Analytical Design of Hypersonic Ramjet Inlets for Space Rapid Transit

Joyce Mo[*,a], Maya Zevensky[a], Ms. Layla Mohsen[a], Shannon Filer[a], Mariana Altomare[a], and Michael Paluszek[a]

[a]*Princeton Satellite Systems, Plainsboro, NJ*
[*]Corresponding author

Abstract

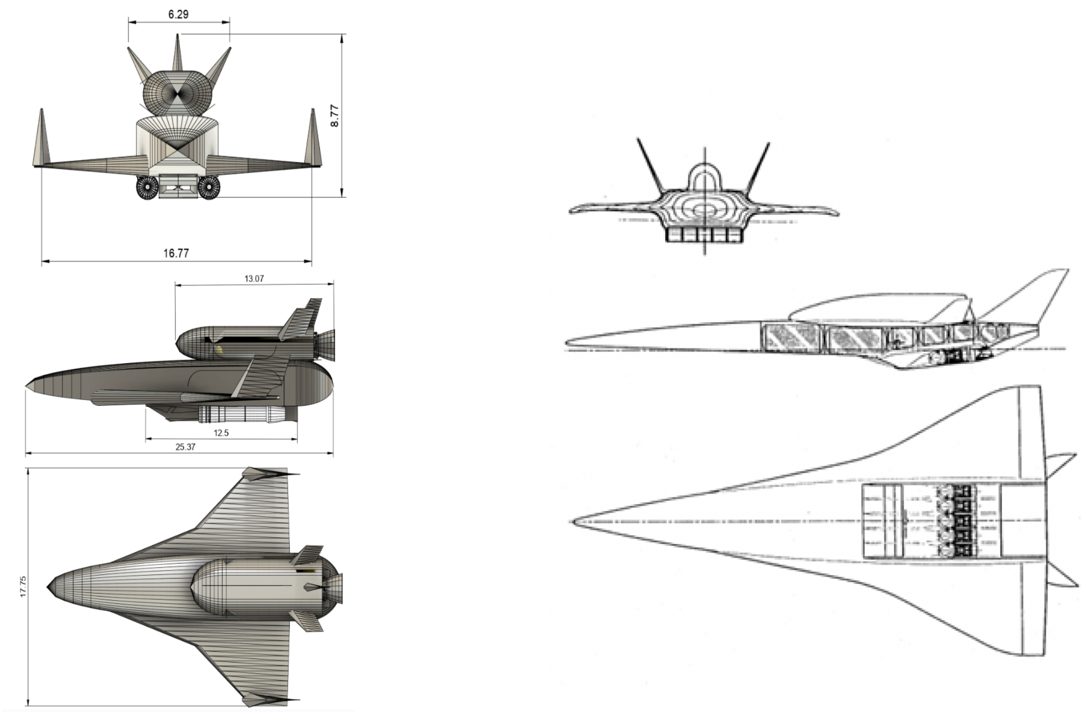
Airbreathing engines have been studied for improving the efficiencies of hypersonic propulsion systems, whereby all the needed oxygen for combustion is captured from the atmosphere as opposed to carried oxidizers. Airbreathing engines include turbojets, ramjets, scramjets, and dual-combustion ramjets. For a hypersonic, two stage to orbit launch vehicle, turbo-ramjets have been proposed for the first stage to reach Mach 6.8, as seen in Germany's Sanger II. Turbo-ramjets have also been flown successfully on the SR-71 Blackbird, which harnessed 2 Pratt & Whitney's F58 turbojets and transitioned to ramjet behavior at Mach 2. Princeton Satellite Systems has been developing a smaller hypersonic, two stage to orbit launch vehicle called Space Rapid Transit for a 500 kg payload to LEO. Space Rapid Transit uses a dual-flow path turbofan-ramjet engine for the first stage to reach Mach 5 and 40 km altitude. This consists of 2 Pratt&Whitney F135 turbofans and 1 ramjet. The turbofans operate on jet fuel. The ramjet is designed for hydrogen fuel and is comprised of an inlet, a combustor, and a nozzle.

