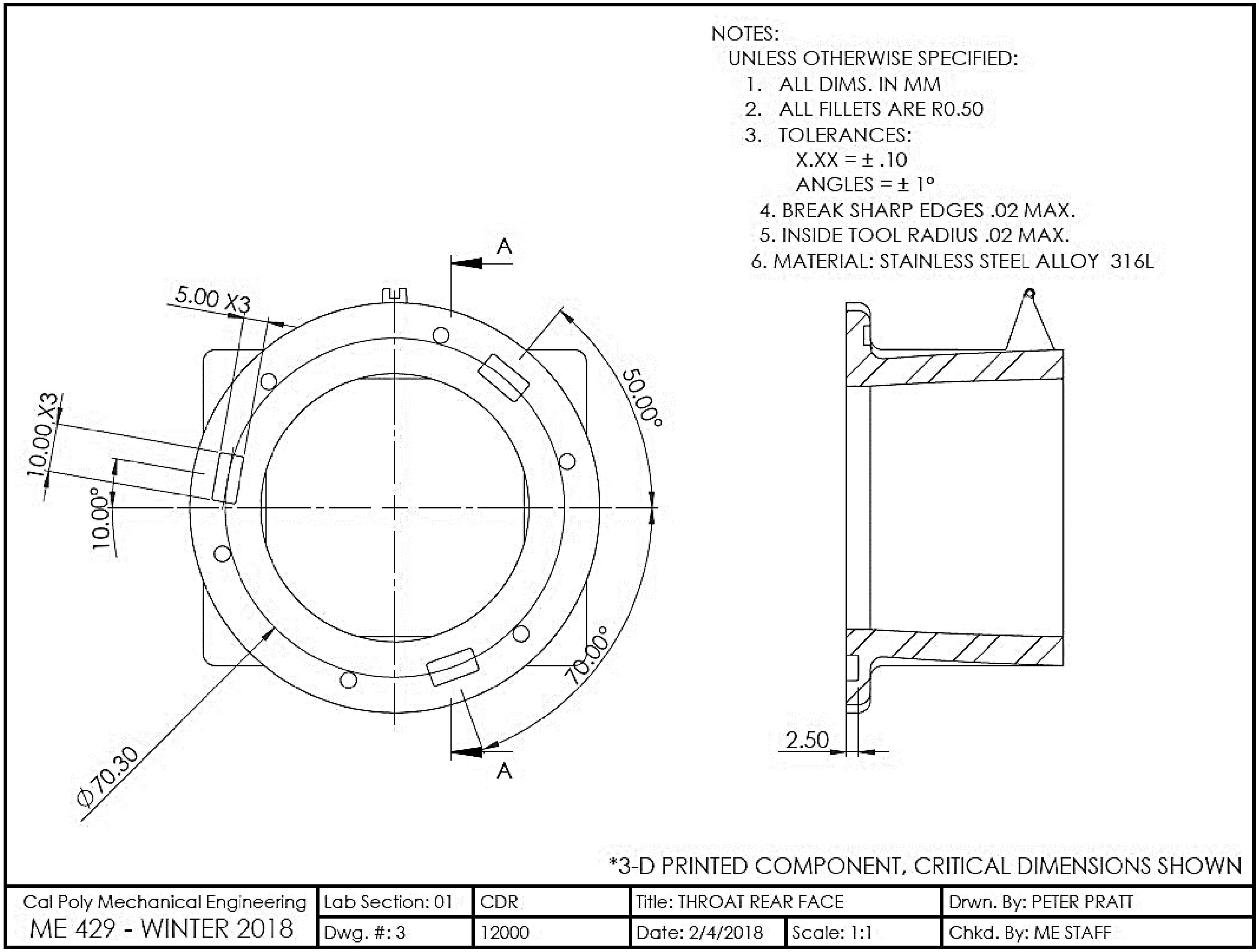


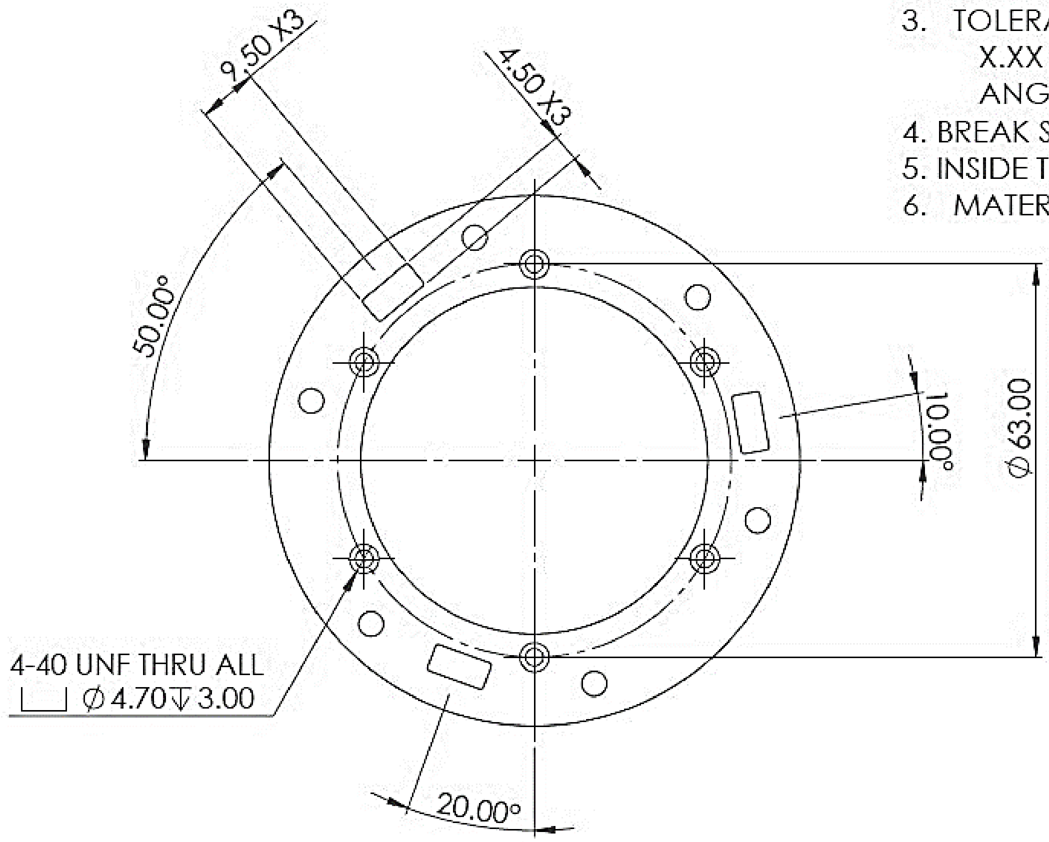


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS ARE R2.50
3. TOLERANCES:
   X.XX = ± .10
   ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L

*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN

Cal Poly Mechanical Engineering	Lab Section: 01	CDR	Title: THROAT		Drwn. By: PETER PRATT
ME 429 - WINTER 2018	Dwg. #: 2	12000	Date: 2/3/2018	Scale: 1:1	Chkd. By: ME STAFF

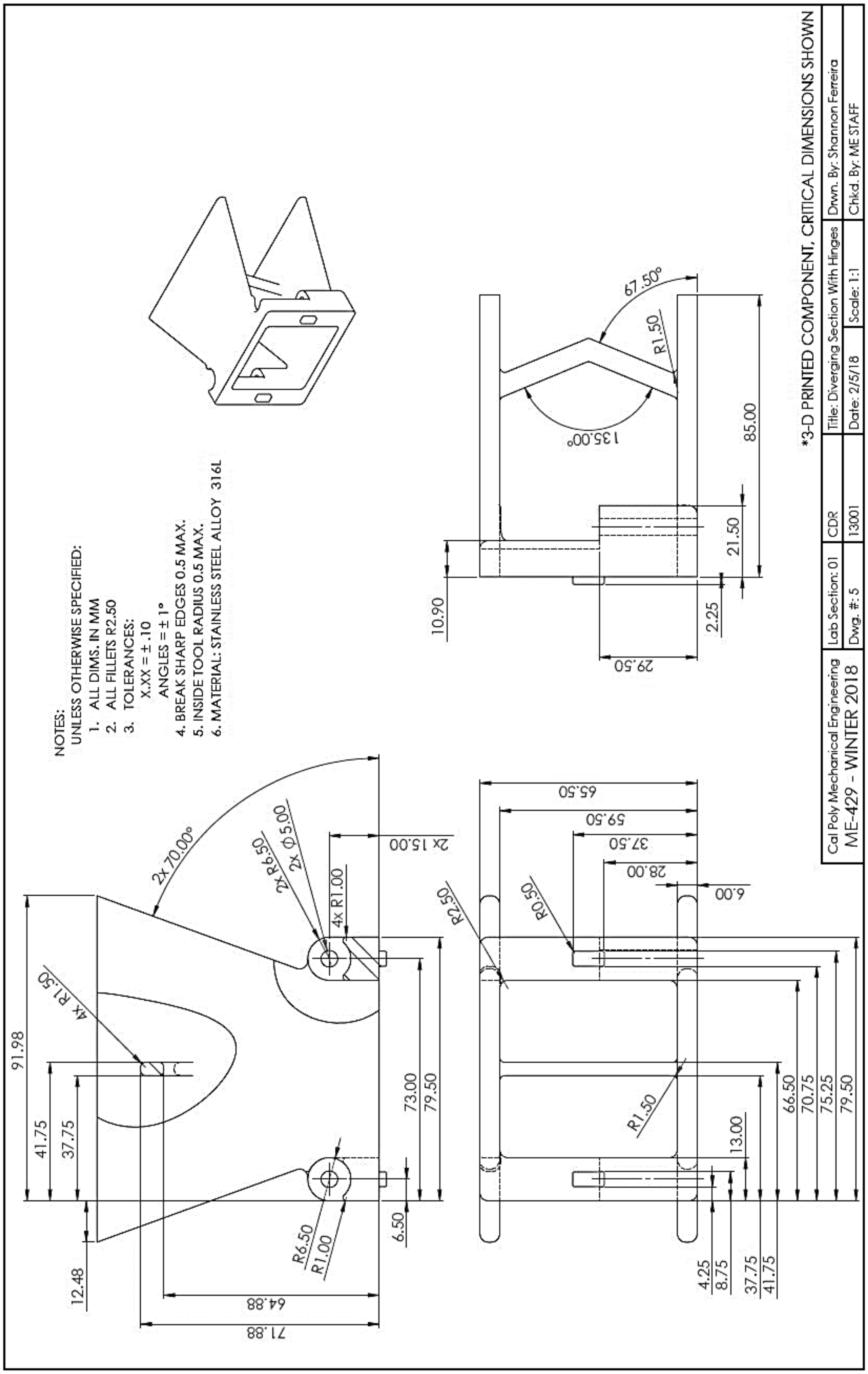

NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS ARE R0.50
3. TOLERANCES:
X.XX = ± .10
ANGLES = ± 1°
4. BREAK SHARP EDGES .02 MAX.
5. INSIDE TOOL RADIUS .02 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
A
A
5.00 X3
10.00 X3
10.00°
50.00°
70.00°
Ø70.30
2.50
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
Cal Poly Mechanical Engineering
ME 429 - WINTER 2018
Lab Section: 01
Dwg. #: 3
CDR
12000
Title: THROAT REAR FACE
Date: 2/4/2018
Scale: 1:1
Drwn. By: PETER PRATT
Chkd. By: ME STAFF

