University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

Supersonic **Air**-**B**reathing **R**edesigned **E**ngine **Nozzle**
Conceptual Design Document

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1.0 Information

1.1 Project Customer

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2. Project Description

2.1. Project Purpose

The purpose of the SABRE-Nozzle is to model, manufacture, and verify a supersonic nozzle integrated into a JetCat P90-RXi micro-jet engine to expand its envelope of performance. The nozzle will also be able to be manufactured using additive processes with the goal of increased portability and ease of integration. The JetCat P90-RXi is one of many miniature turbojet engines that are used for remotely piloted aircraft (RPA), both civilian and military. New technology and the increasing demand for superior performance motivates the purpose of researching new ideas capable of increasing the efficiency and effectiveness of such engines. In this case, the miniature turbojet engine has a good performance, but lacks the efficiency factor as only so much thrust can be achieved without increasing the specific fuel consumption of the engine. An overarching goal of the SABRE-Nozzle is to increase Thrust to Weight ratio for the JetCat P90-RXi, which will require a careful balance between thrust increases while avoiding drastic weight increases.

A successful supersonic turbojet engine would indeed be capable of accelerating subsonic turbine exhaust to supersonic conditions with the addition of a new nozzle design. Ideally, the Thrust to Weight ratio of the engine would increase and the specific fuel consumption would decrease to maintain or increase the efficiency of the engine. The supersonic turbojet engine would expand the performance envelope such that remotely piloted aircraft could have an expanded mission profile without the need of an entirely new engine. In this case, only the engine's nozzle would be changed–or rather replaced–with an easy integration process.

2.2. Objectives

The project will accomplish the goals as outlined below in Figure 1. The Objective Matrix is viewed in chronological order from left to right, with three distinct levels of success corresponding to each heading. Minimal levels of success are those found in the Level 1 designation; absolute levels of success correspond with the Level 3 designation. The increase in thrust of 20% was determined based on expectations of engine pressure and temperature losses during operation. The SABRE-Nozzle team believes that 20% is a very attainable thrust increase. The output performance gap of 10% was determined to allow for slight off-design nozzle performance during testing, while still maintaining an overall thrust increase of 10%. The engine analog 15% allowance was determined to still allow the flow in the nozzle to reach supersonic conditions in the case that test stand cannot perfectly replicate engine stock exhaust. Pressure ratios are the driving force behind the nozzle's overall performance. Losses of up to 20% were designated to maintain a high enough pressure ratio to, once more, reach supersonic conditions. As for the time length values in the level 1 and level 2 , the 30 seconds is a time requirement given by the customer stating that the team will be evaluated based on the engine's performance for 30 seconds. In level 2, the 90 seconds is based on the fact that from previous years, the engine takes about 60 seconds to stabilize and reach steady-state conditions, therefor 90 seconds would be necessary for the engine to stabilize and for 30 seconds of engine performance analysis. Lastly, to achieve level 3 success, the nozzle has to survive and produce desired exit conditions 3 times. The reasoning behind testing it 3 times for success is that the Nozzle would have to be tested to survive the level 1 requirement, then the level 2 requirement when ready, and lastly, a full survival test at the engine's max throttle conditions. Tests done in previous years recorded that the a full test at full throttle lasts about 4 minutes. So to actually analysis the successful design of the nozzle, the material of the nozzle shall withstand 3 test experiments for the desired time in each level of success.

Table 1. Objective Matrix for project Objectives

	Model/Simulation	Design/Manufacturing	Testing
Level 1	- Model stock engine exhaust with given parameters (T, P,$\dot{m}$, V) - Model air in nozzle changing from subsonic flow to supersonic flow - No decrease of T/W	- Manufacture convergent-divergent nozzle that fits and can attach to JetCat engine - Material survives the exhaust environment for at least 30 seconds	- Replicate an engine analog that simulates exhaust velocity and temperature, within 15% of stock engine conditions
Level 2	- Increase in thrust of 20%	- Nozzle built using additive manufacturing, where material survives testing environment for at least 90 seconds	- Engine analog shall model exhaust pressure within 20% of stock engine conditions
Level 3	- Verification that modelled nozzle and manufactured nozzle have output performance within 10% of one another	- Nozzle built using additive manufacturing that can be reused 3 times and not fail in the testing environment - Material survives testing environment for 4 minutes	- Nozzle integrated and tested with the JetCat engine producing desired exit conditions

2.3. CONOPS

The Concept of Operations (CONOPS) is shown in Figure 1. The engine will start up in nominal conditions and then will be throttled up to maximum throttle. There it will achieve maximum thrust, at which point the exhaust gas will directed through the converging/diverging nozzle which will accelerate the exit thrust from subsonic to supersonic speeds. Due to the engine's temperamental nature, an analogous test bed will be created to test and verify the nozzle design and performance. The addition of a nozzle capable of supersonic speeds will allow small subsonic engines to gain the ability to reach supersonic speeds without an entire redesign of the engine. This expands the reach that, in this case, the engine can perform without losing much of its thrust to weight ratio.

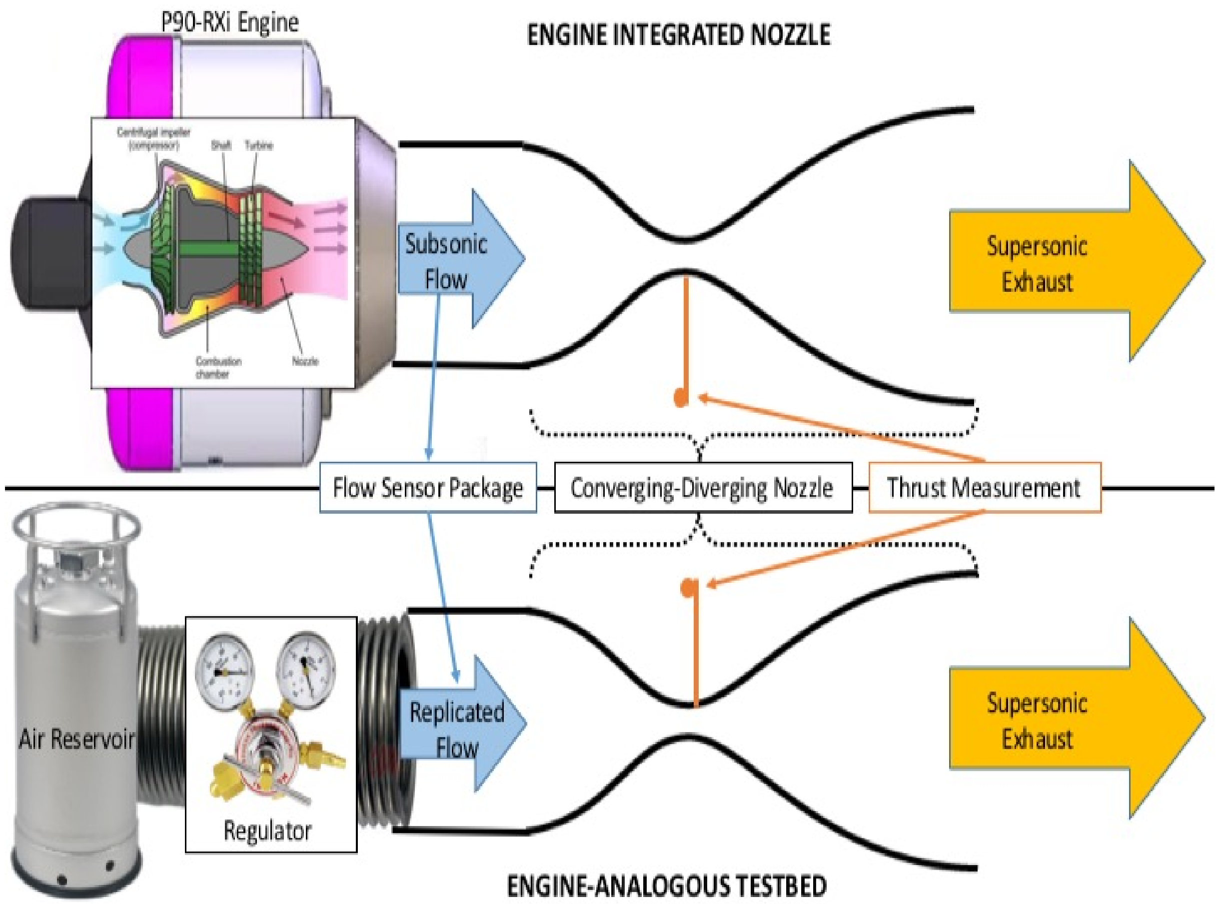

Figure 1. SABRE-Nozzle Concept of Operations

2.4. Functional Block Diagram

The following functional block diagrams, found in figures 2 and 3, separate our two available options for testing a nozzle that will be designed to accelerate flow from subsonic to supersonic speeds. The provided equipment, engine, fuel system, and control system will output an exhaust. These flow conditions will be measured prior to developing the nozzle. Once the nozzle is developed, the nozzle will be attached to the engine so that the flow can be directed through it. The flow exiting the nozzle will then be measured to verify that the flow is indeed supersonic. In the event of inevitable engine failure, an analog test engine will be used as shown in figure 3. The specific operations of this system and its mechanical and structural properties are still undecided because of the many available options for testing. It is known that a pressure tank and heat source will be required to replicate the engine exhaust conditions. The subsonic flow conditions measured from the pre-existing engine will be the parameters guiding the subsonic flow being replicated in the analog engine.

The larger bold boxes outlining the systems differentiate between pre-existing equipment and the equipment which needs to be manufactured, procured, or purchased.

