The Design and Aero Thermodynamic Analysis of An Inversely Derived Scramjet Configuration

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Presented By
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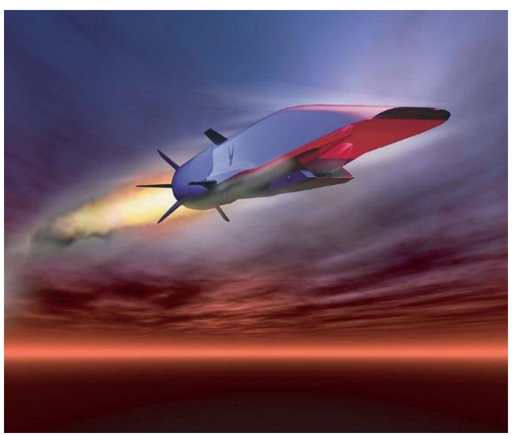
Outline

- Introduction
- Morphing Scramjet Model-Two Phase Approach
  - Phase I: Forebody
    - 2D oblique shock theory
    - 2D - 3D transfer
    - Validation
    - Summary of forebody
  - Phase II: Aft-Body
    - Modified Quasi 1-D tool development
    - Validation of the Quasi 1-D tool
    - Configuration test
    - Configuration results
    - Proof of concept

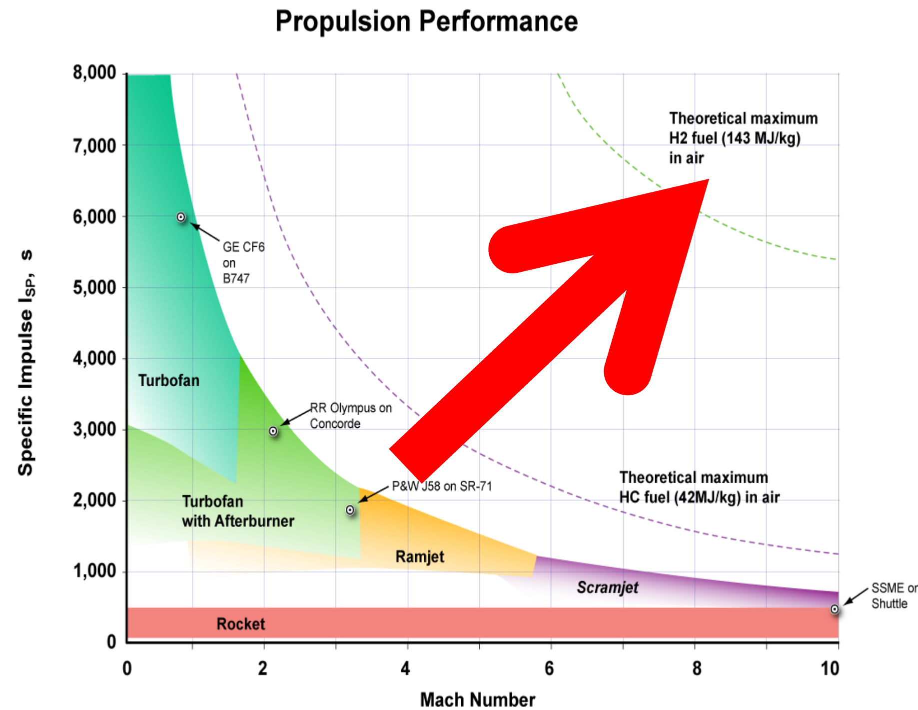
Taking Humans to Space

- US, China, India, Europe are creating & designing concepts
- In US, Several exists, at US Research Agencies & Academia
- Our Concept at NCAT!



NASA - http://antwrp.gsfc.nasa.gov/apod/ap040329.html

NCAT Focus: Optimized Scramjet Engine



By Kashkhan - CC BY-SA 3.0, https://upload.wikimedia.org/wikipedia/commons/4/4f/Specific-impulse-kk-20090105.png

- Higher specific impulse than rocket engines
- Does not need to carry it's own oxidizer
- Potential for high reusability and practicality over rockets

My Research Approach

1. Create A 3D-Shape generator that incorporates

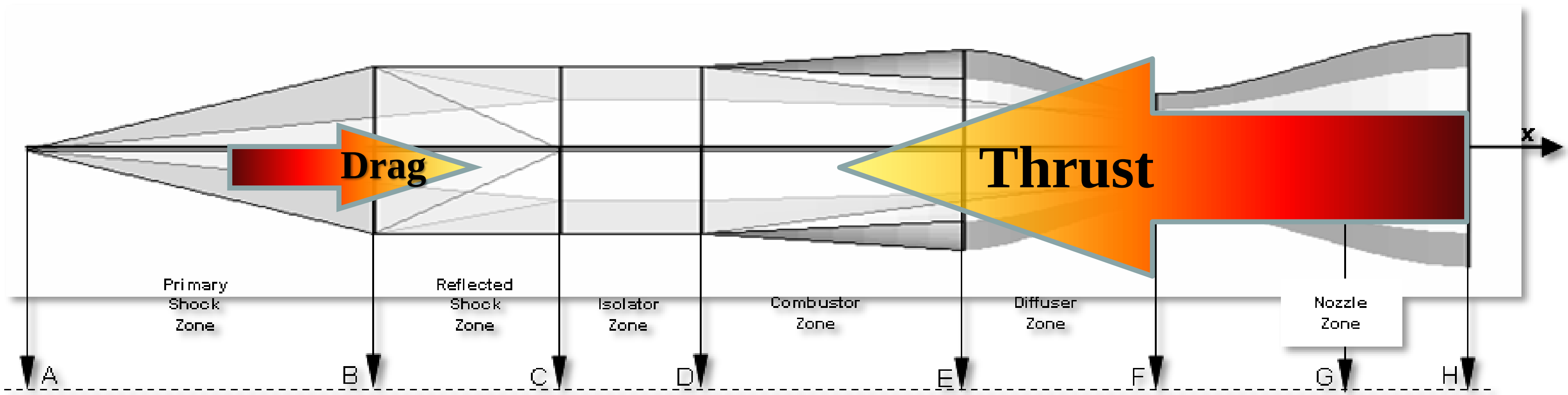
i. Aerodynamically Coupled Forebody: Inlet-Isolator (Mach 3-8)

ii. Oblique, Quasi-1D and Pseudo-Shock/Shock Train Relationships

2. Create An Internal 3D-Shape generator that incorporates

i. Simplified Injector, mixing and combustor models

ii. Quasi-1D (Mach 3 – 8) Aerodynamics/Combustor/Nozzle



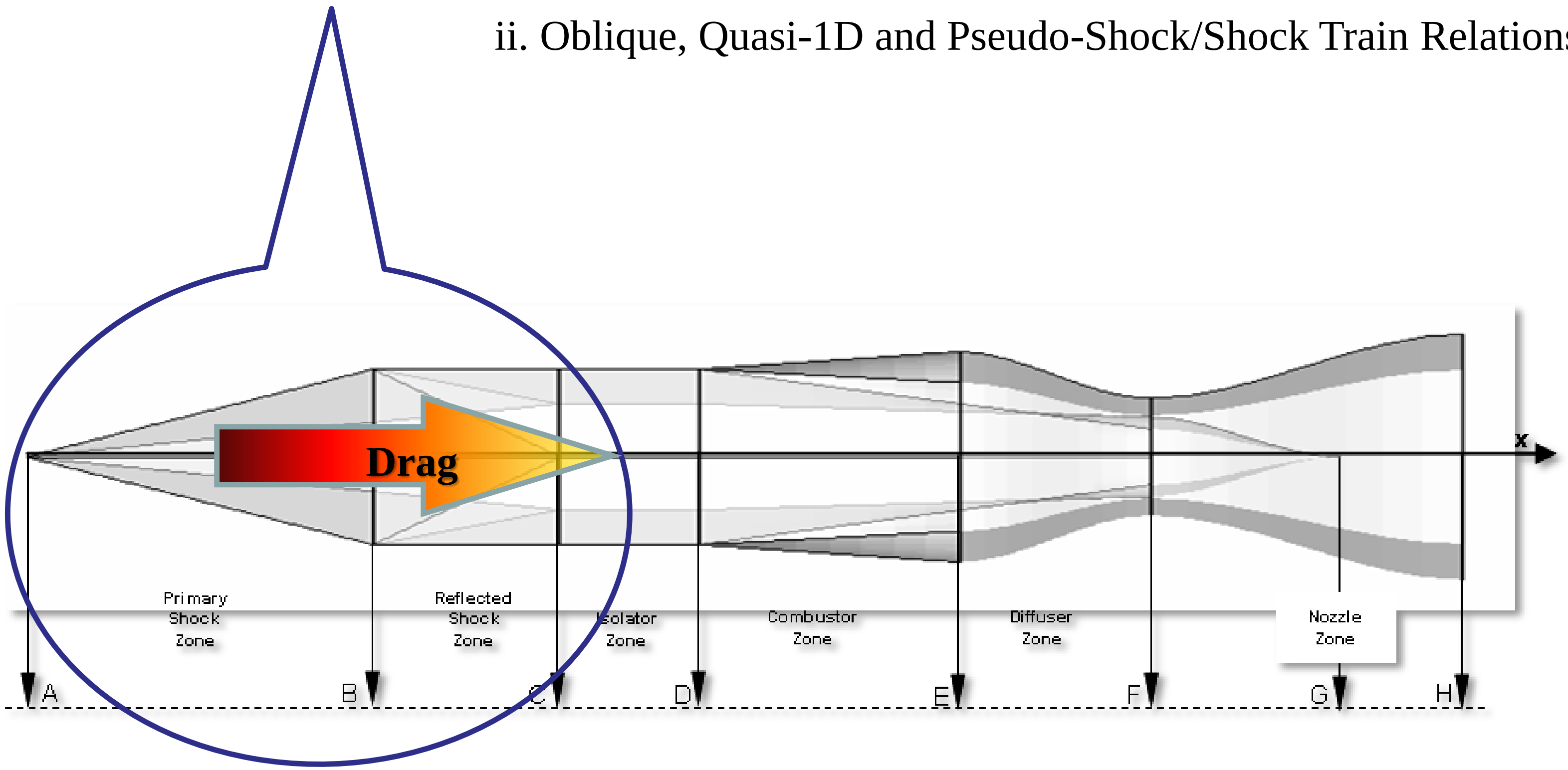
✓ **Optimized for Maximum 'Thrust to Drag' Ratio**

The Conceptual Design Process

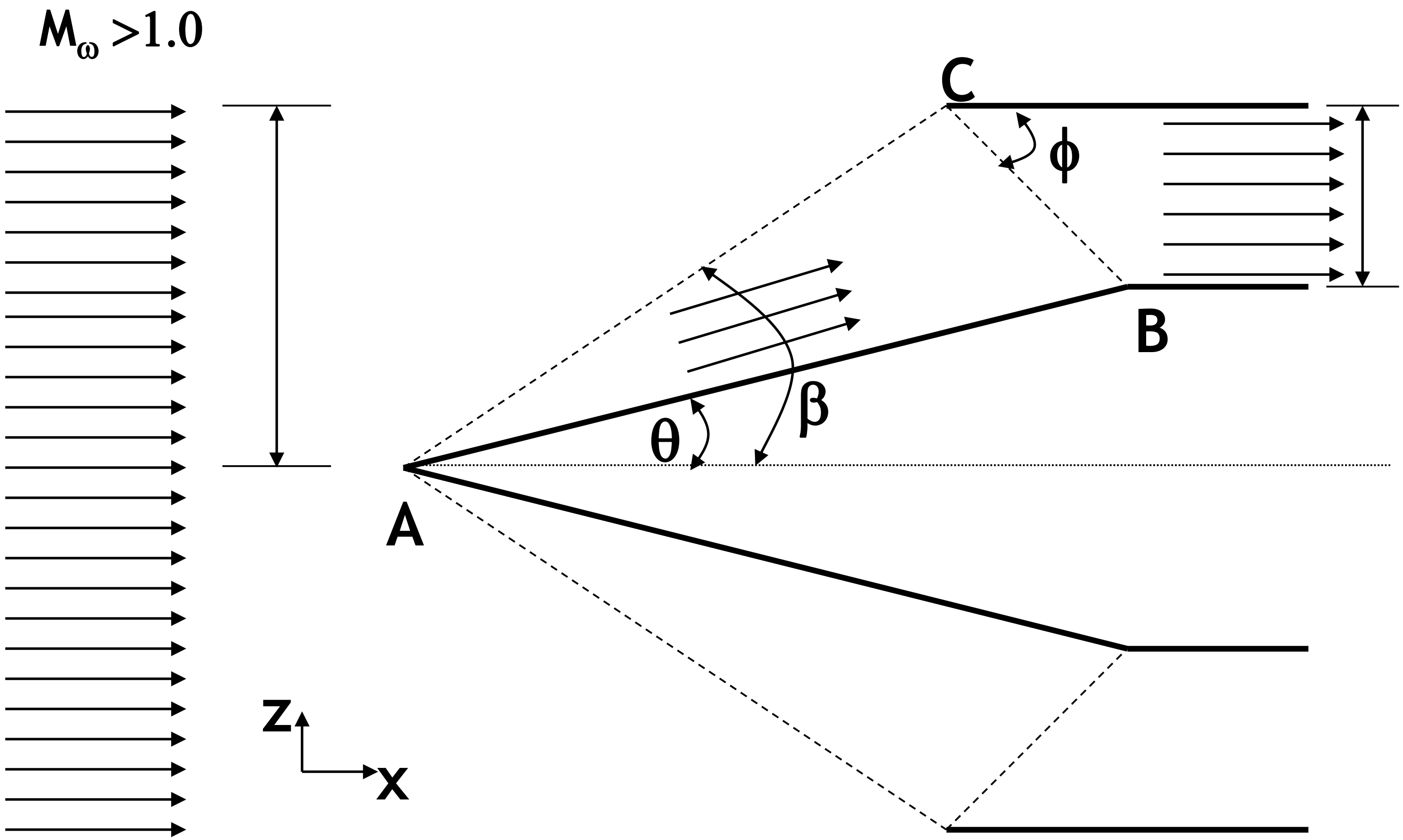
1. Create A 3D-Shape generator that incorporates