For optimal ramjet behavior, the inlet needs to be designed to form a series of oblique shocks to sufficiently compress the air flow to subsonic speeds for combustion in the combustor. As air passes through the inlet, it loses kinetic energy and increases in pressure. As the velocity of the vehicle increases, the oblique shock positions change, leading to off-optimal behavior for the operation envelope of the ramjet. Thus, ramjets are currently limited to Mach 3 to 6. Another challenge of the 2-turbofan and ramjet configuration for Space Rapid Transit is the controlled blocking of the incoming freestream airflow during transitions from the turbofans to the ramjets at Mach 1.2. Insufficient control may lead to inlet upstart, whereby shockwaves are expelled upstream out of the inlet aperture due to instabilities. This paper examines variable inlet geometry to improve upon the pressure recovery ratio of the ramjet inlet through SUPIN.

1. Introduction

Hypersonic aircraft present favorable business cases, enabling hypersonic airliners and horizontal launches to space in a two stage to orbit launch configuration. Some of the advantages of air-breathing engines include higher specific impulse, operations up to 75 km altitudes, and overall lighter mass roll-ups since the oxidizer does not need to be carried.[1] The Sanger II harnessed air-breathing engines for the first stage, designed to reach Mach 6.8 and 31 km altitude.[2] Hypersonic flight has been previously achieved, as seen in NASA's X-43A that flew at Mach 9.68 in the upper atmosphere and Boeing X-51 Waverider that sustained Mach 5.1 for 210 s.[3, 4] The Lockheed SR-71 is another example of a supersonic aircraft that successfully flew. However, at least 2 models of the SR-71 were destroyed due to inlet unstart, shockwaves escaping out of the aperture of the engine inlets. In the case of the SR-71, internal pressure in the J58 turbofans was too great and caused shockwaves to blow out to the aperture.[5] Therefore, the inlet design of any new air-breathing engine configuration must be studied thoroughly before any build process to reduce the risk of failures that drive up cost and time.

Princeton Satellite Systems is developing a new horizontal-takeoff vehicle named Space Rapid Transit (SRT). This vehicle is designed for a 500 kg payload that can reach low Earth orbit (LEO). SRT is a two stage to orbit design, with a first stage called the Ferry and a reusable second stage called the Orbiter. The horizontal takeoff and landing, as well as the small size of the vehicle, would allow for quick refueling and launching from most currently operational airfields around the world without the need for specialized launchpads.[6, 7, 8, 9, 10, 11] The most recent SRT design is composed of two Pratt & Whitney F135 turbofans and one hydrogen-fueled ramjet. In terms of the concept of operations, SRT will start with horizontal takeoff only using the F135 turbofans, followed by hypersonic acceleration using the ramjet to separation altitudes. In this case, the ramjet will be used for only a couple of seconds to reach Mach 5.3.[12]



(a) **(b)**

Figure 1: (a) SRT CAD (b) Sanger II diagrams[13]

Other laboratory-tested hydrogen-fueled ramjets were demonstrated for Mach 3.6.[14] However, air-breathing hydrogen-fueled ramjets have not been fully flight-tested. Renewed interest in ramjets is seen in other commercial entities building or studying ramjets.[15] Ramjets in general consist of 3 main regions: the inlet, combustor, and nozzle. Ramjets use the forward speed of the vehicle to provide air as an oxidizer in the combustor. Ramjets require subsonic conditions within the combustor. One of the most challenging aspects of air-breathing ramjet design is the inlet, which needs to reduce the air velocity to enable subsonic combustion.[1] In this case, our goal is to try to achieve compression of freestream air from Mach 5.3 to below Mach 1 for subsonic combustion, which makes for a more challenging inlet design problem due to the larger difference of compression required to achieve the larger change. For this study, we examine potential inlet designs to meet the mission objectives of SRT.

