University of Colorado - Boulder

ASEN 4018 - Senior Projects

Offset S-duct PRopulsion Inlet (OSPRI)
Conceptual Design Document (CDD)

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1.1 Project Customer

Name: Capt Riley Huff
Email: riley.huff.1@us.af.mil
Phone: (937) 656-4098

1.2 Project Team

Name: Tim Breda Email: Timothy.Breda@colorado.edu Phone: (203) 974-9846	Name: Harrison Methratta Email: Harrison.Methratta@colorado.edu Phone: (503) 780-5461
Name: Joey Derks Email: Joseph.Derks@colorado.edu Phone: (720) 388-0955	Name: Joshua Seedorf Email: Joshua.Seedorf@colorado.edu Phone: (970) 630-4270
Name: Zak Dmitriyev Email: Zakhar.Dmitriyev@colorado.edu Phone: (303) 718-2972	Name: Michael Vogel Email: Michael.Vogel@colorado.edu Phone: (303) 619-6707
Name: Ryan Joseph Email: Ryan.Joseph@colorado.edu Phone: (617) 780-9990	Name: William Watkins Email: William.Watkins@colorado.edu Phone: (210) 882-7414
Name: Dishank Kathuria Email: Dishank.Kathuria@colorado.edu Phone: (720) 394-5285	Name: John Wissler Email: John.Wissler@colorado.edu Phone: (307) 331-2423

2 Project Description

2.1 Description and Background

The P100-RX is a micro turbojet engine developed by JetCat. It is a popular propulsion platform for many small-scale fixed-wing UAV applications. Weighing only 2.38 lbs, it is capable of supplying 22.5 lbf of thrust at 152,000 RPM [9]. Its power-to-weight ratio is superior to traditional propeller-driven propulsion systems. In order to maximize freestream air entering the engine, this off-the-shelf engine is commonly mounted offset from the airframe centerline. Integrating the engine into the fuselage would reduce the exposed surface area and overall drag. This requires diverting freestream airflow into the engine intake via an inlet duct.

Goldstein (1938) [6] and Schlichting (1955) [16] both characterized the flow of a fluid in a pipe bend. The centripetal force provided by the pressure gradient due to the bend is not sufficient for the faster fluid in the center, and This causes the faster fluid to move to the outside of the bend and the slower fluid to move to the inside of the bend. This results in secondary flows (i.e., vortices) being formed in the pipe.

Rowe (1970) [11] also studied the flow in pipe bends, focusing on the behavior of the induced secondary flow, instead of on the fully developed flow; that is, the flow far downstream of the turns. He found that, for a large turn-radius-to-hydraulic-diameter ratio (R/D), the measured flow pattern is "reasonably well-predicted" in a single long bend, up to a bend angle of about 75 degrees. He also studied a 45^o-45^o S bend. While doing so, he found that the secondary flow on the inside of the bend was fully developed by 45 degrees. 30 degrees after the bend direction reversal, a low pressure "bubble" had formed in the center of the pipe and the secondary flow was fully detached from the pipe wall.

Since Rowe (1970), S-ducts have been studied with varying degree turns, R/D ratios, and area ratios. Sullivan et al (1982) [18] studied a 45^o-45^o S-duct. The results were similar to Rowe (1970). Vakili et al (1983) [21] examined the flow in a 30^o-30^o duct with an R/D of 5. While there was no flow separation, they found that the secondary flow generated after the first turn is forced to the outside of the duct due to the secondary flow generated by the 2nd turn. Vakili et al (1985) [22] continued their original research, this time changing the duct to a diffusing duct with an area ratio of 1.51. This resulted in a secondary flow after the first turn that separated and was not observed to reattach by the end of the S-duct.

Successful design of an S-duct results in a high total pressure recovery and a low distortion at the exit of the inlet, known as the Aerodynamic Interface Plane (AIP), while being as short as possible.

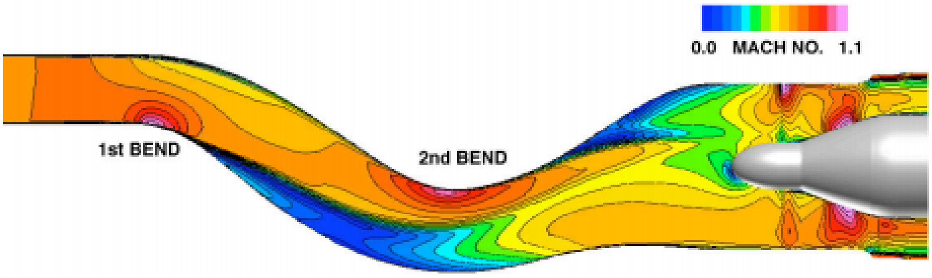


Figure 1: Illustration of Flow Inside an S-Duct

However, this is difficult to achieve for a number of reasons. As outlined above, a longer and gentler turning (high R/D) duct lends itself to better conditioned flow at the AIP. However, a shorter inlet gives a higher score for the OSPRI project. Additionally, the flow of an S-duct is harder to simulate. 2D simulations do not give a good representation of the flow throughout the duct, and 3D simulations are computationally intensive and still over-estimate the total pressure recovery compared to experimental results. The purpose of the OSPRI project is to design and build an S-duct inlet for use with the JetCat P100-RX (Fig X, below) for the Air Force Research Lab's (AFRL) Aerospace Propulsion Outreach Program (APOP), as well as design and build a testing apparatus able to measure various parameters of the flow in the inlet in order to inform the design and simulation of the S-duct inlet.

In order to compete in the APOP competition, the closest outer edge of the inlet capture area must be 6 inches from the centerline of the engine. This offsetting of the JetCat P100-RX will allow AFRL to further study S-duct inlets for use in small scale UAVs that use the JetCat P100-RX, and will allow them to incorporate the engine into the fuselage of said UAVs to reduce drag. Potential implementations of the S-duct inlet are explored in Section 4.1.

In order to have an informed design process for the S-duct inlet, OSPRI will also produce an experimental testing apparatus. This testing apparatus will be used to measure various parameters of the airflow outside of, through, and at the end of the inlet. At a minimum, the testing apparatus will measure total pressure at the front of the inlet and at the compressor face of the engine, as these are the measurements that AFRL will be taking during the competition testing. However, the OSPRI testing apparatus will be used to aid in the design and simulation of the S-duct inlet, so in addition to the total pressure measurements it will also map the distortion and total pressure distribution at discrete stations along each iteration of the inlet. The methods explored in order to create this map are discussed below in Section 4.2.

2.2 Objectives

The levels of success and corresponding objectives of OSPRI are provided in Table 1, below. The levels of success start with a correctly functioning test rig. This is crucial to have, as the test rig will measure the performance of the inlet and the engine, and will inform inlet design and redesign. Performance of the inlet will then be evaluated, followed by the engine performance being measured. The ultimate level of success will be a verification that the inlet performs according to the scoring criteria for APOP.

Level	Objectives
1	A test rig is designed and manufactured that is capable of: mapping total pressure distribution and distortion at discrete locations along the inlet length, the inlet entrance, and the compressor face; providing mass flow comparable to the JetCat P100-RX engine across the full RPM range using a TBD mass flow surrogate; attaching to both the inlet and front face of the engine simultaneously; measuring the thrust produced by the engine and the Thrust Specific Fuel Consumption (TSFC); and interfacing with multiple inlet designs.
2	Experimental verification of the test rig's ability to measure thrust and TSFC compared to known data.
3	Experimental verification of the test rig's ability to characterize the flow within a standalone TBD known inlet design and performance.
4	Experimental verification of an inlet with total pressure recovery above 90% across the full simulated RPM range of the engine.
5	Experimental verification of nominal engine operation over full RPM sweep with inlet attached that meets level three objectives and increases TSFC by no more than 10% and decrements thrust by no more than 10%.
6	Experimental verification of nominal engine operation over full RPM sweep with inlet attached, with total pressure recovery $\geq$ 98%, TSFC increased by no more than 5%, and thrust decreased by no more than 5%.

Table 1: Specific Levels of Success and Corresponding Objectives.

2.3 CONOPS

OSPRI will consist entirely of ground based static tests. However, as there are multiple components to be designed, there will be three test and design phases: the first will be for the experimental test rig and will detail how the test rig will be validated; the second will focus on the inlet design; the last phase will combine the test rig, inlet, and engine. These phases are combined into one CONOPs diagram, Fig. 2. This is followed by a second CONOPs diagram, Fig. 3, which will outline how the S-duct inlet will be tested by AFRL at Wright-Patterson AFB, Ohio.

2.3.1 Test Rig Verification

The test rig plays a major factor in the success of the OSPRI project. It must measure a host of information, and output performance metrics of both the inlet design and the engine. Specifically, it must map the total pressure and distortion distributions within the inlet at the entrance, at discrete locations along the duct, and at the Aerodynamic Interface Plane (AIP), the plane of the inlet that is closest to the compressor face of the engine. When an inlet is being tested without the engine attached, the test rig will have a mass flow surrogate that must be capable of generating the same mass flow as the engine across the full RPM sweep of the engine. Finally, the test rig must also be capable of measuring the thrust and TSFC of the engine across the full RPM sweep.

Before the test rig can be used to verify inlet design, it must itself be tested to ensure it is giving accurate data. This will be done incrementally, beginning with a testing of the total pressure/distortion mapping using the mass flow surrogate. Then, a known inlet design will be attached to the test rig, and the total pressure/distortion measurements will be compared to the data for the inlet. Finally, the inlet will be removed and the engine will be attached. The engine will be run through the full RPM range, and the thrust and TSFC measured will be compared to baseline data for the JetCat P100-RX.

2.3.2 Inlet Testing

While the test rig is being designed, built, and tested, designs for the S-duct inlet will be simultaneously explored. Using the baseline design discussed in Section 6, Computational Fluid Dynamics (CFD) simulation software will be used to model the flow through the inlet over the range of mass flows required for the P100 engine. If the CFD predicts that the inlet meets the design requirements, the inlet will proceed to manufacturing. If not, the inlet will be re-designed, using the CFD data to inform the re-design.