i. Aerodynamically Coupled Forebody-Inlet-Isolator (M 3-8**)**

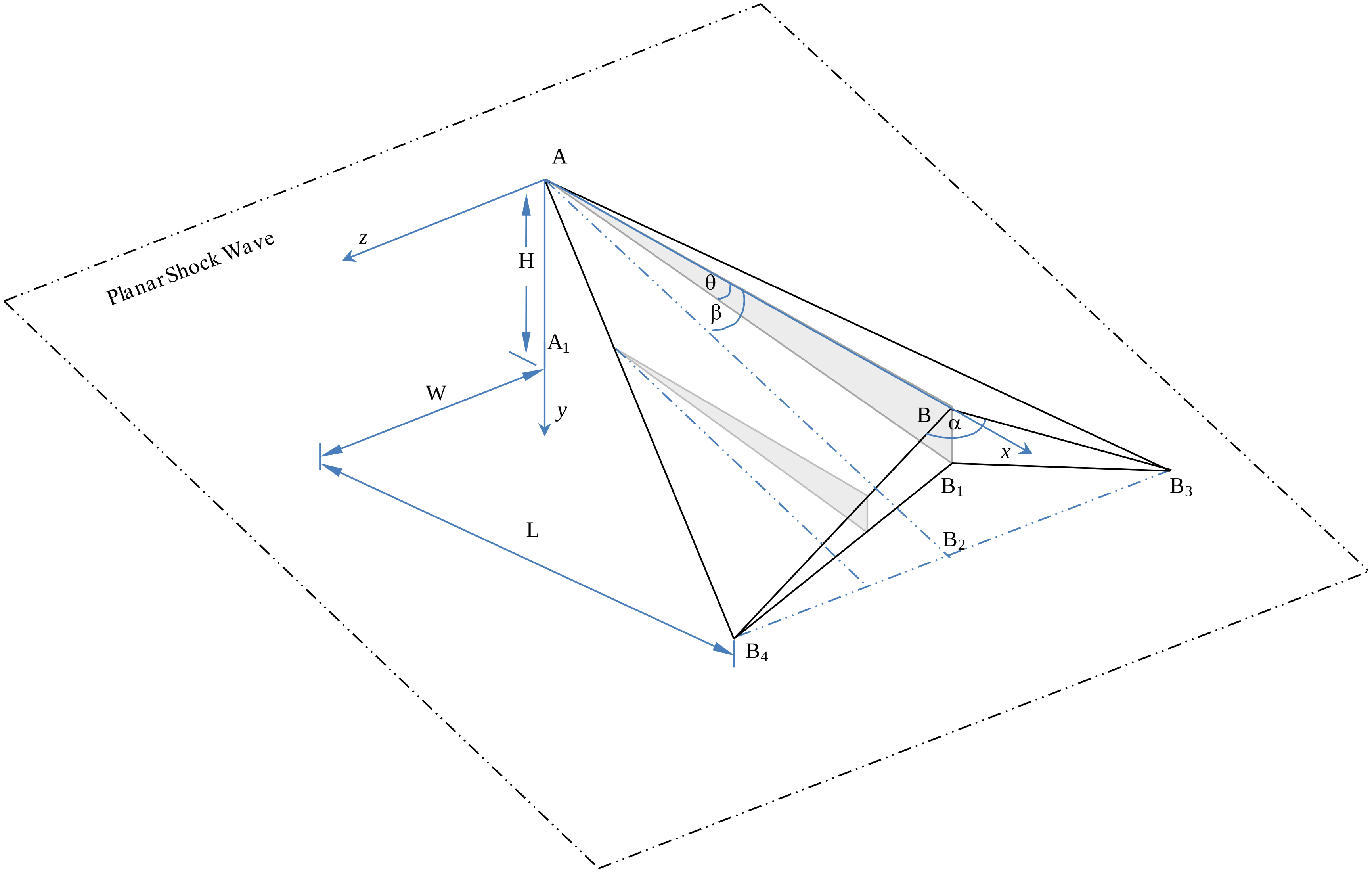
ii. Oblique, Quasi-1D and Pseudo-Shock/Shock Train Relationships



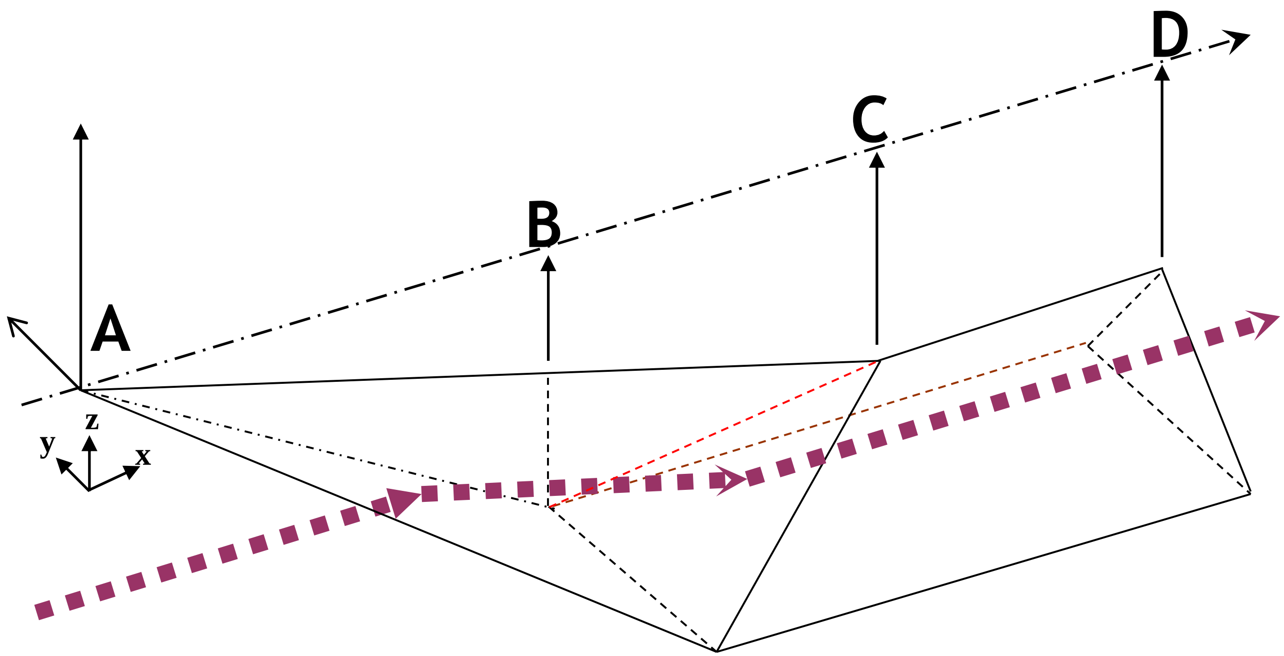
NCAT Inverse Design Method for the Forebody

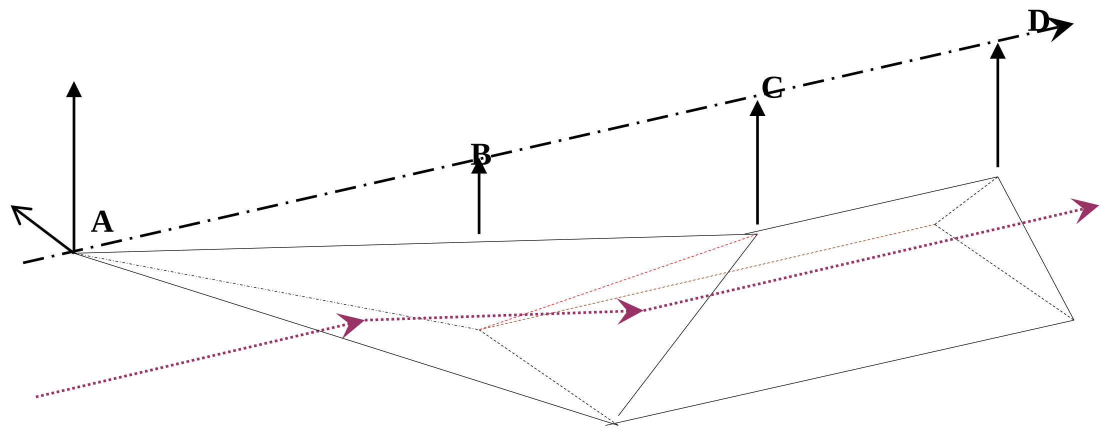


Caret Waverider Design Concept

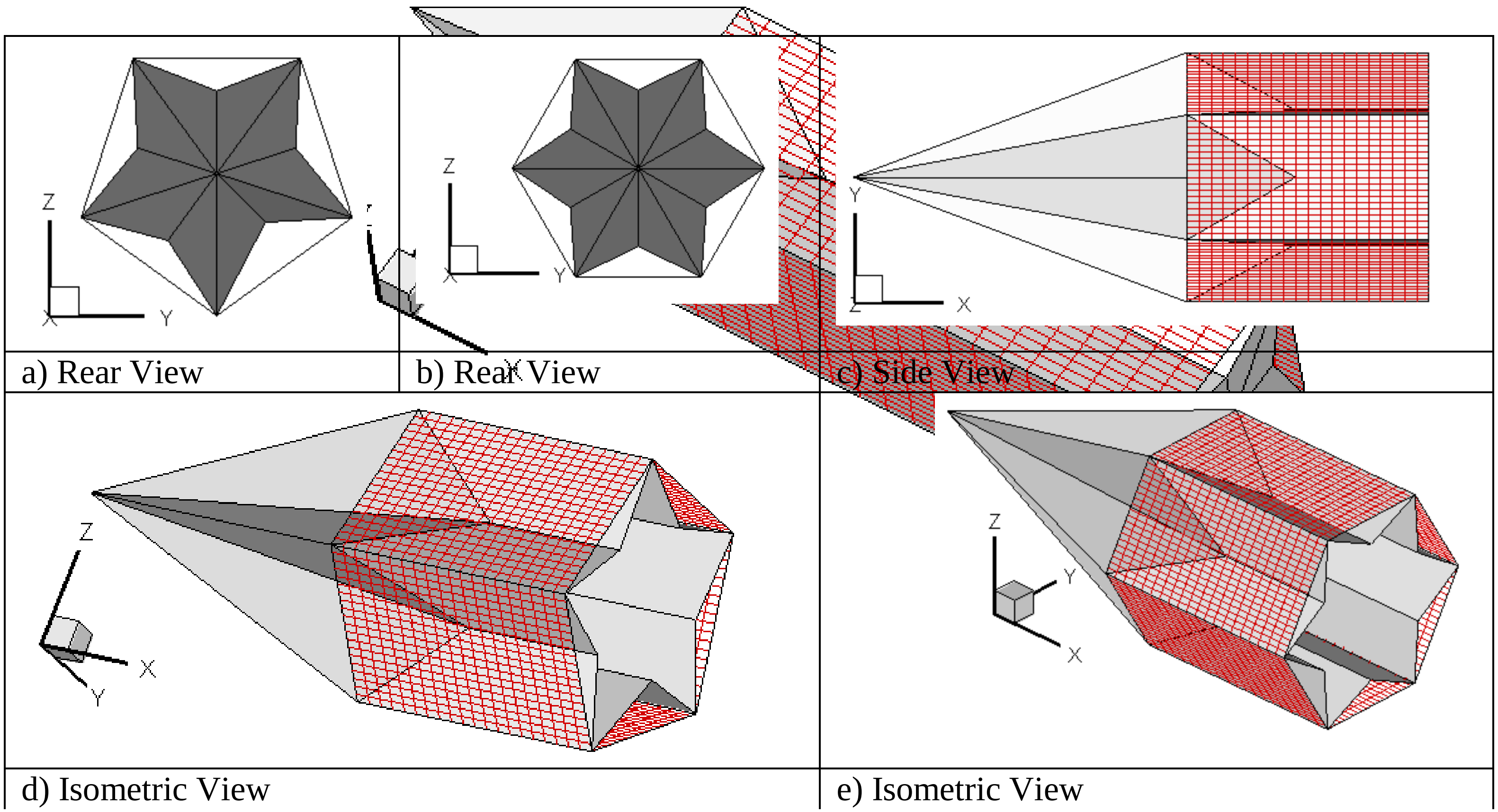


3-D Steam Tube Flow Path





Hypersonic Inlets



a) Rear View

b) Rear View

c) Side View

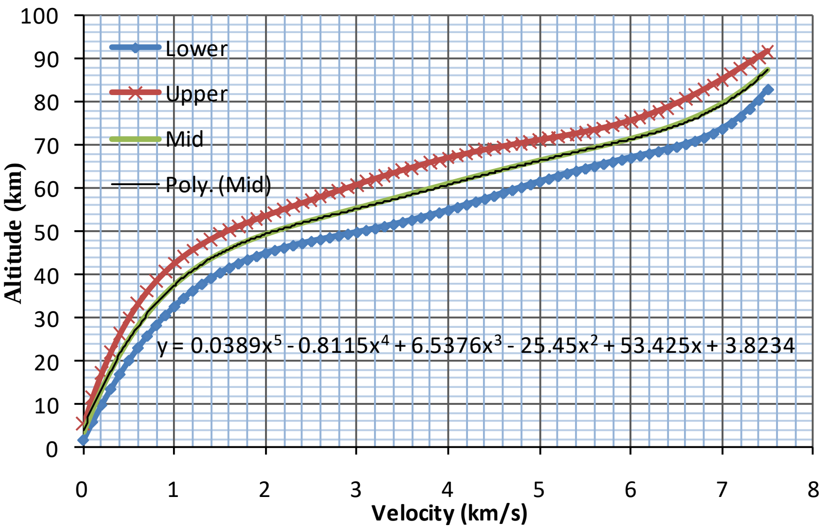
d) Isometric View

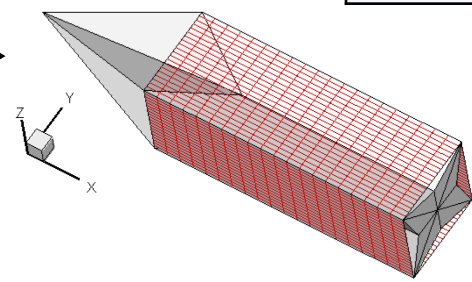
e) Isometric View

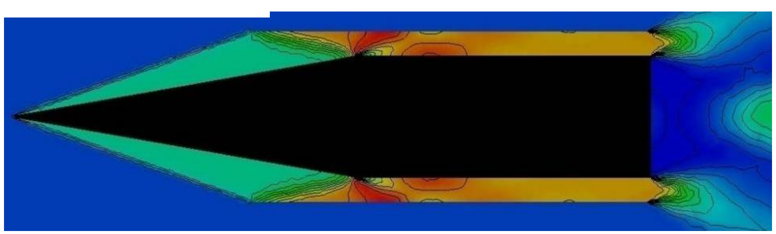
Objective: Creation of Hypersonic Inlet Configurations with predictive performance capability