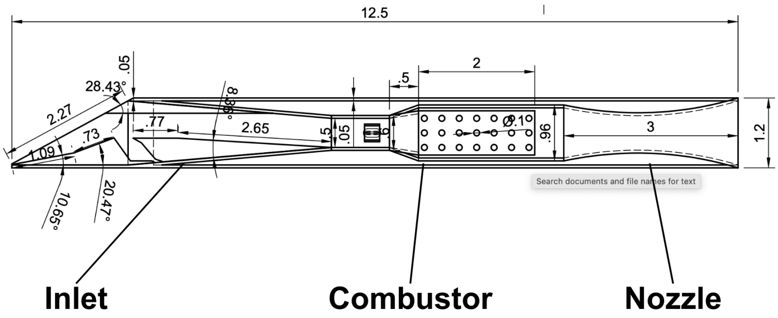


Figure 2: Overview of major ramjet components, units in meters.

1.1 Mission Objectives

The trajectory of Space Rapid Transit from takeoff to 350 km is shown.[12]

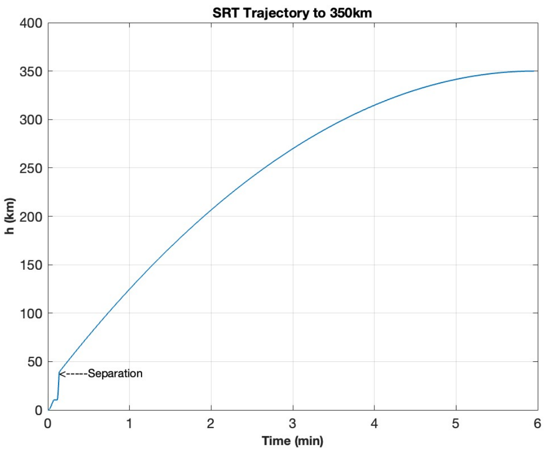


Table 1: (b) Ramjet Requirements

Parameter	Value
Flight Conditions	
Angle of Attack	3.46°
Altitude	40 km
Engine Parameters	
Combustor Length	1.2 m
Combustor Width	2.4 m
Combustor Shape	Rectangular
Combustion Mach Number	0.38

Figure 3: SRT to 350 km altitudes and associated table of ramjet freestream conditions during SRT's operation.

Based on the trajectory, the highest Mach number that the ramjet would need to reach is Mach 5.3 in order to achieve the desired separation altitude of 40 km. At this altitude, the freestream conditions that the ramjet inlet needs to be designed for are shown in Table 1. Another requirement is a total pressure recovery greater than 46%, in line with the U.S. military specification MIL-E-5007E.[5, 16]. The pressure recovery of the inlet is also correlated with the engine efficiency. In general, a 1.5% loss in engine thrust can be assumed for each 1% loss in total pressure.[17] The 0.38 Mach number for combustion was selected based on a general rule of thumb for subsonic combustion:[18]

$$\frac{M_{EF}}{M_{FS}} = \sqrt{\frac{T_{FS}}{T_{EF}}} \approx \sqrt{\frac{400}{2800}} \approx 0.38 \tag{1}$$

For supersonic inlets in general, the use of ramps and conical forebodies extended ahead of the internal duct of the inlet is used to create oblique shock and Mach waves to decelerate the air flow.[5] We examine designs that harness a 2D flow path with a mixed-compression inlet. The first design has a rectangular inlet face with a three-ramp configuration, and the second design is an axisymmetric spike inlet with a circular cross-sectional combustor. Both inlet types have been successful in supersonic laboratory demonstrations or have been flight-tested on other aircraft and engine types.