2.3.3 Engine + Inlet Testing

After the test rig has been verified to work correctly and an initial design of the inlet is selected, the performance of the S-duct inlet will be evaluated. The test rig will be configured for operation without the engine attached (i.e., with the mass flow surrogate attached), and the S-duct inlet will be attached and set up for testing. The total pressure and distortion distributions along the inlet length will be measured by the test rig and compared to both the levels of success and the competition requirements. If the inlet has a total pressure recovery below 90%, the inlet will be redesigned, re-manufactured, and then tested again. If the total pressure recovery is above 90% but below the competition scoring threshold of 98%, or if there is a large amount of distortion, the inlet will be re-designed, re-manufactured, and tested again if time permits.

Following the development of an acceptable inlet design, the inlet, test rig, and the engine will be combined in order to evaluate the final objectives of the OSPRI project. After the test rig is configured for testing with the engine (i.e., the mass flow surrogate is removed), the engine and inlet will be connected to the test rig and set up. The engine will be started and run through the full RPM range, pausing at a number of RPMs for long enough to get a steady-state dataset. The total pressure and distortion will be mapped along the inlet length, and the thrust and TSFC will be measured. The data will be compared to the objectives and competition scoring criteria to determine what level of success has been determined.

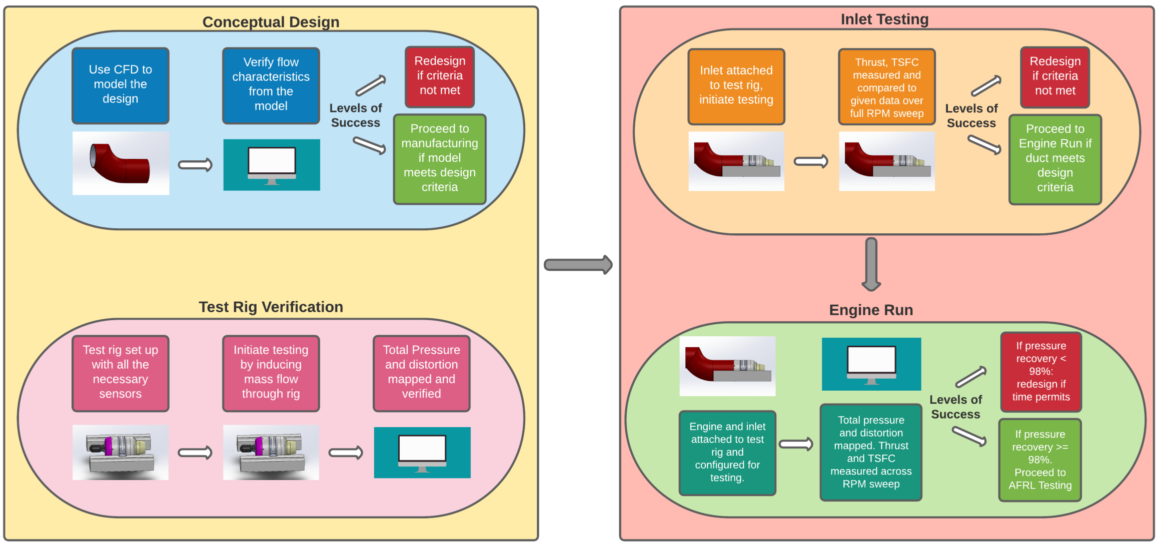


Figure 2: Design CONOPs

2.3.4 AFRL Competition

The OSPRI project will culminate in the team traveling to AFRL at Wright-Patterson AFB, Ohio, in order to test the final S-duct inlet design. The CONOPS for this test has been provided by AFRL and is subject to change at their discretion. AFRL will have an engine pre-configured with a transition piece that will measure the total pressure recovery of the inlet and the thrust and TSFC of the engine. The inlet will be attached to the transition piece, and the engine will be started. Measurements will be taken across the full RPM sweep of the engine to determine how the S-duct inlet performs. Using this data, the inlet will then be scored according to the AFRL grading scale.

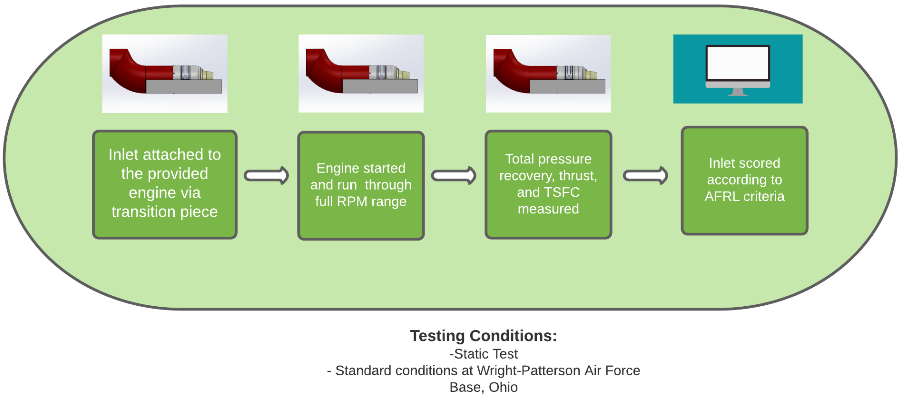


Figure 3: AFRL Testing CONOPs

2.4 Functional Requirements

The design of the S-duct inlet for the JetCat P100-RX engine is a self-contained project and does not rely on a larger system. The functional requirements for the OSPRI project stem primarily from the APOP competition scoring material, and are back-developed from the design requirements given by AFRL. Specifically, the OSPRI team will:

1. Design, build, and validate an S-duct inlet for use with the JetCat P100-RX turbojet engine that performs according to AFRL's objectives.
2. Design, build, and validate a test rig capable of measuring critical inlet performance metrics and inform inlet design.

2.5 FBD

The functional block diagrams for both the test rig and the engine are shown in Figs. 4 and 5 below.

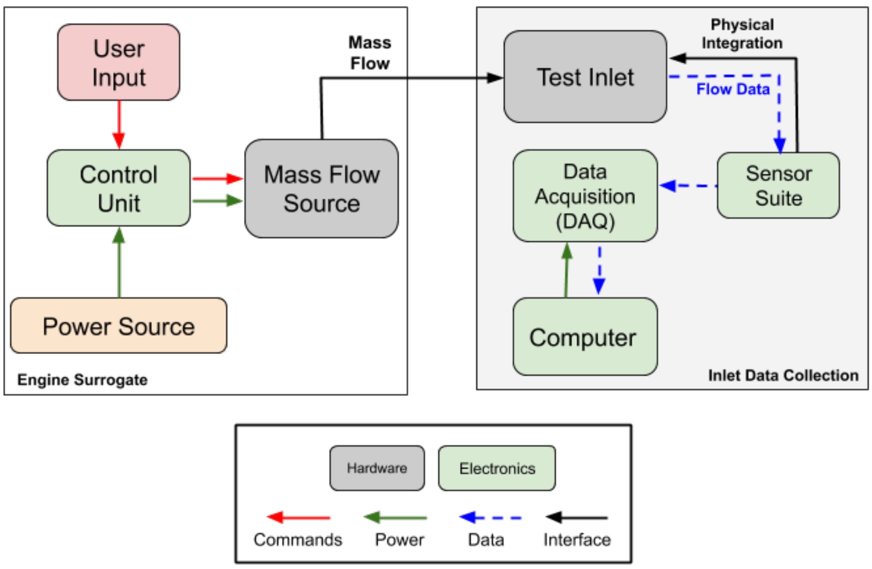


Figure 4: Test Rig FBD

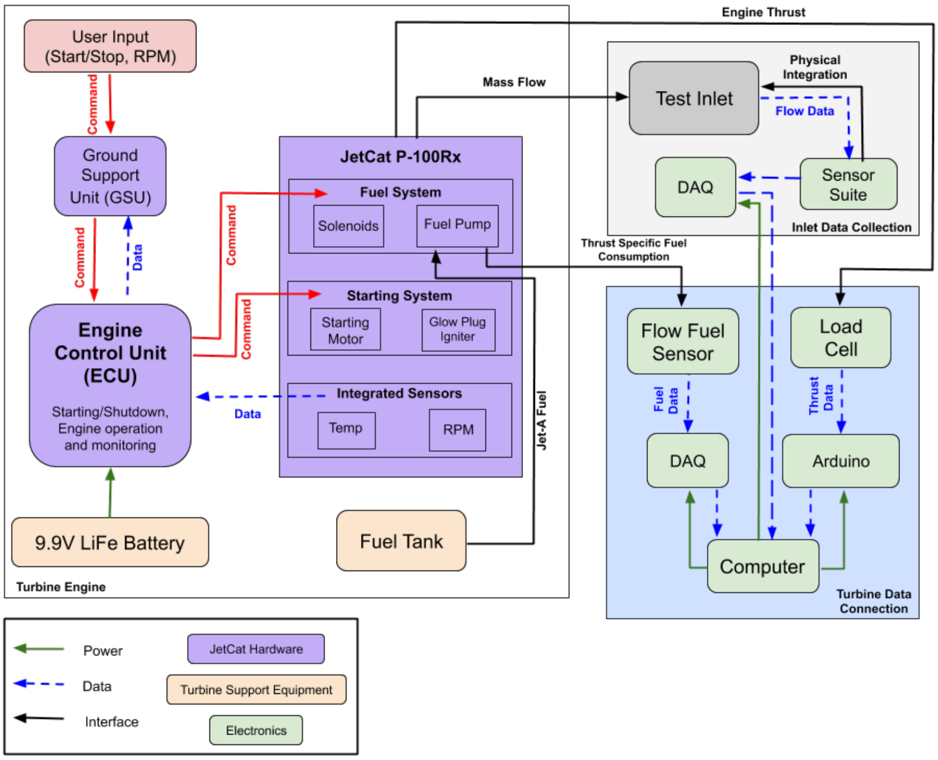


Figure 5: JetCat Turbine Engine FBD

3 Design Requirements

1. Design, build, and validate an S-duct inlet for use with the JetCat P100-RX turbojet engine that performs according to AFRL's objectives.

   1.1. The inlet must interface with the AFRL transition piece.

      i. Motivation: During testing at AFRL, the transition piece will be pre-attached to the engine in order to expedite testing times for each team.

      ii. Verification: The transition piece will be replicated by the OSPRI team according to a.step file and the inlet will be test fit. Additionally, the test rig design will use the same attachment method as the transition piece.