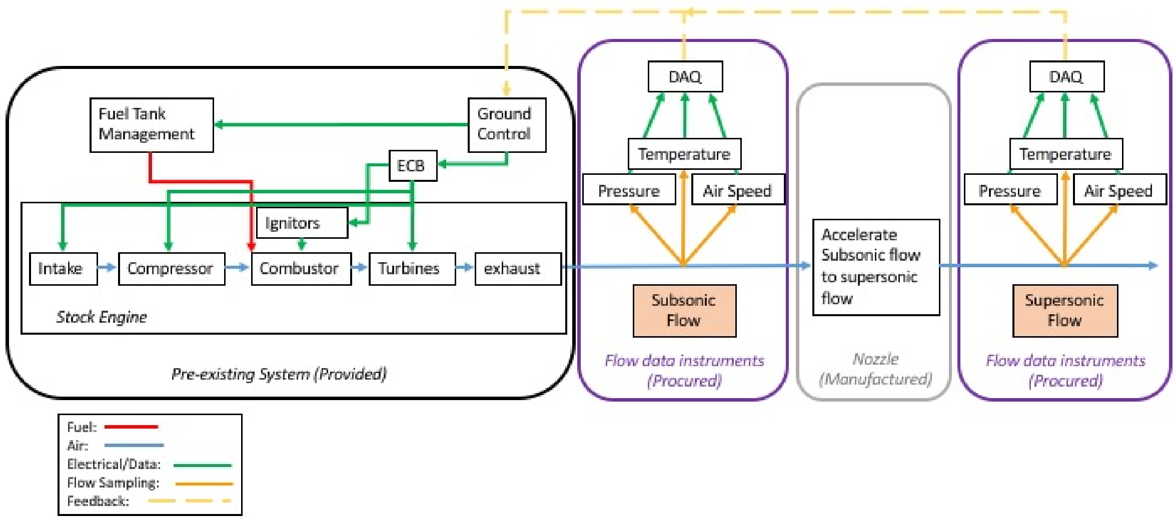

Figure 2. SABRE-Nozzle Functional Block Diagram for Engine Integration

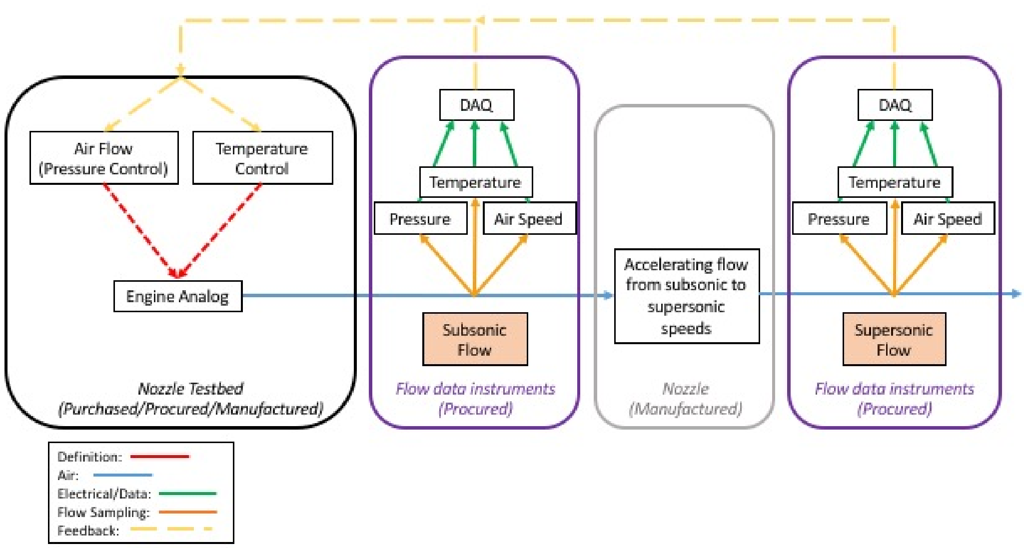

Figure 3. SABRE-Nozzle Functional Block Diagram for Analog Integration

2.5. Functional Requirements

The functional requirements outline how the final SABRE-Nozzle system will operate. These following requirements will guide the design process and design requirements necessary for a successful operation. The following functional requirements overlay the major objectives of the system that can be feasibly addressed within the time constraints of Aerospace Senior Projects.

FR 1 The Nozzle shall accelerate the flow from subsonic to supersonic conditions.

FR 2 The Nozzle shall not decrease the Thrust/Weight ratio.

FR 3 The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.

FR 4 The Nozzle shall be able to withstand engine operation for at least thirty seconds.

3. Design Requirements

FR 1 The Nozzle shall accelerate the flow from subsonic to supersonic conditions.

DR 1.1 The flow through the nozzle shall be choked such that the nozzle exit flow Mach is greater than 1.
Motivation: A Level 1 success goal given to the team by the AFRL was to convert the subsonic jet engine exhaust to supersonic velocities. Therefore, the exit exhaust velocity must be greater than Mach 1.
Verification: Measure the exhaust velocity via the designed testbed.

FR 2 The Nozzle shall not decrease the Thrust/Weight ratio.

DR 2.1 The total configuration weight shall not exceed (120 N), which is the expected thrust of the engine with attached nozzle after consideration for engine losses.
Motivation: The maximum total configuration weight of 120 N is equal to the expected thrust of the engine with the designed nozzle in use because the thrust to weight ratio must not decrease.
Verification: Successful verification of **DR 2.1.1**.

DR 2.1.1 The material chosen for the nozzle shall be such that the weight of the nozzle configuration does not exceed (120 N minus the engine weight without nozzle).
Motivation: In order to ensure that the total configuration weight doesn't exceed 120 N, the material the nozzle is made out of must be chosen carefully because the weight of the engine without the nozzle doesn't change. Therefore, the weight of the nozzle is of utmost importance.
Verification: Weighing the total configuration to check that it weighs less than or equal to 120 N.

DR 2.2 The thrust of the engine shall be increased to (120 N)
Motivation: The thrust created by the engine will increase due to the new higher exhaust velocity. 120 N was selected as 62.5% of the absolute maximum thrust that could be achieved with the engine's pressure ratio between the exit of the turbine and the exit of the nozzle. Because the exact engine losses are still unknown, a design envelope of 37.5% will still allow for design success in the case that native engine losses are substantial.
Verification: Measuring the static thrust of the engine-nozzle configuration using the designed testbed.

DR 2.2.1 The pressure ratio of the turbine exit to the ambient pressure shall be at least 1.98:1 to achieve supersonic flow.
Motivation: In order to minimally achieve the desired 120 N of thrust for **DR 2.2**, the pressure ratio between the exit of the turbine and the exit of the nozzle must be at least 1.98:1. A lower pressure ratio would not allow for the desired thrust to be achieved, and even lower pressure ratios would make supersonic flow impossible.
Verification: Measurements will be taken of the stagnation pressure of the flow at the exit of the turbine. The atmospheric stagnation pressure of Boulder, CO is known.

FR 3 The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.

DR 3.1 The Nozzle shall be manufactured with additive manufacturing.
Motivation: The AFRL specified in their project description that additive manufacturing shall be used to manufacture the nozzle.
Verification: The nozzle is manufactured using additive manufacturing.

DR 3.1.1 The Nozzle shall be manufactured with a smooth interior.
Motivation: A rough surface on the interior of the nozzle could cause for larger turbulent boundary layers to form.
Verification: Inspect to ensure no rough or rib-like features exist on the interior of the nozzle.

DR 3.2 The inlet of the nozzle diameter shall not exceed the turbine exit diameter of TBD value.
Motivation: There must not be a gap in the integration of the nozzle with the JetCat Engine so that there is no excessive loss of pressure before the inlet of the nozzle.
Verification: Measure and verify the diameter of the inlet of the nozzle is less than the diameter of the turbine exit.

DR 3.3 The exit diameter of the nozzle shall not exceed the nacelle diameter.
Motivation: The area of the nozzle presented to the free-stream flow shall not be bigger than the nacelle of the JetCat Engine because this would cause additional drag.
Verification: Measure and verify the exit diameter of the nozzle is less than or equal to the nacelle diameter.

DR 3.4 Successful integration of the nozzle shall not render the engine inoperable after the nozzle is detached and the engine is returned to its stock configuration.
Motivation: The designed SABRE-nozzle shall be a "bolt-on" component of the engine. It is desired that the nozzle be able to be installed, used, and then removed so the engine retains its stock configuration with the stock nozzle.
Verification: The SABRE-nozzle can be installed, used, and then removed such that the JetCat Engine is back in its stock configuration.

FR 4 The Nozzle shall be able to withstand engine operation for at least thirty seconds.

DR 4.1 The nozzle material shall have a melting point higher than 1600 C.
Motivation: The most extreme temperature experienced in the engine is 1600 C so the nozzle shall be able to withstand this temperature to ensure operation on the engine without material failure.
Verification: The melting point of the material will be measured via infrared sensors and a means of heating the material.

DR 4.1.1 (Fatigue of material) The pressure at 1200 K shall not fatigue material.
Motivation: The pressure experienced at the engine exhaust temperature may cause deformities and fatigue in the nozzle materials.
Verification: Inspecting to see that the nozzle has not deformed after operation on the engine.

DR 4.2 The nozzle shall be designed such that there are no physical instabilities present during integration and operation.
Motivation: During operation on the JetCat engine the nozzle will experience high frequency vibrations from the engine running. We are concerned that the vibrations may loosen the integration of the nozzle to the engine and cause for catastrophic failure.
Verification: Testing of the nozzle integrated with the JetCat engine on a vibration table to ensure high frequency vibrations don't cause a failure of the integration hardware.

DR 4.3 No parts shall become detached during a 30s test.
Motivation: The AFRL specified in their project description that the nozzle shall be able to operate on the engine for at least 30 seconds. During this 30 second operation the nozzle shall not become detached from the engine for a successful testing.
Verification: Upon the completion of a 30 second long test with the engine, the nozzle must still be attached to the engine as it was before the test.

DR 4.4 The thrust of the engine shall not decrease over a 30s span.
Motivation: The requirement of not decreasing the thrust to weight ratio, **FR 2**, must be fulfilled during the required 30 second test, **FR 4**. The weight of the total configuration will be constant throughout the test so the thrust must not decrease throughout the test in order to maintain the thrust to weight ratio.
Verification: The thrust will be measured via our designed testbed throughout the 30 second test. A load cell will be used to measure the thrust.