Design inputs	
Mach Number	5
Length of the Primary Shock Zone	1(m)
Shock Angle	17.5°
Cruising Flight Altitude	f(M)

Assumed: A Given Flight Path





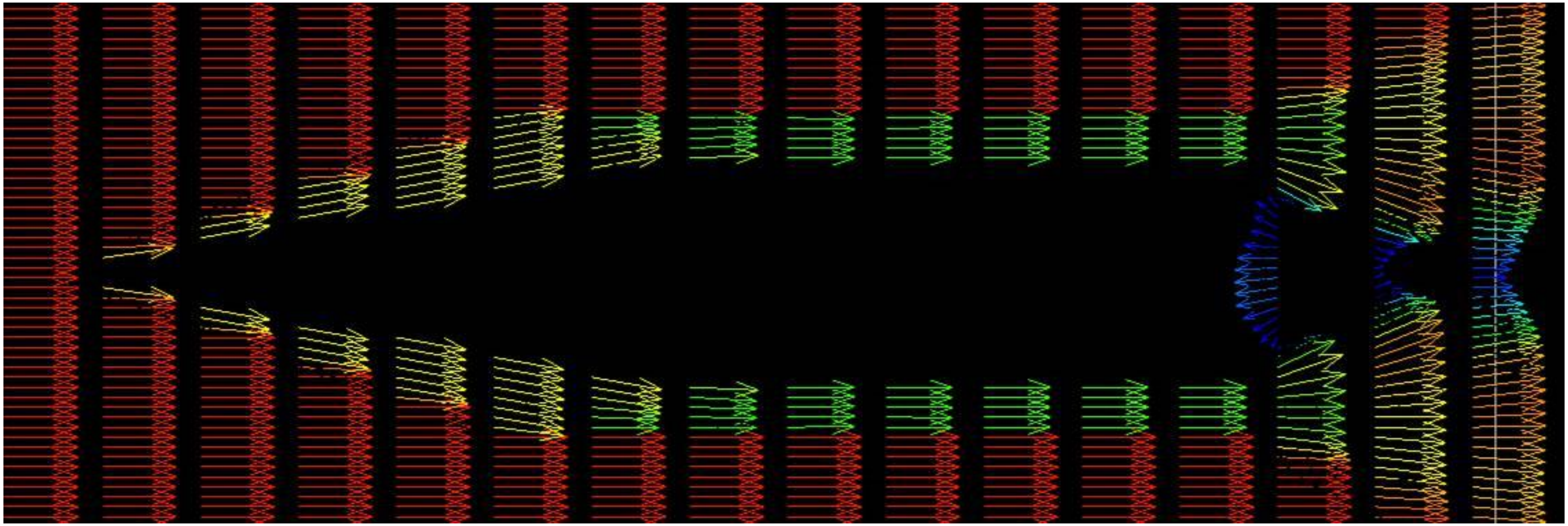


Compare Design Predictions to CFD Evaluation

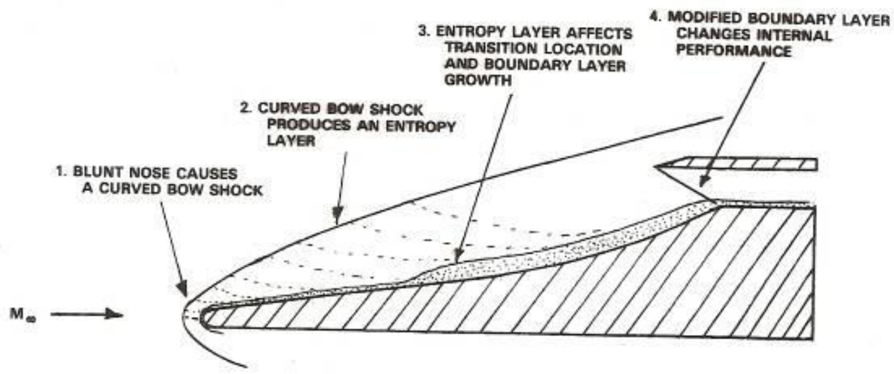
Ideal: 2D & 3D
Viscous: 2D & 3D

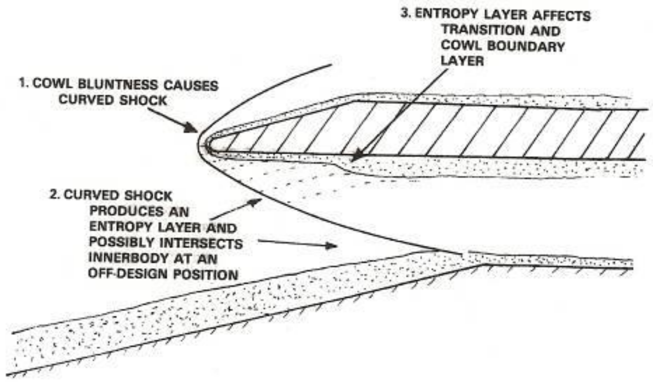
- **Case 1: Ideal 3D**

Velocity Distribution – CFD Code

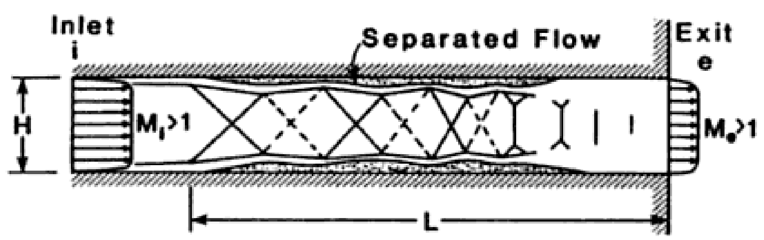


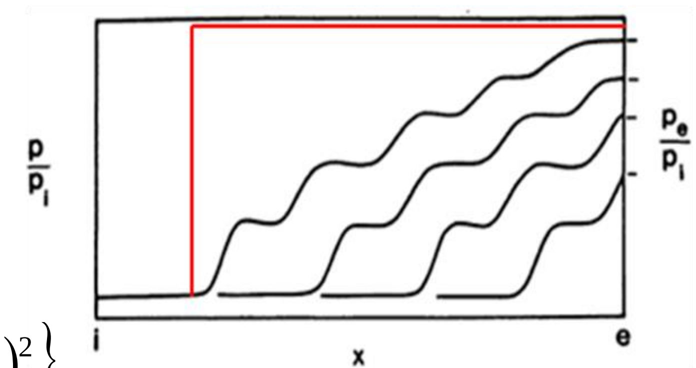
1. Leading Edge & SBLI Effects – Conduct Systematic Geometric Manipulations





2. Isolator Sizing - Validate/Improve Billig's ISTI Relations



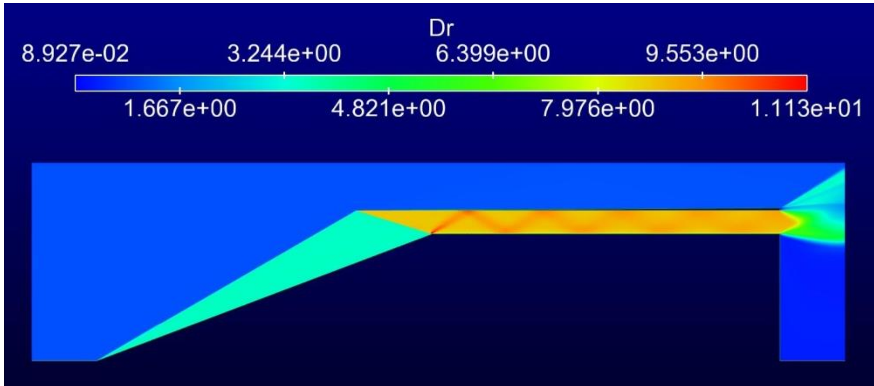


$$\left(\frac{L}{H}\right)_{Isolator} = \frac{\sqrt{\theta/H}}{(\mathrm{Re}_\theta)^{\frac{1}{4}}} \frac{\left\{50\left(\left(P_{out}/P_{in}\right)+1\right)+170\left(\left(P_{out}/P_{in}\right)-1\right)^2\right\}}{M_{in}^2-1}$$