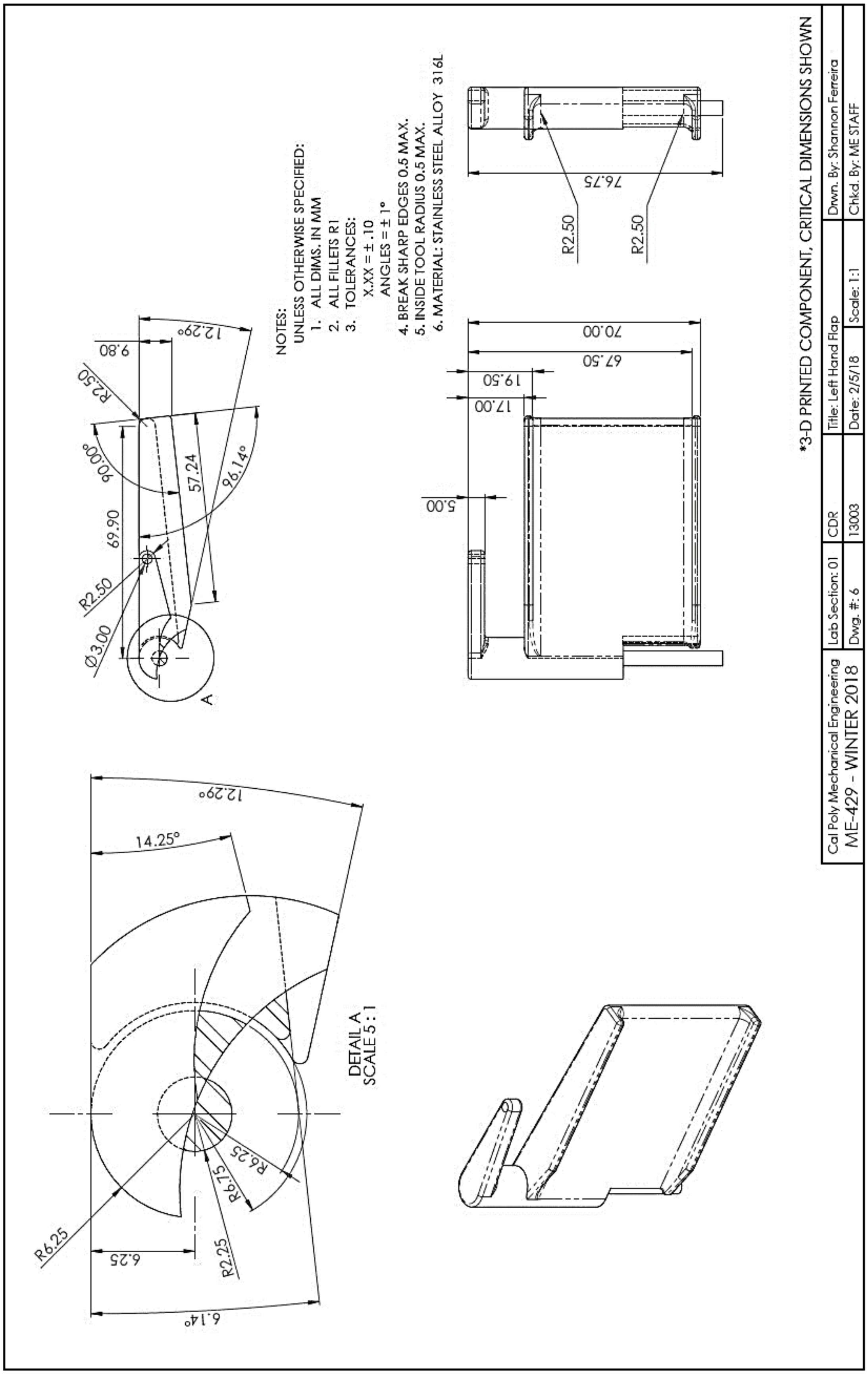


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS ARE R0.50
3. TOLERANCES:
    X.XX = ± .10
    ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L

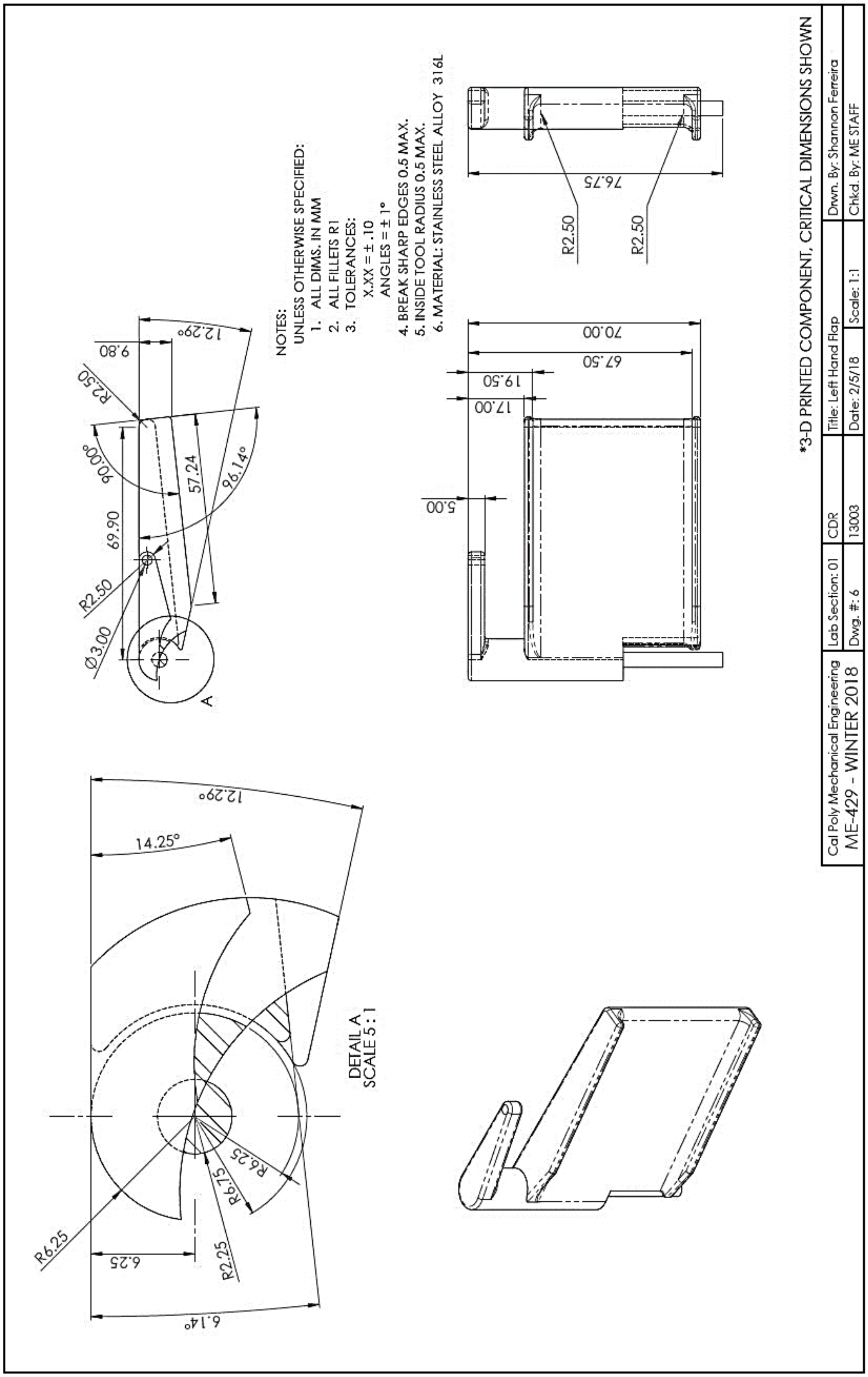
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN

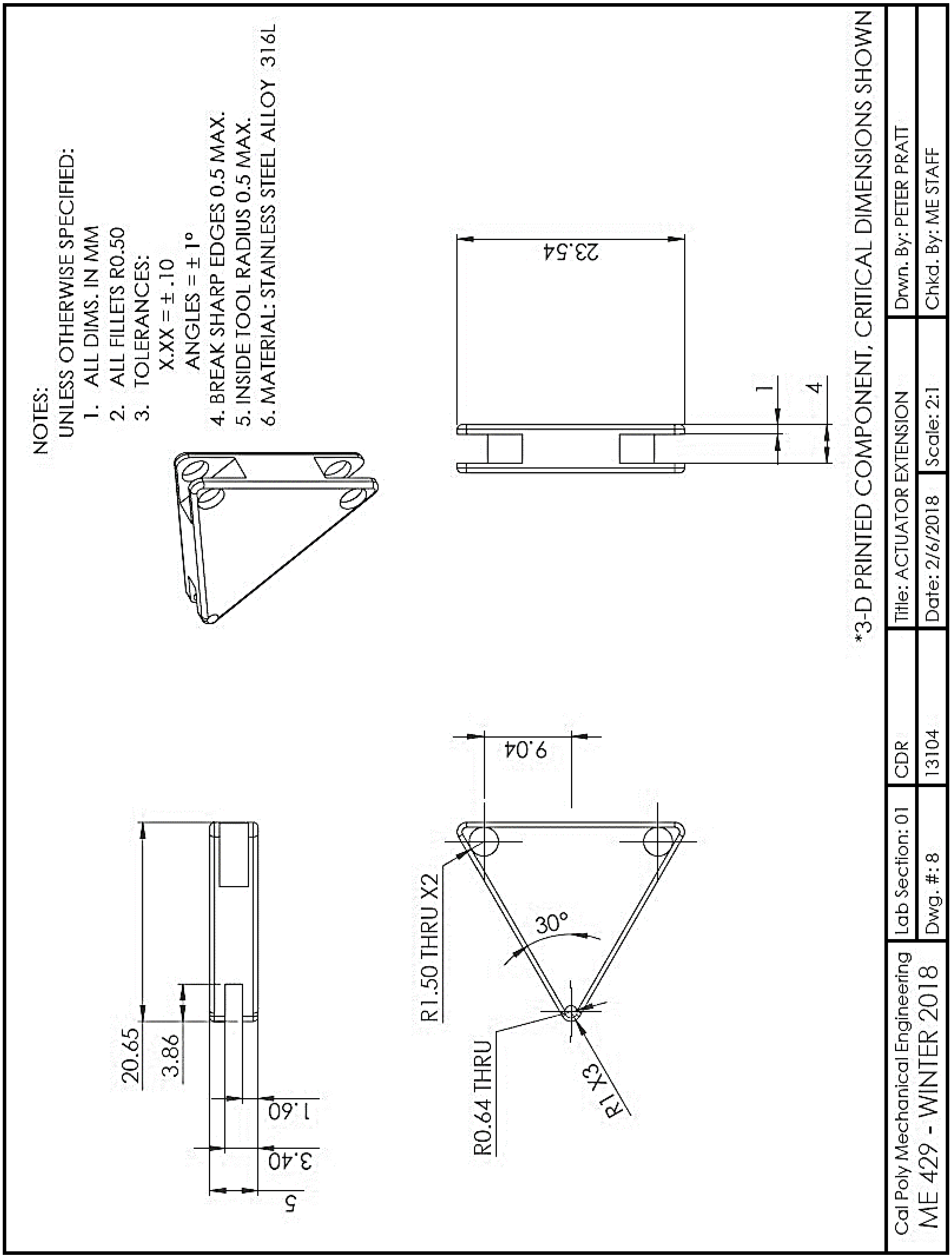
Cal Poly Mechanical Engineering	Lab Section: 01	CDR	Title: MOUNTING FLANGE FRONT FACE		Drwn. By: PETER PRATT
ME 429 - WINTER 2018	Dwg. #: 4	11000	Date: 2/4/2018	Scale: 1:1	Chkd. By: ME STAFF


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS R2.50
3. TOLERANCES:
X.XX = ± .10
ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
Cal Poly Mechanical Engineering
ME-429 - WINTER 2018
Lab Section: 01
Dwg. #: 5
CDR
13001
Title: Diverging Section With Hinges
Date: 2/5/18
Scale: 1:1
Drwn. By: Shannon Ferreira
Chkd. By: ME STAFF



*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS R1
3. TOLERANCES:
X.XX = ± .10
ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
DETAIL A
SCALE 5 : 1
A
R6.25
6.25
R2.25
R6.75
R6.25
6.14°
14.25°
12.29°
Ø3.00
R2.50
69.90
90.00°
57.24
96.14°
R2.50
9.80
12.29°
5.00
17.00
19.50
67.50
70.00
R2.50
R2.50
76.75
Cal Poly Mechanical Engineering
ME-429 - WINTER 2018
Lab Section: 01
Dwg. #: 6
CDR
13003
Title: Left Hand Flap
Date: 2/5/18
Scale: 1:1
Drwn. By: Shannon Ferreira
Chkd. By: ME STAFF