   1.2. The inlet will have a 6-inch offset from the centerline of the engine to the nearest outside edge of the capture area.

      i. Motivation: Inlet offset distance as prescribed by AFRL.

      ii. Verification: The distance between the centerline of the engine and the nearest outside edge of the capture area will be measured.

   1.3. The inlet will have a total pressure recovery of $\geq$ 98% across the RPM sweep of the engine.

      i. Motivation: Part of primary scoring criteria for the APOP competition.

      ii. Verification: Measurement via test rig of total pressure recovery both with engine attached and unattached.

   1.4. The maximum thrust decrement of the engine must be $\leq$ 5% while the inlet is attached.

      i. Motivation: Part of primary scoring criteria for the APOP competition.

      ii. Verification: Thrust produced by the engine while the inlet is attached will be compared to a baseline performance test of the engine.

   1.5. The maximum TSFC increment of the engine must be $\leq$ 5% while the inlet is attached.

      i. Motivation: Part of primary scoring criteria for the APOP competition.

ii. Verification: Engine TSFC while the inlet is attached will be compared to a baseline performance test of the engine.

1.6. The inlet should have an axial length between 12 inches and 24 inches, with the objective being 12 inches.

i. Motivation: The secondary scoring criteria for the APOP competition incorporate the axial length of the inlet. A shorter axial length results in a higher score. The length comes from the length-to-offset ratios of previously studied S-ducts, which range from 2 to 4.

ii. Verification: The axial length of the inlet will be measured to determine its axial length.

2. Design, build, and validate a test rig capable of measuring critical inlet performance metrics and inform inlet design.

2.1. The test rig must be capable of mapping the total pressure distribution at the inlet entrance, the AIP, and between the first and second turns, at a minimum.

i. Motivation: The total pressure recovery is a primary scoring criteria for APOP. In order to inform inlet design, a mapping of the total pressure must be made to understand where the inlet design is lacking.

ii. Verification: Before testing the inlet, the test rig will be verified in a known total pressure and against a known inlet design.

2.2. The test rig must be capable of mapping the distortion distribution throughout the inlet.

i. Motivation: Reduction of the distortion produced by the inlet is a secondary scoring criteria for APOP. Mapping the distortion is necessary in order to make sound judgements for a redesign of the inlet.

ii. Verification: Before testing the inlet, the test rig will be verified against a known inlet design.

2.3. The test rig must be capable of measuring key engine parameters.

i. Motivation: Multiple engine parameters are secondary scoring criteria for APOP.

ii. Verification: Measured values will be compared to baseline data for the JetCat P100-RX.

i. The test rig must be capable of measuring the thrust produced by the engine.

A. Motivation: Thrust decrement is a secondary scoring criteria for APOP.

B. Verification: The thrust produced will be compared to published and previous team thrust data for the engine.

ii. The test rig must be capable of measuring the TSFC of the engine.

A. Motivation: TSFC increment is a secondary scoring criteria for APOP.

B. Verification: TSFC will be compared to published and previous team data for the engine.

2.4. The test rig must be capable of interfacing with multiple different inlet designs.

i. Motivation: Swapping inlet designs should not require the test rig to be remanufactured.

ii. Verification: Each inlet will be designed to function with the test rig and will not require it to be remanufactured.

4 Key Design Options Considered

4.1 Ducted Inlet Design Options

4.1.1 Passive vs. Active Inlet Flow Control System

Passive Inlet System

Passive flow control systems use advanced inlet geometry to mitigate the formation of swirls, turbulent flows, and reducing boundary layer separation. Examples of passive inlet flow control systems include boundary layer diverters, as seen on an F-22 in Figure 8, vortex generators (VG's) as shown on the F-111 in Figure 6, which reduce flow separation, and Kline-Fogleman stepping, which purports to prevent separation along the airfoil. The former two have been applied in a wide variety of subsonic aeronautical settings to reduce flow separation and swirl formation without the need for moving parts or additional powered systems. An article published in the Journal of Aerospace Engineering outlines how adding a bump to the top surface of a serpentine inlet can push the boundary layer toward the sides of the ducted inlet, improving the capability of the flow near the top surface to resist the adverse pressure gradient. In this way, advanced geometry placed in calculated positions can have a huge benefit to flow losses. A downside to passive inlet or flow control systems is they are designed for one flight condition, usually cruise, and are inefficient at other design points.

Pros	Cons
• No additional mechanical complexity (reliability/risk) • Weight Savings • Low/No Maintenance Costs • Easier modeling, simulation, and analysis	• Possible Performance Losses • Designed for one flight condition

Figure 6: Example of Vortex Generator on F-111 Inlet

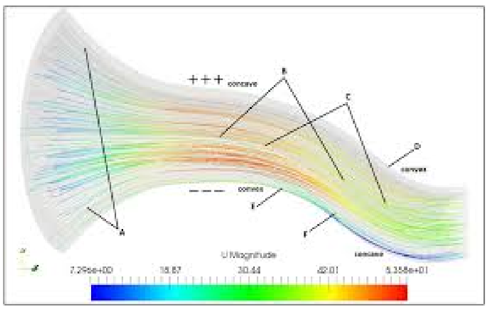


Figure 7: Illustration of flow inside a duct

Active Inlet System

An active inlet flow control system is one which includes movable or controllable parts, such as actuators to move control surfaces, gas tanks to inject more air at stagnation points, or a flow generator to maintain laminar flow at various portions of the inlet. This entails the use of an advanced electronics system to dictate control surfaces or other active flow control elements in exchange for a minimal gain in pressure recovery at low flow speeds, compared with a passive system . They can achieve less flow separation in the inlet at multiple design points if designed properly, however the complexity of the system would far outweigh the benefits in our particular case. These systems typically show much more benefits to supersonic flow control, and seem to be out of the scope for this project.

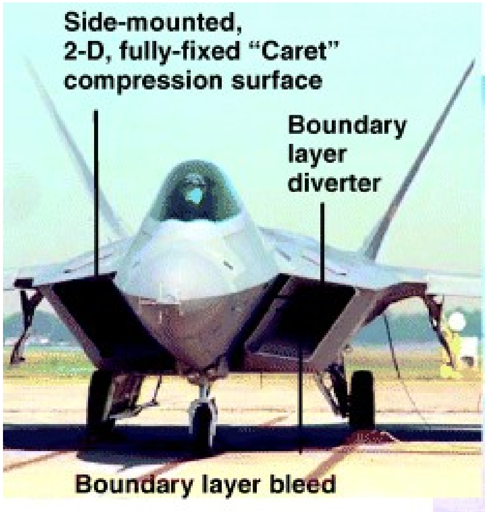


Figure 8: Example of an F-22 Inlet

Pros	Cons
• Better flow management • Potential for more total pressure recovery • Less focus on inlet geometry	• High Complexity • Moving parts, advanced electronics and mechanics • Complicated CFD

4.1.2 Inlet Cross Section and Shape

Non-Circular Inlet Cross Section (Aspect Ratio < 1)

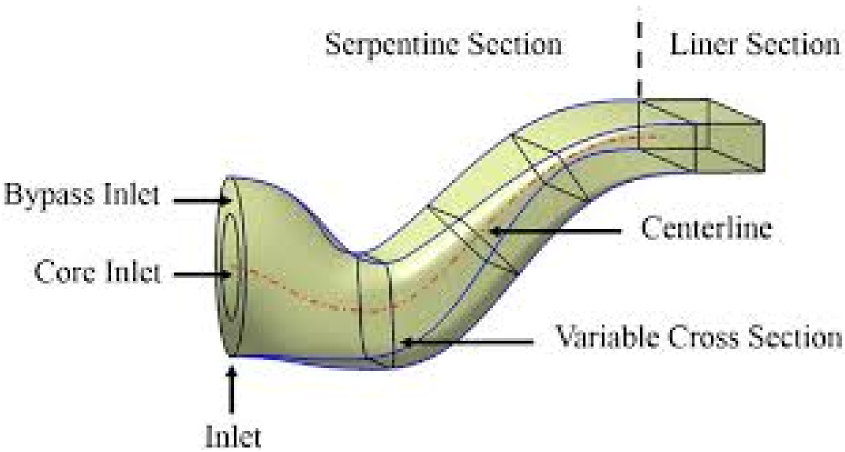


Figure 9: S-Duct with a non circular bypass inlet cross section

An inlet with an aspect ratio < 1, where aspect ratio is $\frac{height}{width}$, would sport an elliptical or rectangular cross section at the entrance of the inlet and would gradually loft down to match the shape of the inlet transition piece designed by AFRL. A study analyzed the influence of aspect ratio on serpentine inlets and found that an aspect ratio of .75 proved to be the most efficient in terms of total pressure recovery in CFD simulations [5].

Pros	Cons
• Proven to have less flow losses	• Additional design complexity • Manufacturing complexity • 3D simulation required to explore benefits of changing aspect ratio

Circular Inlet Cross Section (Aspect Ratio = 1)

An inlet with a circular cross section at the entrance of the duct would provide for less complexity in design and integration. Per the study mentioned above, a circular cross section seemed to perform the poorest in CFD modelling. However, the highlighted pros of this design option are 2D simulation, which is significantly more feasible to accomplish than 3D, and is possible because of the uniform cross sectional shape of the inlet. This seems like the best option for the task at hand.