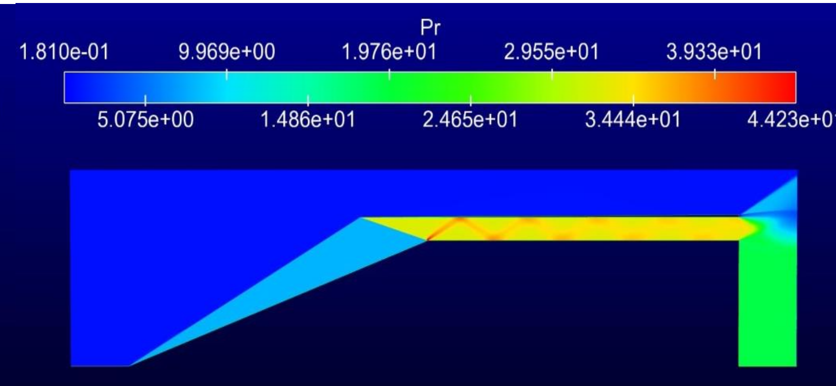
Euler Flow Field Results

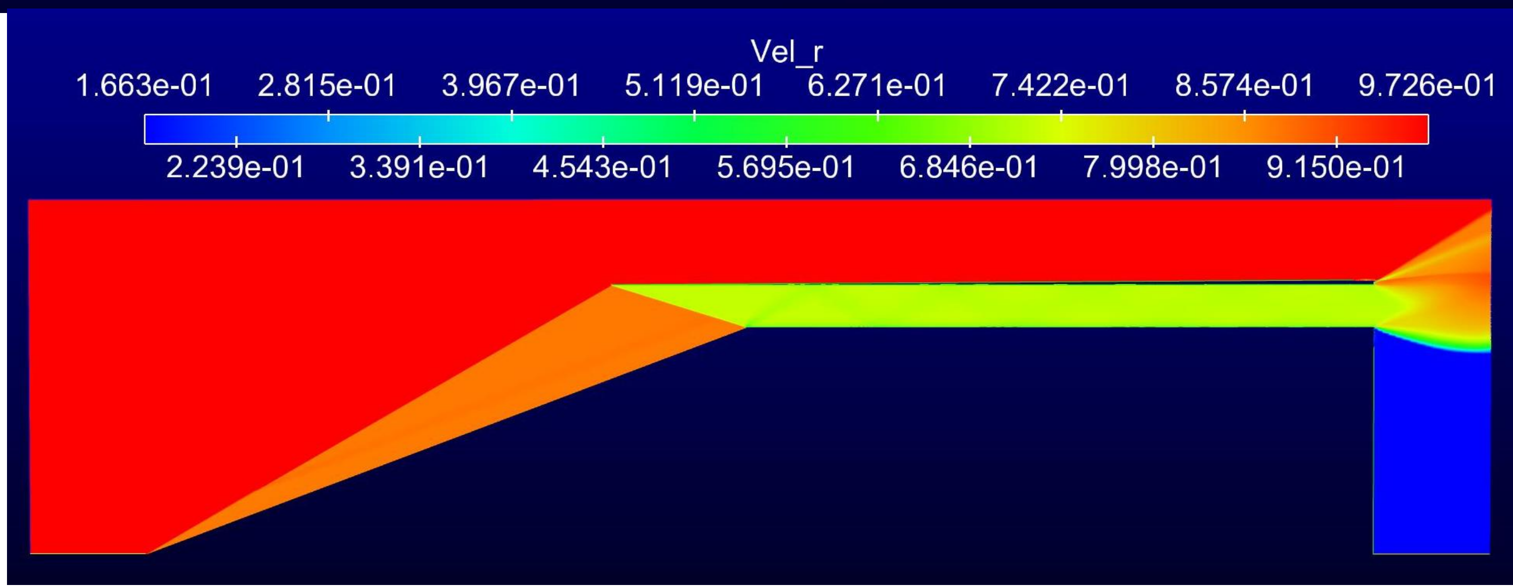
Case 2: viscous effect

Density Field



Pressure Field

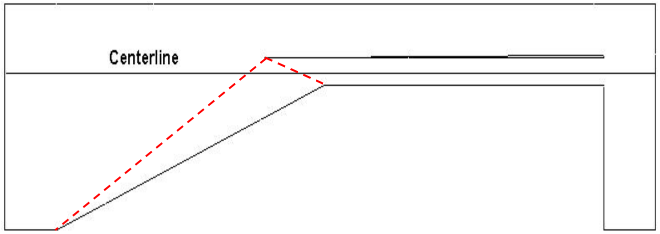




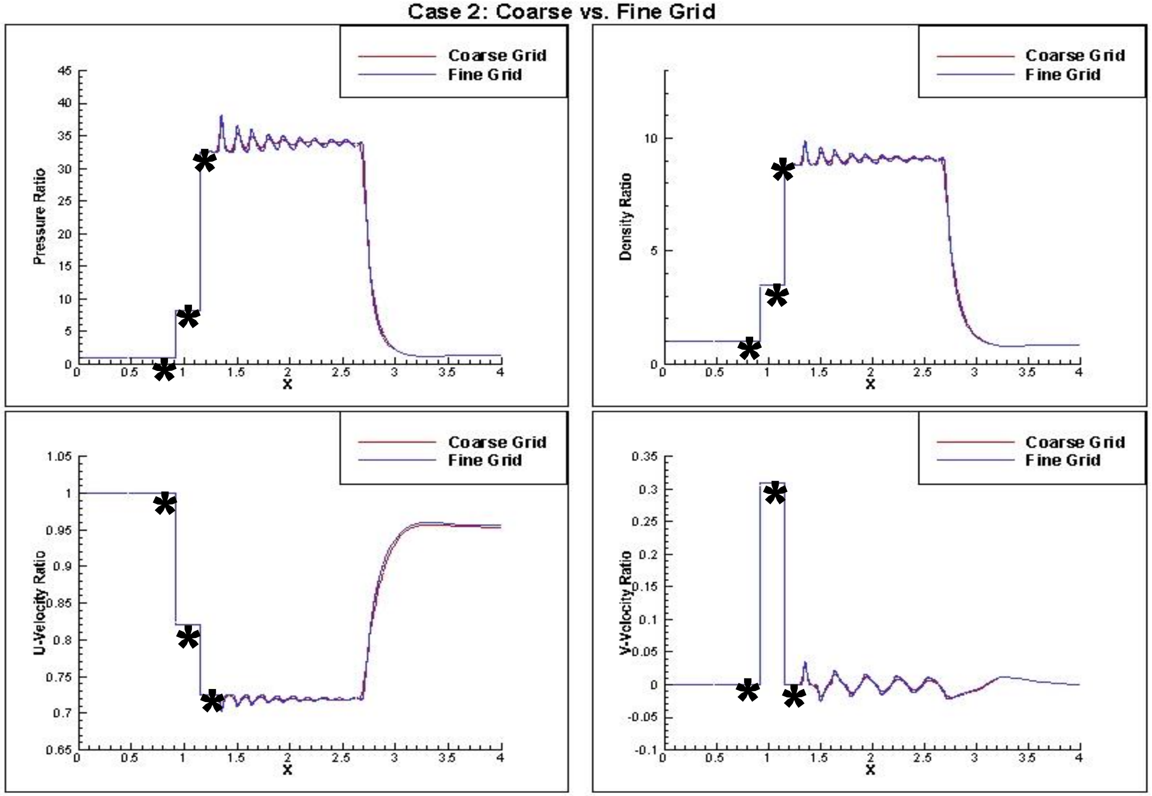
Validation Data Along Isolator Centerline

* Predictions

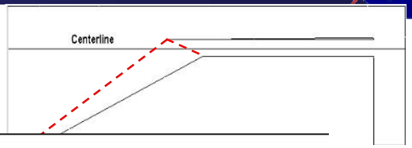
Fine Grid = 1,474,442 cells
Coarse Grid = 272,432 cells



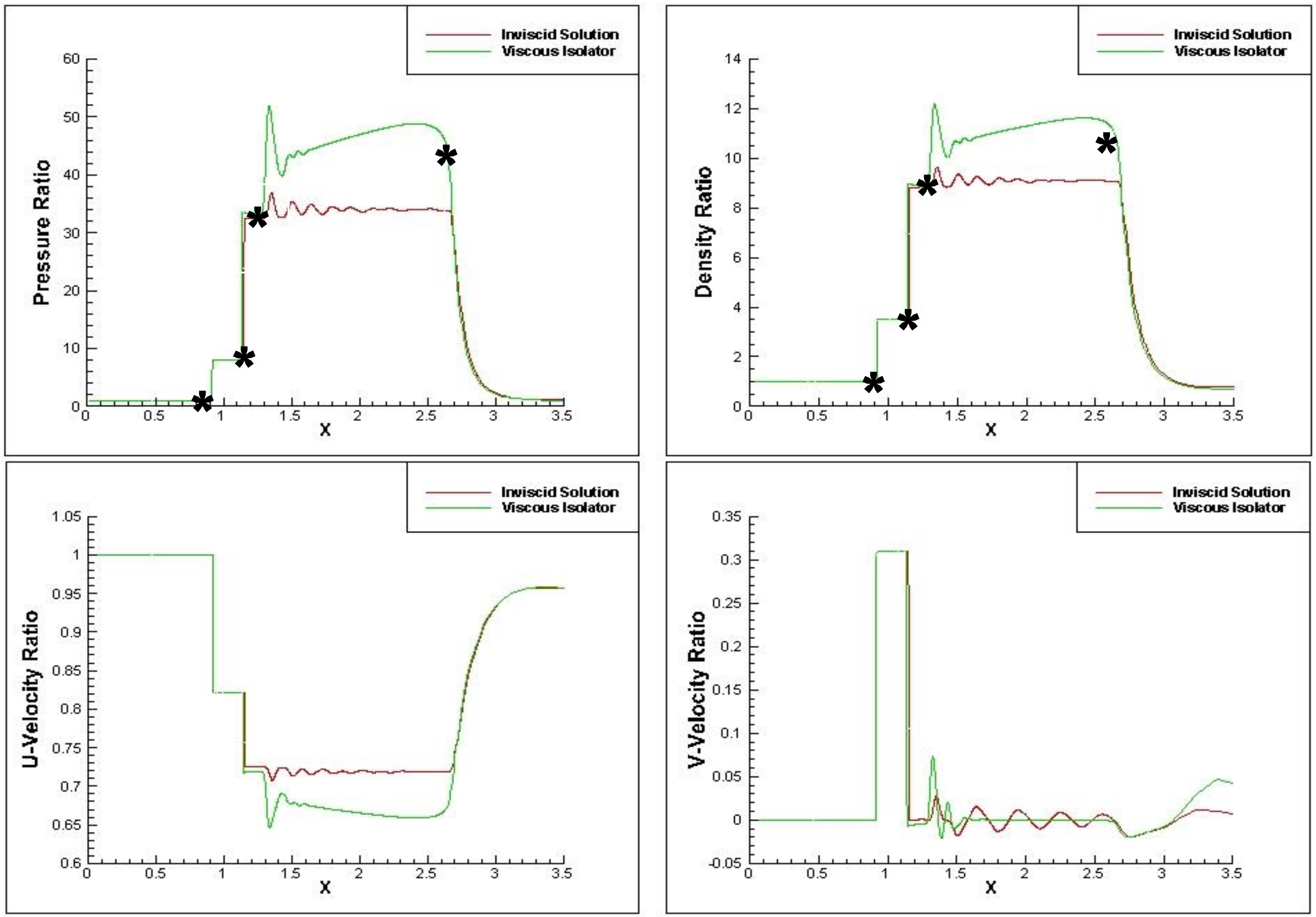
Zoomed: Isolator Validation Data



Viscous & Inviscid Solution



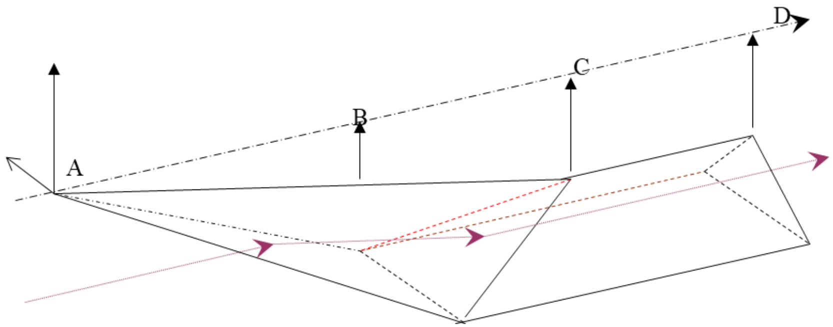
Case 2: Isolator Performance



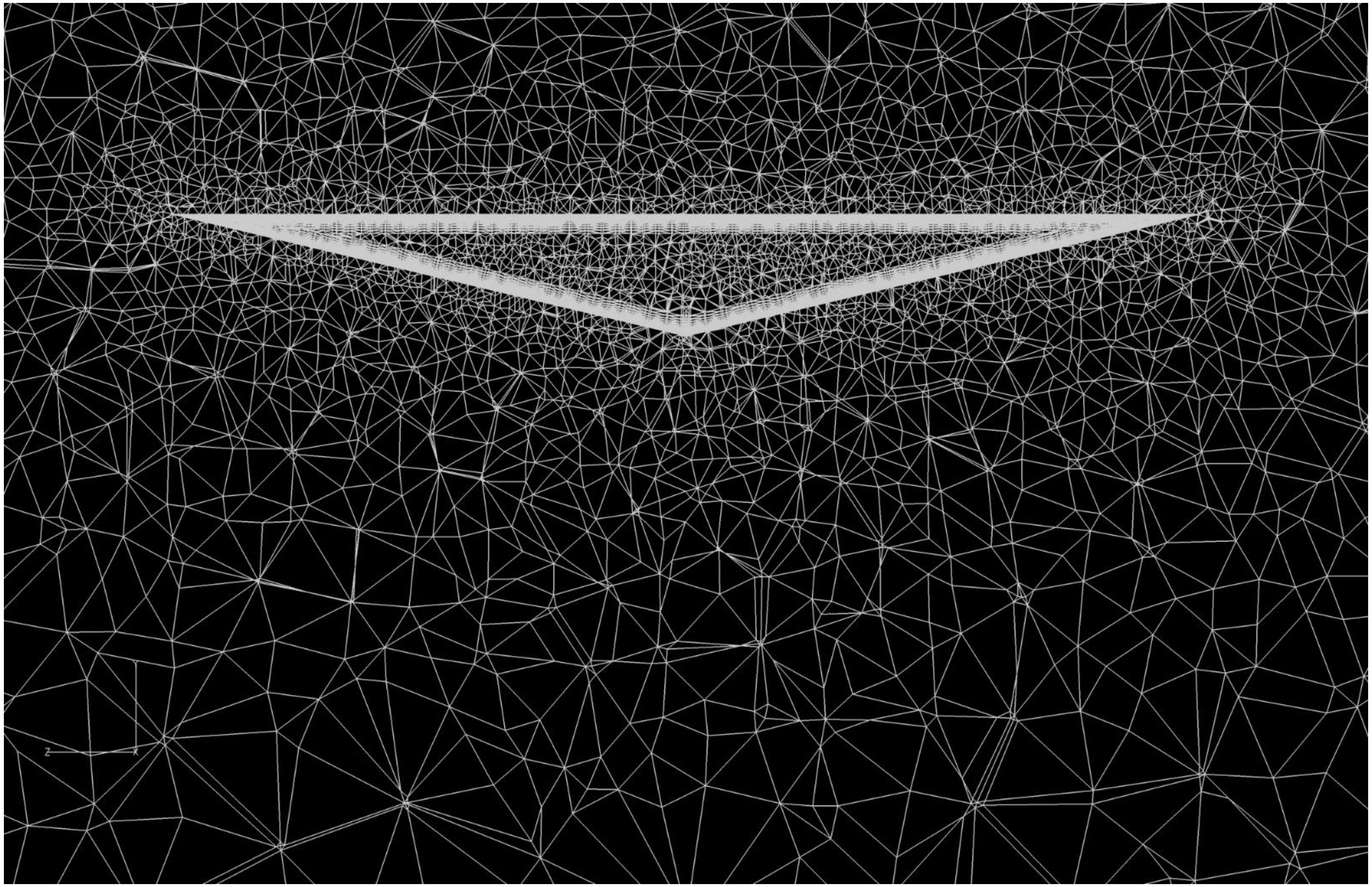
3-D Viscous Studies

Case 4

- **Elements**
  - **6.7 M**
- **Nodes**
  - **1,165,267**
- **Estimated Memory**
  - **14.75 GB**