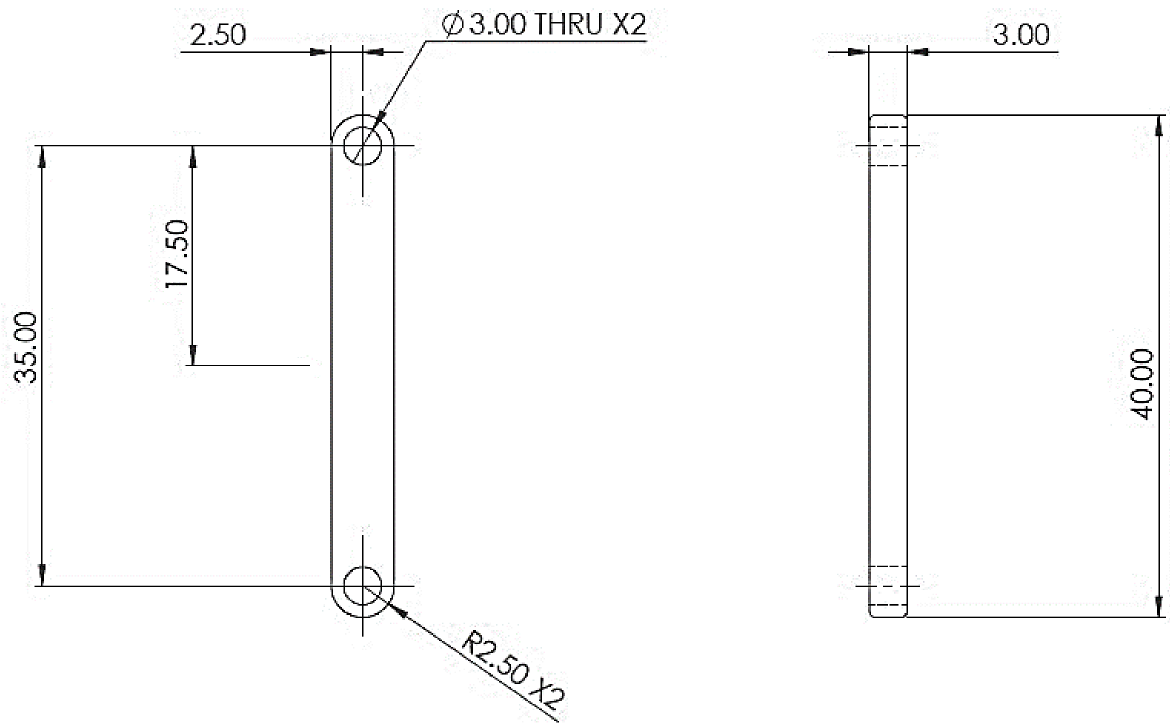

NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS R1
3. TOLERANCES:
X.XX = ± .10
ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
DETAIL A
SCALE 5 : 1
A
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
Cal Poly Mechanical Engineering
ME-429 - WINTER 2018
Lab Section: 01
Dwg. #: 6
CDR
13003
Title: Left Hand Flap
Date: 2/5/18
Scale: 1:1
Drwn. By: Shannon Ferreira
Chkd. By: ME STAFF
6.14°
12.29°
14.25°
R6.25
6.25
R2.25
R6.75
R6.25
Ø3.00
R2.50
69.90
90.00°
57.24
96.14°
R2.50
9.80
12.29°
5.00
17.00
19.50
67.50
70.00
R2.50
R2.50
76.75


NOTES:
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN MM
2. ALL FILLETS R0.50
3. TOLERANCES:
X.XX = ± .10
ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L
20.65
3.86
1.60
3.40
5
R1.50 THRU X2
R0.64 THRU
R1 X3
30°
9.04
23.54
1
4
*3-D PRINTED COMPONENT, CRITICAL DIMENSIONS SHOWN
Cal Poly Mechanical Engineering
ME 429 - WINTER 2018
Lab Section: 01
Dwg. #: 8
CDR
13104
Title: ACTUATOR EXTENSION
Date: 2/6/2018
Scale: 2:1
Drwn. By: PETER PRATT
Chkd. By: ME STAFF

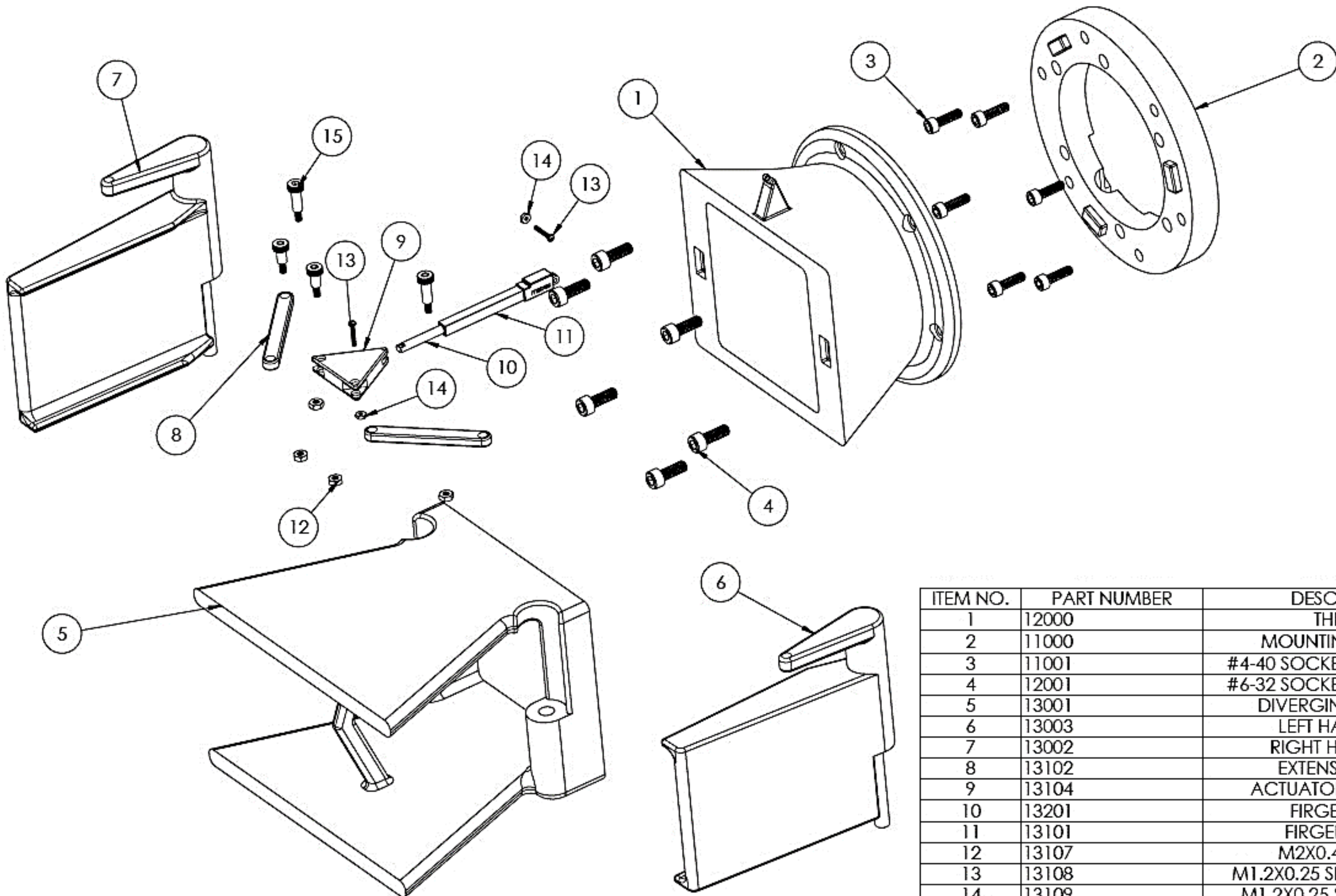
NOTES:

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN MM
2. ALL FILLETS R0.50
3. TOLERANCES:
   X.XX = ± .10
   ANGLES = ± 1°
4. BREAK SHARP EDGES 0.5 MAX.
5. INSIDE TOOL RADIUS 0.5 MAX.
6. MATERIAL: STAINLESS STEEL ALLOY 316L



Cal Poly Mechanical Engineering	Lab Section: 01	CDR	Title: ACTUATION ARMS		Drwn. By: PETER PRATT
ME-429 - WINTER 2018	Dwg. #: 9	13102	Date: 2/6/2018	Scale: 2:1	Chkd. By: ME STAFF



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	12000	THROAT	1
2	11000	MOUNTING FLANGE	1
3	11001	#4-40 SOCKET HEAD SCREW	6
4	12001	#6-32 SOCKET HEAD SCREW	6
5	13001	DIVERGING SECTION	1
6	13003	LEFT HAND FLAP	1
7	13002	RIGHT HAND FLAP	1
8	13102	EXTENSION ARM	2
9	13104	ACTUATOR EXTENSION	1
10	13201	FIRGELLI ROD	1
11	13101	FIRGELLI BODY	1
12	13107	M2X0.4 HEX NUT	4
13	13108	M1.2X0.25 SLOTTED SCREW	2
14	13109	M1.2X0.25 STEEL HEX NUT	2
15	13106	M2X0.4 8mm	2
16	13105	M2x0.4 5mm	2

Cal Poly Mechanical Engineering	Lab Section: 01	CDR	Title: FULL ASSEMBLY		Drwn. By: PETER PRATT
ME-429 - WINTER 2018	Dwg. #: 10	N/A	Date: 2/9/2018	Scale: 1:1.2	Chkd. By: ME STAFF

Appendix M: Purchased Parts Details

Part	Link to Datasheets and Related Information
M2x0.4 Thread Size, 5mm Long	https://www.mcmaster.com/#90265a112/=1bi05ta
M2x0.4 Thread Size, 8mm Long	https://www.mcmaster.com/#90265a114/=1bi068y
4-40 Thread Size, 3/8" Long	https://www.mcmaster.com/#96006a213/=1bi1tj2
6-32 Thread Size, 3/8" Long	https://www.mcmaster.com/#96006a253/=1bi1u2v
M1.2 x 0.25 mm Thread Steel Hex Nut	https://www.mcmaster.com/#91828a004/=1bi1vqb
M2 x 0.4 mm Thread Steel Hex Nut	https://www.mcmaster.com/#94150a305/=1bi1w48
M1.2 x 0.25mm Thread, 8mm Long	https://www.mcmaster.com/#91800a085/=1bi1wmt
Firgelli Classic Linear Actuators	https://www.firgelliauto.com/products/linear-actuators
Firgelli 2 Channel Remote Control System	https://www.firgelliauto.com/products/two-channel-remote-control-system

Appendix N: Budget and Procurement List

Indented Budget:

Assembly Level	Part Number	Description				Vendor	Qty	Cost	Ttl Cost
		Lvl0	Lvl1	Lvl2	Lvl3				
0	10000	Final Assy				------			
1	11000		Variable Nozzle			------			
2	11001			Top Flap		OnlineMetals	1		0
2	11002			Top Flap Support		OnlineMetals	1		0
2	11003			Top Inner Flap		OnlineMetals	2		0
2	11004			Middle Flap Support		OnlineMetals	1		0
2	11005			Bottom Inner Flap		OnlineMetals	1		0
2	11006			Bottom Flap Support		OnlineMetals	1		0
2	11007			Bottom Flap		OnlineMetals	1		0
2	11100			Pivoting Side Flaps		------			
3	11101				Left Flap	OnlineMetals	1		0
3	11102				Right Flap	OnlineMetals	1		0
3	11103				Left Rod	OnlineMetals	1		0
3	11104				Right Rod	OnlineMetals			0
2	11200			Actuation System		------			
3	11201				Top Left Rod Extension	OnlineMetals	1		0
3	11202				Bottom Left Rod Extension	OnlineMetals	1		0
3	11203				Top Right Rod Extension	OnlineMetals	1		0
3	11204				Bottom Right Rod Extension	OnlineMetals	1		0
3	11205				Firgelli Linear Actuator	Firgelli	2	109.99	219.98
3	11206				Bolts	Mcmaaster	1		0
3	11207				Mounting Hardaware	Mcmaaster	1		0
3	11208				BEARING/BUSHING	Mcmaaster	4		0
1	12000		Exhaust Extension Duct			------			
2	12001			Circular Flange		OnlineMetals	1		
2	12002			Throat		OnlineMetals	1		
2	12003			Square Flange		OnlineMetals	1		
2	12004			Bolts		Mcmaaster	6		
						Total Parts	**32**		**219.98**