4. Key Design Options Considered

From the key design requirements in Section 3, different design methods are considered to define the whole design space to ensure all possibilities are investigated. The SABRE-Nozzle can be identified by three main Design Options: Nozzle Design, Nozzle Testbed, and Nozzle Integration. The Nozzle Design encompasses all the theoretical designs capable of achieving supersonic flow at the exit of the Nozzle. The motivation of the nozzle testbed study comes from the uncertainty of the engine working with the integration of the nozzle. The Nozzle integration encompasses the different methods of attaching the nozzle to the existing engine, but in the case that the engine does not actually work, the nozzle testbed encompasses the different components capable of reproducing the exhaust conditions to test and validate the nozzle performance. The design tree seen in Figure 4 shows the breakdown of the design space.

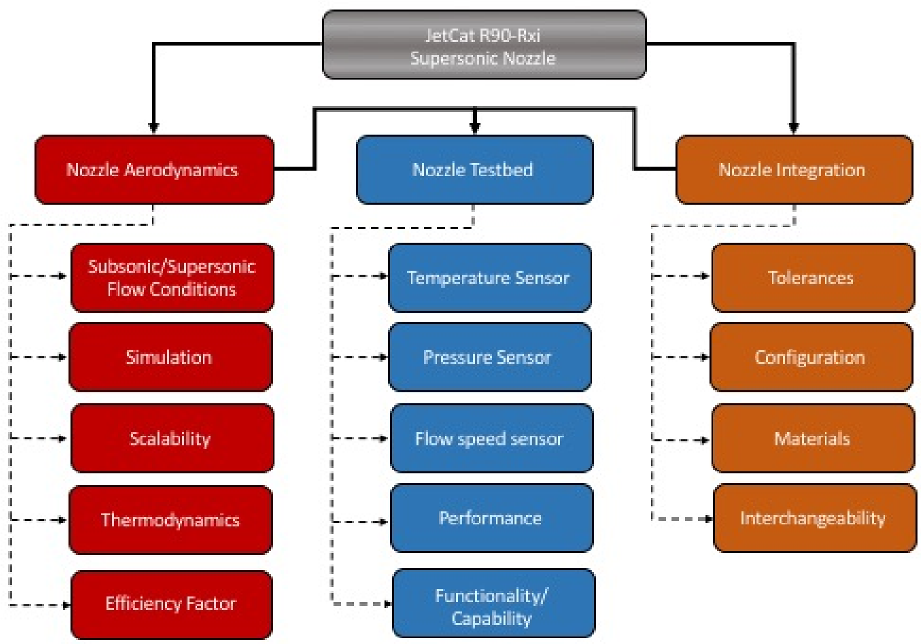

Figure 4. SABRE-Nozzle Design tree

4.1. Nozzle Design

Six distinct nozzle configurations have been considered. The first is the classic de Laval nozzle design. The de Laval nozzle consists of a smooth transition from convergent geometry to the sonic throat condition, with an expansion at the back of the nozzle to allow the flow to continue to accelerate beyond the sonic condition. The second geometry is an annular convergent-divergent nozzle. The stock engine nozzle has a cone-shaped plug that covers the turbine bearings. The interior of the annular nozzle would extend from the bearing hub similar to the function of the current plug, and possess convergent-divergent geometry to enable flow acceleration. The third geometry considered is the expansion-deflection nozzle, similar to the annular nozzle, the expansion-deflection nozzle also utilizes a center-body plug. The fourth nozzle configuration is a Minimum Length Nozzle (MLN). Minimum length nozzles are characterized by a sharp turn at the throat which expands the flow close to the maximum Prandtl-Meyer fan angle. The fifth nozzle configuration is a Variable Geometry configuration. Variable Geometry nozzles are typically found in modern military aircraft and allow for optimization for different flight conditions. The final consideration is non-geometric, and is velocity control via methods of heat transfer.

4.1.1. de Laval Nozzle

The de Laval nozzle is the most common supersonic nozzle. This nozzle is often referred to as a bell nozzle due to its distinctive bell shape. This nozzle is also very well researched due to its popularity and historical use throughout modern aerodynamics. The nozzle features a duct of varying cross sectional area in the flow-wise direction. The cross-sectional area drops as the nozzle converges to a minimum throat area, and then cross-sectional area increases throughout the divergent section to allow flow acceleration past the sonic point (shown in Fig. 5). The de Laval nozzle is popular due to the relatively simple design and fixed geometry, as well as the smooth contours which help avoid flow separation throughout the nozzle.

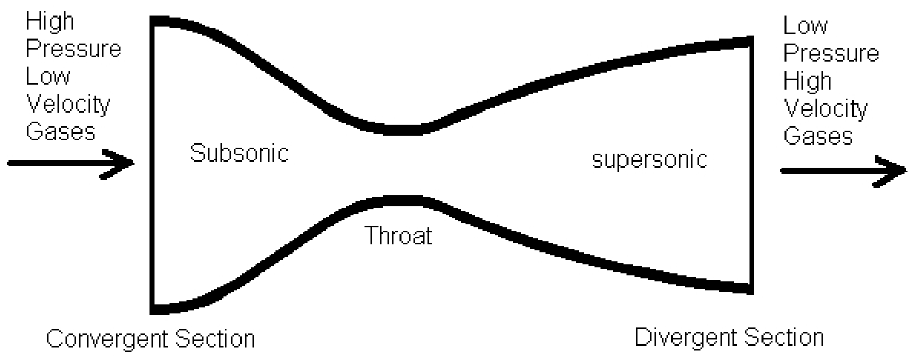

Figure 5. de Laval Nozzle cross-section

Table 2. Pros and Cons of the De Laval Nozzle

Pros	Cons
Common Design (well researched)	No altitude compensation
Minimal Material Usage	Smooth geometry requires a potentially long nozzle
Single Piece Design	

4.1.2. Annular Convergent-Divergent Nozzle (ACD Nozzle)

The JetCat stock nozzle consists of a plug, which is fitted over the bearings of the turbine, and a convergent nozzle section. The Annular Convergent-Divergent geometry will serve two purposes; it will both protect the turbine bearings and allow the flow to accelerate. Rather than vary the area of the external nozzle itself, it is possible to achieve supersonic flow with a fairly constant external nozzle area and a variable internal annulus area. With a constant outer nozzle diameter, the annulus will grow larger to converge flow, and then grow smaller to allow the flow to continue to accelerate beyond the sonic point. The ACD nozzle will require the manufacturing of both a nozzle exterior and interior, as well as the successful integration of these two pieces. An ACD nozzle would allow for the removal of the stock JetCat nozzle, while maintaining the necessary thermal protection for the turbine components. The following Figure 6 offers a conceptualization of this ACD geometry. As opposed to the more traditional de Laval nozzle which relies on the exterior nozzle geometry to converge and diverge, the ACD nozzle will rely on the interior geometry to converge and diverge the flow.

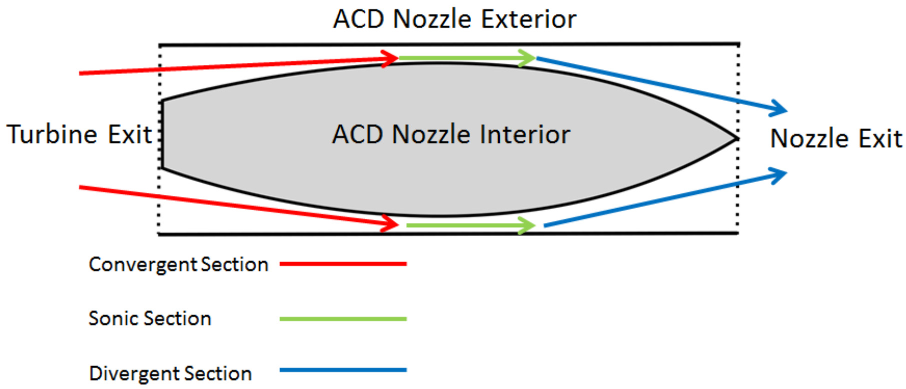

Figure 6. Annular Convergent-Divergent Nozzle Conceptualization

Table 3. Pros and Cons of the Annular Converging-Diverging Nozzle

Pros	Cons
Reduce flow recirculation around current dome-shaped plug	Possibility of increased boundary layer losses (Two surfaces with ACD vs. One with de Laval)
Nozzle can be designed to turbine exit conditions	Difficult to re-integrate with engine thermocouple sensor
Nozzle exterior will be cylindrical and easy to handle	Increased material quantities increase weight

4.1.3. Variable Geometry Nozzle

Variable geometry nozzles are featured on many fighter jets due to the high efficiency across a range of altitudes and Mach numbers. Variable geometry nozzles achieve this higher efficiency by changing the cross sectional area of the divergent section of the nozzle so that the exit pressure matches ambient pressure. This design avoids the negative effects (adverse thrust losses) of over- and under-expansion by pressure matching to the exit ambient pressure. Variable geometry nozzles require sophisticated actuators and software to precisely change the geometry during flight such that desired performance is achieved. Variable geometry nozzles usually have over-laid panels which are controlled by a hydraulic actuator to open and close the nozzle, like the petals of a flower, as shown in Fig. 7.