1.2 Axisymmetric Spike Inlets

Early ramjet and turbo-ramjet development in the 1950s–1970s made extensive use of axisymmetric spike inlets, as seen from supersonic wind tunnel research and flight-test programs.[19] These designs featured a central conical or ogive spike placed ahead of the inlet cowl, which generated an oblique shock system to slow and compress the incoming supersonic airstream. By adjusting spike position axially, designers could match the shock structure to the freestream Mach number, minimizing spillage drag and ensuring stable inlet operation. Flight programs such as the SR-71 employed translating axisymmetric spikes to achieve controlled shock positioning across Mach 2 to 3 flight regimes.[5]

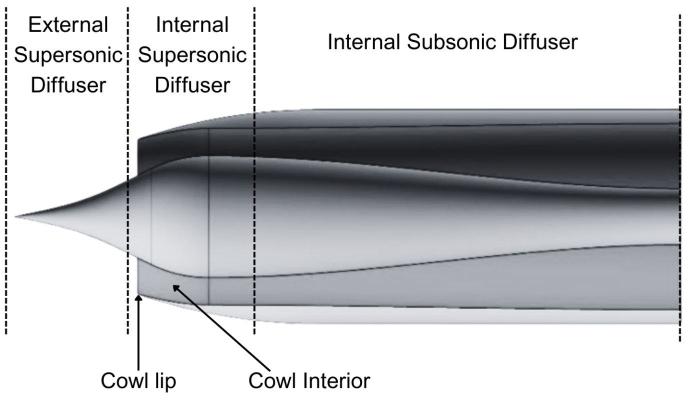


Figure 4: Overview of an axisymmetric spike inlet

Circular inlets are naturally compatible with axisymmetric spike or pitot designs, which generate a radially symmetric system of oblique shocks. This symmetry simplifies structural loads and provides good pressure recovery across a wide range of angles of attack. Circular inlets also integrate well with round nacelles and fuselage pods, as used in turbojet afterburning fighters.

1.3 2D Mixed-Compression Inlets

A mixed compression inlet combines external compression by ramped oblique shocks with internal compression inside an isolator region. This balance allowed higher total pressure recovery than pure external-compression inlets, while avoiding the excessive length, weight, and thermal loads associated with fully internal compression systems. They can be designed to integrate with either circular or rectangular combustors. Rectangular inlet faces have been used in supersonic flight since Concorde in 1969. Concorde was designed for Mach 2.0 and utilized two square ramjet intakes. The pressure recovery at Mach 2.0 was 95%, where most of the pressure loss was on the final of three ramps with a strong, oblique shock. The Concorde ran successfully until 2000, when a passenger jet fatally crashed due to a piece of metal debris on the runway. The program was discontinued in 2003.[20, 21]

Another successful rectangular inlet was used on the North America XB-70 Valkyrie. Valkyrie flew at Mach 3.0 at an altitude of 70,000 feet for a total of 92 hours of flight time.[22] While rectangular inlets are not as widely used as coaxial or axisymmetric inlets, rectangular inlets, such as the Concorde, were used because they were mechanically simple and robust.

2. Inlet Design Considerations

For any inlet, there are 2 main requirements:

1. Bring the inlet flow to the engine to the highest possible stagnation pressure, measured by Inlet Pressure Recovery π_d.
2. Provide the required engine mass flow rate, which can be limited by choking of the inlet.

Supersonic and hypersonic flight speeds have an added requirement of bringing compression as close to isentropic as possible. Metrics to analyze an engine inlet include the mass flow rate balance. The inlet capture flow rate W_L at cross section L can be approximated as

$$W_L = A_L \frac{P_{tl}}{\sqrt{T_{tl}}} \phi_L$$

A_L is the cross-sectional area, P_{tl} and T_{tl} are the averaged pressure and temperature at the cross section, and ϕ_L is the flow function expressed as

$$\phi = M \sqrt{\frac{\gamma}{R}(1 + \frac{\gamma - 1}{2} M^2)^{-(\gamma+1)/2(\gamma-1)}}$$