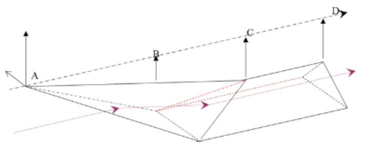


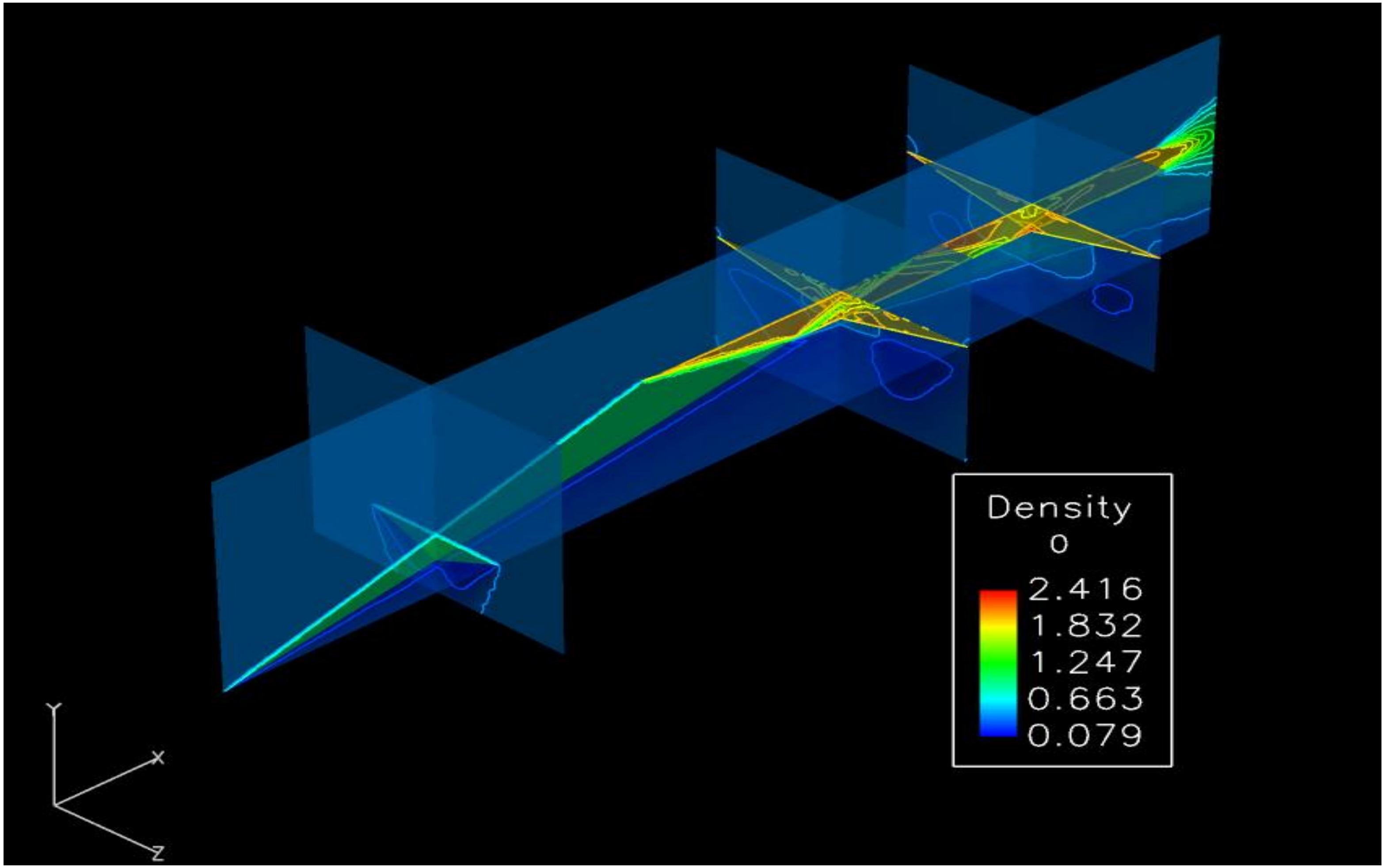
3-D Viscous Studies – Grid Generation



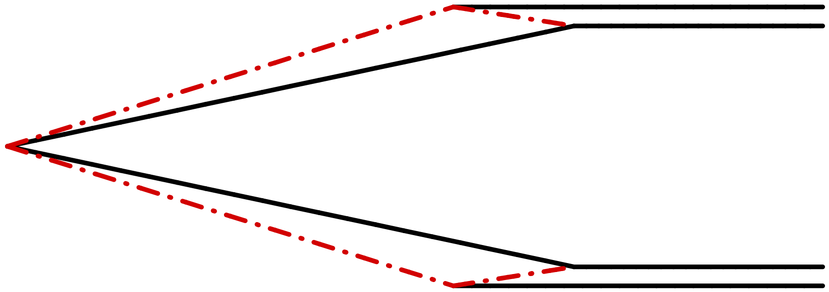
Irregular grid with clustering

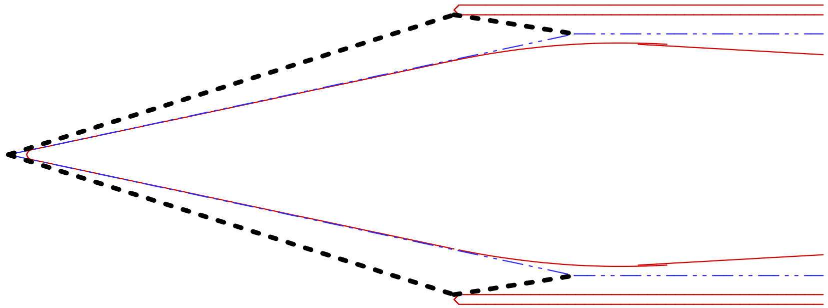
3-D CFD Studies – Internal Flow Path



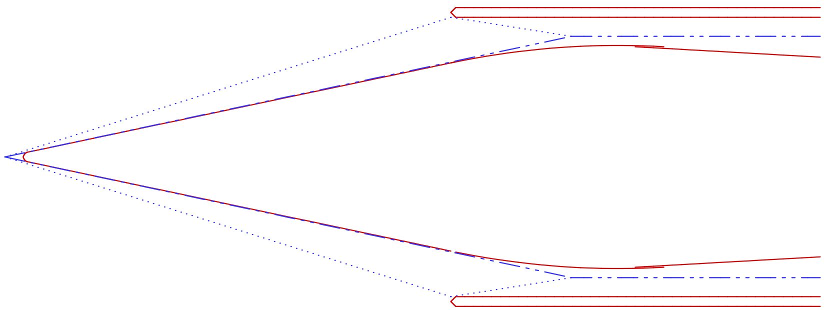


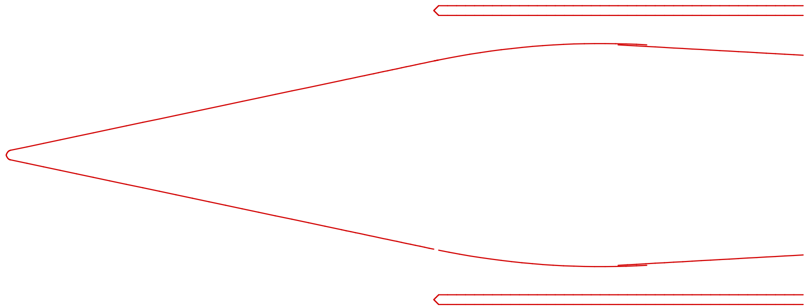
Viscous Modification of the Hypersonic Inlet





Inverse Design – Euler Model





Inverse Design – w/ Viscous Modifications

Transformed model based off viscous effects

Combustor-Nozzle Section/ Aft-Section

2. Create A Internal 3D-Shape generator that incorporates

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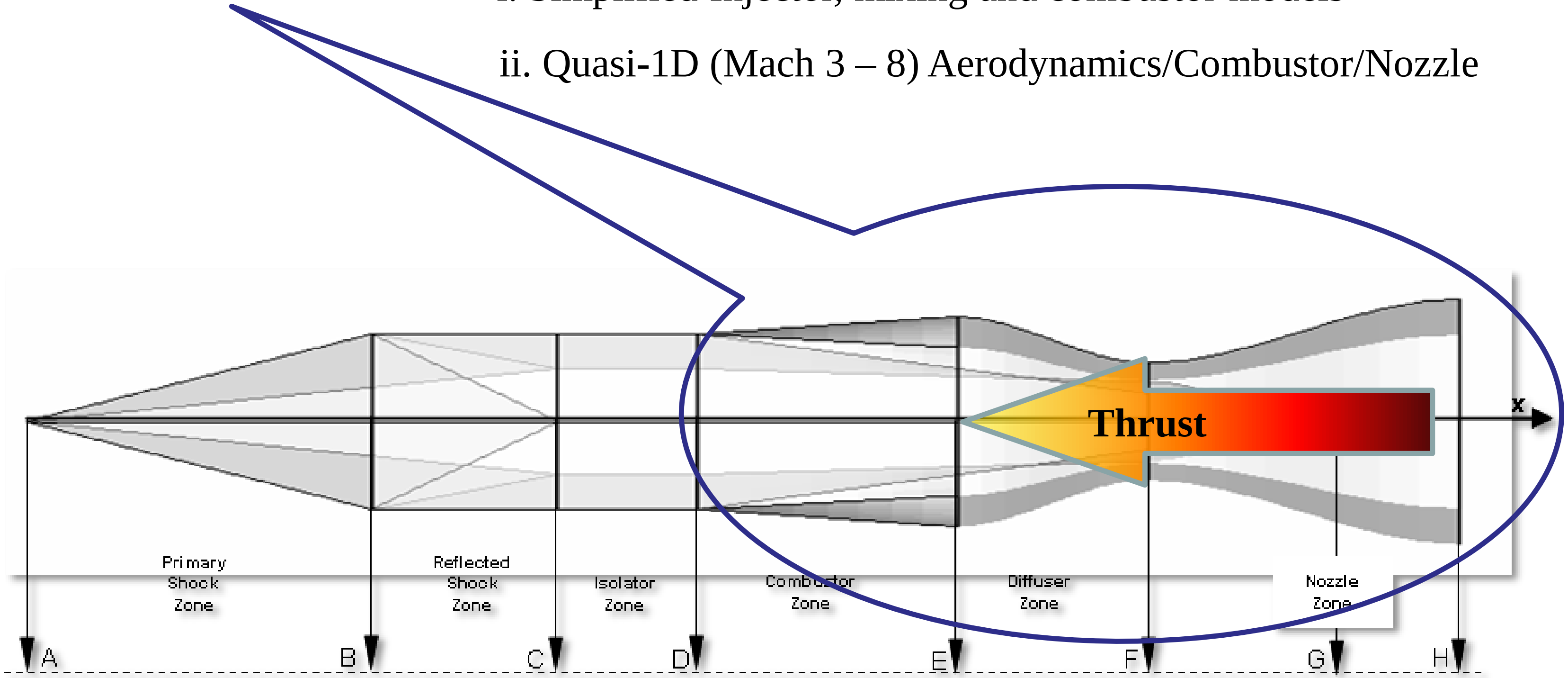
ii. Quasi-1D (Mach 3 – 8) Aerodynamics/Combustor/Nozzle



Responsible for Thrust generation

Taylor Series

Solution: (a) Euler Method, (b) Runge-Kutta (Thomas)

Description	Aerodynamic Quantities	Symbols
Area Influence	$\frac{1}{A}\frac{dA}{dx}$	$\frac{1}{y_1}\frac{dy_1}{dx}$
Heating Influence	$\frac{1}{c_p T}\frac{\delta Q - dH_0}{dx}$	$\frac{1}{y_2}\frac{dy_2}{dx}$
Friction Influence	$\frac{4C_f}{D_h} - 2\chi\frac{1}{\dot{m}_{air}}\frac{d\dot{m}_{fuel}}{dx}$	$\frac{1}{y_3}\frac{dy_3}{dx}$
Fuel Injection Influence	$\frac{1}{\dot{m}_{air}}\frac{d\dot{m}_{fuel}}{dx}$	$\frac{1}{y_4}\frac{dy_4}{dx}$
Combustion Chemistry Influence	$\frac{1}{W_M}\frac{\delta W_M}{dx}$	$\frac{1}{y_5}\frac{dy_5}{dx}$
High Temperature Influence	$\frac{1}{\gamma}\frac{\delta\gamma}{dx}$	$\frac{1}{y_6}\frac{dy_6}{dx}$

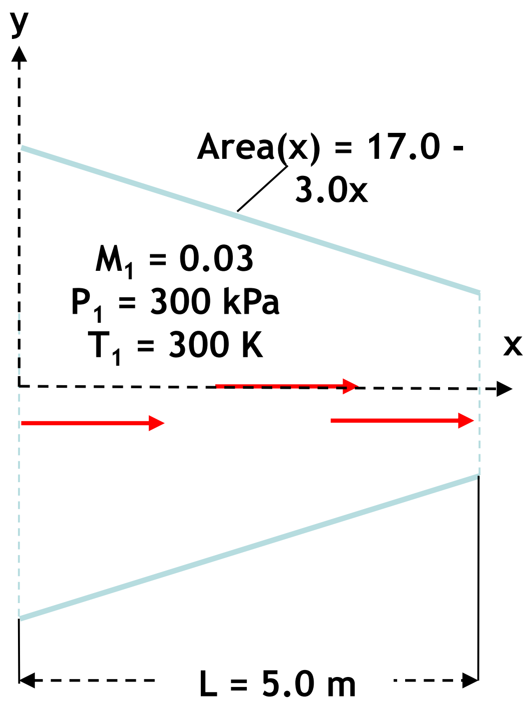
$$\frac{1}{M}\frac{dM}{dx} = C_{1,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{1,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{1,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{1,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{1,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{1,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

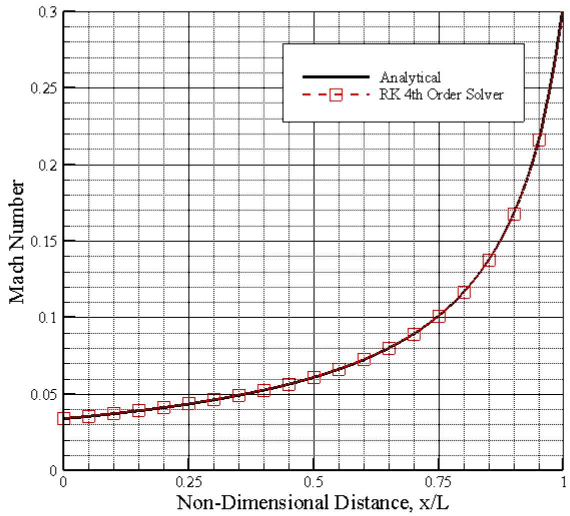
$$\frac{1}{T}\frac{dT}{dx} = C_{2,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{2,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{2,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{2,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{2,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{2,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

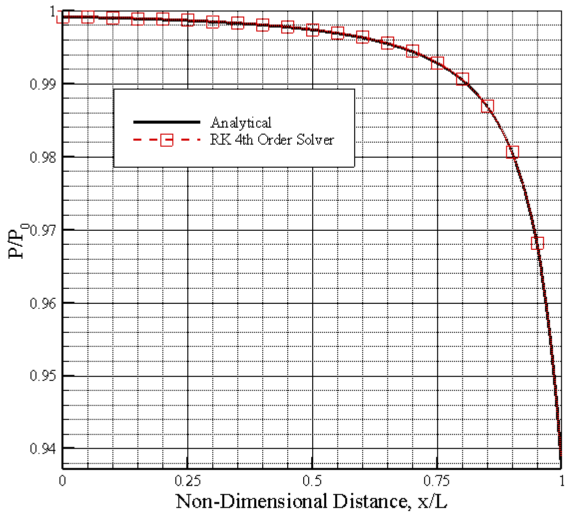
$$\frac{1}{P}\frac{dP}{dx} = C_{3,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{3,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{3,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{3,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{3,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{3,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