Appendix O: Testing Details (DVP)

TEST PLAN										TEST REPORT			
Item No	Specification #	Analysis/Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1		Section Lengths	Each printed subsection height must not exceed 4 inches.	Erin	SP-1	1	C						
2		Square Converging Cross-Section Dimensions	Negligable flow losses.	Erin	SP-1	1	C						
3		Converging Section Loft Contour	Negligable flow losses.	Erin	SP-1	1	C						
4		Fillet Radii	Meets SLM printer requriements.	Erin	SP-1	1	C						
5		Side Flap Curve Contour	Negligable flow losses.	Erin	SP-1	1	C						
6		Bolt Loads and Sizing	Maximum Force, each bolt = 180N	Peter	SP-1	1	C						
7		Pressure Loads on Side Flaps	Maximum Actuator Loads	Peter	FP	1	Sub						
8		Actuator System Mounts Loads	Actuator system will not deflect under maximum operating conditions.	Peter	SP-2	1	Sub						
9		Hinge Loads	Hinges will not deflect under maximum operating conditions.	Peter	SP-2	1	C						
10		Fillet Loads	Joints between parts can handle thrust loads.	Erin	SP-2	1	Sub						
11		Flange Structures	Flanges are thick enough to take bolt loads and transfer thrust forces to engine structure.	Peter	SP-2	1	Sub						
12		Vibrations Loads	Fasteners don't loose torque.	Peter	FP	1	Sub						
15		Deflection of top & bottom flaps under applied loads.	Maximum Value = 0.001 m	Shannon	SP-2	1	C						
16		Side flaps & actuation system deflections at maximum thrust position.	Maximum Value = 0.003 m	Shannon	SP-2	1	Sub						
17		Heat transfer to actuation system.	Maximum Temperature, Outside Nozzle Walls = 550 K	Shannon	FP	1	Sub						
18		Heat transfer to engine back face.	Maximum Temperature, Engine Back Face = 550 K	Shannon	FP	1	C						
19		Heat transfer to instrumentation.	Maximum Temperature = Maximum Instrumentation Ratings	Shannon	FP	1	Sub						
20		Time to cool down between runs.	Safe Value	Shannon	SP-2	1	Sys						
21		Bolt holes and P5 cutout.	Bolt hole cutouts cannot expand to a point at which threads would unload.	Shannon	SP-2, FP	2	C						
22		Interferance of flaps.	Flaps cannot interfere during maximum engine run time at maximum operating conditions.	Shannon	FP	1	Sub						
23		Hardware integration between nozzle extension and SR-30 engine.	No Fail	Erin	SP-1, SP-2, FP	3	Sub						
24		Deflection of top & bottom flaps under applied loads.	Maximum Value = 0.001 m	Shannon	SP-2	1	C						
25		Bolt pull-out test on six turbojet integration bolts.	Minimum Force, each bolt = 180 N	Peter	SP-2	6	C						
26		Actuation system functionality; controlled and uncontrolled.	No Fail	Peter	SP-2	1	Sub						
27		Actuation system loads.	Minimum Force = 180 N	Peter	SP-2	1	Sub						
28		Alterations in SR-30 performance with nozzle attachment.	Pressure and Temperature limits of engine are not exceeded.	Erin	SP-2, FP	2	Sys						
29		Heat transfer through nozzle walls.	Maximum Temperature, Outside Nozzle Walls = 550 K	Erin	SP-2	1	Sys						
30		Nozzle flow parameters: Velocity, Temperature, Pressure	Maximum limits of nozzle design are not exceeded.	Erin	SP-2	1	Sys						

Appendix P: Risk Assessment

designsafe Report

Application:	Sample Machine / Product	Analyst Name(s):	Joe Maintenance, Jane Engineer, John Doe
Description:	This example analysis shows some of the basics of a risk assessment.	Company:	Acme Products
Product Identifier:		Facility Location:	Ann Arbor, Michigan, USA
Assessment Type:	Detailed		
Limits:	sample analysis only!!		
Sources:	personnel experiences, ANSI B11 standards, assembly drawings W-Z		
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	operator operating turbojet	mechanical : crushing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-2	operator operating turbojet	mechanical : drawing-in / trapping / entanglement sticking fingers into inlet/outlet	Serious Unlikely	Medium	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-3	operator operating turbojet	mechanical : pinch point sticking fingers into inlet/outlet	Minor Remote	Negligible	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
1-1-4	operator operating turbojet	slips / trips / falls : trip wheels, fuel line, air line, other projects	Minor Likely	Low	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
1-1-5	operator operating turbojet	ergonomics / human factors : duration sound exposure to the engine running	Minor Unlikely	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Minor		Complete [3/15/2018] Lab Techs
1-1-6	operator operating turbojet	fire and explosions : hot surfaces touching the engine while/soon after running	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-7	operator operating turbojet	fire and explosions : flammable liquid / vapor fuel leak	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-8	operator operating turbojet	heat / temperature : burns / scalds touching the engine while/soon after running	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-9	operator operating turbojet	heat / temperature : radiant heat being in/near the exhaust flow	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-10	operator operating turbojet	heat / temperature : severe heat touching the engine while running, passing through the exhaust flow	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-11	operator operating turbojet	noise / vibration : noise / sound levels > 80 dBA sound exposure to the engine running	Minor Very Likely	Medium	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Minor		Complete [3/15/2018] Lab Techs
1-1-12	operator operating turbojet	noise / vibration : interference with communications sound exposure to the engine running	Minor Very Likely	Medium	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Minor		Complete [3/15/2018] Lab Techs
1-1-13	operator operating turbojet	ingress / egress : inadequate means of evacuation trip hazards, single exit, indirect path	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-14	operator operating turbojet	material handling : excessive weight moving the engine	Moderate Unlikely	Low	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-15	operator operating turbojet	environmental / industrial hygiene : emissions exhaust exposure	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-1-16	operator operating turbojet	ventilation / confined space : loss of exhaust blockage of exhaust	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-1-17	operator operating turbojet	ventilation / confined space : smoke combustion too wet, fuel contaminated	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-1-18	operator operating turbojet	chemical : chemical emissions exhaust flow	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-1-19	operator operating turbojet	fluid / pressure : explosion / implosion break in combustion chamber	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
1-1-20	operator operating turbojet	fluid / pressure : fluid leakage / ejection fuel leak	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-1-21	operator operating turbojet	fluid / pressure : high pressure air pressure line break	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
1-2-1	operator misuse	mechanical : crushing sticking fingers into inlet/outlet	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-2	operator misuse	mechanical : cutting / severing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-3	operator misuse	mechanical : drawing-in / trapping / entanglement sticking fingers into inlet/outlet	Serious Unlikely	Medium	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-4	operator misuse	mechanical : unexpected start press start while key is in ignition	Moderate Unlikely	Low	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-5	operator misuse	mechanical : break up during operation fracture, loose bolts	Catastrophic Remote	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Catastrophic		Complete [3/15/2018] Lab Techs
1-2-6	operator misuse	mechanical : impact something breaks off	Catastrophic Remote	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Catastrophic		Complete [3/15/2018] Lab Techs
1-2-7	operator misuse	electrical / electronic : energized equipment / live parts engine running	Moderate Unlikely	Low	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-8	operator misuse	electrical / electronic : unexpected start up / motion press start while key is in ignition, breaks not locked	Serious Unlikely	Medium	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-9	operator misuse	slips / trips / falls : debris something breaks off	Serious Remote	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Serious		Complete [3/15/2018] Lab Techs
1-2-10	operator misuse	fire and explosions : uncontrolled ignition sources issues with ignition or fuel lines	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-11	operator misuse	fire and explosions : hot surfaces touching engine while running	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-12	operator misuse	fire and explosions : flammable gas exhaust flow	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-13	operator misuse	fire and explosions : flammable liquid / vapor fuel leak	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-14	operator misuse	fire and explosions : improperly mixed chemicals mixing fuels	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-15	operator misuse	heat / temperature : burns / scalds touching the engine	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-16	operator misuse	heat / temperature : radiant heat exposure to exhaust flow	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-17	operator misuse	heat / temperature : severe heat exposure to exhaust, touching engine	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-18	operator misuse	noise / vibration : noise / sound levels >120 dBA instantaneous sound exposure to the engine running	Moderate Unlikely	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Moderate		Complete [3/15/2018] Lab Techs

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-19	operator misuse	noise / vibration : loss of hearing acuteness sound exposure to the engine running	Moderate Very Likely	High	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)	Moderate		Complete [3/15/2018] Lab Techs
1-2-20	operator misuse	noise / vibration : equipment damage running too high with nozzle closed	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-21	operator misuse	ingress / egress : inadequate lighting working too early/late	Minor Remote	Negligible	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
1-2-22	operator misuse	ingress / egress : inadequate means of evacuation trip hazards, single exit, indirect path	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-23	operator misuse	ingress / egress : material storage interference improperly putting away engine, fuel	Minor Remote	Negligible	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
1-2-24	operator misuse	ingress / egress : blocked / locked pathway or door locking lab door, scattering material	Serious Unlikely	Medium	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-25	operator misuse	environmental / industrial hygiene : hazardous waste fuel leaking	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-26	operator misuse	environmental / industrial hygiene : carcinogens fuel byproducts	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-27	operator misuse	environmental / industrial hygiene : poisons fuel	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-28	operator misuse	environmental / industrial hygiene : ozone depleting substances fuel?	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-29	operator misuse	environmental / industrial hygiene : emissions fuel	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-30	operator misuse	environmental / industrial hygiene : contamination fuels, mixing fuels	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-31	operator misuse	ventilation / confined space : confined space too much CO2, too many contaminents	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-32	operator misuse	ventilation / confined space : loss of exhaust too much CO2, too many contaminents	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-33	operator misuse	ventilation / confined space : lack of fresh air too much CO2, too many contaminents	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-34	operator misuse	ventilation / confined space : smoke walled in; less fresh air	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-35	operator misuse	ventilation / confined space : air contaminants too much CO2, too many contaminents	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-36	operator misuse	ventilation / confined space : recirculating air breathe in exhaust	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-37	operator misuse	chemical : reaction to / with irritant chemicals fuel exhaust	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-38	operator misuse	chemical : mixing incompatible chemicals mixing fuels while refilling	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-39	operator misuse	chemical : chemical emissions fuel exhaust	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
1-2-40	operator misuse	fluid / pressure : high pressure engine explodes	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
1-2-41	operator misuse	fluid / pressure : pneumatics rupture engine explodes	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
1-2-42	operator misuse	fluid / pressure : explosion / implosion engine explodes	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
1-2-43	operator misuse	fluid / pressure : fluid leakage / ejection fuel leak, air leak	Moderate Remote	Negligible	existing casing and operation directions	Moderate		Complete [3/15/2018] Turbine Technologies
1-2-44	operator misuse	fluid / pressure : high pressure air engine explodes	Catastrophic Remote	Low	existing casing and operation directions	Catastrophic		Complete [3/15/2018] Turbine Technologies
2-1-1	maintenance technician adjust controls / settings / alignment	mechanical : crushing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-2	maintenance technician adjust controls / settings / alignment	mechanical : cutting / severing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions	Serious		Complete [3/15/2018] Turbine Technologies
2-1-3	maintenance technician adjust controls / settings / alignment	mechanical : pinch point sticking fingers into inlet/outlet	Minor Likely	Low	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
2-1-4	maintenance technician adjust controls / settings / alignment	slips / trips / falls : trip wheels, fuel line, air line, other projects	Minor Very Likely	Medium	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
2-1-5	maintenance technician adjust controls / settings / alignment	ergonomics / human factors : posture bending to hook things up	Minor Likely	Low	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
2-1-6	maintenance technician adjust controls / settings / alignment	ergonomics / human factors : lifting / bending / twisting bending to hook things up, taking off casing for repairs	Minor Likely	Low	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
2-1-7	maintenance technician adjust controls / settings / alignment	ingress / egress : inadequate lighting courtyard fenced in	Minor Remote	Negligible	existing casing and operation directions	Minor		Complete [3/15/2018] Turbine Technologies
2-2-1	maintenance technician set-up or maintenance	mechanical : crushing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-2	maintenance technician set-up or maintenance	mechanical : cutting / severing sticking fingers into inlet/outlet	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-3	maintenance technician set-up or maintenance	mechanical : pinch point sticking fingers into inlet/outlet	Minor Likely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-2-4	maintenance technician set-up or maintenance	slips / trips / falls : trip wheels, fuel line, air line, other projects	Minor Very Likely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-5	maintenance technician set-up or maintenance	ergonomics / human factors : posture connecting fuel lines	Minor Likely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-6	maintenance technician set-up or maintenance	ergonomics / human factors : lifting / bending / twisting connecting fuel lines	Moderate Likely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-7	maintenance technician set-up or maintenance	ingress / egress : inadequate lighting shaded courtyard	Minor Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-8	maintenance technician set-up or maintenance	material handling : stacking / storing taking off casing when doing repairs	Minor Likely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-9	maintenance technician set-up or maintenance	material handling : excessive weight taking off casing when doing repairs	Moderate Unlikely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-10	maintenance technician set-up or maintenance	environmental / industrial hygiene : hazardous waste handling fuels	Serious Likely	High	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-11	maintenance technician set-up or maintenance	environmental / industrial hygiene : contamination mixing fuels	Serious Likely	High	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-2-12	maintenance technician set-up or maintenance	chemical : skin exposed to toxic chemical handling fuels	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