Pros	Cons
• Simpler to manufacture • Can do analysis with 2D Simulation	• Proven to have more flow losses

4.1.3 Length of Inlet

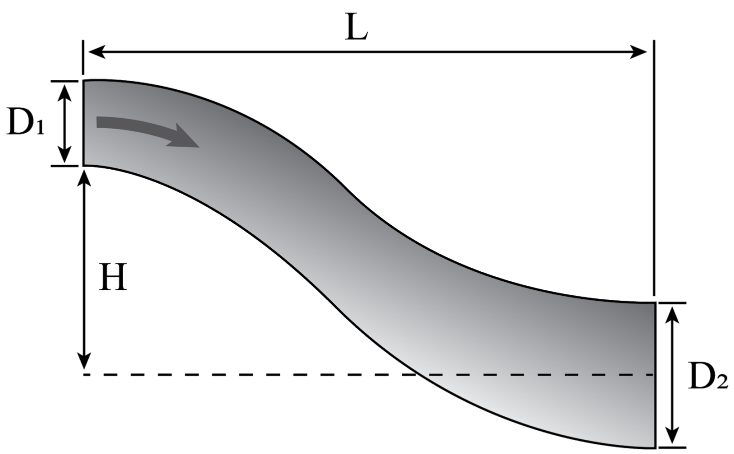


Figure 10: Inlet Dimensions

Figure 10 outlines the major dimensions for the inlet. The offset, H, is fixed at 6 inches for the competition, and the outlet diameter, D2, is fixed as 4 inches by the adapter provided by APOP. The inlet diameter, D1, the length, L, as well as the geometry in between can be optimized to achieve maximum total pressure recovery at the desired test conditions.

Shorter Inlet (6in < L < 10in)

The inlet length dictates the sharpness of the bends in the inlet. A shorter inlet will have sharper bends, increasing probability of flow separation and causing a decrease in pressure recovery. This could also potentially lead to uneven pressure distributions which can damage to the engine. Shortening the inlet does have its benefits however, it reduces the amount of material required, decrease manufacturing times, and be easier to integrate onto a smaller air-frame. Additionally, a shorter inlet will also increase the score at the APOP competition,, as axial length and total inlet volume are taken into consideration for scoring.

Pros	Cons
• More rapid manufacturing • Less material and weight • Higher score by AFRL	• More flow separation around bends

Longer Inlet (10in $<$ L $<$ 14in)

A longer inlet length would smooth bends in the inlet, reducing flow separation due to sharp curves. This suggests better total pressure recovery, however the cost and complexity of manufacturing is increased. Additionally, integration into an air-frame would be more difficult. It is also possible that longer inlets could see complications from the formation of the boundary layer, flow separation can still occur naturally along a lengthy surface, increasing distortion in the flow. Another downside is because AFRL considers the total volume and axial length of the inlets for scoring, points will be more favored towards shorter, smaller by volume inlets.

Pros	Cons
• Minimizes flow separation from curves • Better conditions for undisturbed flow	• Requires more material • May be more difficult to manufacture • Increases the volume of the inlet

4.1.4 Area Ratio

Inlet Diffuser (Converging-Diverging)

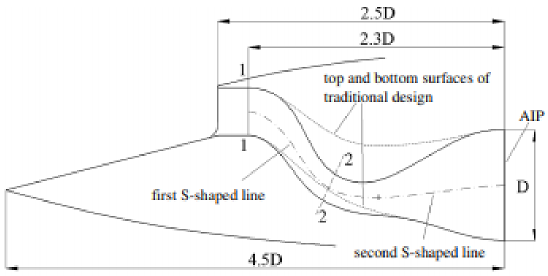


Figure 11: Example of Converging-Diverging Inlet

A converging-diverging S-duct inlet would be able to accelerate the flow as it passes through the inlet entrance and around the bends in the duct. The subsonic flow acceleration will aid in the decrease of flow separation as it navigates through the inlet. The flow can then be slowed again in the divergent portion of the duct in order to achieve the necessary pressure for entrance to the engine compressor. However, the duct itself will be difficult to manufacture as a result of the flow area changes along the length of the duct.

Pros	Cons
• Minimal flow separation	• Difficult to manufacture

Inlet Diffuser (Diverging)

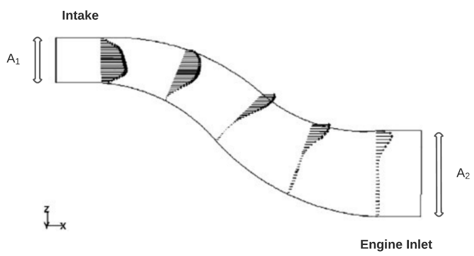


Figure 12: Example of Inlet Diffuser

A diffuser shaped S-duct would have a narrow inlet capture area. This decreases the velocity of the air flowing through the inlet, and is useful during flight at increased speeds. On a static test stand, this will make it more difficult for the engine to intake the correct amount of mass for it to run, and may decrease performance.

Pros	Cons
• Allows for increased performance at speeds above inlet air speed	• Limited operation conditions

4.2 Testing Apparatus Design Options

The primary objective of the testing apparatus is to produce qualitative or quantitative data describing the flow inside a given inlet which will be beneficial to the development of further iterations of inlets. A significant quantity of the data will be pressure data along the inlet length, the inlet entry and exit. Thus suitable pressure sensors will be required, where a collection of methodologies and sensors will have to be chosen in order to gain beneficial insight into the flow structure of the inlet. Furthermore, mass flow must be derivable from the sensor data, requiring a flow temperature and velocity measurement as well. Placement of select sensors and mounting mechanisms are also crucial and must be considered during the final probe selection. Finally, pressure distortions across the engine face must also be determined to ensure safe operation of the JetCat P100-RX and must be measurable with one or more of the sensors. This is critical as during operation significant fluctuations in total pressure on the turbine blades can lead to damage and potential structural failures.

4.2.1 Pressure Sensors

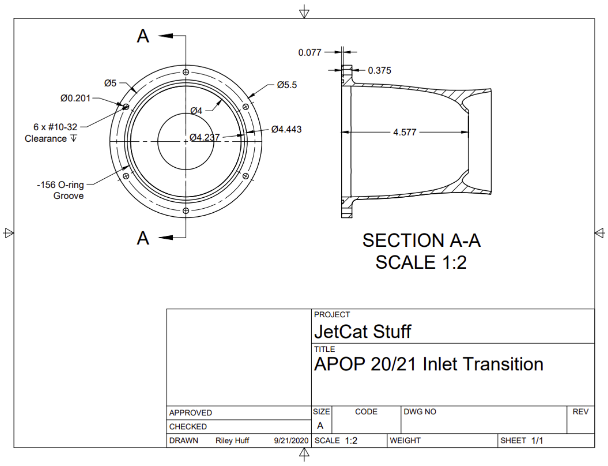


Figure 13: AFRL Engine-Inlet Adapter

The selection of sensors to be used in this experiment is dependant on the nature of the flow. A significant characteristic of flow is its mach number which determines whether the flow behaves as a compressible or incompressible fluid. Equation 1, derived from mass continuity, was used to approximate the velocity of the flow by assuming uniform velocity and density across a particular area in the inlet [4]. The manual for the JetCat P100-RX lists the mass flow as 0.23 kg/s [9] and the engine-inlet adapter used by AFRL, figure 13, has an internal diameter of 4 in (10.16 cm) where it interfaces with the designed inlet. Assuming a sea-level air density of 1.225 kg/m^3 for this mass flow rating, the flow velocity is calculated to be 23.16 m/s in equation 2. This is approximately Mach 0.07 which is well below the usual threshold for compressibility, Mach 0.3 [2]. In order for the flow velocity to reach Mach 0.3, the diameter of the inlet would have to reduce to 1.89 in (4.8 cm) as calculated in equation 3. This calculation suggests that the flow through the final inlet is likely to be incompressible, simplifying calculations and providing more flexibility in the selection of sensors.

$$\dot{m} = v \cdot A \cdot \rho \tag{1}$$

$$v = \frac{0.23\ \frac{kg}{s}}{(\frac{\pi}{4} \cdot (0.1016\ m)^2) * 1.225\ \frac{kg}{s}} = \mathbf{23.16\ \frac{m}{s}} \tag{2}$$

$$D = \sqrt{\frac{4}{\pi} \cdot \frac{0.23\ \frac{kg}{s}}{102.9\ \frac{m}{s} \cdot 1.225\ \frac{kg}{m^3}}} = \mathbf{0.048\ m} \tag{3}$$

Pitot Probe

Pitot Probes are designed to directly measure the total pressure of a flow. The device is a widely available, low cost and minimally invasive measurement apparatus. It is reliable and simple enough to be utilized within the confines of this project. This technology has decades of proven flight heritage, and the governing principles that characterize this sensor's behavior are well understood.

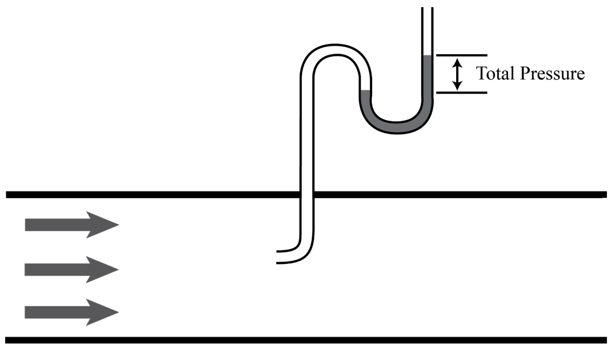


Figure 14: Pitot Probe Cross-Section

Pros	Cons
• Economical • Minimal flow obstruction • Proven flight heritage and reliability	• Inaccuracies with non-parallel flow • Equations assume adiabatic and steady flow- can lead to inaccuracies

Kiel Probe

The Kiel probe is another pressure measurement device that is used to compute the stagnation pressure of a moving fluid. The Kiel probe utilizes guides around a central pitot sensor as shown in Fig. 15 below and sometimes a shroud over the entrance. Both types aim to straighten incoming non-parallel flow at the inlet entry to reduce error from varying flow angles when determining stagnation pressure [8]. Due to this additional structure the sensor is bulkier than the pitot tube and has a greater effect (i.e. greater flow distortion) on the flow. This sensor would provide more accurate pressure readings towards the inlet entry as well as in turns where flow is expected to be non-parallel.

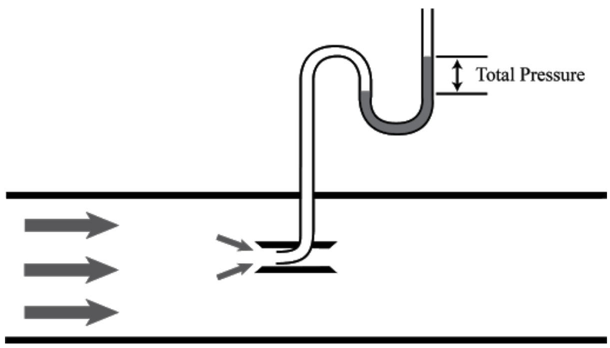


Figure 15: Kiel Probe Cross-section

Pros	Cons
• Economical • Less inaccuracy with non-parallel flow	• Greater flow obstruction than Pitot sensors • Governing equations and principles are not well understood.