γ is the ratio of specific heats, R is the universal gas constant, and M is the Mach number. The adiabatic compression efficiency based on enthalpy is also considered, where

$$\eta_c = \frac{h_{L_{final}} - h_x}{h_{L_{final}} - h_L}$$

3. Design Method

3.1 MATLAB

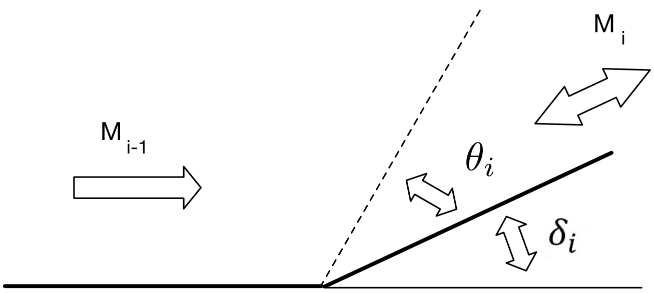


Figure 5: Oblique shock over a ramp.

Ramp angles were selected with Oswatitch's criterion in consideration. The Oswatitch criterion states that maximum shock pressure recovery is obtained when the shocks are of equal strength.[**?**]

$$M_{i-1} sin\theta_i = C \tag{2}$$

where C is a constant, θ is the angle as labeled in figure **??**, and M_{i-1} is the upstream Mach number. We first used MATLAB and oblique shock relations to assess potential ramp angles to use in the external supersonic compression region of the inlets to maximize pressure recovery.

3.2 Sizing and Aerodynamic Analysis

We used NASA SUPIN (Supersonic Inlet Design and Analysis Tool) to generate geometry files (.xyz and .stl) of inlets with input parameters, such as the ramp angles, engine face size, upstream and downstream Mach numbers. We also used SUPIN to assess an initial inlet capture flow rate balance, pressure ratio, Mach number, and temperature along averaged cross-sections along the inlet. This is under the assumption of quasi-1D flow, whereby the area of the passage varies along cross sections through the inlet flow path. Some methods, such as for oblique shock waves and the method of characteristics, use planar geometry assumptions. SUPIN also assumes a perfect gas, allowing for intermolecular forces to be neglected, and a calorically perfect gas. For this study, the expected freestream air temperatures are not to exceed 1800°R.

For both the axisymmetric spike and mixed-compression inlets, we examined the method of characteristics solution for the internal subsonic diffuser. The method of characteristics is a technique to solve a series of partial differential equations by transforming them into ordinary differential equations along "characteristic curves". In particular, we examined the variation of the grid. If the characteristic lines are bunched up or overlapping, then that is a sign that the diffuser is too short. The parameters defining the length of the internal supersonic diffuser downstream of the cowl shock were increased incrementally until the grid lines looked straight.[5, 23]

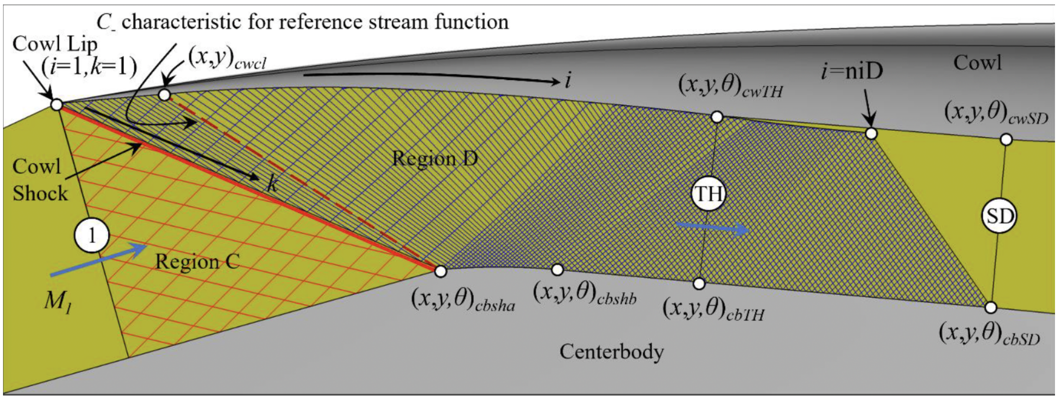


Figure 6: Characteristic net for the supersonic diffuser downstream of the cowl interior shock wave.[5]