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2-2-13	maintenance technician set-up or maintenance	fluid / pressure : high pressure air engine explodes	Catastrophic Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-1	maintenance technician trouble-shooting / problem solving - running engine	mechanical : drawing-in / trapping / entanglement fuel line, air line	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-2	maintenance technician trouble-shooting / problem solving - running engine	mechanical : unexpected start engine	Moderate Unlikely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-3	maintenance technician trouble-shooting / problem solving - running engine	mechanical : break up during operation engine	Catastrophic Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-4	maintenance technician trouble-shooting / problem solving - running engine	electrical / electronic : energized equipment / live parts engine	Serious Unlikely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-5	maintenance technician trouble-shooting / problem solving - running engine	fire and explosions : uncontrolled ignition sources fuel on start up	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-6	maintenance technician trouble-shooting / problem solving - running engine	fire and explosions : hot surfaces touching the engine while/soon after running	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-7	maintenance technician trouble-shooting / problem solving - running engine	fire and explosions : flammable gas fuel / air	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-8	maintenance technician trouble-shooting / problem solving - running engine	fire and explosions : flammable liquid / vapor fuel	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-9	maintenance technician trouble-shooting / problem solving - running engine	fire and explosions : improperly mixed chemicals fuel	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-10	maintenance technician trouble-shooting / problem solving - running engine	heat / temperature : burns / scalds touching the engine while/soon after running	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-11	maintenance technician trouble-shooting / problem solving - running engine	heat / temperature : radiant heat engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-12	maintenance technician trouble-shooting / problem solving - running engine	heat / temperature : severe heat touching the engine while running, passing through the engine exhaust	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-13	maintenance technician trouble-shooting / problem solving - running engine	noise / vibration : noise / sound levels > 80 dBA sound exposure to the engine running	Moderate Likely	Medium	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
2-3-14	maintenance technician trouble-shooting / problem solving - running engine	noise / vibration : noise / sound levels >120 dBA instantaneous sound exposure to the engine running	Moderate Unlikely	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
2-3-15	maintenance technician trouble-shooting / problem solving - running engine	noise / vibration : loss of hearing acuteness sound exposure to the engine running	Moderate Unlikely	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
2-3-16	maintenance technician trouble-shooting / problem solving - running engine	noise / vibration : equipment damage engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

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2-3-17	maintenance technician trouble-shooting / problem solving - running engine	noise / vibration : interference with communications sound exposure to the engine running	Minor Unlikely	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
2-3-18	maintenance technician trouble-shooting / problem solving - running engine	ingress / egress : inadequate means of evacuation trip hazards, single exit, indirect path	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-19	maintenance technician trouble-shooting / problem solving - running engine	ingress / egress : material storage interference other projects in lab	Serious Unlikely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-20	maintenance technician trouble-shooting / problem solving - running engine	ingress / egress : blocked / locked pathway or door trip hazards in lab	Serious Unlikely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-21	maintenance technician trouble-shooting / problem solving - running engine	environmental / industrial hygiene : emissions exhaust	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-22	maintenance technician trouble-shooting / problem solving - running engine	ventilation / confined space : smoke exhaust	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-23	maintenance technician trouble-shooting / problem solving - running engine	ventilation / confined space : air contaminants exhaust	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-24	maintenance technician trouble-shooting / problem solving - running engine	chemical : chemical emissions exhaust	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-25	maintenance technician trouble-shooting / problem solving - running engine	fluid / pressure : high pressure engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

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2-3-26	maintenance technician trouble-shooting / problem solving - running engine	fluid / pressure : pneumatics rupture engine	Catastrophic Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-27	maintenance technician trouble-shooting / problem solving - running engine	fluid / pressure : explosion / implosion engine	Catastrophic Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
2-3-28	maintenance technician trouble-shooting / problem solving - running engine	fluid / pressure : high pressure air engine	Catastrophic Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-1	passer by / non-user work next to / near machinery - in propulsion lab	slips / trips / falls : trip wheels, fuel line, air line, other projects	Minor Very Likely	Medium	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-2	passer by / non-user work next to / near machinery - in propulsion lab	fire and explosions : hot surfaces engine	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-3	passer by / non-user work next to / near machinery - in propulsion lab	fire and explosions : flammable liquid / vapor fuel, exhuast	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-4	passer by / non-user work next to / near machinery - in propulsion lab	heat / temperature : burns / scalds touching the engine while/soon after running	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-5	passer by / non-user work next to / near machinery - in propulsion lab	heat / temperature : radiant heat engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-6	passer by / non-user work next to / near machinery - in propulsion lab	heat / temperature : severe heat touching the engine while running, passing through exhaust flow	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

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3-1-7	passer by / non-user work next to / near machinery - in propulsion lab	noise / vibration : noise / sound levels > 80 dBA being near the engine while running	Moderate Likely	Medium	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-8	passer by / non-user work next to / near machinery - in propulsion lab	noise / vibration : interference with communications being near the engine while running	Minor Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-9	passer by / non-user work next to / near machinery - in propulsion lab	ingress / egress : inadequate means of evacuation trip hazards, single exit, indirect path	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-10	passer by / non-user work next to / near machinery - in propulsion lab	environmental / industrial hygiene : emissions exhaust	Serious Remote	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-11	passer by / non-user work next to / near machinery - in propulsion lab	ventilation / confined space : confined space exhaust in small courtyard	Moderate Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-12	passer by / non-user work next to / near machinery - in propulsion lab	ventilation / confined space : smoke exhaust	Moderate Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-13	passer by / non-user work next to / near machinery - in propulsion lab	ventilation / confined space : air contaminants exhaust	Moderate Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-1-14	passer by / non-user work next to / near machinery - in propulsion lab	chemical : chemical emissions exhaust	Moderate Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-1-15	passer by / non-user work next to / near machinery - in propulsion lab	fluid / pressure : high pressure engine	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-16	passer by / non-user work next to / near machinery - in propulsion lab	fluid / pressure : explosion / implosion engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-1-17	passer by / non-user work next to / near machinery - in propulsion lab	fluid / pressure : high pressure air engine	Serious Remote	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
3-2-1	passer by / non-user walk near machinery - outside of propulsion lab	noise / vibration : noise / sound levels > 80 dBA sound exposure to the engine running	Moderate Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-2-2	passer by / non-user walk near machinery - outside of propulsion lab	noise / vibration : interference with communications sound exposure to the engine running	Minor Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
3-2-3	passer by / non-user walk near machinery - outside of propulsion lab	environmental / industrial hygiene : emissions fuel, exhuast	Minor Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-2-4	passer by / non-user walk near machinery - outside of propulsion lab	chemical : chemical emissions exhaust	Minor Remote	Negligible	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
4-1-1	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	mechanical : pinch point sticking fingers into inlet/outlet	Minor Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
4-1-2	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	ergonomics / human factors : posture moving engine, taking off casing	Minor Likely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
4-1-3	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	ergonomics / human factors : duration sound exposure to the engine running, bending	Minor Likely	Low	lab safety protocols (earplugs and eyeglasses, warning signs outside lab for passerbys)			Complete [3/15/2018] Lab Techs
4-1-4	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	ergonomics / human factors : lifting / bending / twisting handling casing during repairs	Minor Likely	Low	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
4-1-5	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	ingress / egress : inadequate lighting courtyard	Minor Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies
4-1-6	electrician / controls technician - assuming engine is not connected to power source repair / replace/test wiring / systems	environmental / industrial hygiene : poisons fuel	Moderate Remote	Negligible	existing casing and operation directions			Complete [3/15/2018] Turbine Technologies

Appendix Q: Guide for Testing Nozzle Performance

Intended for a Constant Area Hot-Fire Operation Test

Description: Determine how the addition of a constant-area nozzle impacts performance of the SR-30 turbojet engine, measure flow parameters through the nozzle, and determine the nozzle loading during engine hot-fire operation.

Location: Aerospace Propulsion Laboratory

Required Materials:

- Safety glasses
- Earplugs
- SR-30 Turbojet MiniLab System (engine, existing instrumentation, and DAQ system)
- Nozzle throat
- Nozzle flange
- Four #10-32 UNF Stainless Steel Socket Head Screws
- Six #4-40 UNC Stainless Steel Socket Head Screws
- Bolt torque-meter
- Aluminum plate (for operator protection)

Required Instrumentation:

- Barometer (Ambient Pressure)
- Thermometer (Ambient Temperature)
- Thermocouples:
    - Engine Back Plate Skin Temperature
    - Station 6 Flow Temperature
- Pressure Probes:
    - Station 6 Flow Pressure
- Strain Gauges
- Decibel-meter
- Vibrometer

Test Protocol:

1) Record the ambient barometer and thermometer readings from the lab equipment.
2) If the engine has been running, ensure that engine is off and wait until all temperature and pressure readings have returned to ambient.
3) Assemble the variable nozzle system and attach to the engine. Measure and record the bolt torque.
4) If not already attached, position thermocouple to the back-face of the turbojet, near the mounting flange region.
5) Position a thermocouple along the inside of the throat wall, near the mounting flange attachment point. Attach a thermocouple to the outside of the throat wall, in the same region as the inside thermocouple.
6) Position a pressure probe in the center of the nozzle exit. Put a thermocouple in the middle of the nozzle exit flow.
7) Turn on the DAQ and make sure the units are correct (L/s, Pa, N, etc.). Zero units where applicable and possible.
8) Start the DAQ recording before engine startup to record all initial readings for baseline offsets to use in future calibration; take baseline data with engine off for two minutes. Record the initial temperature reading for the back plate, the initial wall temperature on the inside and outside, and initial T6 and P6 readings.
9) Set up the aluminum plate between the test operators and the MiniLab System. Maintain direct access to instrumentation readouts.
10) Run the engine at idle position for three minutes, closely monitoring the data to ensure it doesn't exceed safety limits. If it does, turn off the engine immediately and abort the test.
11) Continue running the engine at idle for another two minutes. Record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6, and the decibel level.
12) Slowly ramp engine to maximum throttle position, monitoring the temperatures and pressures to ensure that they do not exceed safety limits. If measurements begin to approach the limits, stop ramping up and record the engine speed. Continue recording data for three minutes. Record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6, and the decibel level.
13) Slowly return engine to idle position. Continue recording data for two minutes. Record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6, and the decibel level.
14) Turn off the engine. Monitor the back plate temperature. Record how long it takes for the plate to cool to 30°C or ambient (whichever is higher).
15) Perform post-test checks.