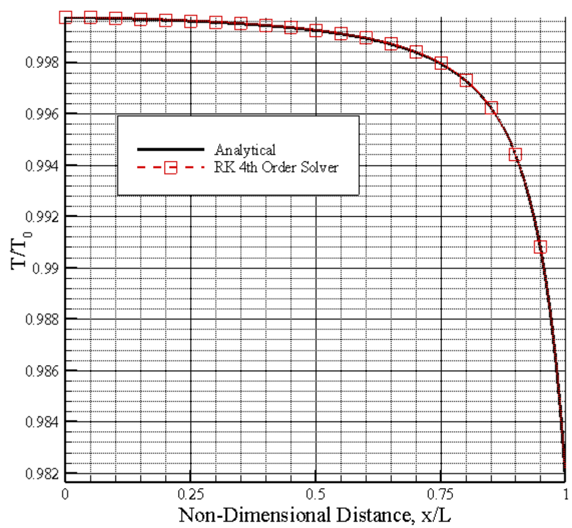
Modified Quasi 1-D Tool Development (validation)

Area Only, Convergent Duct, Subsonic





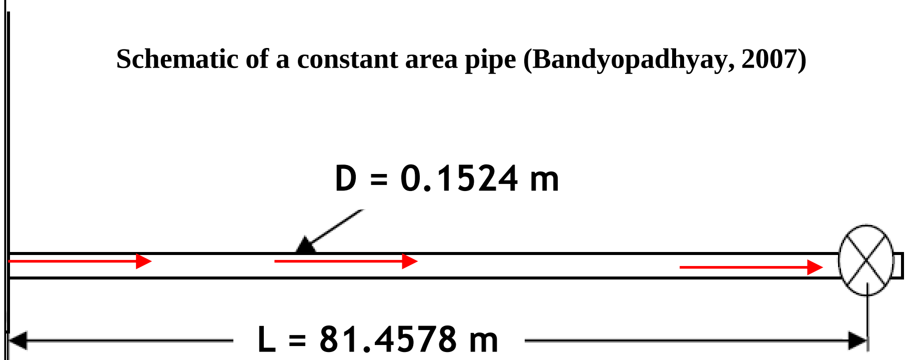


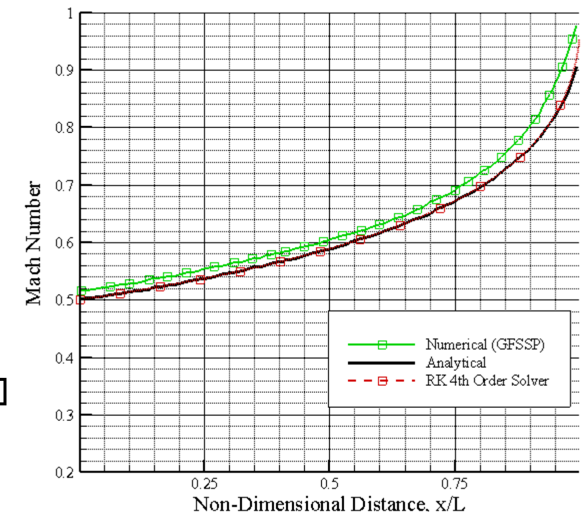


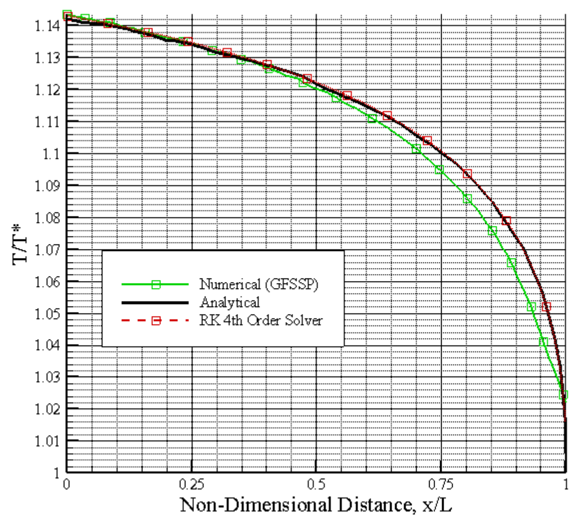
Fanno Flow

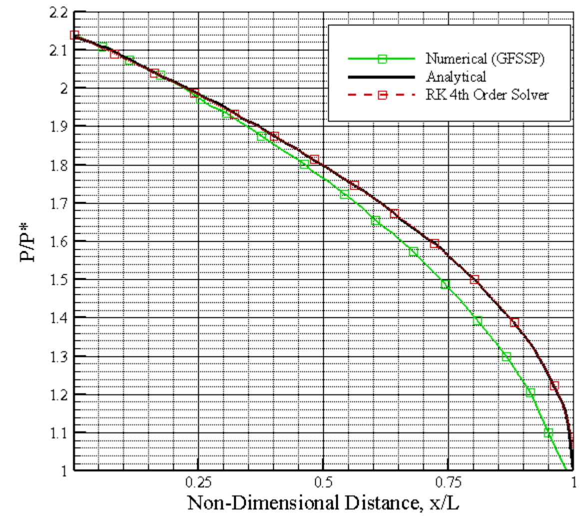
$M_1 = 0.5$
$P_1 = 344737.865$ Pa
$T_1 = 299.817$ K
$c_f = 0.0005$
$P^* = 161235.613$ Pa
$T^* = 262.315$ K

Schematic of a constant area pipe (Bandyopadhyay, 2007)

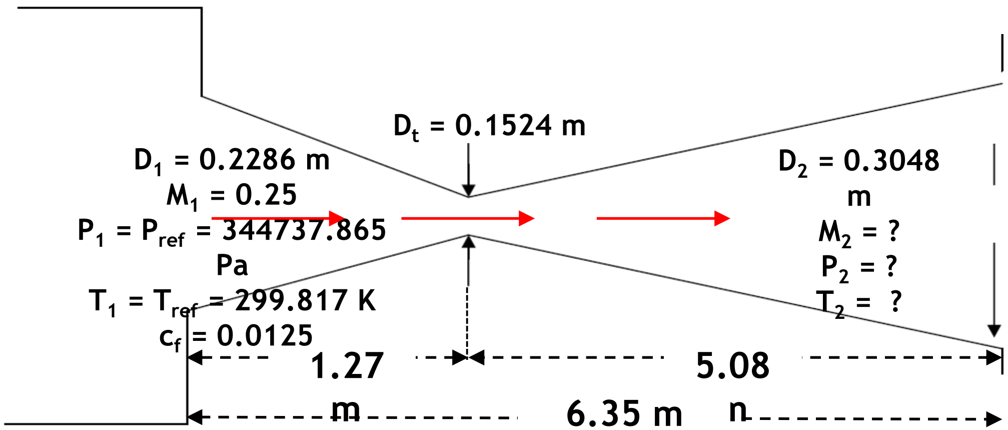




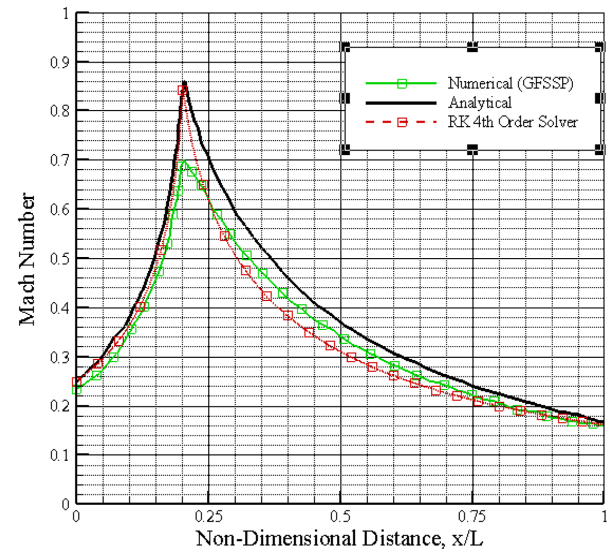


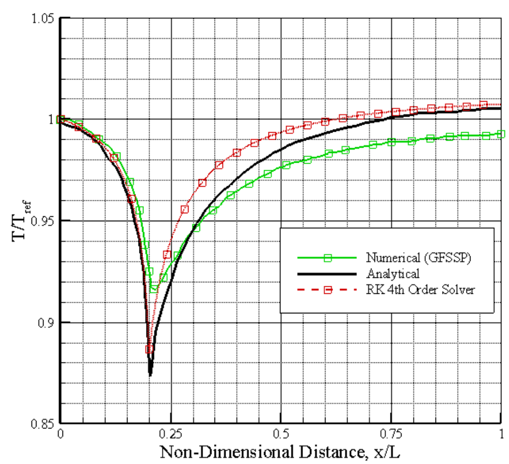


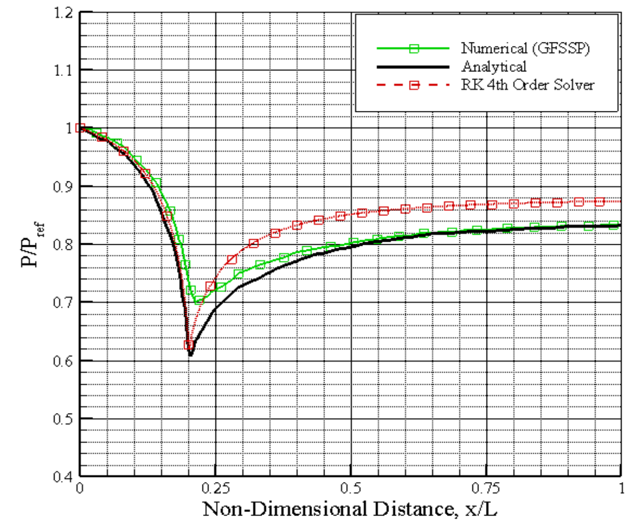
Quasi 1D with Friction



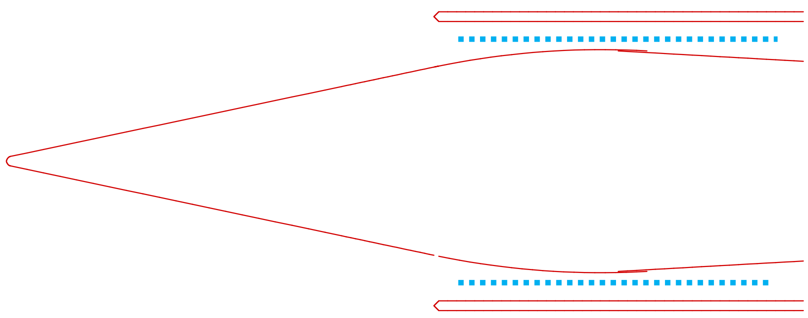
Ref. Bandyopadhyay, 2007

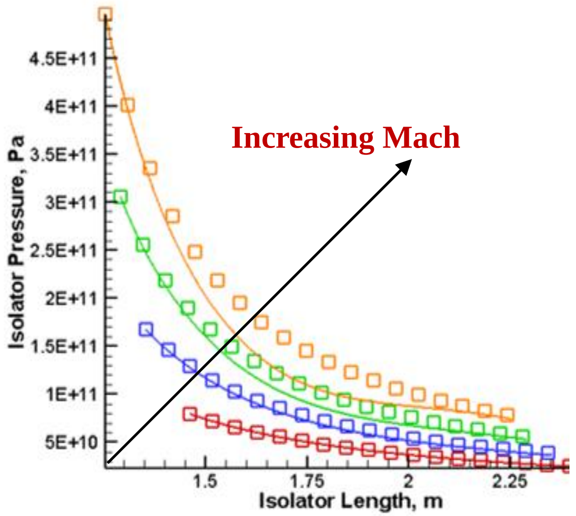


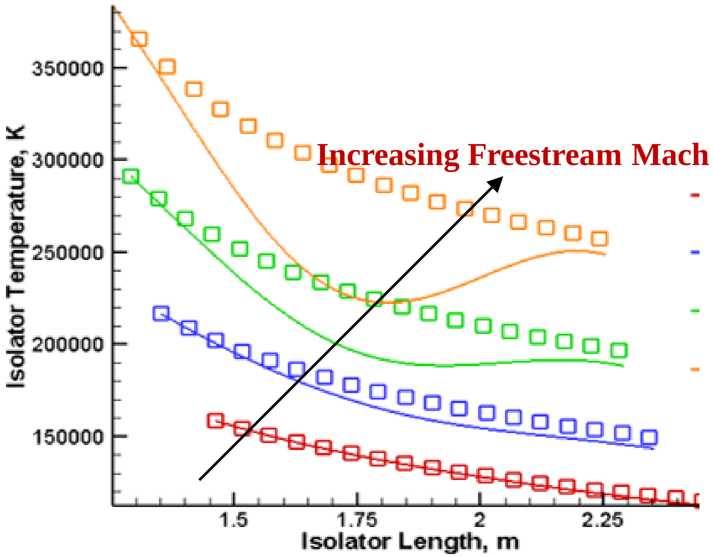


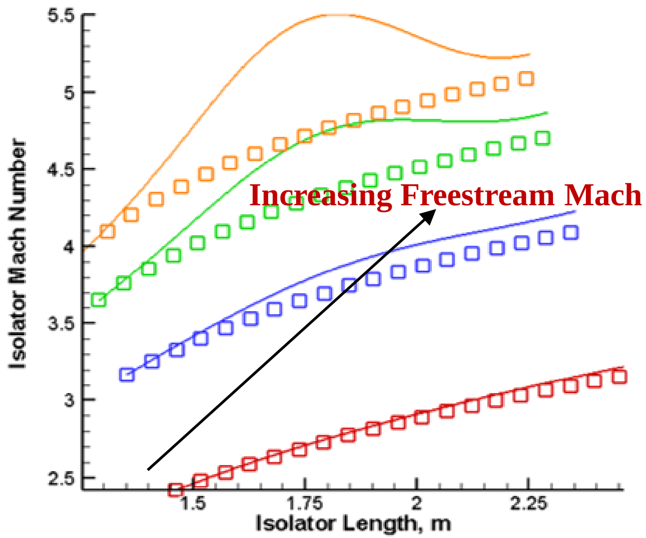


Quasi 1-D Inlet Evaluation (M = 5-8)