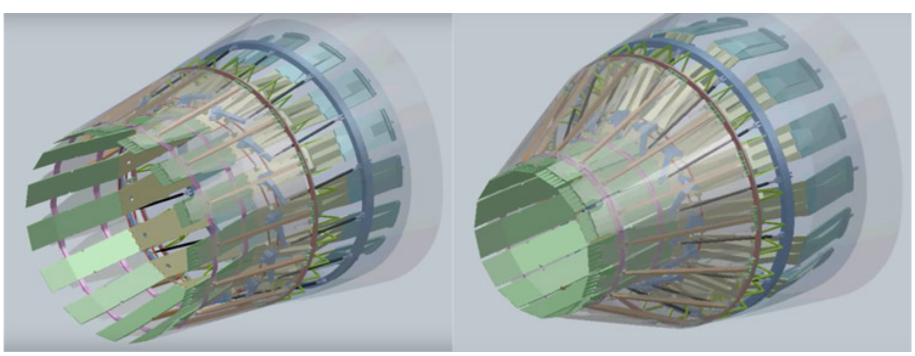

Figure 7. Variable Geometry Nozzle: fully open (left), fully closed (right)

Table 4. Pros and Cons of the Variable Geometry Nozzle

Pros	Cons
Common Design (well researched)	Additional Material
Altitude Compensation allows for Pressure Matching	Many Moving Parts
User can throttle up and down while maintaining high efficiency	Requires Actuator for Control
	Requires Sensors to determine flight velocity and altitude
	Requires Software to control actuators

4.1.4. Expansion-Deflection Nozzle

Expansion-deflection nozzles are designed much like that of a typical bell-shaped nozzle for supersonic flow expansion except a plug or pintle is placed into the center of the throat and part of the diverging section[5] (see Fig. 8). The flow is accelerated from sonic conditions at the throat of the nozzle to supersonic through the use of Prandtl-Meyer expansion fans. The flow is also deflected towards the outsides of the divergent section of the nozzle, leaving a wake behind the plug or pindle. Due to the use of using Prantl-Meyer expansion fans to accelerate flow to supersonic velocities the length of the nozzle can be designed shorter than the typical bell-shaped nozzle.[5] A list of advantages and disadvantages of using a expansion-deflection nozzle is included below in Table 5.

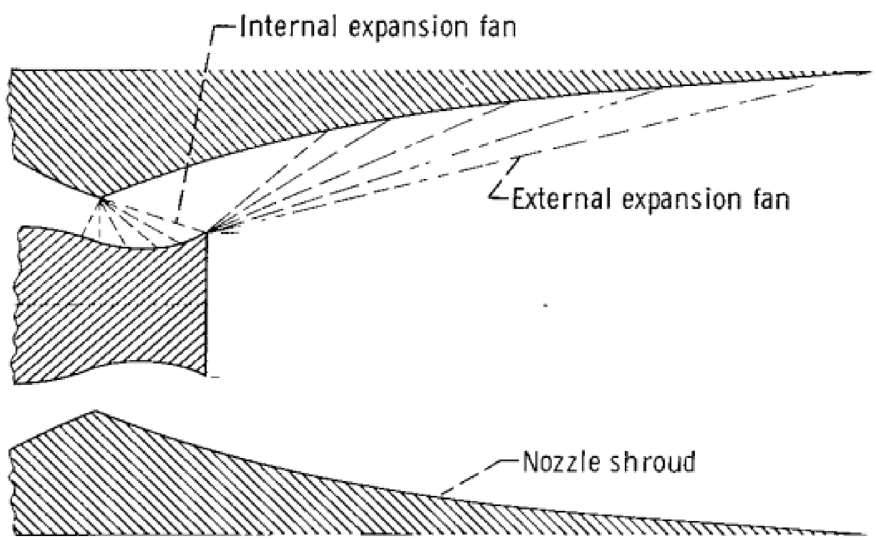

Figure 8. Diagram showing how prandtl-meyer expansion fans accelerate flow in a expansion-deflection nozzle.[6]

Table 5. Pros and Cons of the expansion-deflection nozzle.

Pros	Cons
Shorter nozzle length (decrease in weight)	Complexity (integrating plug in nozzle throat)
Altitude compensation	Typical application has been in space based systems

4.1.5. Minimum Length Nozzle (MLN)

Minimum length nozzles allow for the supersonic flow to expand to its maximum Mach number in a reduced distance. MLN are characterized by a sharp throat turn angle which is designed to realize the turn angle for some desired exit Mach number according to Prandtl-Meyer expansion fan analysis. For the purposes of the SABRE-Nozzle, MLN offer a solution which has the possibility to reduce necessary material quantities for manufacturing, and therefore realize a higher Thrust to Weight ratio. The sharp turn designed immediately after the sonic condition is typically treated as a finite region with a very small radius of curvature; this region may see flow separation, though the favorable pressure gradient throughout the nozzle will likely handle any flow separation issues. A MLN is visualized below in Figure 9. Note the distinct difference in the sonic section between the de Laval design at left and the MLN configuration at right.[2]

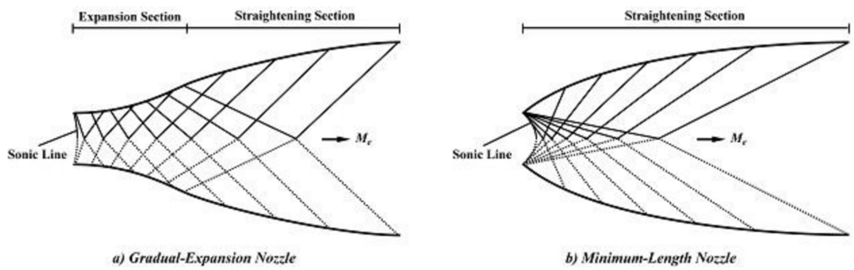

Figure 9. Gradual Expansion Nozzle vs Minimum Length Nozzle

Table 6. Pros and Cons of the Minimum Length Nozzle

Pros	**Cons**
Reduced material leads to reduced weight	Sharp corner could lead to flow separation at the nozzle corner
Relatively small nozzle can be easily transported	
Short nozzle eliminates thermal considerations for a longer design	

4.1.6. Heat Transfer for Flow Velocity Control

Heat transfer can be used to accelerate or decelerate air flow depending on whether or not the flow is subsonic or supersonic. If the air flow is subsonic, then heating the flow will accelerate the flow to Mach 1 while cooling the flow will decelerate the flow. Supersonic flow exhibits inverse behavior. Heating supersonic flow decelerates the flow towards Mach 1 while cooling the flow will accelerate it.

The Rayleigh Flow model demonstrates these behaviors for subsonic and supersonic flow. By definition, Rayleigh Flow refers to frictionless, non-adiabatic flow through a constant area duct.[8] It is important to note that the stagnation temperature and pressure change within this model. The stagnation temperature is of interest because the transfer of heat in or out of the flow to control flow velocity is the objective. Adding heat to the flow for both subsonic and supersonic flows causes the flow to approach Mach 1. Heated flow that approaches this limiting value is considered to be thermally choked. One of the governing equations for the Rayleigh Flow model includes the dimensionless change in entropy, ΔS, as a function of Mach number, M. This equation is included below:[8]

$$\Delta S = ln[M^2(\frac{\gamma+1}{1+\gamma M^2})^{\frac{\gamma+1}{\gamma}}] \tag{1}$$

Eq. 1 above is plotted against dimensionless enthalpy, H, in Fig. 10 below. H can also be represented as the ratio of static temperature to the temperature where thermal choking occurs, $\frac{T}{T^*}$.

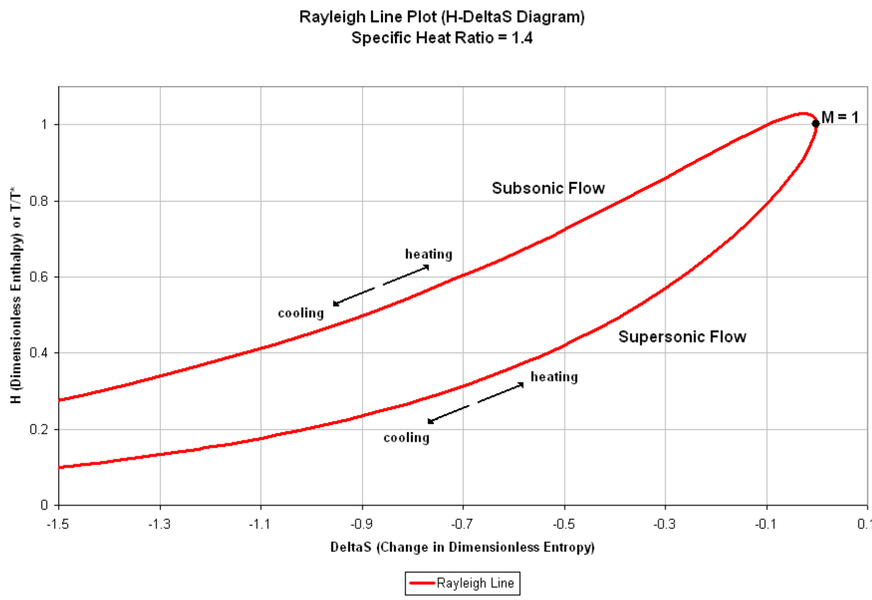

Figure 10. Plot of ΔS vs. H that shows the effects of heating flow.[8]

Fig. 10 above shows the behaviors mentioned earlier. As the ratio $\frac{T}{T^*}$ increases, heat is transferred into the flow which increases the Mach number of subsonic flow and decreases the Mach number of supersonic flow. The cooling of supersonic flow to accelerate the flow to higher Mach numbers can also be explained in another way. Using the definition of the speed of sound:

$$a = \sqrt{\gamma R T} \tag{2}$$

As the temperature, T, of the flow decreases, the speed of sound, a, also decreases. Due to the Mach number being defined as the ratio of the flow velocity over the local speed of sound, as the speed of sound decreases the Mach number will increase.

There are distinct advantages and disadvantages to this method of accelerating subsonic flow to supersonic conditions by means of heat transfer. Below in Table 7 these advantages and disadvantages are listed:

Table 7. Table of pros (advantages) and cons (disadvantages) for using heat transfer to control flow velocity.