Static Surface Tap

Static Surface Taps are small pressure sensors placed perpendicular to the flow direction along the surface of the test item. Static pressures can be used to approximate the total pressure for incompressible flows. This begins with equation (1) for the velocity in a Venturi tube. This requires two areas and their respective mean static pressures. This velocity can then be used in equation (2) to calculate the total pressure [2].

$$v_2 = \sqrt{\frac{2}{\rho}\frac{p_1 - p_2}{(1 - \frac{A_2}{A_1})^2}} \tag{4}$$

$$P_t = P + \frac{1}{2}\rho v^2 \tag{5}$$

This concept does not obstruct the inlet in any way and could use many pressure transducers to get a total pressure profile along the entire length of the inlet during a single test. Alternatively, fewer transducers could be used by only measuring the static pressure at two points in the inlet during each test. The remaining static pressure ports would need to be plugged during these tests to prevent air from flowing through the holes.

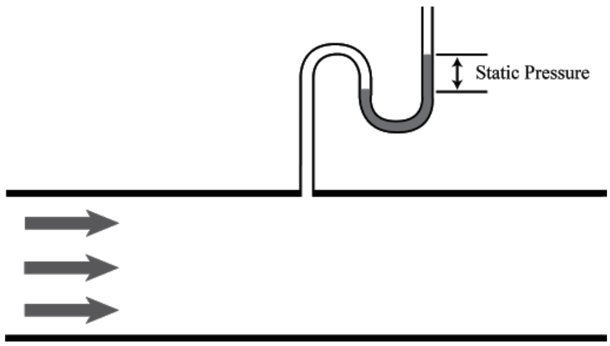


Figure 16: Static Pressure Port Cross-Section

Multiple static pressure ports would be required at any point along the inlet to calculate a reasonably accurate total pressure. Some level of flow separation is expected in the inlet which will lead to turbulent flow. This means that differences in static pressure could be observed around the same axial point on the inlet. Multiple static ports provide an average static pressure for the entire point, giving the most accurate predictor of total pressure. Unfortunately, this same issue prevents static pressure ports from being used to determine the distribution of total pressure. Thus, while static pressure ports provide a simple way of measuring mean total pressure anywhere in the inlet, a different probe would be required to directly measure the total pressure distribution at the end of the inlet before advancing from a mass flow simulator to the actual engine.

Pros	Cons
• Requires no specialized probe hardware	• Requires two measurement points at a time
• Zero flow obstruction	• May not give accurate total pressure distribution with significant flow separation
• Proven method for flow speed measurement	• Assumes steady incompressible flow
• Can provide a total pressure profile for the entire inlet	• Requires an area ratio not equal to 1

4.2.2 Temperature Sensors

Thermocouples

A simple yet versatile tool, thermocouples are a reliable instrument for measuring temperatures. Thermocouples can be used to measure temperature indirectly through voltage by using the thermoelectric effect. Two different metals in contact will produce a measurable voltage difference when exposed to extreme temperatures. Knowing the thermodynamic properties of the metals can allow the user to interpret the measured voltage as temperature. Because thermocouples are so low-profile, they can easily be fitted into very small systems such as that of a JetCat inlet or other sensor mounts. Having many thermocouples can crowd an area however, as each requires two wires to function while all of the thermocouples need to be attached to a hub external from the testing area.

Pros	Cons
• Inexpensive • Minimal flow distortion • Wide temperature range	• Not Incredibly sensitive • Susceptible to electrical noise

Resistance Temperature Detector

The RTD sensor measures temperature through the resistance of a pure metal sample. As a continuous current is passed through the metal and it is heated or cooled the resistance observed in the metal changes and is indicative of its temperature. Various types of metals are used to produce sensors capable of temperature readings up to 1200°F with accuracies of about +/- 6 °F.

Pros	Cons
• Highly accurate	• Expensive • Damaged easily through vibrations • Relatively limited temperature range

4.2.3 Velocity Sensors

Anemometer

Conventional anemometers measure flow velocity through the use of a fan or a series of cups on moment arms. The force of the airflow causes these components to spin, allowing for the calculation of lateral flow velocity through the use of kinematic equations. The method has a long heritage and as such, the devices tend to be reliable; however, conventional anemometers tend to be bulky due to the large moment arms or fan blades disrupting airflow in the case of the later and impractical sizes for the former [19].

Pros	Cons
• Proven utility and reliability • Economical	• Bulky fan blade design restricts and alters flow • Hard to get internal inlet measurements

Hot Wire Anemometer

Hot wire anemometers are relatively small flow velocity testing devices. These utilize a thin heated wire with known thermal conductivity and observe the power required to maintain the heated element at a constant temperature. The power required can be utilized to compute the flow velocity. Some devices operate at a constant current, monitoring the temperature of the filament instead, avoiding possible overcurrenting.

Pros	Cons
• Minimal flow distortion • Ideal for unsteady flow measurements	• Right angle velocity measurement only • Fragile

4.2.4 Qualitative Observation

Smoke Wire Flow Visualization

The smoke wire method utilizes an electrically heated wire covered in oil to produce smoke trails through a test geometry in a flow. A longitudinal cross section of an inlet is closed on this side with a transparent barrier through which the flow can be observed. Further concepts may involve manufacturing the inlet design out of transparent materials to avoid undesired effects on the flow from the cross sectional cut. Additionally, a good light source as well as a camera is required to allow for close analysis of the flow structure.

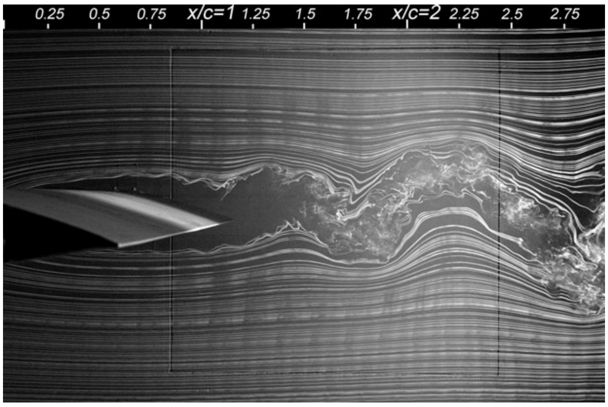


Figure 17: Smoke Wire Flow Simulation

Pros	Cons
• Minimal required equipment • Detailed 3D flow structures	• Cross section may affect flow structures • Cannot be utilized in conjunction with sensors • No quantitative measurements

Surface Flow Visualization

Similarly to the smoke wire flow method, surface flow techniques can also be utilized to visualize a flow qualitatively. This method employs a surface coating which interacts with a chemical in the flow when in contact, as such, the surface flow structures can be analyzed by the reaction pattern on the surface. An example of such a test is shown in Figure 18 below. Unlike the cross-section technique mentioned above, a full inlet is used and as such is more representative of the actual flow but only allows for surface flow observation. This technique is commonly utilized to analyze if separation of the flow occurred along curved surfaces.

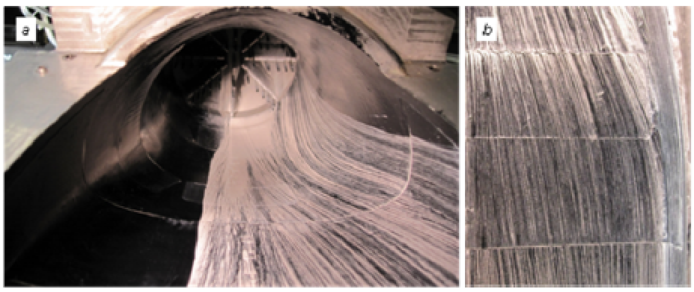


Figure 18: Surface Oil-Flow Visualization

While this methodology does not produce quantitative data, the qualitative analysis of the flow structure would be beneficial to the iterative design approach that will be taken throughout the manufacturing processes of the project.

Pros	Cons
• Minimal required equipment • Detailed surface flow structures	• Requires Cleanup • Cannot be utilized in conjunction with sensors • No quantitative measurements

4.2.5 Sensor Utilization

Slotted Inlet Concept

One potential implementation for collecting data during testing of the inlet is to design a small slot that runs down the length of the inlet. This slot would allow for the use of an internal, movable pressure measurement device. The measurement device would use rails not too dissimilar to the system for the movable pitot tube that is on the wind tunnel owned by the University of Colorado's school of Aerospace Engineering. These rails would be mounted external to the inlet and allow the device to have movement in 2 axes (along the x and z axis in a plane as shown in Figure 20) allowing for data to be collected throughout the entire length of the inlet. This slot in the inlet may have an effect on the internal flow, but this may be minimized through the use of covering/filling the slot with either tape or some other means. Another version of the same inlet could be manufactured with another slot rotated orthogonally to the first. The movable measurement device could then be used on another orthogonal plane within the inlet. This approach would allow for data to be collected at nearly any location in the inlet with minimal disturbances to the flow. This approach is not all that dissimilar to many practices in industry, especially in regards to wind tunnel testing. Movable pressure measurement devices are seen in many undergraduate labs of the University of Colorado school of Aerospace Engineering.