Data Record:

Before Engine Startup:

Ambient Pressure		in H2O
Ambient Temperature		°C
Initial Back Plate Temperature		°C
Initial Bolt Torque		N-m

At Engine Idle Position:

Station 6 Temperature		°C
Station 6 Pressure		N-m
Nozzle Inside Wall Temperature		°C
Nozzle Outside Wall Temperature		°C
Back Plate Temperature		°C
Decibel Level		dB

At Engine Maximum Throttle Position:

Station 6 Temperature		°C
Station 6 Pressure		N-m
Nozzle Inside Wall Temperature		°C
Nozzle Outside Wall Temperature		°C
Back Plate Temperature		°C
Decibel Level		dB

Note: For engine performance parameter test data, see DAQ data spreadsheet collections.

Post-Test Checks:

Time for Back Plate to Cool From Maximum Temperature to 30°C		sec
Final Bolt Torque		N-m

	Yes/No	**Detailed Notes**
Did the engine reach full throttle position?		
Did the throat crack?		
Did any parameters exceed safety limits?		

Appendix R: Student Operating Manual for Labs

Description: Determine how the addition of a constant-area nozzle impacts performance of the SR-30 turbojet engine, measure flow parameters through the nozzle, and determine the nozzle loading during engine hot-fire operation.

Location: Aerospace Propulsion Laboratory

Required Materials:

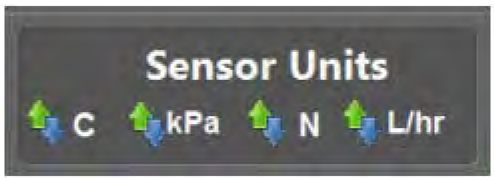
- Safety glasses
- Earplugs
- SR-30 Turbojet MiniLab System (engine, existing instrumentation, and DAQ system)
- Nozzle (attached to engine)
- Data from without the nozzle attached (provided by a prior lab).

Required Instrumentation:

- Barometer (Ambient Pressure)
- Thermometer (Ambient Temperature)
- Thermocouples:
    - Engine Back Plate Skin Temperature
    - Station 6 Flow Temperature
- Pressure Probes:
    - Station 6 Flow Pressure

Test Protocol:

1) Record the ambient barometer and thermometer readings from the lab equipment.
2) If the engine has been running, ensure that engine is off and wait until all temperature and pressure readings have returned to ambient.
3) Confirm a thermocouple is connected to the back-face of the turbojet, near the mounting flange region, a second is along the inside of the throat wall (near the mounting flange attachment point), a third is attached to the outside of the throat wall (in the same region as the inside thermocouple), and a fourth is in the middle of the nozzle exit flow.
4) Confirm there is a pressure probe positioned in the center of the nozzle exit.
5) Turn on the DAQ and make sure the units are all metric. Zero units where applicable and possible.



6) Start the DAQ recording before engine startup to record all initial readings for baseline offsets to use in future calibration; take baseline data with engine off for two minutes. Record the initial temperature reading for the back plate, the initial wall temperature on the inside and outside, and initial T6 and P6 readings.
7) Run the engine at idle position for three minutes, closely monitoring the data to ensure it doesn’t exceed safety limits. If it does, turn off the engine immediately and abort the test.

8) Once it seems to have reached steady state (takes approximately one minute), record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6, and the decibel level.
9) Slowly ramp engine to maximum throttle position, monitoring the temperatures and pressures to ensure that they do not exceed safety limits. If measurements begin to approach the limits, stop ramping up and record the engine speed. Continue recording data for another three minutes.

10) Once it has achieved steady state again (takes approximately one minute), record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6.
11) Slowly return engine to idle position. Continue recording data for two minutes. Record the temperature reading for the back plate, the wall temperature on the inside and outside, T6 and P6, and the decibel level.

12) Adjust the nozzle to a different area ratio and repeat the test at least two more times (use a new data sheet per test). By the end of it, you should have at least one set of data for the nozzle converged, diverged, and at a constant area.
13) Turn off the engine. Monitor the back plate temperature. Record how long it takes for the plate to cool to 30°C or ambient temperature (whichever is higher).

Known Safety Concerns:

Students should not be allowed to operate the engine with the nozzle attached until nozzle and engine have been evaluated in tandem for hot-fire safety and performance at all throttle levels.

All other known safety concerns (such as the high temperatures of the exhaust) can be found in the engine operation manual, which should be referred to for general set up and operation.

Data Record:

Before Engine Startup:

Ambient Pressure		in H2O
Ambient Temperature		°C
Initial Back Plate Temperature		°C

At Engine Idle Position:

	First Run		Second Run	
Station 6 Temperature		°C		°C
Station 6 Pressure		N-m		N-m
Nozzle Inside Wall Temperature		°C		°C
Nozzle Outside Wall Temperature		°C		°C
Back Plate Temperature		°C		°C

At Engine Maximum Throttle Position:

Station 6 Temperature		°C
Station 6 Pressure		N-m
Nozzle Inside Wall Temperature		°C
Nozzle Outside Wall Temperature		°C
Back Plate Temperature		°C

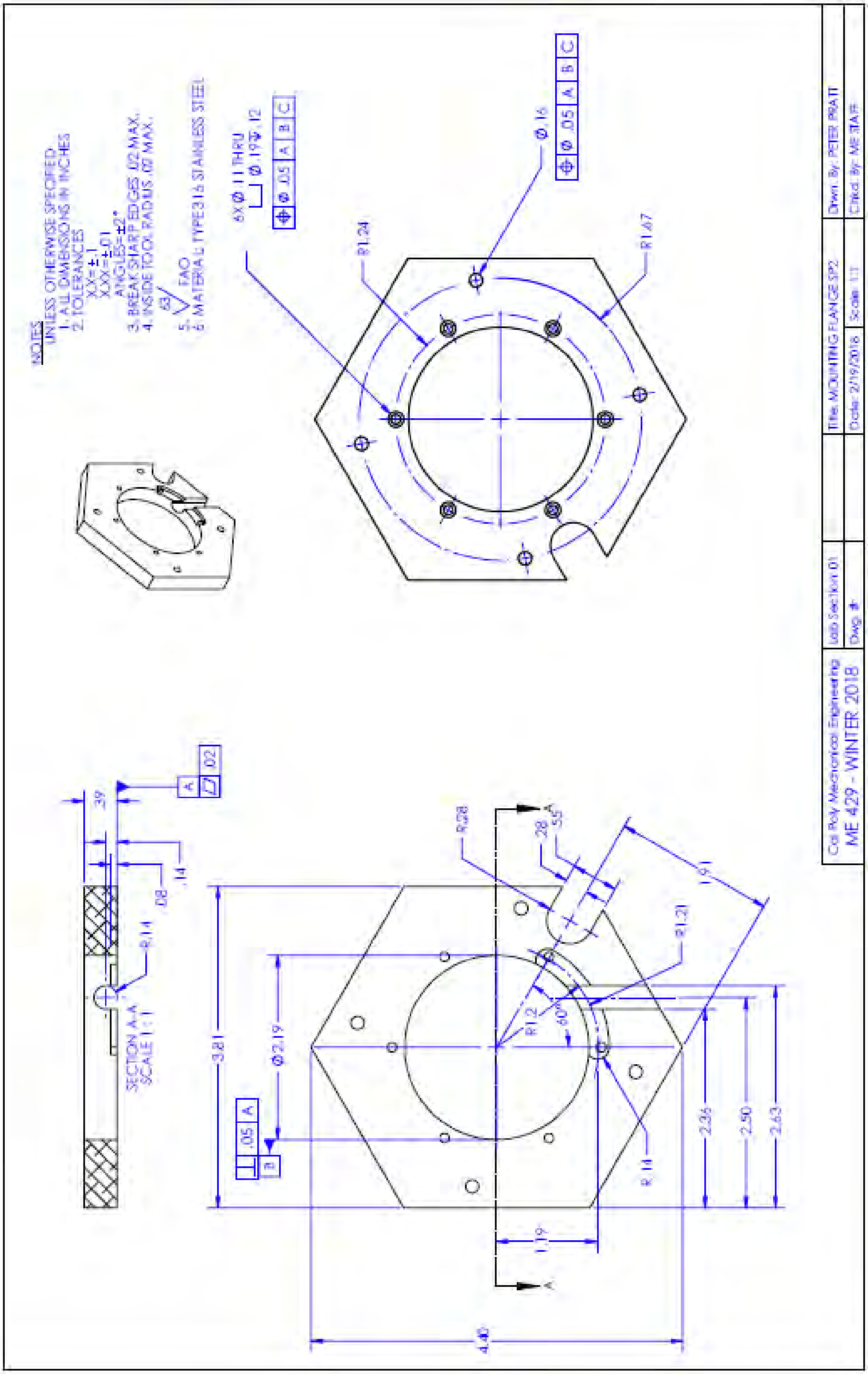
Note: For engine performance parameter test data, see DAQ data spreadsheet collections.

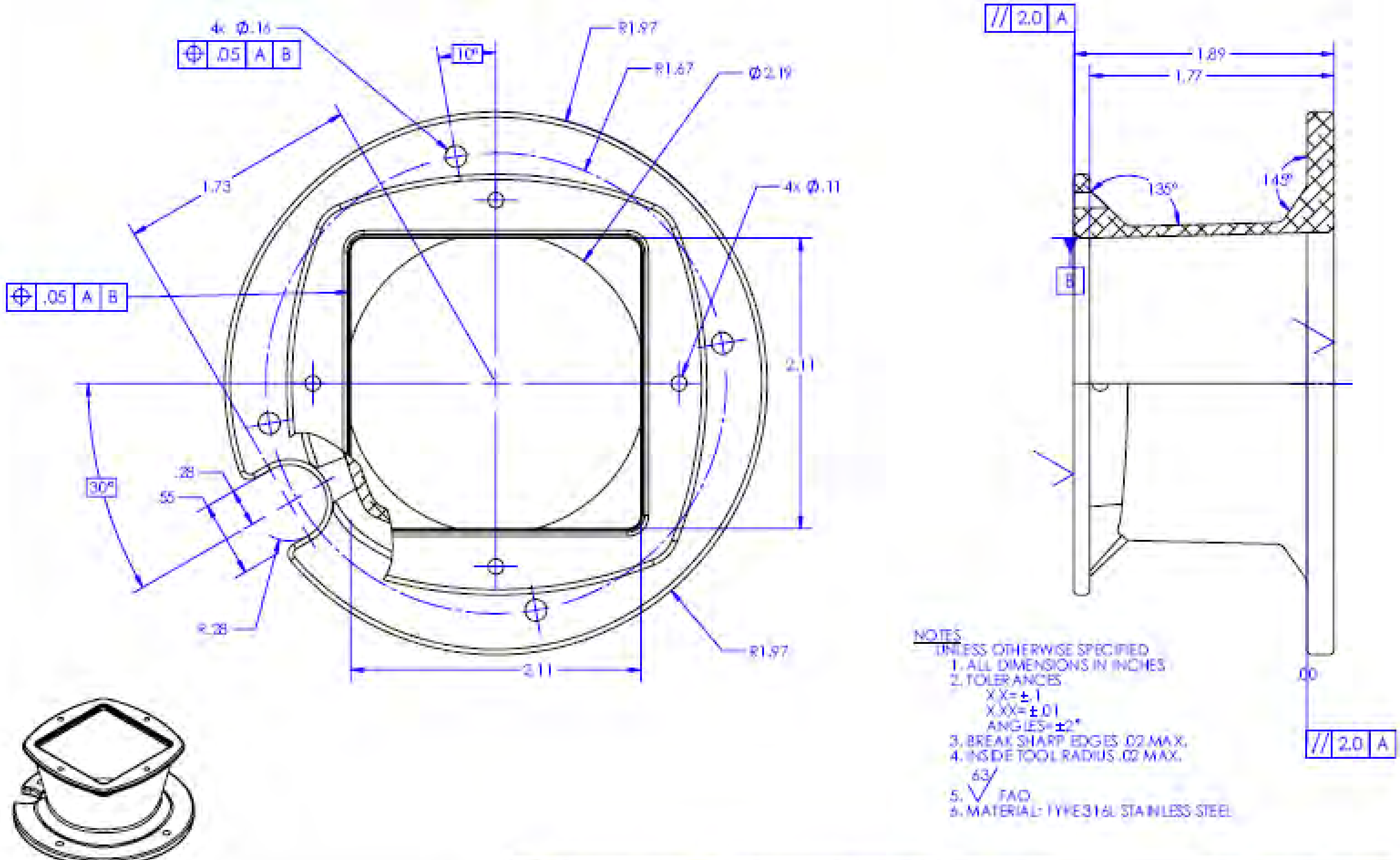
During/After Cool-Down:

Time for Back Plate to Cool From Maximum Temperature to 30°C		sec

	Yes/No	**Detailed Notes**
Did the engine reach full throttle position?		
Did the throat crack?		