Pros	Cons
Simplistic nozzle design (constant area)	Additional system to heat or cool flow
Accelerates subsonic flow to supersonic flow	Length of nozzle needed to heat and cool flow (affects weight)

4.2. Nozzle Testbed

4.2.1. Testing on JetCat Engine vs. Engine Analogue

Using the JetCat engine as a test bed for the nozzle would provide the best conditions in testing and validating a nozzle design. However, the difficulty in running the engine in a non-stock configuration, as well as the complexities in the stock engine control unit (ECU) and engine sensor board (ESB), have lead previous design efforts to a standstill. The SABRE-Nozzle team realizes that full integration with the stock engine will likely lead to engine shutdown. There exist enigmatic failsafes within the JetCat engine which are closely guarded by JetCat personnel, and it is likely that SABRE-Nozzle team efforts to force the engine to bypass these failsafes will be unsuccessful. The best means to troubleshoot these failsafes would be to produce a new ECU and ESB. This process will be very time-intensive and require extensive troubleshooting;

however, CU has legacy ECU and ESBs from previous work on the JetCat engine. Data is available from the previous REAPER project, wherein thorough ECU and ESB work was performed.[4]

The test stand for the engine would only need minor modifications to measure the nozzle exit conditions. Minor modifications will ultimately reduce costs associated with developing a completely new test stand. The largest cost, however, is predicted to be one of time. Large quantities of time would have to be spent designing a functioning ECB and ESU. If there were no time restrictions upon this project, it would be entirely feasible to pursue a redesign of the JetCat Engine's electronic system. The following Table 8 lists advantages and disadvantages of pursuing testing on the stock engine.

Table 8. Pros and Cons of Engine Test bed

Pros	Cons
Will produce correct flow conditions	Development of new ESB and ECU is costly
Low cost to use legacy ECU and ESB	Failsafes could stop tests
Success can be immediately evaluated	Will likely take many man-hours

4.2.2. Hot-flow vs. Cold-flow Testbed

The following figure depicts how a cold flow test might be conducted to prove the supersonic capabilities of the designed nozzle.

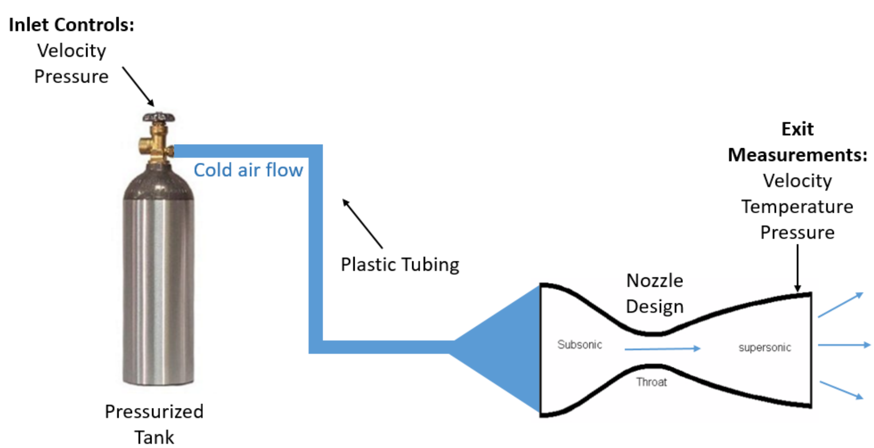

Figure 11. Cold Flow Testbed Conceptual Diagram

The pressure from the tank would be able to be controlled. To read and control the velocity, the tank would have a volumetric flow reader. The density of the flow can be calculated from the ideal gas law, and the mass flow rate could then be calculated from the volumetric flow rate and the density. The flow would be delivered from the pressure tank valve by plastic tubing, which would attach to a sleeve that wraps around the inlet of the nozzle. Because extreme temperature is not a consideration, the nozzle material could be plastic or another inexpensive and easily obtainable material.

One important consideration that needs to be made about the engine testbed is whether or not the flow experiments need to be conducted at the same hot temperature that the engine operates at. To determine the sensitivity of the nozzle system on temperature, a model has been created with certain assumptions. These assumptions are that the flow through the nozzle can be treated isentropically, air through the nozzle can be treated as a perfect gas, and the flow through the nozzle is steady.

Figure 12 shows the relationship between temperature and velocity for different Mach numbers.

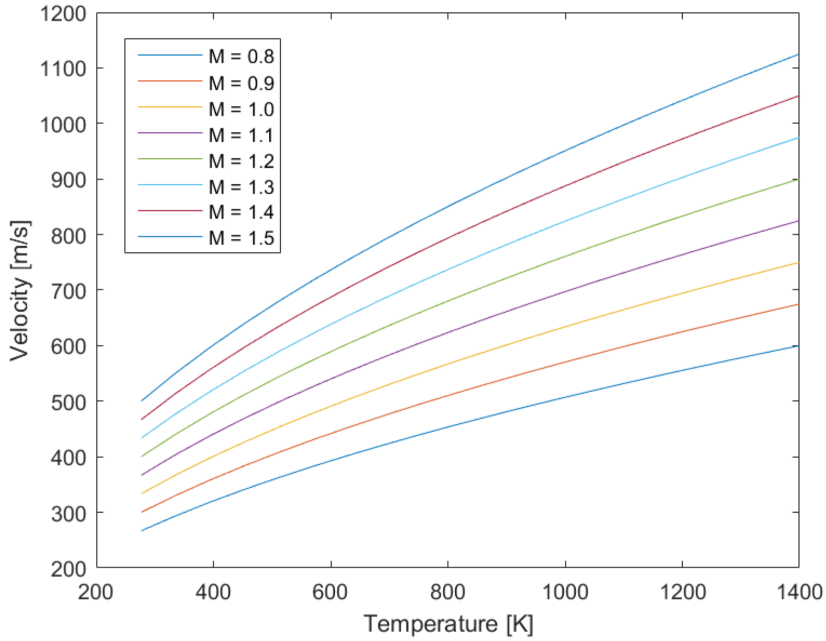

Figure 12. Temperature vs. Velocity at Varying Mach Numbers

From this figure it can be seen that if the temperature and velocity of a flow is known, the Mach number can be calculated.[1] This can be helpful because if the Mach number from the exit of the engine (the inlet of the nozzle) is known, and the temperature at the inlet of the nozzle is known to be room temperature, the velocity can be controlled to provide an accurate simulation of the flow. The same concept can be used at the throat and the exit of the nozzle. Because Mach number only depends on temperature and velocity as variables, if the temperature and velocity can be measured at the throat and the exit, the Mach number can be calculated, and the nozzle design can be validated.

However, this relationship alone does not prove that the properties of the flow itself would be the same in a cold flow test as they would in a hot flow test. Specifically, it is crucial to consider the possible formation of shock waves. Shock waves are only present in supersonic flows, and they greatly change the downstream properties once one forms. Therefore, it is important to determine the affect that temperature could have on the formation of shock waves. A shock wave is formed when a wave moves faster than the local speed of sound. The local speed of sound can be expressed by the equation $a = \sqrt{\gamma RT}$ where γ and R are known constants, and T is the temperature. From this relationship, it can be seen that the speed of sound is a function solely of temperature, and therefore the formation of shocks depends on temperature as well. A cold flow would not provide accurate conditions for shock wave formation that might be present once the nozzle is tested with the actual engine. The following figure depicts how a hot-flow test would be conducted for the nozzle.

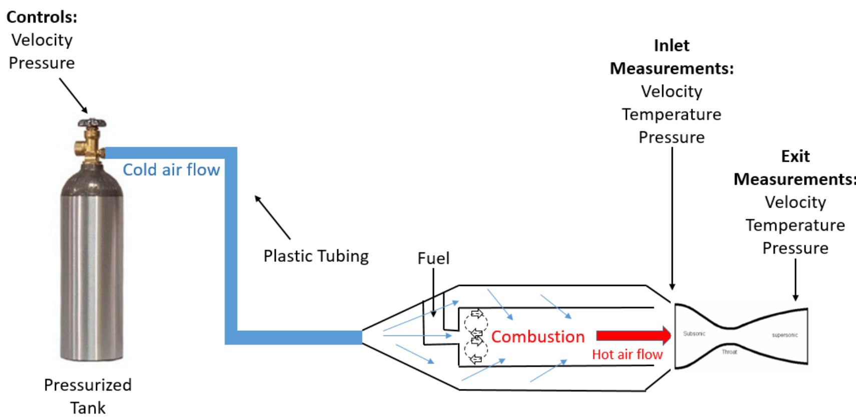

Figure 13. Hot Flow Testbed Conceptual Diagram

As seen in the figure, the concept for the hot flow would be similar to the cold flow, except that combustion would take place before the air enters the nozzle. Essentially, it is mimicking the piece of the engine that we need in order to reach the actual engine temperatures. The flow properties at the inlet will need to be measured to make sure that they are consistent with what we expect the flow properties out of the actual engine to be. The sensors for our inlet and exit measurements will need to be able to withstand extreme heat and still function properly. Additionally, the combustion chamber and the nozzle will need to be made out of material that can withstand extreme heat. These factors will greatly add to the cost of the engine analog, but will provide a more accurate representation of the actual flow that is being modeled.

Table 9. Pros and Cons of the Cold Flow Test Bed

Pros	Cons
Inexpensive and easily obtainable parts	Ability of material to withstand temperature would need to be tested separately
Many nozzle designs can be tested	Based off of many flow parameter assumptions
Abundance of resources on test method	Can be difficult to maintain constant flow speed
Sensors would not need to withstand extreme temperatures	

Table 10. Pros and Cons of the Hot Flow Test Bed

Pros	Cons
Models flow properties more accurately	Need high quality materials
Tests how the nozzle withstands heat	May be difficult to control inlet flow parameters from pressure tank
Validity of nozzle design easier to prove	More dangerous than cold flow test

4.2.3. Actual Size vs. Scaled Nozzle

The nozzle could be tested in the actual size configuration or a scaled configuration. When testing a scaled configuration of the nozzle the main concern is that the flow represents the actual flow. In a scaled supersonic nozzle there is a concern that the flow could prematurely choke, meaning the flow reaches sonic conditions before the throat. The premature choking is caused by the boundary layer of the flow decreasing the effective diameter of the nozzle and causing it to choke before the throat.