Pros	Cons
• Simple Manufacturing • Infinite longitudinal measurement locations • Easy to use on multiple different inlet • Easily movable sensor	• Will need 2 versions of the inlet to get 3D data • Possibility for there to be small aerodynamic disturbances from the slot or the slot's cover

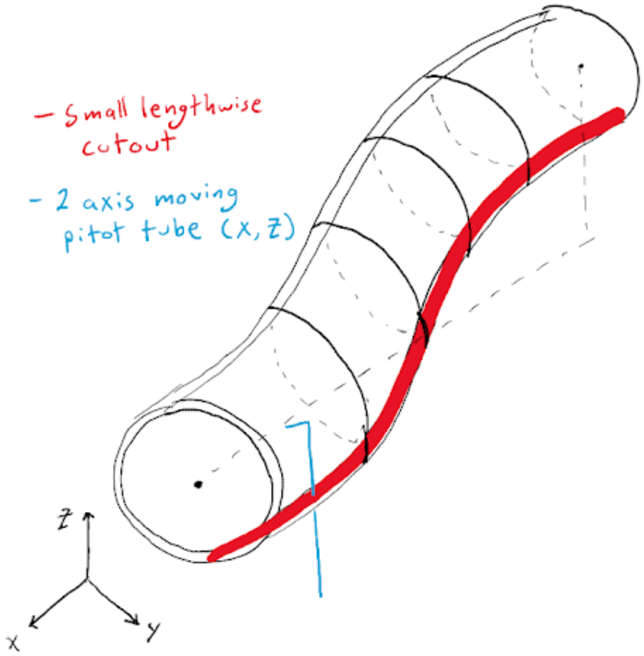
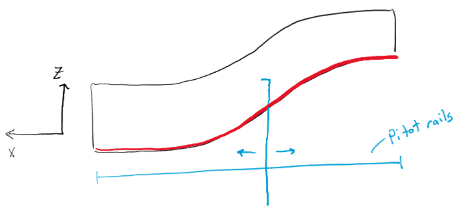


Figure 19: Slotted Pitot Tube Isometric View



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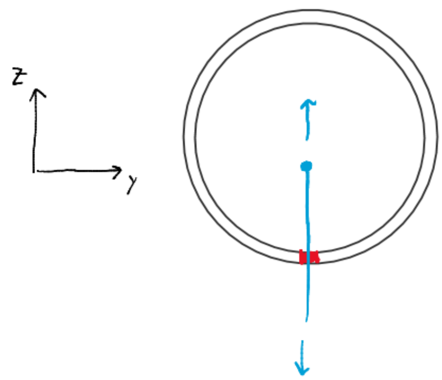

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Figure 20: Side and Front View

Inlet Sectioning Concept

Another potential implementation for collecting data during testing is the use of a segmented inlet building approach. A full inlet design would be decomposed into different segments and tested sequentially. The inlet would be manufactured such that the sections would easily assemble (such as bolting together) allowing for an iterative or a building up testing approach. These segments would give the team the ability to test and understand the aerodynamic effects along the length of the inlet. This would allow for an easy relocation of measurement sensors (such as a total pressure rake) at various locations along the inlet length. The data from such measurements would provide detail regarding the flow structure and could greatly improve iterative designs of the inlet. The mass flow surrogate would then attach behind the rake to drive the flow and simulate an engine for the iterative test approach.

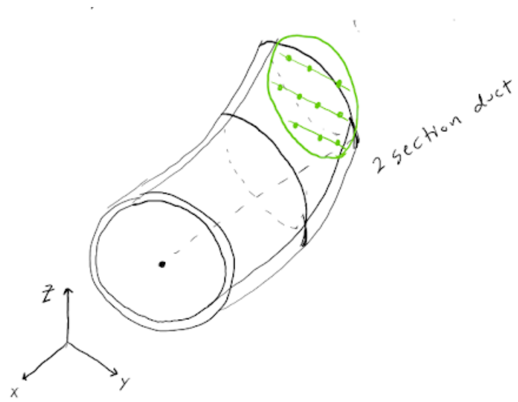

Figure 21: Inlet Sectioning: 2 Step Inlet

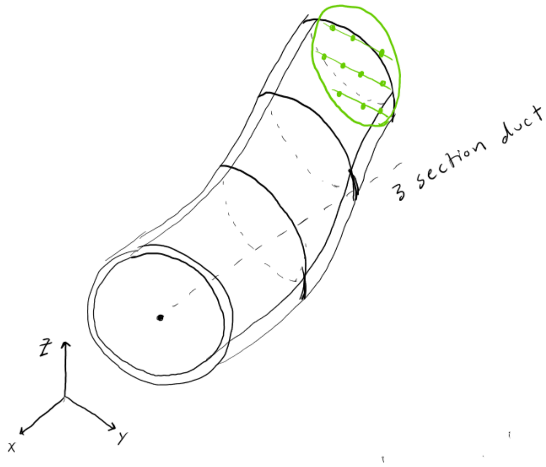

Figure 22: Inlet Sectioning: 3 Step Inlet

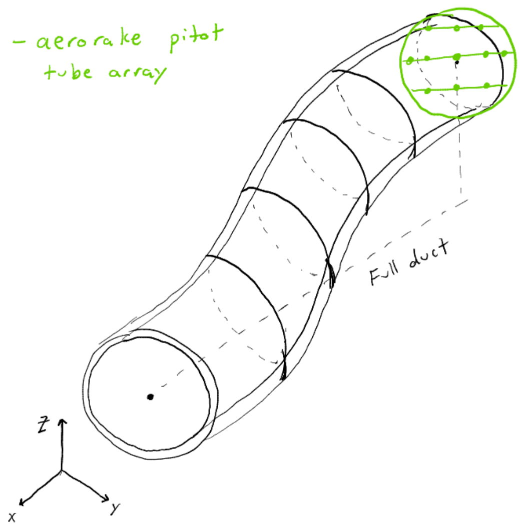

Figure 23: Inlet Sectioning: Complete 5 Step Inlet

Pros	Cons
• Various rake placement opportunities • Can focus on one area getting a total picture of the aerodynamic effects at that location	• Section seams affect flow • Finite longitudinal measurement locations • Requires more manufacturing with all the sections • Sensor array may need to change shape/size as the inlet's cross section may change along its length • May not fully capture downstream effects of inlet in middle sections without the rest of the inlet

Discrete Locations

Discrete placement of probes is one of the simpler mechanical solutions, where sensors would at most have 1 dimensional movement into the flow from the surface and are otherwise fixed. This sensor placement has only minimal effects on the flow as no further openings are created and unused sensor locations can be sealed easily. This placement of sensors is commonly used for static pressure surface taps to characterize the surface flow behaviour of inlets. They are simple to install and only minutely affect the flow structure. Surface sensors are best placed in areas where separation of the boundary layer is most likely i.e. any turns within the inlet.

Pros	Cons
• Minimal flow effect • Highly adaptable to different inlet designs	• Max 1 dimensional movement • Difficult to determine representative pressure distribution model for full flow

4.2.6 Mass Flow Surrogate

In order to perform preliminary tests of the inlets without risking damage to the expensive turbine engine, another source for mass flow is needed. Damage to the engine can occur due to various types of aerodynamic effects that may be unknown until physically tested (such as choked flow or counter-swirl). After capturing the baseline mass flow rates for an unmodified JetCat P-100Rx (calculated through equation 1), the mass flow through the inlet can be precisely replicated without the use of the actual engine. To replicate this mass flow rate of the JetCat engine, the mass flow rate of the surrogate will be calibrated through equation 1.

Previous Senior Project Air Tank System

One potential option to generate this mass flow is to use a pressurized air tank system. The University of Colorado school of Aerospace Engineering has kept a past senior project which manufactured large pressurized air tanks and an associated test section. Faculty have given us permission to use this system as a source of mass flow for inlets. This approach is not all that dissimilar to a blow-down or many supersonic wind tunnels.

Pros	Cons
• Allow for precisely controlled air to be used for testing • Large tanks allow for long tests	• Need to reassemble old senior project to a functioning level • Long lead time to get functioning • Long lead time in between tests to recharge the large tanks

Windtunnel

Another potential approach for mass flow would be to test an inlet in a wind-tunnel. This is a common industry approach to test and evaluate various aerodynamic designs of all different types. This legacy approach is considered as the University of Colorado school of Aerospace Engineering has two different subsonic wind tunnels that potentially could be used to test inlets. With this design option it is important to consider the constraints of the equipment as well as staff and scheduling. One of the two wind tunnels at CU is used for graduate studies and research and will most likely be unavailable to us. The second has a test section with dimensions 12”x12”x24” and thus may be too small to test the inlet within it. Additionally, this wind tunnel is also utilized by many classes in the undergraduate aerospace program, thus testing would need to be scheduled well in advance putting a significant and complex time constraint on the team. Lastly, due to COVID, testing using the university wind tunnels may not be not be available to students whatsoever.

Pros	Cons
• Established method of aerodynamic testing • Can run long test runs	• Community resource/Scheduling required • May require much extra work to get needed mass flow in inlet • Small test section dimensions

Electric Ducted Fan

Another potential option as a mass flow surrogate is to use an electric ducted fan (EDF) as a replacement of the JetCat turbine engine. EDF’s are widely used in the radio controlled aircraft industry and come in many different sizes (ranging from 50 mm diameters all the way to 195 mm and beyond) giving many different options for mass flow and air velocities. Additionally, it is easy to control the power levels of EDFs which will allow the team to precisely control and calibrate the mass flow entering into a test inlet.

Pros	Cons
• Economical • Ease of operation and controllability • Lengthy test duration with current battery technology	• Possible need for extremely large EDF to produce comparable mass flow rates in the inlet • No manufacture reported mass flow data

4.2.7 Other Considerations

Test Stand Structural Support

In order to ensure the test inlet and associated testing equipment remain stationary and secure during testing, a support structure will need to be developed. This structure will need to be capable of interfacing with the existing JetCat test stand and to function as a stand alone test stand without the JetCat engine. For this task 3D printing and aluminium extrusions are currently being considered.

5 Trade Study Process and Results

5.1 Ducted Inlet Trade Study

5.1.1 Trade Study Methodology

The evaluation criteria in the farthest left column of the table were theorized based directly upon project requirements and design objectives. Total pressure recovery and distortion are a score criteria provided by AFRL and therefore holds the most weight for scoring purposes. Ease of simulation is important in understanding the obstacles a certain design may face aerodynamically, and is critical to assessing design success. Designs that require 3D flow were scored much lower than 2D simulation due to time management and complexity constraints. Manufacturing process is also accounted for in the scoring criteria since complex structures could affect the timeline and cost of the project. Lastly, in order to ensure the system is durable and less costly, an evaluation of technical complexity was added. The scoring system is based on a 1 to 5 scale, with 1 being the lowest score a design can be assigned for a particular criteria, while 5 is the ideal score and best case for a certain criteria. All scores are color coated to further identify their evaluation in the scope of this trade study. Weight calculations for each evaluation criteria follow the formula below. This column is added to be able to quantify these criteria for simplicity in comparisons.

$$\text{Weighted Total} = \frac{\text{Score}}{\text{\# of Criteria}} \tag{6}$$

5.1.2 Anticipated Total Pressure Recovery

Using technical knowledge of the forces at play in a particular system, a certain design criteria can be evaluated to what degree it can affect flow or harbor separation, causing a loss in total pressure. This category is weighted the most heavily due to total pressure recovery being a direct design requirement given by AFRL. The word "anticipated" is included to denote the theoretical impact of the particular design on total pressure recovery in exchange of hard data.