Combustor-Nozzle Section/ Aft-Section

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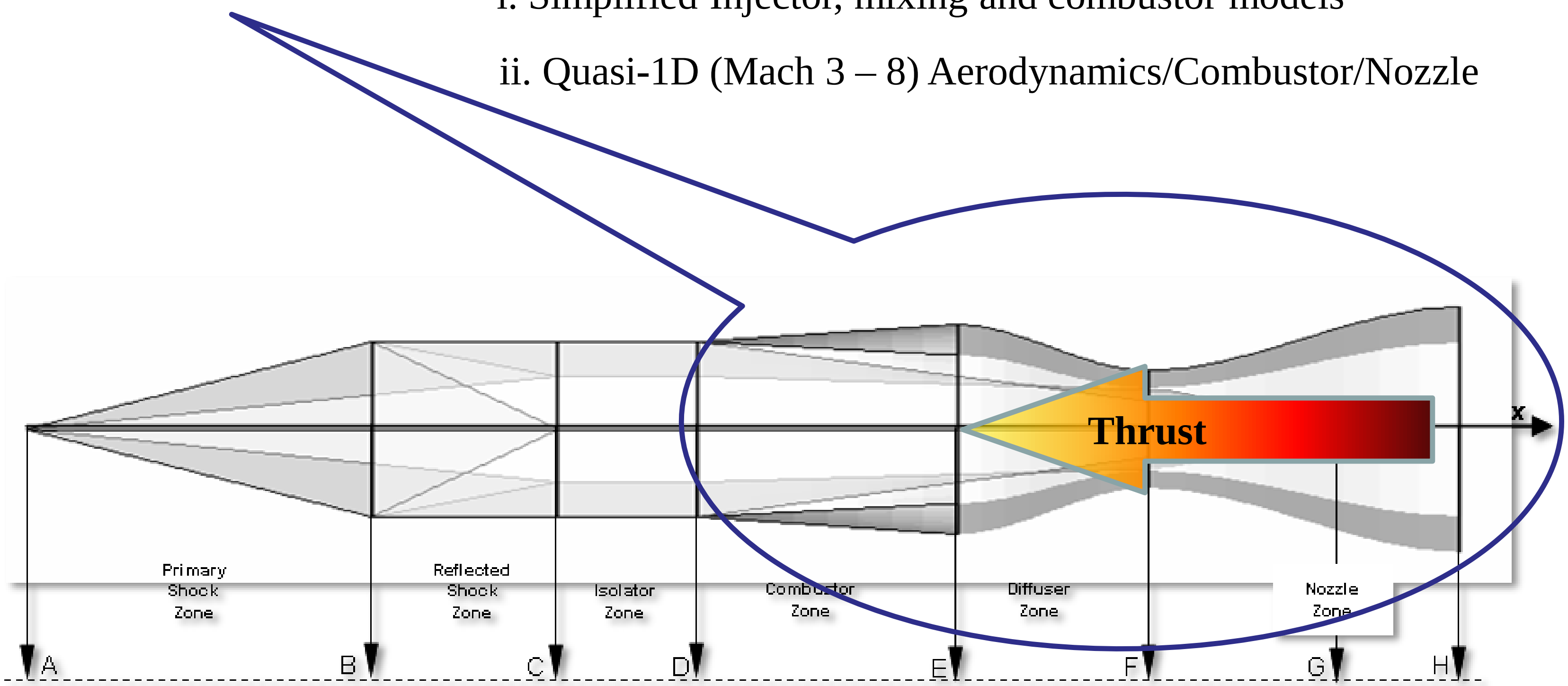
ii. Quasi-1D (Mach 3 – 8) Aerodynamics/Combustor/Nozzle



Responsible for Thrust generation

Quasi 1-D Tool

Taylor Series

Solution: (a) Euler Method, (b) Runge-Kutta (Thomas)

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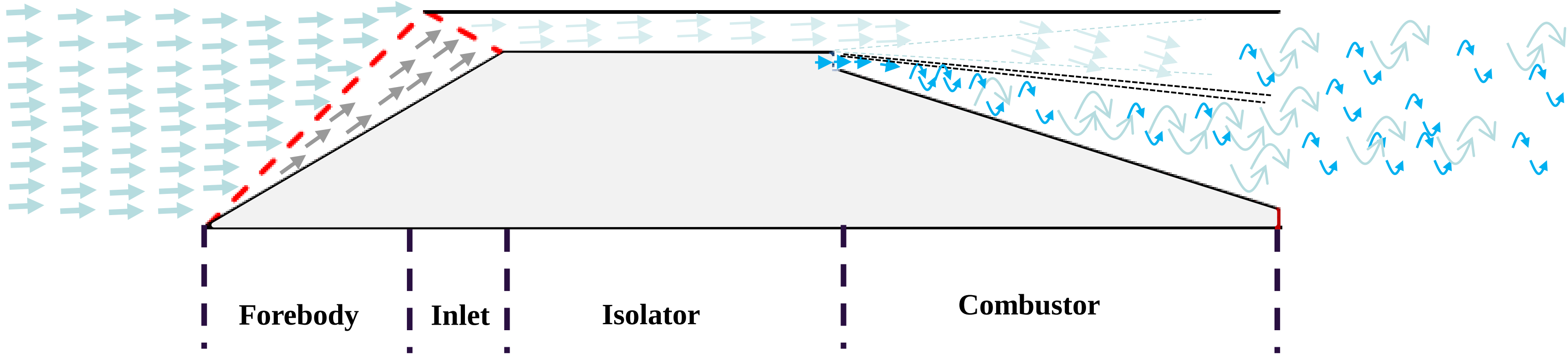
$$\frac{1}{M}\frac{dM}{dx} = C_{1,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{1,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{1,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{1,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{1,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{1,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

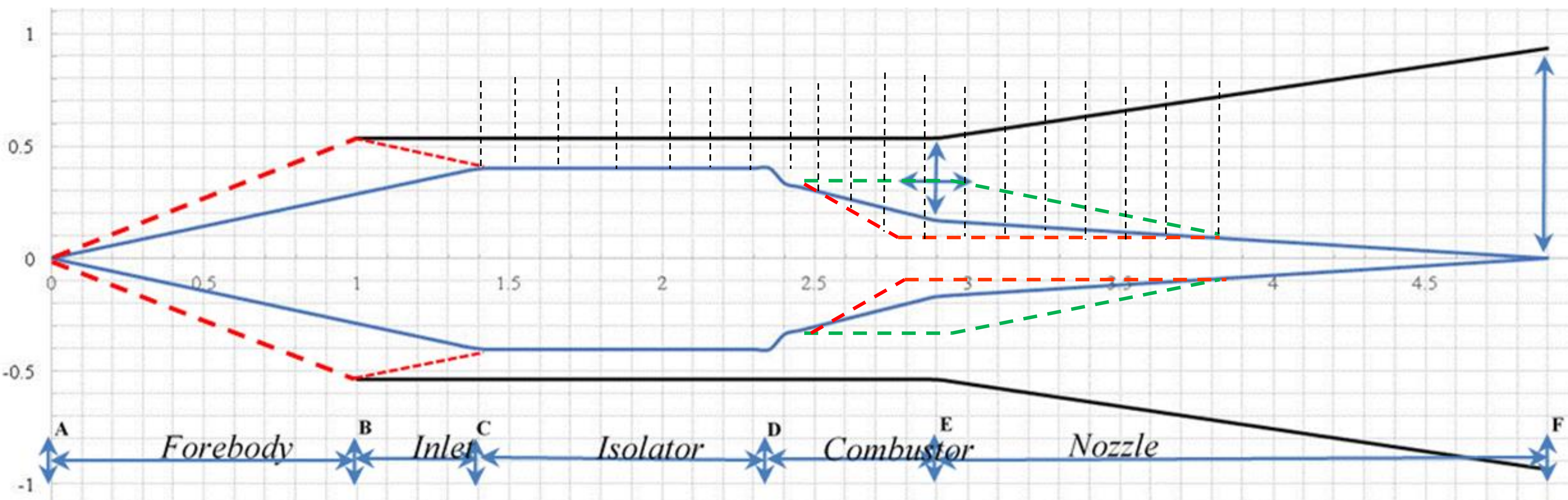
$$\frac{1}{T}\frac{dT}{dx} = C_{2,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{2,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{2,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{2,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{2,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{2,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

$$\frac{1}{P}\frac{dP}{dx} = C_{3,1}\frac{1}{y_1}\frac{dy_1}{dx} + C_{3,2}\frac{1}{y_2}\frac{dy_2}{dx} + C_{3,3}\frac{1}{y_3}\frac{dy_3}{dx} + C_{3,4}\frac{1}{y_4}\frac{dy_4}{dx} + C_{3,5}\frac{1}{y_5}\frac{dy_5}{dx} + C_{3,6}\frac{1}{y_6}\frac{dy_6}{dx}$$

Flow Path Simulation



Combustor - Nozzle section / aft-section



- High speed aerodynamics is driving this design.
- This section is dominated by viscous effects,
- which results in a very complicated flow field.
- Conventional CFD tools cannot capture the flow physics we're after.

Quasi 1-D Tool Usage

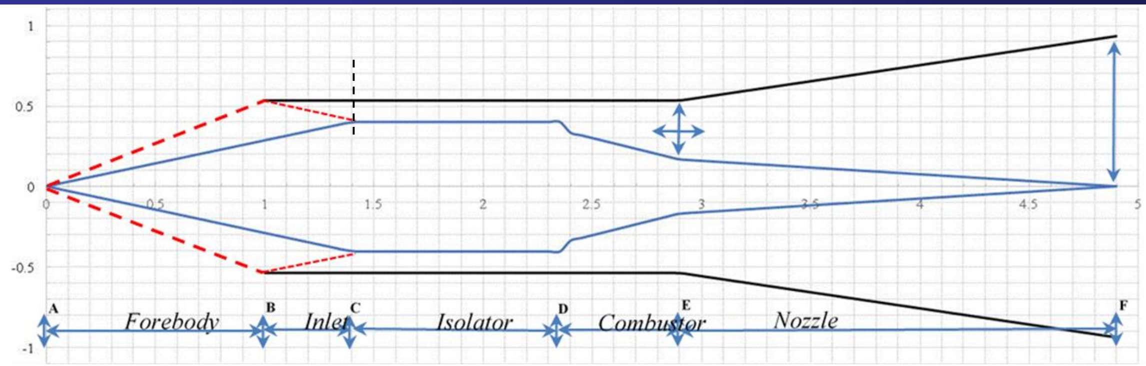
We have Six influence coefficients :

Description	Aerodynamic Quantities	Symbols
Area Influence	$\frac{1}{A}\frac{dA}{dx}$	$\frac{1}{y_1}\frac{dy_1}{dx}$
Heating Influence	$\frac{1}{c_p T}\frac{\delta Q - dH_0}{dx}$	$\frac{1}{y_2}\frac{dy_2}{dx}$
Friction Influence	$\frac{4C_f}{D_h} - 2\chi\frac{1}{\dot{m}_{air}}\frac{d\dot{m}_{fuel}}{dx}$	$\frac{1}{y_3}\frac{dy_3}{dx}$
Fuel Injection Influence	$\frac{1}{\dot{m}_{air}}\frac{d\dot{m}_{fuel}}{dx}$	$\frac{1}{y_4}\frac{dy_4}{dx}$
Combustion Chemistry Influence	$\frac{1}{W_M}\frac{\delta W_M}{dx}$	$\frac{1}{y_5}\frac{dy_5}{dx}$
High Temperature Influence	$\frac{1}{\gamma}\frac{\delta\gamma}{dx}$	$\frac{1}{y_6}\frac{dy_6}{dx}$

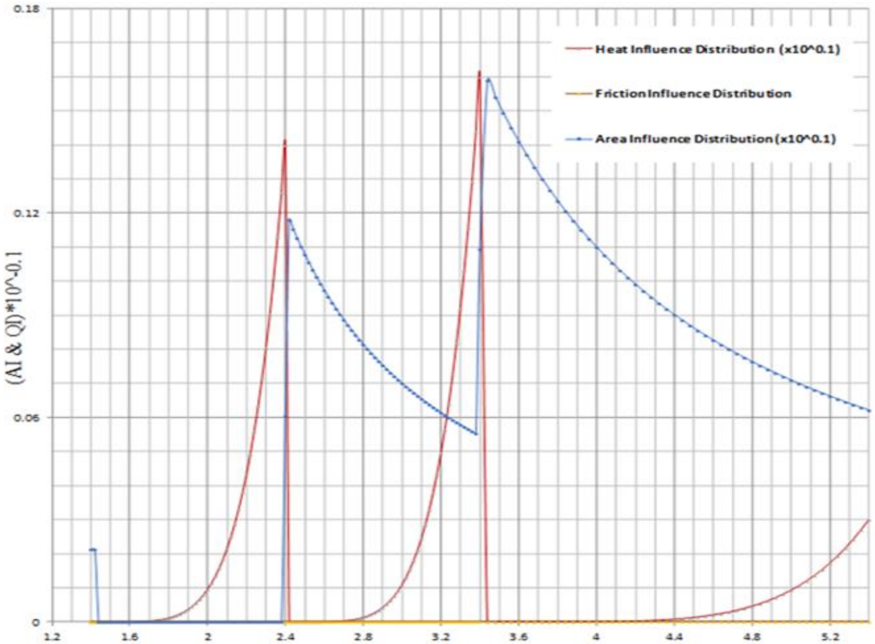
Design inputs:

Description	Numbers		Dimension
Flight Altitude	30.0		km
Mach Number	5.0		
Wedge Angle	16.0		Degrees
Forebody Length	1.0		m
Fractional x & y Lengths of ID Values			
Isolator Design Parameters	1.0	0.9	
Combustor Design Parameters	1.0	0.8	
Nozzle Design Parameters	1.0	0.0	