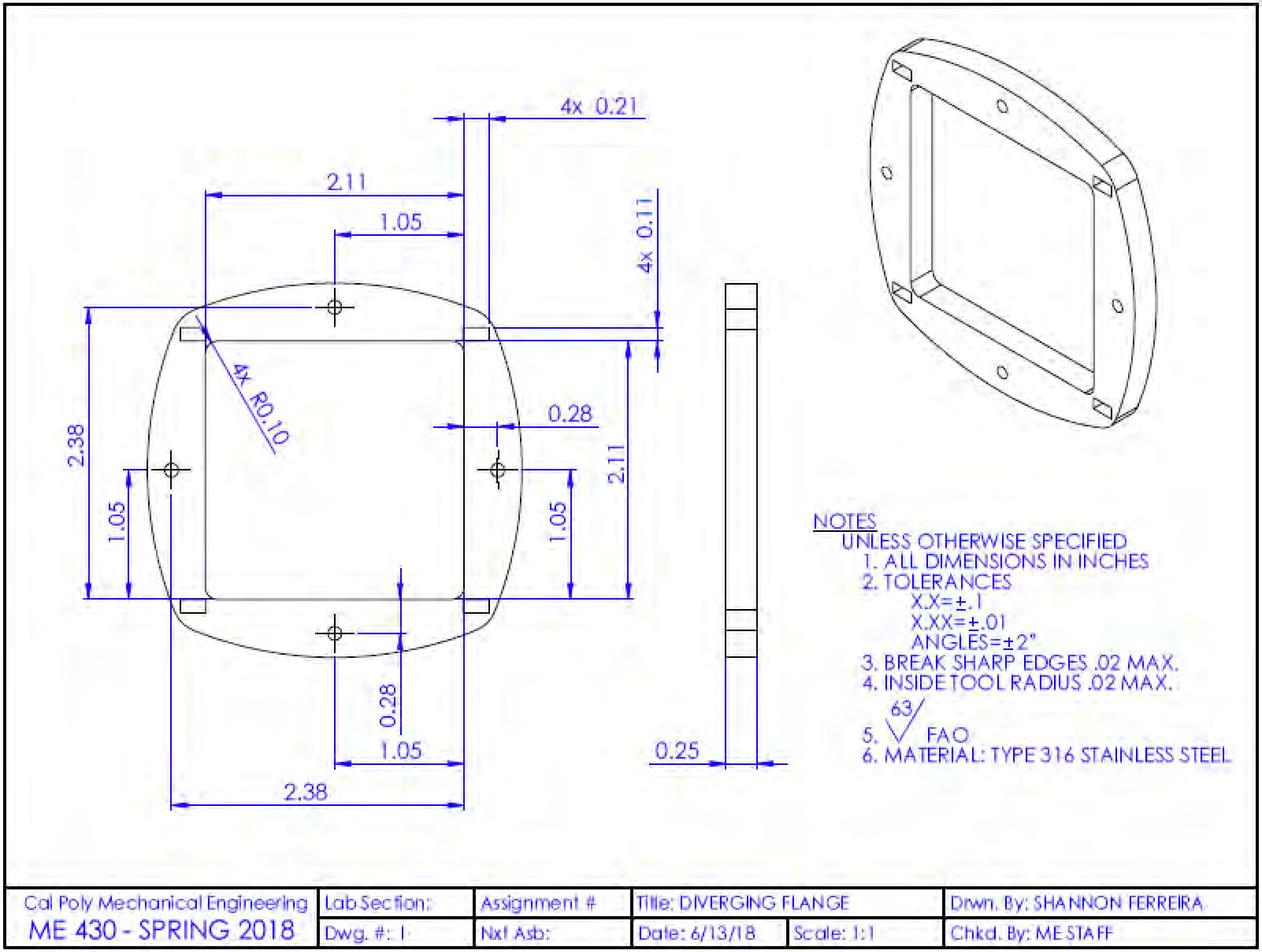
Appendix S: Complete Drawings Package (Final)

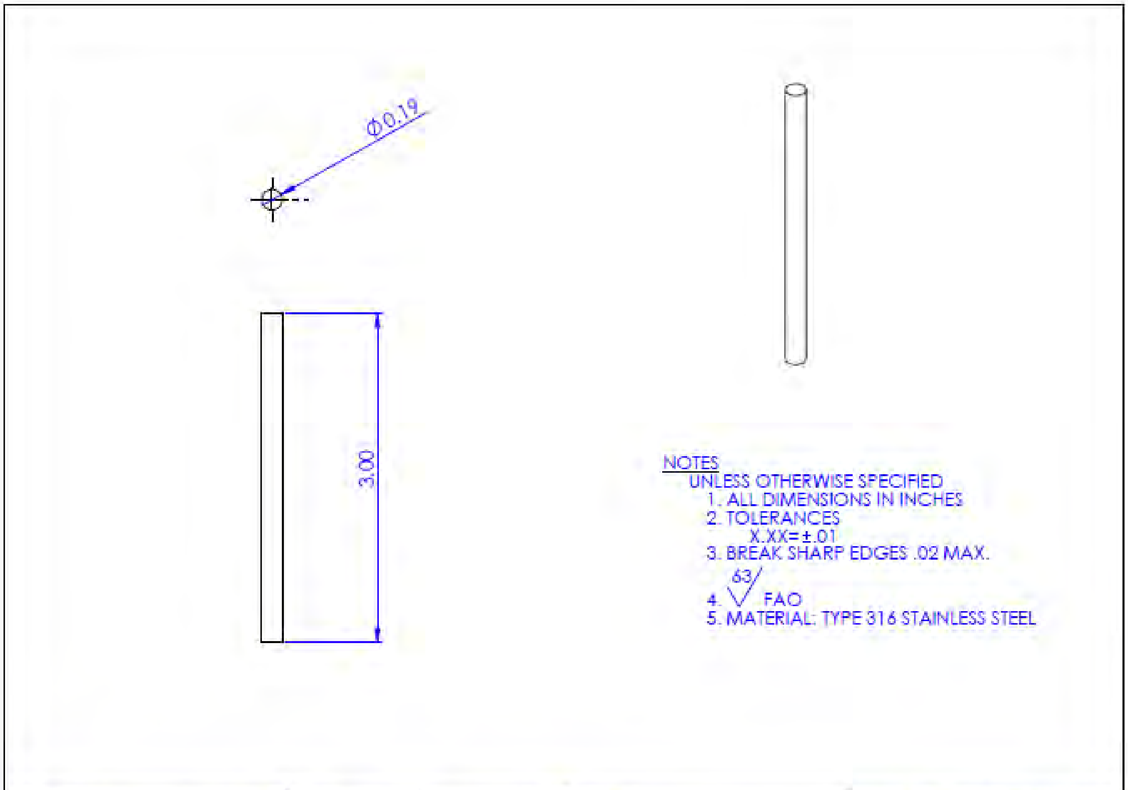




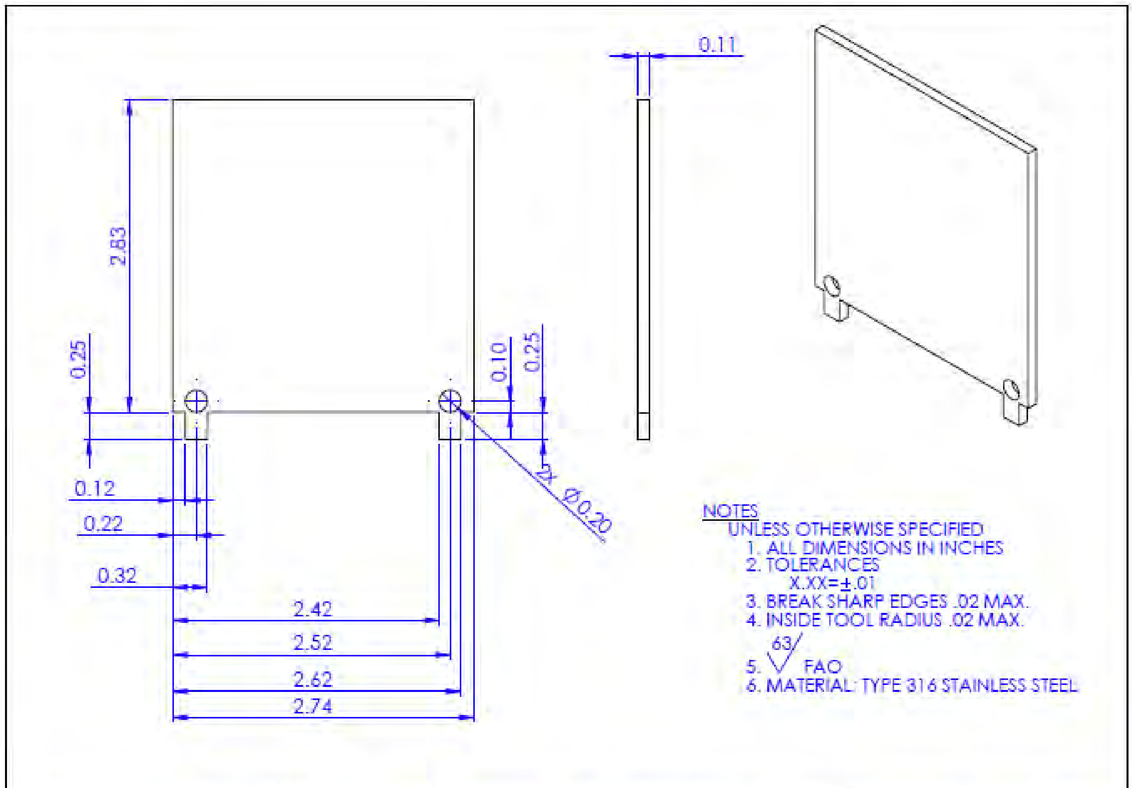
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
X.X= ±.1
X.XX= ±.01
ANGLES= ±2°
3. BREAK SHARP EDGES .02 MAX.
4. INSIDE TOOL RADIUS .02 MAX.
5. 63 FAO
6. MATERIAL: TYPE 316L STAINLESS STEEL

Cal Poly Mechanical Engineering ME 429 - 2018	Lab Section 01	Model: SP-2	Title: Throat		Drwn. By: Shannon Ferreira
	Dwg. # 2	Nxt Asb:	Date: 2/19/18	Scale 3:2	Chkd. By: ME STAFF