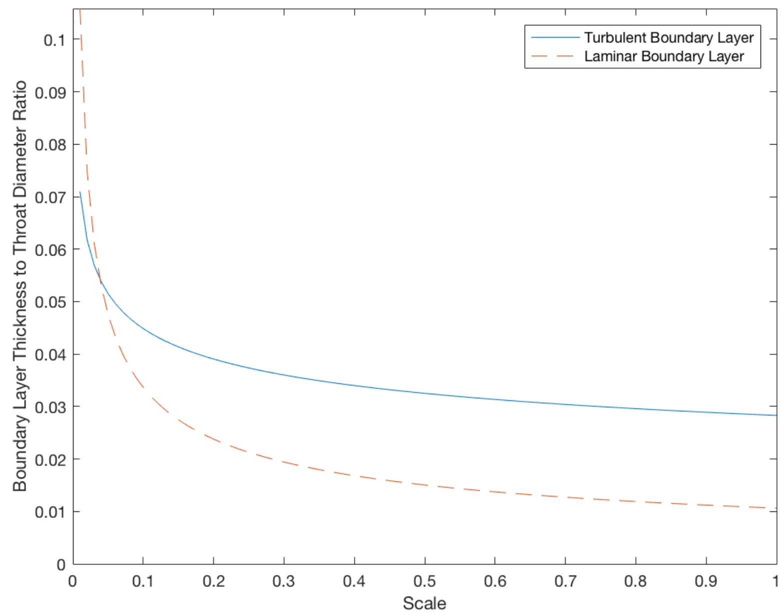

Figure 14. Ratio of Boundary Layer Thickness to Throat Diameter vs. Scale

Pros	Cons
Represents actual geometry	More expensive to manufacture
Easier to verify/validate	More difficult to test

Table 11. Actual Size Nozzle

Pros	Cons
Cheaper to manufacture	Possible to prematurely choke flow
More testing resources	Assume flow represents actual flow

Table 12. Scaled Nozzle

4.3. Nozzle Integration

Four main design options were considered for the integration process of the nozzle and the engine. The goal of this component is to address the safety aspect and complexity of mounting a new nozzle onto the existing engine. The redesigned nozzle must accelerate the flow to supersonic speeds, but shall not permanently effect the performance of the stock engine with the change of the nozzle.

Each option was addressed as it would apply to the engine with the nozzle attached. A pros and cons list is included for each of the design options. The main trade study to make a distinction between each option is later discussed in Section 5 of this report.

4.3.1. Complete Nozzle Replacement

The first option considered to integrate the supersonic capable nozzle design with the engine is to remove the stock nozzle currently attached to the engine and replace it with a newly designed nozzle. This configuration can be seen in Figure 15 where it depicts the old nozzle being removed and a new nozzle, that is designed to achieve supersonic flow from the exhaust flow from the turbine, replacing it.

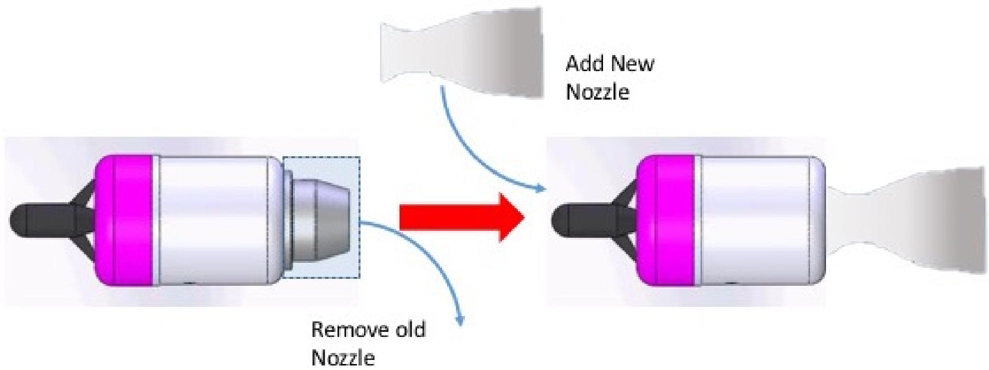

Figure 15. Nozzle replacement depiction

The Nozzle will consist of a converging section that curves inward to compress and accelerate the air flow. The nozzle then smoothly curves out forming the throat and then diverges to accelerate the flow beyond Mach 1. With a converging/diverging Nozzle that is only constructed of one continuous piece, the complexity of the nozzle is low.

Main advantages of this design are that the integration swap is simple, no flow turbulence will occur from sharp turns or gaps, and the only restriction that the nozzle has to be designed to is the mounting section at the exit of the turbine. This design also offers the benefit that the old nozzle will be completely unaffected and will not be structurally altered to compensate for the new nozzle.

However, a major disadvantage to this design is that the flow conditions produced from the stock engine have data values obtained from the exit or near the exit of the original nozzle and not the exact exit of the turbine. With this flaw in data measurements, the simulation analysis of this nozzle will not be completely accurate since the beginning dimensions of the converging section will not exactly match that of the original nozzle. This will have to be addressed by obtaining data at the exit of the turbine to best simulate the flow conditions within this nozzle design. The summary of the Pros and Cons of using this type of integration process are provided in Table 13

Table 13. Pros and Cons of the Complete Nozzle replacement Integration Design

Pros	Cons
Single piece Nozzle design	Need whole new nozzle if any defects appear
Only physical restriction is nozzle inlet	No structural support for end of nozzle
Old nozzle is not permanently effected	Stock engine not completely maintained
No flow interruption	Tolerances of integration

4.3.2. Nozzle extension and Overlapping Extension

The second options to look at for nozzle integration is either attaching an extension to the stock nozzle, by either welding or bolting, and creating an overlapping ”sock” that allows the new nozzle to slip over the stock nozzle as shown in 16 and 17.

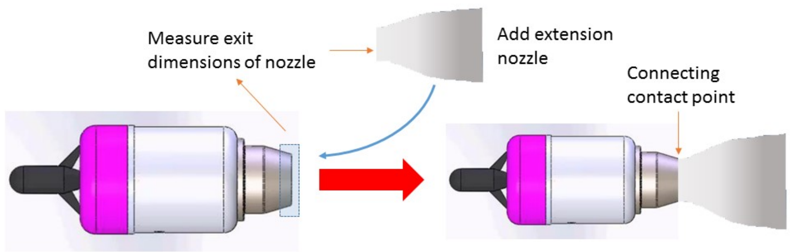

Figure 16. Nozzle Attachment Depiction

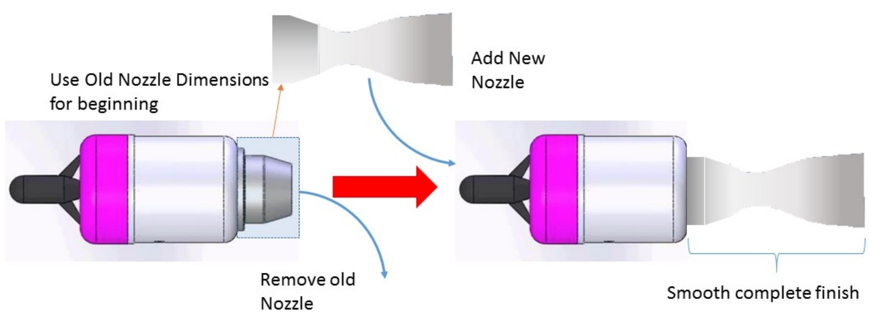

Figure 17. Nozzle "Sock" Depiction

Should the nozzle be attached directly to the stock nozzle, the stock nozzle would need to be modified in order to accept the extension. This can be done by either bolting or welding the extension to the stock nozzle. Both of these methods do require the stock nozzle to be modified which ultimately makes the stock nozzle no longer usable. This could cause conflict with testing and ultimately render the engine useless should the modified nozzle not work and prevent the engine from operating. Directly attaching the extension nozzle to the stock nozzle can be cost effective but at the same time, could be very expensive. Should the extension nozzle be bolted, all that would be needed to be attached would be 3 bolts and 3 holes drilled into the stock nozzle. If there is a compatible welding match in materials between the stock nozzle and manufactured extension, both parts would need to be shipped to a third party to do the welding. Neither the resources nor the welding skills are available on campus and the precision that the welding would require will require a machine to perform it. Attaching it directly to the nozzle does however cut down on manufacturing costs compared to the other options because less material would have to be used.

Should a sock style design be used, an extra test stand would have to be developed to hold the nozzle in place over the stock nozzle. This would allow for re-usability of the stock nozzle but would add manufacturing time. This would also add more weight than the other options as the unit holding the nozzle at the proper height would have to be taken into account and ultimately have to be factored into the final thrust to weight ratio. Another problem that exists is sealing the manufactured nozzle onto the existing nozzle. Incomplete sealing between the stock on the manufactured nozzle could cause the problems with achieving supersonic flow.

Table 14. Pros and Cons of Attaching Manufactured Nozzle to Stock Nozzle

Pros	Cons
Less manufacturing material required	Sealing issues at high temperatures
	Permanent change to nozzle
	Stock engine not completely maintained
	Tolerances of integration

Table 15. Pros and Cons of "Sock" Configuration

Pros	Cons
Stock nozzle maintained	Sealing issues at high temperatures
End of nozzle structurally supported	Heavy test stand
	Manufacturing complexity
	Tolerances of integration

4.3.3. Nozzle Dome Replacement

The third option considered for nozzle integration involves modifying a dome within the nozzle of the JetCat to converge and diverge the flow. To avoid any confusion about which part is being considered here, a figure is provided below.