5.1.3 Anticipated Pressure Distortion

Pressure distortion is the discrepancy in pressure in a cross sectional area of the inlet duct. It's effects can influence the efficiency of the compressor stages of the jet engine. An ideal inlet will introduce flow at a constant pressure in a cross sectional area of the inlet. Issues stemming from a non-ideal inlet may have vast pressure differences in the same cross sectional area, in the best case affecting performance and in the worst destroying the jet engine. This is unlikely, but should still be taken into consideration.

5.1.4 Technical Complexity

Technical complexity denotes the general intricacy of the system or design. Aspects that contribute to a higher technical complexity could be the addition of extra parts, added weight in need of structural support, or requiring changes to our test apparatus in order to test the design. A lower level of complexity is scored higher due to less probability of failure during testing, integration, and implementation.

5.1.5 Ease of Simulation

Ease of simulation refers to relative simplicity of modeling and implementing CFD analysis of inlet designs. More complex simulations would involve 3D shapes, loops, complex initials states, and high fidelity meshing for example. Less complex simulations are 2D, simpler geometry, with simple initial states. These factors influence the difficulty of implementing accurate CFD simulations and speedy recovery of useful information on designs.

5.1.6 Ease of Manufacturing

Ease of manufacturing encompasses the particular design's simplicity in fabrication. A product or design which only contains one type of material or minimum parts is significantly more desirable to manufacture than one with multiple different parts made of varying materials. Varying materials would also require added thought or design in integration and assembly. Priority weighting is given to designs containing materials or fabrication techniques which can be done here at CU whether it be 3D printing, lathing, or laser cutting in the ITLL/Ideaforge rather than being sent out to a manufacturer.

5.1.7 Trade Matrix

Criteria	1	2	3	4	5
Anticipated Total Pressure Recovery (35%)	Little to No Anticipated Pressure Recovery	Serious flow losses anticipated	Moderate anticipated total pressure recovery	Theorized total pressure recovery nearing AFRL standards	Guaranteed total pressure recovery equal to AFRL standards
Anticipated Pressure Distortion (20%)	Major distortion, engine may fail	Distortion in Problematic areas	Distortion is present	Little to no Distortion in non-problematic areas	No distortion
Ease of Simulation (15%)	No further design relevant data can be obtained from measurements	Data requires processing and design changes are based upon many assumptions	Data requires processing and allows for some identification of design changes	Data requires processing but allows for improvement to design iterations	Data allows for easy identification of design concerns
Ease of Manufacturing (15%)	Sensors and mounting systems cannot be adapted to new designs	Complications will occur adapting to new design, concerns may not be resolvable	Complications may occur adapting to new design, concerns are resolvable	Minor easily resolvable concerns transferring to new design	Sensors can easily be adapted for new design
Technical Complexity (15%)	Structural or part failure every test run	Structure or part needs replacements every test run	Structure or part requires minor adjustments every test run	Structure or part requires monitoring but no adjustments or replacements every test run	Structure or part needs no monitoring and little to no maintenance

5.2 Evaluation Criteria for Inlet Trade Study

5.2.1 Passive vs. Active Inlet System

Factor	Weight	Passive System	Active System
Anticipated Total Pressure Recovery	0.35	4	4.5
Anticipated Pressure Distortion	0.20	4	4.2
Ease of Simulation	0.15	5	2
Manufacturing Ease	0.15	5	2
Technical Complexity	0.15	5	1
Weighted Totals		4.5	3.2

5.2.2 Inlet Cross Section and Shape

Factor	Weight	Non Circular	Circular
Anticipated Total Pressure Recovery	0.35	4.5	4
Anticipated Pressure Distortion	0.20	3.5	4
Ease of Simulation	0.15	2.5	4.5
Manufacturing Ease	0.15	3.5	4
Technical Complexity	0.15	3	4
Weighted Totals		3.6	4.1

5.2.3 Length of Inlet

Factor	Weight	Shorter Inlet	Longer Inlet
Anticipated Total Pressure Recovery	0.35	4	4.5
Anticipated Pressure Distortion	0.20	4	4.5
Ease of Simulation	0.15	4	4
Manufacturing Ease	0.15	4	3.5
Technical Complexity	0.15	4	4
Weighted Totals		4	4.2

5.2.4 Area Ratio

Factor	Weight	CD Inlet	D Inlet
Anticipated Total Pressure Recovery	0.35	4	3
Anticipated Pressure Distortion	0.20	4.2	3.5
Ease of Simulation	0.15	4	4
Manufacturing Ease	0.15	3	4
Technical Complexity	0.15	3	4
Weighted Totals		3.7	3.6

5.3 Evaluation Criteria for Total Pressure Measurement Trade Study

5.3.1 Flow Obstruction (35%)

When considering probe selection, flow obstructed by the sensor must be considered on the small scale of the inlet and engine. Significant flow obstruction from one probe may result in erroneous measurements at another. Included in this criteria are also thermal effects on the flow from a sensor.

5.3.2 Accuracy (20%)

When selecting between different sensor types, the accuracy of the method being used is very important. Given the complexity of the fundamental problem in this project, collection of accurate data becomes more critical. Accuracy is determined by propagating the error of a typical sensor through the required calculations, for example, the uncertainty of a pressure transducer for use with pressure probes.

5.3.3 Pertinence to Iterative Design Approach (20%)

This criteria of the trade study concerns itself with the application of the data recorded with a given sensor to the project's iterative design approach. It is based on how quickly and easily conclusions about the current design can be made from the data the sensor provides and adapted into a new iteration.

5.3.4 Integration Complexity (15%)

Varying with the sensor type, dimensions and intended use, the integration of the sensors will also be a factor that must be considered. Integration of a kiel probe into the flow at various locations will increase the design complexity over the integration of static taps. Additionally, this criteria considers the ease of adaptability of the methodology and sensors to a new inlet design.

5.3.5 Cost (10%)

As the team is limited by a budget, cost considerations are essential, however, as the sensor measurements will be the primary indicators of inlet performance, the cost of sensors will be secondary to their usefulness to the iterative design approach and most other important qualities and criteria mentioned above.

5.3.6 Trade Matrix

Criteria	1	2	3	4	5
Flow Obstruction (35%)	The probe obstructs 20% or more of the inlet area	The probe obstructs 15% of the inlet area	The probe obstructs 10% of the inlet area	The probe obstructs 5% of the inlet area	The probe obstructs 0% of the inlet area
Accuracy (20%)	Propagated error less than or equal to 5% for total pressure	Propagated error less than or equal to 4% for total pressure	Propagated error less than or equal to 3% for total pressure	Propagated error less than or equal to 2% for total pressure	Propagated error less than or equal to 1% for total pressure
Pertinence (20%)	No further design relevant data can be obtained from measurements	Data requires processing and design changes are based upon many assumptions	Data requires processing and allows for some identification of design changes	Data requires processing but allows for improvement to design iterations	Data allows for easy identification of design concerns
Complexity (15%)	Sensors are highly complex, difficult to implement and utilize for testing	Sensors are somewhat complex and have significant difficulty being integrated into the test apparatus	Sensors are easy to use but have significant difficulty being integrated into the test apparatus	Sensors are easy to use but have slight difficulty being integrated into the test apparatus	Sensors are easily assembled, mounted and require minimal setup for testing
Cost (10%)	> $500	> $250	> $100	> $50	< $50

5.3.7 Total Pressure Measurement Trade Study

Factor	Weight	Pitot Probe	Kiel Probe	Static Ports	Anemometer	Hot Wire A.meter
Obstruction	0.35	4.6	3.6	5	1	3.4
Accuracy	0.20	5	5	4	5	1
Pertinence	0.20	5	5	4	3	4
Complexity	0.15	4	4	5	3	4
Cost	0.10	4	2	5	4	3
Weighted Totals		4.61	4.06	4.6	2.8	3.09

5.4 Evaluation Criteria for Sensor Utilization Trade Study

5.4.1 Effect on Flow (30%)

Similarly to the Flow Obstruction criteria above, this criteria considers the effect on the flow of the sensor placement and utilization. This considers both sensors placed in the flow as well as other factors with possible influences on the flow such as mounting mechanisms.

5.4.2 Manufacturing Complexity (20%)

The complexity of the systems being manufactured for this section are of importance to consider. With the dependence on physical testing for this project, there is a need for testing to commence early in the overall schedule. This timeline will greatly favor sensors that can be easily manufactured leading to a small turnaround time and readiness for testing in as little time as possible.

5.4.3 Sensor's Effective Inlet Coverage (20%)

This parameter is an estimate by the team of how much interior coverage each of the different sensor utilization methods can effectively provide good data for the inlet. The scoring is based upon the coverage that can be obtained from each method while taking into account locations and movement capability of sensors without modification to the manufactured test inlet.

5.4.4 Adaptability (30%)

The main focus of this parameter is the ease of transferring sensors from one inlet to another. Many different iterations of inlets will need to have sensors attached throughout the testing phase. Sensors that are more adaptable and easier to install will be favored due to the high changeout rate.