4. Results

4.1 Mahoney axisymmetric spike inlet

Overall parameters selected for the cowl lip, exterior, and throat are based on the sample supersonic external-compression axi-spike inlet described in the SUPIN Manual.[5] The external supersonic diffuser consists of 3 stages and an isentropic second stage. The main parameter varied to achieve a total pressure recovery ratio for the axisymmetric spike inlet was the length of the subsonic diffuser. The final length was settled on 3 ft with ramp angles of 10 degrees, 20 degrees, and 20 degrees.

Table 2: Iterations for Inlet Sizing

Iteration	p_2/p_L	**Mach 2**	$\mathbf{A_{cap}}$ **(ft^2)**
1	0.437231	0.406090	147.376831
2	0.482054	0.338736	139.564911
3	0.481696	0.380340	153.872559
4	0.481650	0.380044	153.758255
5	0.481646	0.380004	153.743622
6	0.481647	0.380000	153.742493

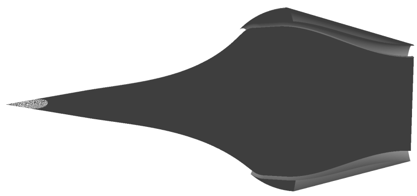


Figure 7: Axisymmetric spike inlet CAD.

The resulting flow rates, pressure recovery ratios, and temperature ratios within the finalized axisymmetric spike inlet are shown below. Station L is the local flow station immediately upstream of the start of the inlet. EX is the flow at the end of the external supersonic compressor. NS represents the conditions immediately downstream of the terminal shock wave. Station 1 is the start of the internal ducting of the inlet, referred to as the cowl lip. Station TH is the geometric throat, station SD is the start of the subsonic diffuser, and station 2 represents the combustor.

Table 3: Flow, Pressure, and Temperature Data at Various Stations

Station	**Flow (lbm/s)**	$W/W_{\mathbf{cap}}$	**Mach**	p_t/p_L	p/p_L	T/T_L
L	209.16045	1.00000	5.30000	1.00000	1.00000	1.00000
EX	209.16045	1.00000	2.52000	0.98758	41.78036	2.91532
NS	209.16077	1.00000	0.51109	0.48495	302.57870	6.28943
1	209.16077	1.00000	0.51109	0.48495	302.57858	6.28942
TH	209.16074	1.00000	0.50849	0.48476	302.99136	6.29260
SD	209.16075	1.00000	0.50898	0.48443	302.68326	6.29200
2	209.16075	1.00000	0.38000	0.48165	325.08447	6.43224

The overall efficiency of the final inlet to meet the design objectives is below. Overall, the inlet achieves a total pressure recovery ratio of 48.16 % with kinematic and adiabatic compression efficiencies of over 95.7%. The length of the whole inlet is 13.25 m, with most of the length designated to the external supersonic diffuser for compression.

Table 4: Inlet Efficiency Parameters

Parameter	**Value**
Inlet Total Pressure Ratio, p_{t2}/p_L	0.48165
Kinetic Energy Efficiency, η_{KE}	0.95868
Adiabatic Compression Efficiency, η_{C}	0.95727
Static Temperature Ratio, T_2/T_L	6.43224
Static Pressure Ratio, p_2/p_L	325.08447

4.2 Mixed-compression inlet

The inlet follows a 50-50 scheme, with half of the compression achieved by external compression, and the other half is internal within the duct. Similar to the axisymmetric spike inlet, the size of the inlet, particularly the length of the internal supersonic diffuser and Mach numbers at the end of the external supersonic compressor and throat regions, was varied until SUPIN converged. Similar to the axi-symmetric spike inlet, the external supersonic diffuser consists of 3 stages and an isentropic second stage. The parameters selected were a Mach number of 3.8 at the end of the external supersonic diffuser and 2.4 at the throat.