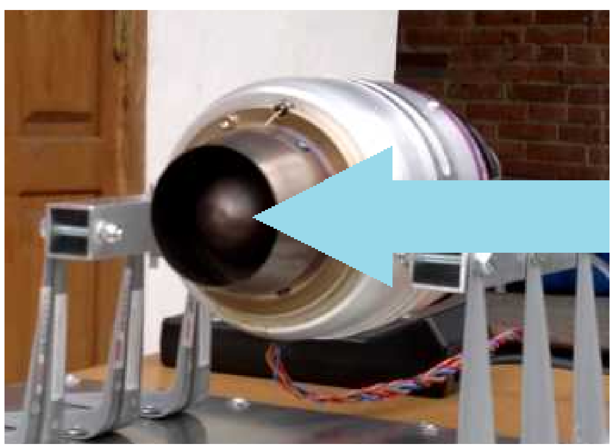

Figure 18. Dome within nozzle to protect the turbine bearing

Picture courtesy of kariboss23, YouTube

As explained in the description of Fig. 18, the dome's purpose inside of the JetCat engine nozzle is to protect the turbine bearing from exhaust heat. In doing so, the dome directs the exhaust flow of the engine in a diverging manner; that is to say, the cross sectional area of the flow becomes larger as the flow exits the nozzle.

This dome presents an opportunity to increase the velocity of the exit flow, and thereby a different integration technique. The dome is attached to the nozzle through three Allen head bolts that come out radially from the nozzle base, and it is through these bolts that any modified dome would be attached. By changing the geometry of the dome, the flow can be converged and diverged in a similar way to the style of a traditional de Laval nozzle. The principle difference in this style of nozzle from the de Laval nozzle is that while the de Laval nozzle alters the flow cross sectional area by changing the nozzle's exterior shape, this style uses a modified nozzle bell to alter flow cross sectional area from the interior of the nozzle.

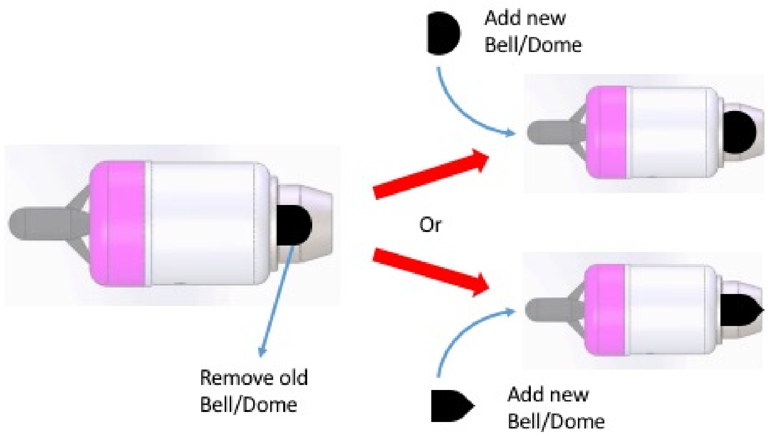

Figure 19. Nozzle Dome change Depiction

This style of nozzle integration has a definite chance of weight savings as the length of the nozzle design would be smaller compared to designs associated with other integration techniques, and the amount of material added onto the stock design is minimal. With this, a cost saving can be assumed since less material would be used and less manufacturing time would be required. Because of the existing bolts in the nozzle for the stock dome, the assembly of any modified dome nozzle would be relatively simple. This is an addition benefit in the event that a wide-scale product piece replacement is desired.

A downside of this integration is the necessary aerodynamics to develop any design for it. Although the cross sectional area determination would not be any more difficult than for a traditional de Laval nozzle, the short length of the nozzle makes shock formation an issue. The designs also need to take the exiting gas vectors into account as some destructive interference would likely happen at the end point of the dome.

Table 16. Pros and Cons of Dome Modification

Pros	**Cons**
Weight Savings	Aerodynamic Complexity
Cost Savings	Small length to work with (stock nozzle)
Simple Integration	
Easy to implement in large scale product change	
Stock nozzle maintained	

5. Trade Study Process and Results

5.1. Nozzle Design

The Nozzle Design trade study is one of the most important trade studies to perform because the overall nozzle success or failure will be based on the selected configuration. The primary concern discussed by the Aerodynamics Team is one of weight; the requirement (**FR 2**) demands that a low-weight option be selected. The secondary consideration was one of cost. Cost will directly be driven by material quantities, and the larger the surface area of the nozzle, the higher the cost will run. The consideration of complexity came next and was weighted just slightly lower than cost. Aerodynamic complexities in design could take up unnecessary amounts of time and team resources during analysis, and with a time constraint on the project, the team wanted to ensure that over-complex designs were carefully considered. The final consideration is that of the altitude envelope. It is well known in the aerodynamic community that classic de Laval nozzles are designed for maximum efficiency and performance at one specific altitude. Because the SABRE-Nozzle will be attached to an aircraft and flown at different altitudes, the team decided to study the importance of creating a design which would be efficient for many altitudes as opposed to just one.

5.1.1. Trade Elements

5.1.1.1. Physical Weight A major design requirement for the nozzle is to maintain, or increase, the thrust to weight ratio of the engine (**FR 2**). To achieve this requirement it is necessary to increase thrust while adding as little weight as possible to the engine. The weight of the nozzle will be directly related to the material used as well as the amount of material necessary for the selected nozzle design. The weight of the chosen design will be a major consideration during the trade study for nozzle design.

5.1.1.2. Cost The nozzle design considerations need to include a capacity for costs incurred during analysis and manufacturing. With a $5,000 budget and a nozzle created with additive manufacturing techniques, cost saving elements must be considered in trade elements. The SABRE-Nozzle team anticipates that the largest costs associated with nozzle design will be twofold; the primary cost will a material one and is directly related to the physical size of the nozzle. The secondary cost will be one of physical limitations of the system. The tolerances which the design must meet are very small, and additive manufacturing techniques which meet small tolerances are likely very expensive.

5.1.1.3. Design Complexity The various design complexities must be addressed in the trade study to consider the amount of time spent in advanced CFD software iterating designs. Simple, historical designs such as the de Laval nozzle might be designed in a weekend, while the Variable Geometry nozzle and Expansion-Deflection nozzle may require many more hours of iteration. The inherent complexities in the system also may require varying levels of CFD complexity to address more intricate geometries.

5.1.1.4. Altitude Envelope Nozzle performance is often limited to a specific altitude at which efficiency is maximum. This trade study seeks to consider the benefits of a nozzle which will perform well for a wide range of altitudes in comparison to a nozzle which is optimized for one specific altitude. A nozzle design which accounts for variable altitudes will have to be either a Variable Geometry nozzle or an Expansion-Deflection nozzle. None of the other designs which have been studied allow for optimal performance at different altitudes.

5.1.2. Trade Study

Table 17. Nozzle Design Trade Study Results

	Weighting	de Laval	Variable Geometry	Annular	Expansion-Deflection	Minimum Length	Heat Transfer
Weight	0.4	4	1	2	2	4	2
Cost	0.3	4	1	2	3	5	2
Complexity	0.25	5	1	3	2	4	1
Altitude Envelope	0.05	1	5	1	4	1	4
Total	**5**	**4.1**	**1.2**	**2.2**	**2.4**	**4.15**	**1.85**

The above weights were determined through individual consideration of each component. Aggregate scores were computed, and the resulting design score is what is seen above. The Minimum Length Nozzle design scored highest and the Variable Geometry Nozzle scored lowest.

5.2. Nozzle Testbed

The Nozzle Testbed trade study is important to the overall purpose of the project, because it will be the main means of validating the design of the nozzle. The trade was split into five categories, those being: cost, flow accuracy, feasibility, and repeatability. The most important aspect was determined to be flow accuracy because this test bed must be sufficient enough to validate to the customer that the nozzle does indeed convert subsonic flow to supersonic flow. The next most important element was determined to be the cost because the budget for this project is strict, and the test bed must be able to be built within this budget. Feasibility is the next important, and it refers to the likelihood that the team will be able to implement the test bed concept that is chosen. Feasibility also includes the idea of safety, because it is important that the concept chosen is not too unsafe to execute. Finally, the next element is repeatability which is describing how many times the test can be conducted. Also under this element, it is determined how many different nozzle designs could be tested in the test rig.

5.2.1. Trade Elements

5.2.1.1. Cost This category was selected for analysis because of the strict budget of $5,000 that the project must adhere to. Some elements that affect the cost for the testbed are the sensor costs, material costs, and other system costs of the engine analog. The restrictive budget affects the concepts because concepts where the materials can be obtained at the university rather than built or purchased will make it easier to stay under-budget. Also, the nozzle must be manufactured by additive manufacturing (see **DR 3.1**), and any nozzle will need to be able to withstand the test bed it is used in.

5.2.1.2. Flow Accuracy This category was selected based on the subsonic to supersonic flow requirement listed as **FR 1** and the thrust/weight and specific fuel consumption requirement listed as **FR 2**. To prove to the customer that the nozzle designed does convert subsonic flow to supersonic exhaust, the flow conditions in the test must have the ability to be matched with the flow conditions that the nozzle would be experiencing on the JetCat engine. Also, the test must have a way of measuring thrust as well because of **DR 2.2** (or measuring elements by which thrust can be calculated), to prove that the thrust/weight ratio has not been decreased by the nozzle. This element selection was also driven by **FR 4**, which is that the nozzle shall be able to withstand engine operation for at least thirty seconds. This drove our concept choice because the testing process needed to include a way that the thrust of the nozzle could be tested as specified by **DR 4.4**. This category was chosen to carry the most weight because it is driven by 3 different functional requirements.

5.2.1.3. Feasibility This category was selected because it is essential that the testbed design selected is one that can be built and used on campus (or at a facility that we have access to), and that the team can understand the overarching concepts behind the test bed and accurately analyze and describe the results. Time is a limiting factor in this aspect, because the schedule of this project is a major constraint. The test bed needs to be finished and ready for testing before the project time frame is over, in order to have a validation of the design for the customer. This was given a high weight because it takes into consideration the schedule, which is believed to be our most limiting factor when it comes to the test bed.

5.2.1.4. Repeatability This category was selected because the test on the nozzle will likely be run more than once. The testbed should be able to be run several times throughout the course of testing, and the components of the test bed should have the ability to be reused. Also under the category of repeatability is the idea that more than one nozzle design could be tested. If a nozzle is expensive to manufacture for a certain type of test, it is likely that more than one design could not be implemented on the test rig. This category was chosen to carry the least amount of weight because the inflexible schedule of the project will likely play a much larger role in the ability to test several nozzles.