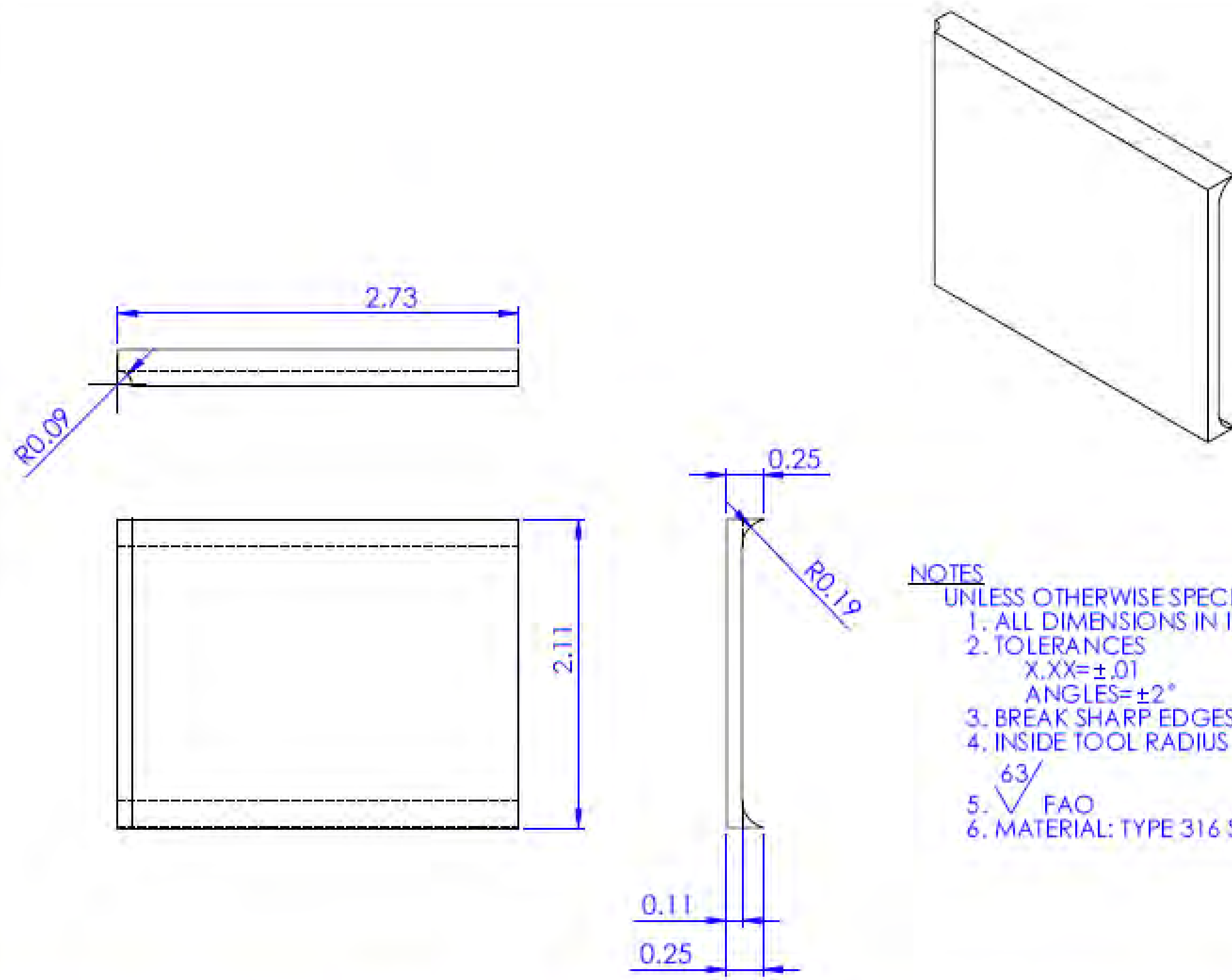

4x 0.21
2.11
1.05
4x 0.11
4x R0.10
0.28
2.38
1.05
2.11
1.05
0.28
1.05
2.38
0.25
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
X.X=±.1
X.XX=±.01
ANGLES=±2°
3. BREAK SHARP EDGES .02 MAX.
4. INSIDE TOOL RADIUS .02 MAX.
5. 63 FAO
6. MATERIAL: TYPE 316 STAINLESS STEEL
Cal Poly Mechanical Engineering
ME 430 - SPRING 2018
Lab Section:
Dwg. #: 1
Assignment #
Nxt Asb:
Title: DIVERGING FLANGE
Date: 6/13/18
Scale: 1:1
Drwn. By: SHANNON FERREIRA
Chkd. By: ME STAFF



Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: ROD		Drwn. By: SHANNON FERREIRA
ME 430 - SPRING 2018	Dwg. #: 2	Nxt Asb:	Date: 6/13/18	Scale: 1:1	Chkd. By: ME STAFF

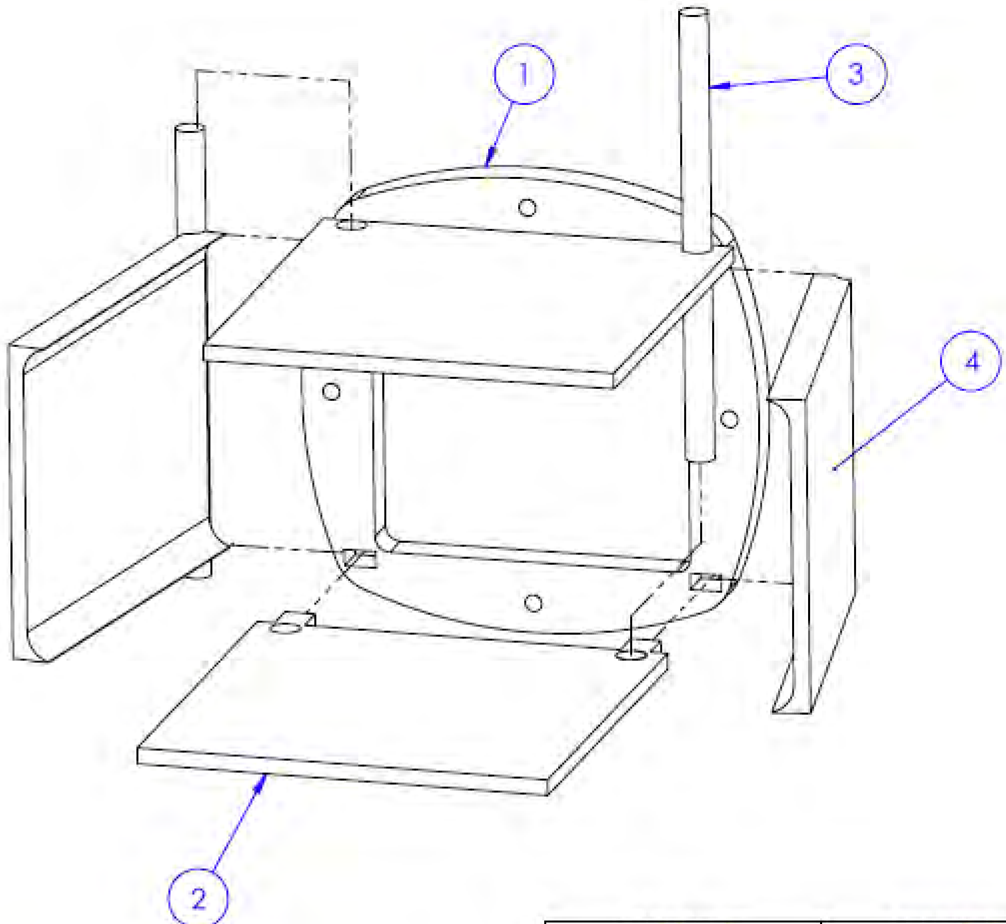


Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: TOP/BOTTOM FLAP		Drwn. By: SHANNON FERREIRA
ME 430 - SPRGING 2018	Dwg. #: 3	Nxt Asb:	Date: 6/13/18	Scale: 1:1	Chkd. By: ME STAFF



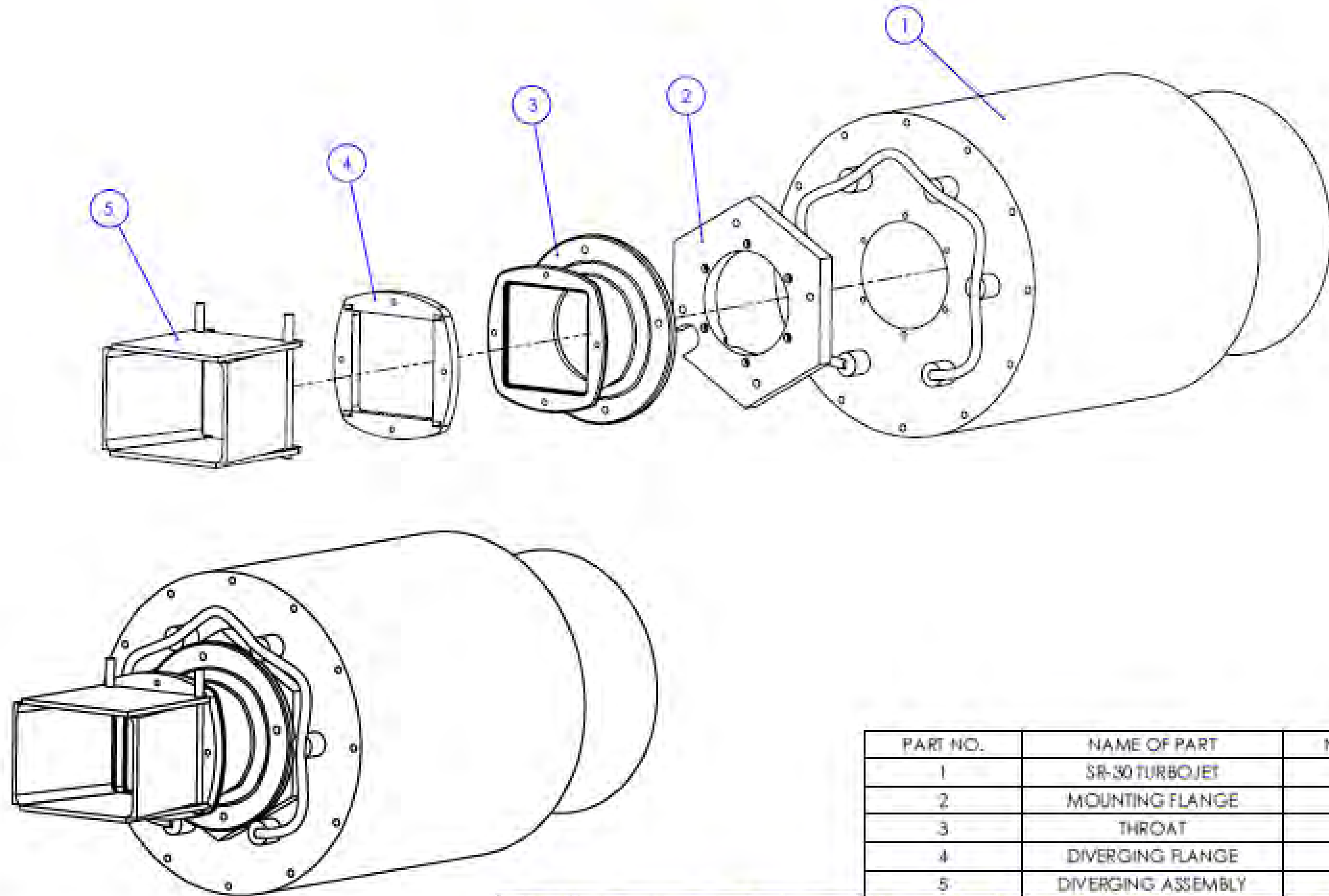
NOTES
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES
X.XX= ±.01
ANGLES= ±2°
3. BREAK SHARP EDGES .02 MAX.
4. INSIDE TOOL RADIUS .02 MAX.
5. 63 √ FAO
6. MATERIAL: TYPE 316 STAINLESS STEEL

Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: SIDE FLAP		Drwn. By: SHANNON FERREIRA
ME 430 - SPRING 2018	Dwg. #: 4	Nxt Asb:	Date: 6/13/18	Scale: 1:1	Chkd. By: ME STAFF



PART NO.	NAME OF PART	NO. OF PARTS
1	DIVERGING FLANGE	1
2	TOP/BOTTOM FLAP	2
3	ROD	2
4	SIDE FLAP	2

Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: DIVERGING ASSEMBLY		Drwn. By: SHANNON FERREIRA
ME 430 - SPRING 2018	Dwg. #:	Nxt Asb:	Date: 6/13/18	Scale: 1:1	Chkd. By: ME STAFF



PART NO.	NAME OF PART	NO. OF PARTS
1	SR-30 TURBOJET	1
2	MOUNTING FLANGE	1
3	THROAT	1
4	DIVERGING FLANGE	1
5	DIVERGING ASSEMBLY	1

Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: FULL NOZZLE ASSEMBLY	Drwn. By: SHANNON FERREIRA
ME 430 - SPRING 2018	Dwg. #	Nxt Asb:	Date: 6/13/18 Scale: 1:2	Chkd. By: ME STAFF