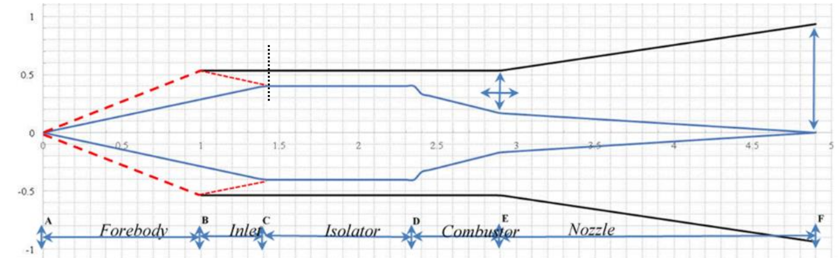
Three Influences for Testing

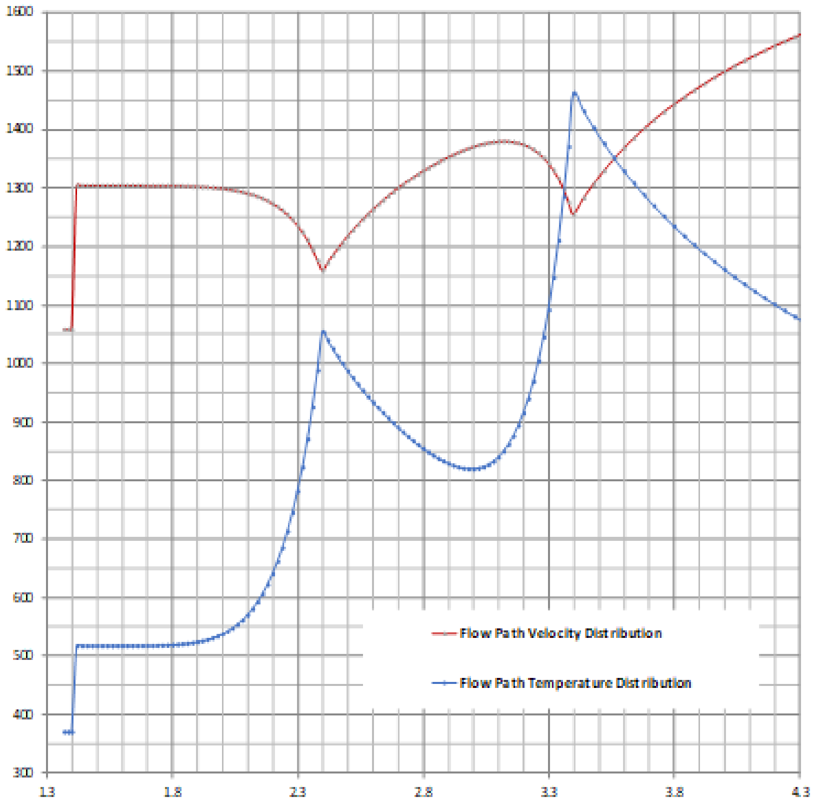


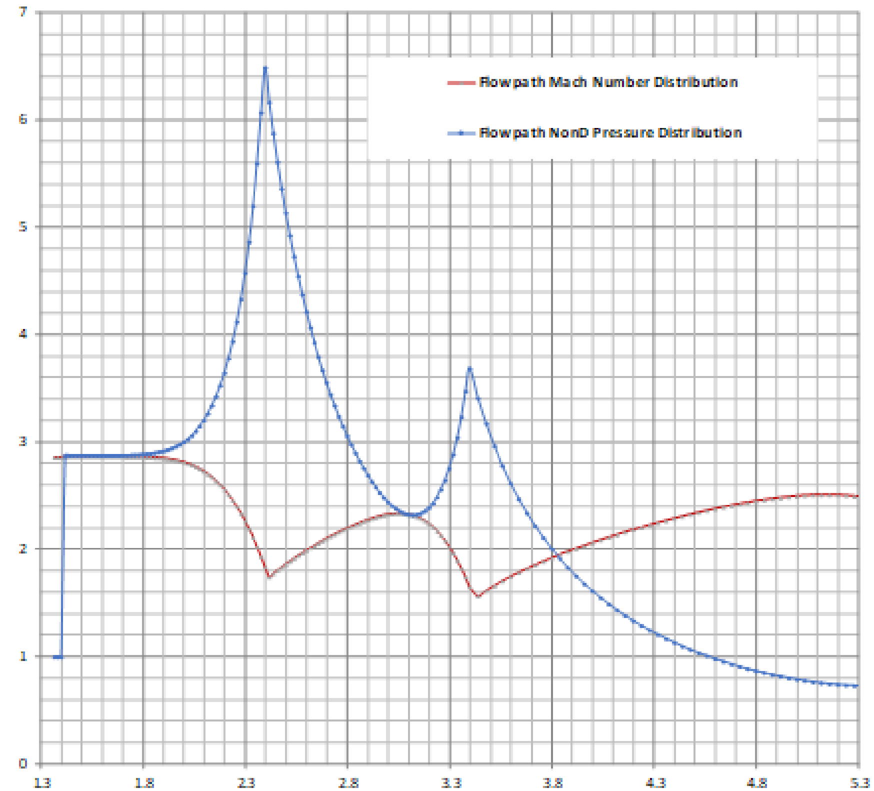
Example with 3 different influences



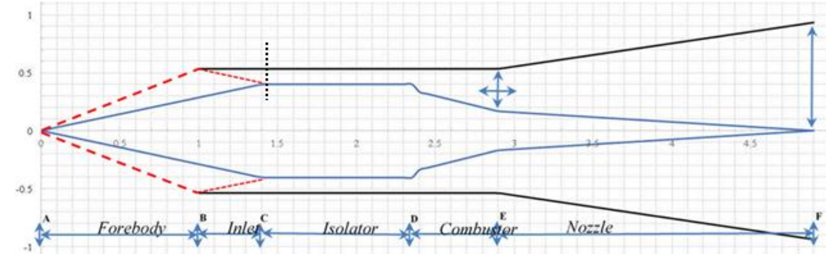
Results Plots Of Flow Properties Distribution

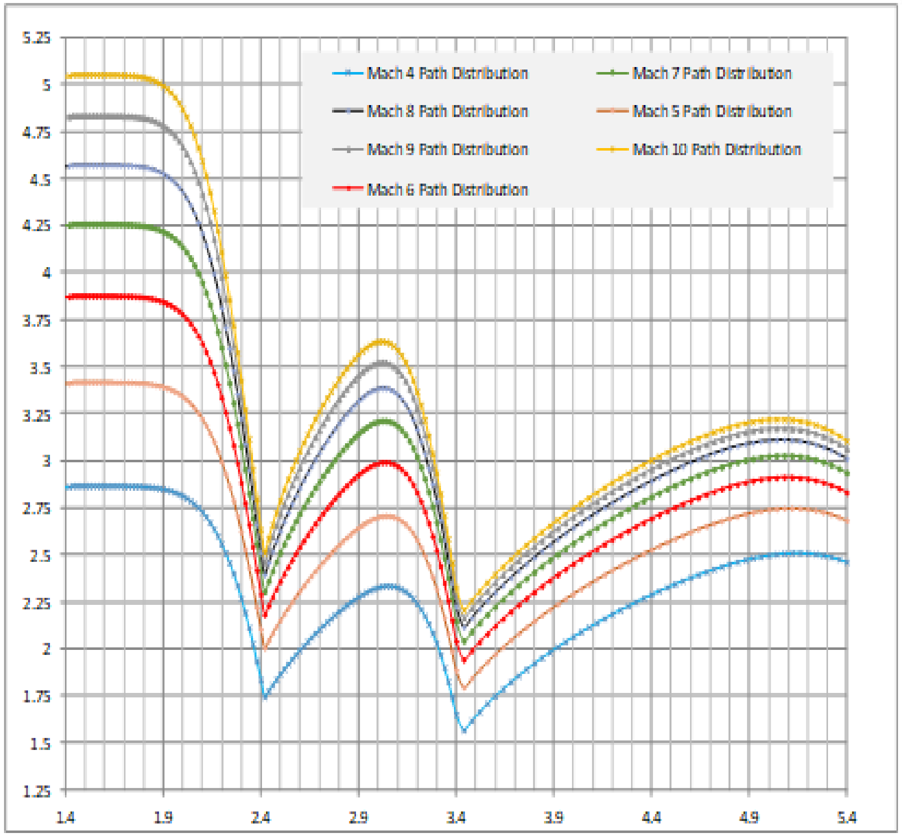


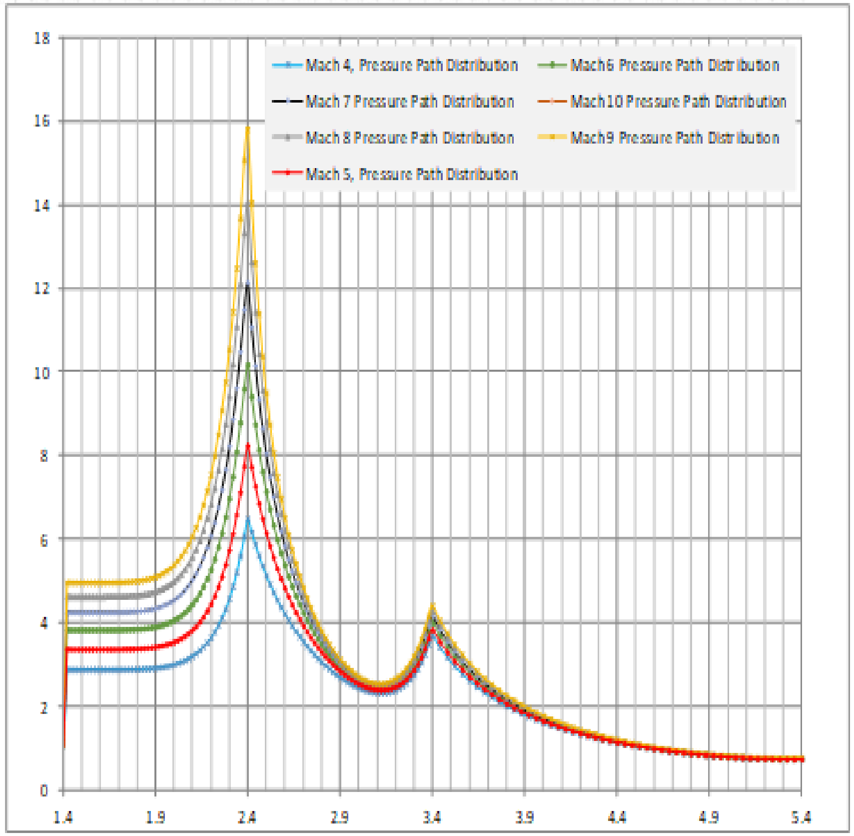




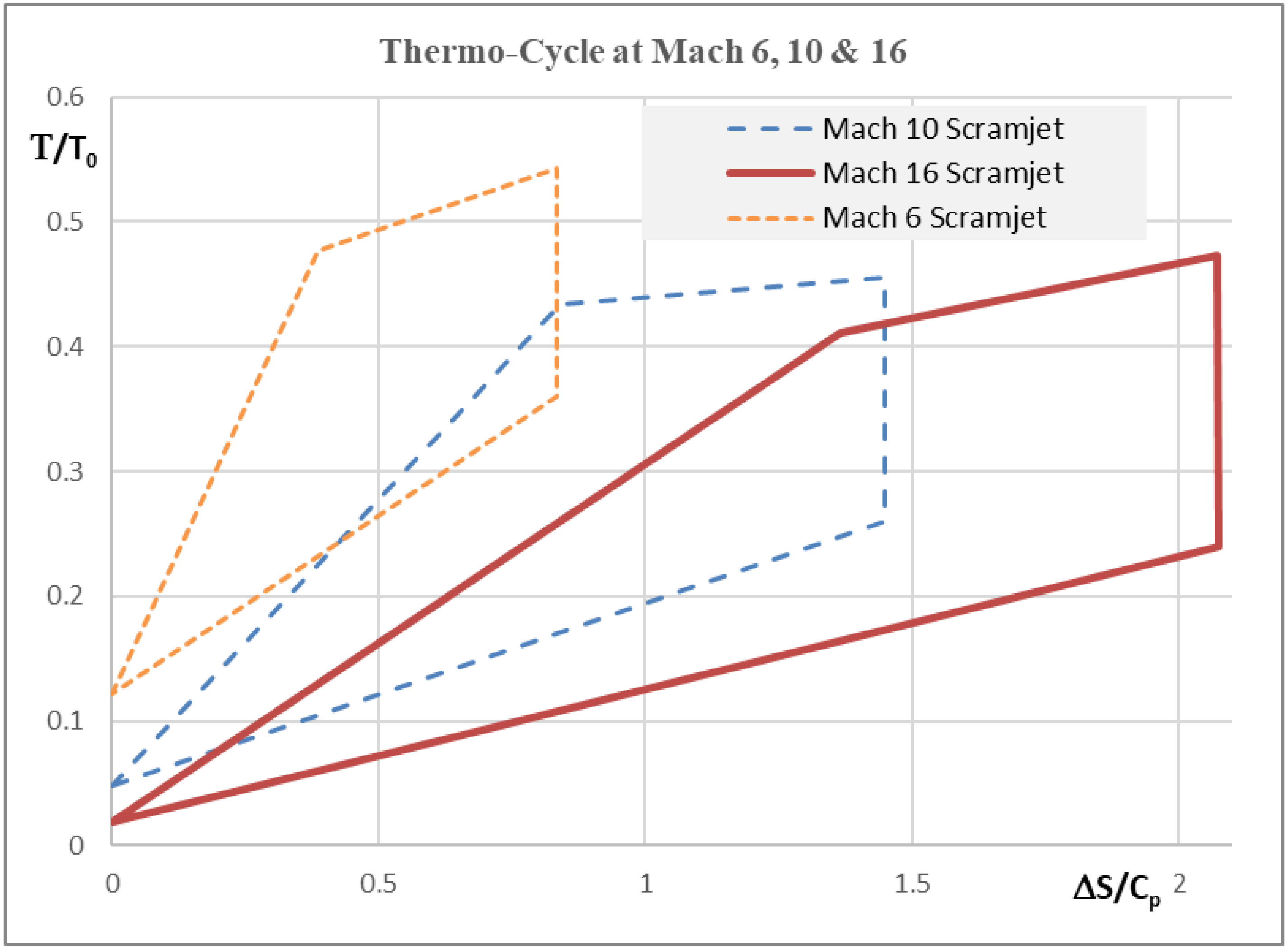
Distribution For Various Mach Number







Thermo-Cycle For The Engine



Thank You
Questions?