Table 5: Iterations for Inlet Sizing

Iteration	p_2/p_L	**Mach 2**	$\mathbf{A_{cap}}$ **(ft^2)**
1	0.461297	0.430429	247.775238
2	0.452752	0.388683	224.001114
3	0.453149	0.379602	219.851685
4	0.453156	0.379995	220.044601
5	0.453156	0.380003	220.047852

The final mixed-compression inlet is shown in figure **??**. The labeled stations are similar to the axisymmetric spike, with an added region called "IN" denoting the end of the internal supersonic diffuser.

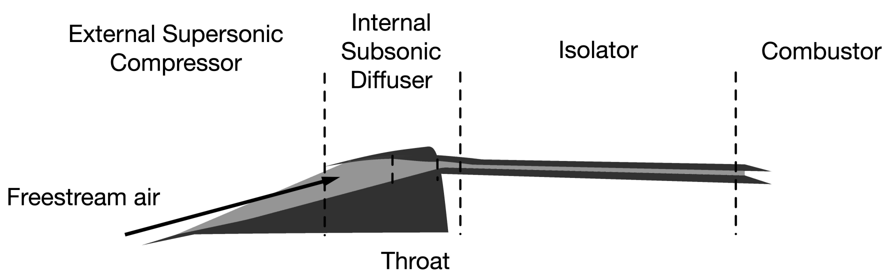


Figure 8: Final 2D mixed-compression inlet designed for SRT.

The performance metrics of the final 2D mixed-compression inlet along different regions are below.

Table 6: Flow, Pressure, and Temperature Data at Various Stations

Station	Flow (lbm/s)	$W/W_{\mathbf{cap}}$	Mach	p_t/p_L	p/p_L	T/T_L
L	437.72824	1.00000	5.00000	1.00000	1.00000	1.00000
EX	437.72824	1.00000	3.80000	0.87248	3.98331	1.54321
1	437.73013	1.00000	3.80000	0.87248	3.98331	1.54321
TH	437.73019	1.00000	2.40001	0.85265	30.85668	2.78810
IN	—	—	2.40001	0.85265	30.85668	2.78810
NS	437.73013	1.00000	0.52312	0.46055	202.21530	5.68866
SD	420.22095	0.96000	0.48607	0.45664	205.55431	5.72927
2	420.22095	0.96000	0.38000	0.45316	217.01994	5.83158

The total pressure recovery achieved for this design is 45.32 %, with a kinematic energy efficiency of 94.9%, and adiabatic compression efficiency of 94.74%. The overall length of the final mixed-compression inlet is 30 m.

Table 7: Efficiency Parameters

Parameter	Value
Inlet Total Pressure Ratio, p_{t2}/p_L	0.45316
Kinetic Energy Efficiency, η_{KE}	0.94925
Adiabatic Compression Efficiency, η_{C}	0.94748
Static Temperature Ratio, T_2/T_L	5.83158
Static Pressure Ratio, p_2/p_L	217.01994