5.4.5 Trade Matrix

Criteria	1	2	3	4	5
Effect on Flow (30%)	Nominal inlet flow heavily affected, data is not representative of inlet performance	Large deviations from nominal flow, data is unlikely to be representative	Some deviations from nominal flow, data may not be representative	Minimal deviations from nominal flow, data is representative of nominal flow	Nominal inlet flow is unaffected
Manufacturing Complexity (20%)	Extreme amount of manufacturing necessary. 2 months and beyond to have sensors fully functioning and ready	Considerable amount of manufacturing necessary. 2 weeks to 2 months to have sensors fully functioning and ready	Fair amount of manufacturing necessary. A few days to 2 weeks to have sensors fully functioning and ready	Little manufacturing necessary. Sensors are ready for testing within a few days	No manufacturing necessary. Sensors are ready for testing immediately
Inlet Coverage (20%)	Sensors can effectively survey and collect data from less than 30 percent of the inlet	Sensors can effectively survey and collect data from 30 to 50 percent of the inlet	Sensors can effectively survey and collect data from 50 to 70 percent of the inlet	Sensors can effectively survey and collect data from 70 to 90 percent of the inlet	Sensors can effectively survey and collect data from more than 90 percent of the inlet
Adaptability (30%)	Sensors and mounting systems cannot be adapted to new designs	Complications will occur adapting to new design, concerns may not be resolvable	Complications may occur adapting to new design, concerns are resolvable	Minor easily resolvable concerns transferring to new design	Sensors can easily be adapted for new design

5.4.6 Sensor Utilization Trade Study

Factor	Weight	Slotted Inlet Concept	Inlet Sectioning Concept	Discrete Locations
Effect on Flow	0.30	4	3	5
Manufacturing Complexity	0.20	3	3	4
Inlet Coverage	0.20	5	3	1
Adaptability	0.30	4	3	4
Weighted Totals		4	3	3.7

5.5 Mass Flow Surrogate

5.5.1 Previous Experience (10%)

When considering the mass flow surrogate selection, the team's previous hardware experience is an important factor to consider. With the challenges associated with internal flows, there will already be several different sources of error and uncertainty inherent with the nature of the problem. By utilizing hardware that the team is already familiar with, any potential sources of error introduced due to the lack of operational knowledge and experience will be minimized. Additionally, familiar hardware will help the team to stay on schedule and minimise unwelcome surprises.

5.5.2 Availability for Testing (30%)

Physical testing of the inlet will be a key component to this project. This will be the main means in which models will be validated, and much of the data on the performance of the inlet will be collected. Multiple inlets will need to be tested through various iterations of tests, many of which will be measuring different parameters. Many tests will need to be conducted throughout the lifespan of this project, all needing a surrogate source of mass flow. The magnitude of testing which needs to be completed makes hardware/test facility availability crucial to this project.

5.5.3 Test Duration (10%)

As mentioned above, many inlets will be put through a barrage of tests measuring many different parameters. The duration of the test is important as a longer test will allow for more data to be collected at one time, minimising experimental errors. Longer tests also lead to fewer tests needing to be performed increasing efficiency and decreasing testing time and expense.

5.5.4 Mass Flow Control/Tuning (20%)

Having the ability to precisely control the mass flow through the test section is critical for the validation, evaluation, and data collection of the inlet. The surrogate mass flow is simulating the effects that the JetCat turbine engine will have on the inlet. Higher fidelity control of the simulated mass flow will only increase the accuracy of the inlet and the overall performance when finally attached to the JetCat.

5.5.5 Test Turnaround Time (10%)

The two main focuses of this parameter will be dictated by how easy a new inlet will be to integrate with the surrogate and by how much time is needed to reset after a test. These factors are important because when on a tight testing schedule, this "dead" time between testing, if not considered, can be immense and heavily restrict the team's testing ability, efficiency, and overall schedule.

5.5.6 Manufacturing Time (20%)

The build time of the surrogate mass flow source needs to be carefully considered in terms of the overall schedule. With the heavy dependence on physical testing for this project, testing will need to commence early in the overall project schedule. This timing puts a heavy emphasis on the need for a fully functional surrogate source in as little time as possible. To accomplish this the speed of manufacturing and assembly of the surrogate source will be key to the project.

5.5.7 Trade Matrix

Criteria	1	2	3	4	5
Previous Experience (10%)	Team/team members have no experience with the system	Team/team members have used system at least 10 times combined	Team/team members have have used system at least 15 times combined	Team/team members have used system at least 20 times combined	Team/team members have routinely utilized the system (more than 30 times combined)
Availability for Testing (30%)	Rare availability/ high competition for use	With extended notice (weeks in advance)/ moderate competition for use	Notice needed (within a week)/ fair competition for use	Short notice (same day)/ light competition for use	Any time/no competition for use
Test Duration (10%)	Test can only be conducted for 10 seconds or less at one time	Test can only be conducted for 11 to 60 seconds at one time	Test can only be conducted for 1 to 3 minutes at one time	Test can only be conducted for 3 to 7 minutes at one time	Test can be conducted for longer than 7 minutes at one time
Mass Flow Control/Tuning (20%)	No means to change/alter mass flow	Mass flow can be changed and altered with significant inconveniences and effort	Mass flow can be changed and altered with inconveniences and moderate effort	Mass flow can be changed and altered with little inconvenience and light effort	Mass flow can be changed and altered with no inconvenience and no effort
Test Turnaround Time (10%)	Delay greater than 1 day between tests	Delay between 1 day and 5 hours between tests	Delay between 5 and 1 hour between tests	No more than 1 hour between tests	No delay between tests
Manufacturing Time (20%)	2 months and beyond to have fully functioning and ready	2 weeks to 2 months to have fully functioning and ready	A few days to 2 weeks to have fully functioning and ready	Fully functioning and ready for testing within a few days	Fully functioning and ready for testing immediately

5.5.8 Mass Flow Surrogate Trade Study

Factor	Weight	Air Tank System	Wind Tunnel	Electric Ducted Fan
Previous Experience	0.10	1	4	5
Availability for Testing	0.30	5	2	5
Test Duration	0.10	3	5	4
Mass Flow Control/Tuning	0.20	3	5	5
Test Turnaround Time	0.10	3	4	4
Manufacturing Time	0.20	2	5	3
Weighted Totals		3.2	3.9	4.4

6 Selection of Baseline Design

6.1 Inlet Baseline Design

A trade study performed on several design options for the S-duct inlet led to an evaluation deeper into what a desirable characteristic meant to the team. The trade matrix outlined for the duct included evaluation criteria such as anticipated pressure loss, anticipated pressure distortion, ease of simulation, ease of manufacturing, and general, technical complexity. The design options analyzed were passive vs. active flow control system, inlet shape and cross sectional design, length of ducted inlet, and the area ratio of the entrance inlet to exit of the inlet. The results were more than useful in choosing a design which best fit the team's needs, priorities, and most importantly, the customer's design requirements.

When assessing the type of flow control system, either passive or active, it was determined that although the active system would most likely have better total pressure recovery and less distortion, the overall complexity and difficulty manufacturing and implementing would outweigh the benefits, and could possibly be a breeding ground for problems downstream. Utilization of a passive flow control system would allow the team to take advantage of certain geometry within the inlet and possible vortex generators to minimize flow losses instead of complex moving parts and added mechanisms which could hinder progress in other areas of the project.

In terms of inlet cross section, a circular inlet which has an aspect ratio equal to 1 would be ideal for simulation purposes and manufacturing purposes. With regards to physical length of the inlet, although a shorter inlet would grant the team more points by AFRL, a longer inlet would lead to less flow losses and pressure distortions due to smoother turns inside the duct itself, another AFRL scored criteria. It was determined that a slightly longer duct would be more beneficial than a slightly shorter duct, but a Monte-Carlo analysis would better provide an exact numerical length.

When discussing area ratio and whether a converging or diverging inlet would be chosen, the conditions for converging inlet would be ideal for smaller flow speeds and provide enough mass flow for critical engine performance, while a diverging inlet would help to simulate a real-life UAV application at higher flow speeds. For this issue, it was decided that a converging-diverging duct would be assessed in the trade study versus a simple diverging duct to compare performance and design requirements. It was found that a converging-diverging inlet is necessary in order to speed up flow to minimize losses throughout the duct and also to slow the flow before the engine entrance to maximize performance. Not only would this help to minimize losses compared to a diverging duct, but it would also provide a more favorable cross sectional pressure distortion.

6.2 Testing Apparatus Baseline Configuration

Sections 5.3 to 5.5 focus on comparing and contrasting the different aspects of the testing apparatus through various trade studies. These trade studies were broken down into a total pressure measurement study (5.3), a sensor utilization study (5.4), and a mass flow surrogate study (5.5). These different studies were used to decide the approaches that will be further investigated for the testing apparatus.

From the total pressure measurement trade study, a combination of the pitot tube and an array of static ports were selected for further investigation as their final weighted scores were nearly identical. The static ports provide the most simple and least obstructive way of measuring the mean total pressure along the length of the inlet, however, they are not capable of providing a reliable estimate of the total pressure distribution across the face of the engine and they require an area ratio which is not equal to zero in order to measure the total pressure. The pitot probe, on the other hand, is a reliable instrument for directly measuring the total pressure with very low flow obstruction. The main downside of the pitot probe is some additional complexity that comes from having to move the probe between measurement locations whether that is through a slot or at various discrete locations. As the pitot and kiel probe operate on the highly similar theoretical assumptions and models and provide minute advantages and disadvantages in different situations, both will be considered as pressure sensors to test non-surface flow structure within the inlet and will be further investigated.

From the sensor utilization trade study, the slotted inlet and the discrete location concepts were both chosen to be further investigated as their final weighted scores were similar. The main strength of the slotted inlet is its ability to provide data at nearly any point within the inlet (primarily focusing on points away from the walls due to boundary layer effects) with minimal disruption of the flow. However, this concept suffers from a slightly increased complexity in manufacturing. Manufacturing complexity is the second concept's main strength as it simply uses various sensors at discrete locations along the inlet walls that will have minimal effect on the flow. The downside to the discrete location concept is that much of the data will only be accurate near the walls. Because of this, these concepts may be used in conjunction with each other as they provide data where the other cannot.

In the mass flow surrogate trade study, the Electric Ducted Fan (EDF) approach was selected with the highest score. This approach will provide the most amount of control over scheduling and control over actual testing parameters while still providing a reasonable testing and manufacturing time. Finally, the fuel flow (which is needed to calculate the thrust specific fuel consumption) and the thrust of the JetCat turbine engine will also need to be measured. To measure thrust load cells were selected and to measure fuel flow, Equflow disposable flow sensors were selected. No trade study was performed on these sensors as they are not primary design drivers and they were both provided to us through the University of Colorado's Aerospace Engineering department.

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