5.2.2. Trade Study

Table 18. Nozzle Testbed Trade Study Results

	Weighting	JetCat Engine	Cold Flow	Hot Flow	Actual Size Nozzle	Scaled
Cost	0.15	4	4	3	3	4
Flow Accuracy	0.4	5	2	4	5	3
Feasibility	0.35	1	4	4	3	3
Repeatability	0.1	3	5	3	4	3
Total	**5**	**3.25**	**3.3**	**3.75**	**3.9**	**3.15**

5.3. Nozzle Integration

The Nozzle Integration trade study is a crucial analysis to be considered because just as it is important to analyze the Nozzle Design and aerodynamics, the integration of the nozzle can have drastic impacts in the final design as well. This trade study was divided into 5 different categories: Work Cost, Mass, Tolerance, Flow Impedance, and Interchangeability. These categories were all weighted differently depending on how much of an impact they had on the functional requirements. The most significant trade element was mass because of the impact it has on cost and thrust to weight ratio.

5.3.1. Trade Elements

5.3.1.1. Work Cost Work cost was selected for analysis because all of the design options require different methods of integration. Cost is associated with time since it costs money for labor and time used for that labor. Some other elements that affect the cost for the nozzle integration are the material selection and the production cost of the nozzle to be built additively.

This analysis is not heavily dependent on the cost of the Nozzle's material, but is more reliant on the cost of time to produce the specific nozzle design and the cost of time to integrate onto the engine. Time is money, so a more complicated design integration will incur a higher cost.

Values for cost were assigned based on how much time certain integration techniques, more accurately their associated designs, would take to produce, and how much material would be required to produce them. The complete nozzle replacement scored high for cost because it would take minimal time to design and little work over-all to produce. The nozzle extension scored low for cost because of the complexities of integration for any probable design. The nozzle "sock" design scored average for cost; although the designs are similar to those for complete nozzle replacement, accommodating the stock nozzle within the designed nozzle adds complexity and therefore more cost. The dome replacement integration scores high for cost because of its minimal size and ease of attachment.

5.3.1.2. Mass Reducing mass additions to the engine was considered a key trade study factor because it is one of the limiting factors of the performance and efficiency of the engine. In order to achieve greater thrust from the engine, with the use of the nozzle, more material is needed for the nozzle design required for supersonic thrust. And with more material, more mass is added.

The mass analysis of each integration design will not rely on the material selection of the new nozzle because that will be minimized for all design options. It will mainly be analyzed by the extra material needed to integrate the new nozzle design with the existing engine.

Values for mass were assigned based on the amount of material required for the designs associated with each integration type. The complete nozzle replacement scored high for mass because the weight of the designed nozzle would not be significantly more than that of the stock nozzle and, depending on the material selection, could likely be lighter than the stock nozzle. The nozzle extension style scored average because mass will definitely be added to the stock design for this integration, even more so because of the mass required for attachment. The nozzle "sock" approach scored low because excessive addition mass will be added for any design of this integration type. Finally, the dome replacement method scored high because the designs associated with this technique are small and require little mass, although will still likely add mass to the stock design.

5.3.1.3. Tolerance Much of this analysis will be reliant on the accuracy of the integration process and how much tolerances can be predicted to effect the nozzle's performance. Depending on the integration design, acceptable tolerances will change. More complex designs will have poor tolerances because the accuracy and precision of integrating the nozzle will be difficult and hard to address.

This analysis will not be heavily weighted compared to other elements because tolerances can be considered, but hard to experimentally analyze. There are currently three adjustable screws that hold the inside the nozzle, thus giving us an example that even those obstructions are not extremely hindering to the engine's performance.

Values for tolerance were assigned based on what tolerances in manufacturing would be required for the designs associated with each integration type. The replacement style scored high for tolerance because the tolerances of the design are not restrictive, however the integration onto the existing nozzle creates some tolerance requirements. The extension approach scored low for tolerance because of the flow restrictions that would result should the manufactured tolerances be too high. The sock integration also scored low for tolerance for the same reasons as the extension integration. The dome style integration scored low for tolerance due to the associated designs' style of converging the flow in a smaller space, and also due to the way in which the dome is attached.

5.3.1.4. Flow Impedance Because the goal of this project is focused around having uniform flow so that the engine exit flow achieves supersonic conditions, it is important that the final chosen design does not inhibit the flow or cause any sort of disturbance that would prevent the flow from becoming supersonic. It is also important that there aren't any blockages in the nozzle for obvious reasons.

Values for flow impedance were assigned based on how much the design styles of each integration type would restrict the flow or its steady movement. The replacement style scored high for flow impedance because the integration would not impede the flow any more than the converging necessary to increase the flow velocity. The attachment integration scored average on flow impedance because any style of attachment will create a non-smooth surface against which the flow will travel. The sock integration scored average as well because of the likeliness that any design using it would create turbulence and pockets of lower pressure. The dome approach scored high for flow impedance because the flow would only be impeded to the extent that it already is for the stock nozzle.

5.3.1.5. Interchangeability Interchangeability encompasses having the ability to change out the nozzles so that the stock engine can be used in its stock configurations but at the same time includes being able to test the new nozzle configuration more than once. Maintaining stock usability is important because the one of the project goals is to maintain as much of the stock nozzle as possible. Having the stock configuration also allows us to validate that supersonic flow has been achieved. Having the ability to test the new nozzle also allows for validation and multiple testing which is a requirement for this project.

Values for interchangeability were assigned based on the integration style's ease of integration and ability to be implemented on a large scale product replacement. Full replacement scored high for interchangeability as any nozzle design would be able to be removed and attached as easily as the stock nozzle. The extension integration scored low for interchangeability because any design would permanently modify the stock parts. The sock approach scored average for interchangeability because any design would be slightly more complicated to integrate than with the stock parts. The dome integration scored low because, as with the stock dome, the nozzle would have to be removed before the dome is removed making integration take longer.

5.3.2. Trade Study

6. Selection of Baseline Design

6.1. Nozzle Aerodynamics

The design options considered in section 4.1 included several different options for nozzle geometry. The design requirement of accelerating the flow to supersonic conditions (**FR 1**) has the implicit requirement of a convergent-divergent nozzle. Considerations of varying levels of complexity were analyzed but the conducted trade study revealed that the simpler design options were ideal. With the major functional requirement including maintaining or increasing the thrust to weight ratio (**FR 2**), the weight of the nozzle was the most heavily weighted design consideration.

Table 19. Nozzle Integration Trade Study

	Weighting	Replacement	Attachment	Sock	Dome Replacement
Work Cost	0.25	5	2	3	5
Mass	0.3	5	3	1	4
Flow Impedance	0.15	5	3	3	5
Interchangeability	0.2	5	1	4	5
Tolerance	0.1	4	2	3	2
Total	**5**	**4.9**	**2.25**	**2.6**	**4.4**

With weight being the major driving factor in design selection, the Minimum Length Nozzle was selected. This nozzle design requires the least amount material, and subsequently material weight, out of all designs considered. Additionally the minimum length nozzle can presumably be manufactured as a single piece, which is beneficial to cost of manufacturing while relaxing the necessary tolerances of the additive manufacturing process (**DR 3.1**).

6.2. Nozzle Test Bed

Based off of the trade study, it was seen that testing on the JetCat engine as the main test for the nozzle would likely not be the best decision. The reason for this was mainly the feasibility; the feasibility of carrying out a test on the JetCat engine itself is a large unknown. Based off of conversations with our advisors and schedule restrictions for the project, it was determined that the feasibility of testing on this should be considered to be quite low. Feasibility carries a large enough weight that it was determined that the JetCat engine test should not be our main means of validating the capabilities of the nozzle design.

When hot and cold flows were compared with one another, it was determined that the cold flow would be a relatively inaccurate depiction of the flow conditions, because of the dependence of shock formation on temperature. It was because of this determination that the hot flow is the concept choice for the test bed that the group will be designing. The hot flow scored the highest in feasibility and flow accuracy, which were determined to be the highest weights for the test bed. It is essential that the nozzle be tested in a hot flow because the formation of shocks can provide reasonable doubt to the customer that the nozzle would not achieve supersonic mach number on a stock engine. However, the cold flow tests would be relatively inexpensive and repeatable with several different nozzle designs. It will have a place in our testing plan in that it will serve as a preliminary test for the nozzle designs (which can be 3D printed on campus using plastic). Then, a nozzle that is tested in the cold flow that reaches supersonic speeds at the exit (as determined by the temperature, velocity, Mach number relationship described above) will be tested in the hot flow to be sure that the formation of shock waves does not affect the thirty second hot test.

When an actual size nozzle was compared with a scaled nozzle for the purposes of testing, it was determined that there is no real advantage to creating a scaled nozzle for testing. The cost difference would not be beneficial enough to make up for the fact that the scaled nozzle would not represent the actual nozzle geometry. For this reason, the actual size nozzle will be used in testing to eliminate possible doubt that the customer could have about our nozzle validation due to scaling.

6.3. Nozzle Integration

After analyzing the possible options for the integration of the manufactured nozzle, complete replacement of the stock nozzle if the best option. Considering all the trade elements, this option scored the highest. The main driving factor being the stock to new nozzle weight ratio, this allows us to optimally achieve **FR 2**, maintaining or increasing thrust to weight ratio. Even though replacing the dome inside the nozzle was a good option in this category, because a significantly less portion of the mass would be modified, it just does not cut it for reducing the weight. This option allows the old engine to maintain its stock configuration should the event of further stock testing be required. This also satisfies **DR 3.4**, allowing the engine to be returned in its stock condition, something attaching a new nozzle onto the stock nozzle was not capable without the additional cost of ordering another stock nozzle from the manufacturer. Complete nozzle replacement also turns out to be the least complex system because no additional parts are required to mount the nozzle on the engine, this allows for convenient mounting and dismounting on and off the engine. It additionally allows for flexibility in the final design shape of the converging and diverging portions of the nozzle.

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