5. Conclusions

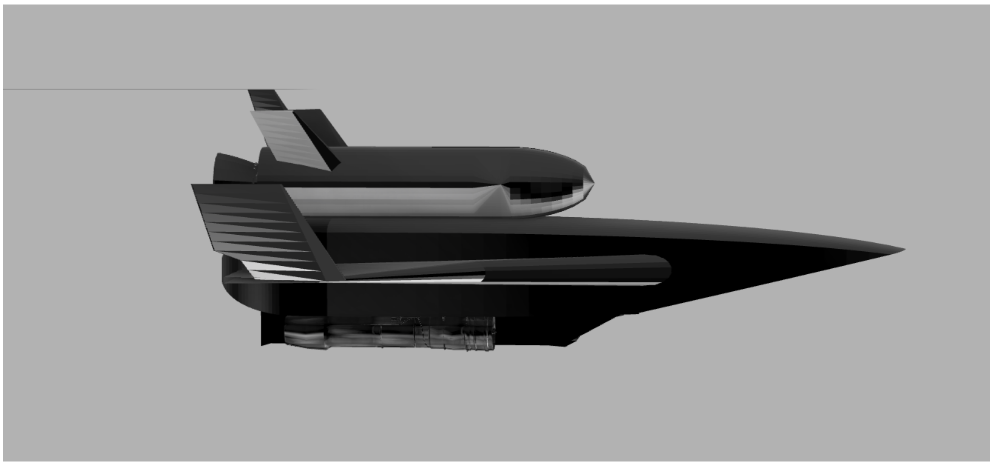


Figure 9: SRT with integrated inlet

This paper analyzes different inlet designs for a ramjet designed for the mission of a two-stage to-orbit launch vehicle. Both an axisymmetric spike and a 50-50 mixed-compression inlet can achieve the 46% desired pressure recovery with differences in overall length and sizes of the inlets. Depending on the density of the material selected, the mass roll-up contributed by the inlets could vary. An average density for carbon composites, a material commonly selected for its heat resistance, is 1.85 g/cc.[24, 25] The selection of the final inlet would depend on the overall mass estimates, integration with aircraft, and drag contributed by the inlet. While the mixed-compression is long, the external supersonic diffuser could be integrated with the forebody of the aircraft, similar to the X-43. The spike provides advantages in improved total pressure recovery without requiring an inlet as long as the mixed-compression inlet. For next steps, a more detailed aerodynamic analysis and computational fluid dynamics to examine localized pressure and temperature distributions would be required. The aerodynamic estimations completed by SUPIN and Wind-US, a hypersonic computational fluid dynamics (CFD) software, suggest that the general parameters analyzed on SUPIN are not drastically different from CFD results, as seen in other papers directly comparing the pressure recovery, Mach, and temperature.[26, 27] However, higher-order accuracy CFD simulations would also provide overviews of more detailed profiles of airflow throughout the entire inlet, rather than the cross-sectional averages at specific parts of the inlet. Another next step is to examine potential subcritical, critical, and supercritical operations of the inlet to ensure that the final geometry selected reduces the risk of inlet unstart. The different components of SRT could be developed in parallel.[12] The ramjet could be tested in hypersonic wind tunnels prior to, or during, the design and prototyping of the rest of the SRT vehicle.

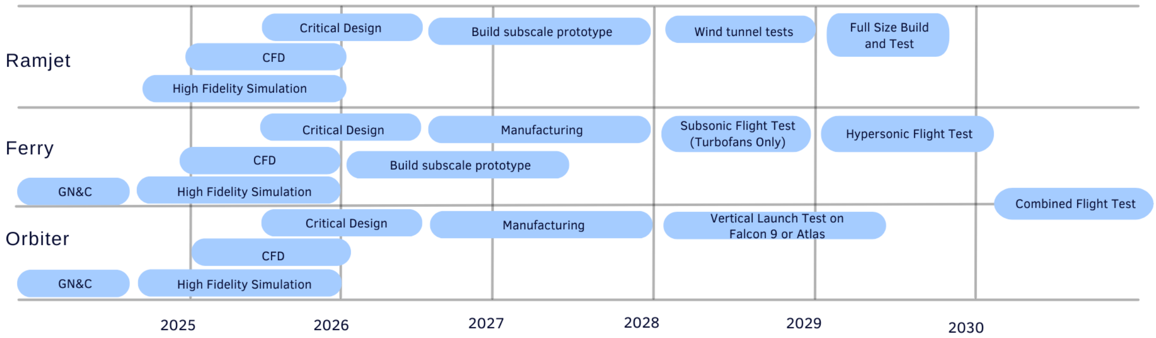


Figure 10: Development timeline for SRT.

6. Acknowledgements

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