DESIGN AND FABRICATION OF SMALL-SCALE SUPERSONIC WIND TUNNEL

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OBJECTIVES

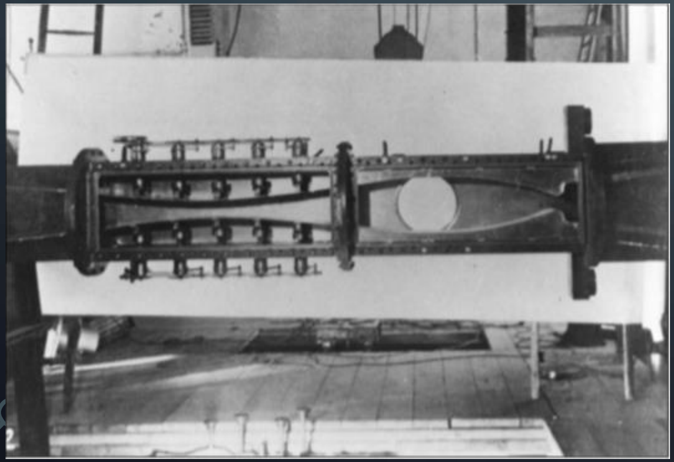
- To design a wind tunnel that has the ability to conduct testing and analysis of aerospace objects and components at speeds greater than Mach 1

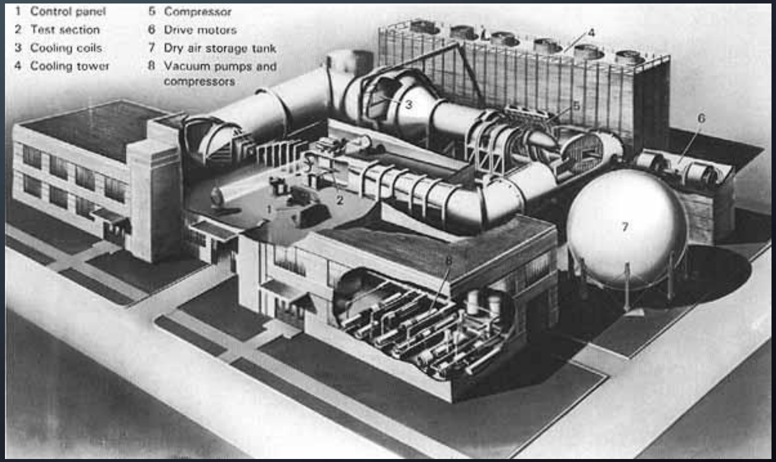
Engineering Requirements

- Highest Supersonic Mach number in the testing chamber
- Subsonic Mach number in the exhaust
- Sonic flow at the throat
- Pressure and Temperature values at every cross sectional area in the tunnel

BACKGROUND HISTORY OF WIND TUNNELS

- In the 19th century forms of wind tunnels existed, however they were not very effective
- One of the most successfully used wind tunnels was a 30-foot by 60-foot machine manufactured by NACA in 1931
- Blowndown tunnels consists of a high pressure at the inlet via chambers of compressed air and atmospheric conditions at the exhaust





HOW IT WORKS

- Utilizes a difference in pressure to achieve the high speed flow
- C-D nozzle to speed up the flow from sub to supersonic
- Diffuser utilized to slow down the flow from super to subsonic before exiting the assembly

Isentropic Relation:

$$\frac{P_0}{P^*} = \left(\frac{T_0}{T^*}\right)^{\frac{\gamma}{\gamma-1}}$$

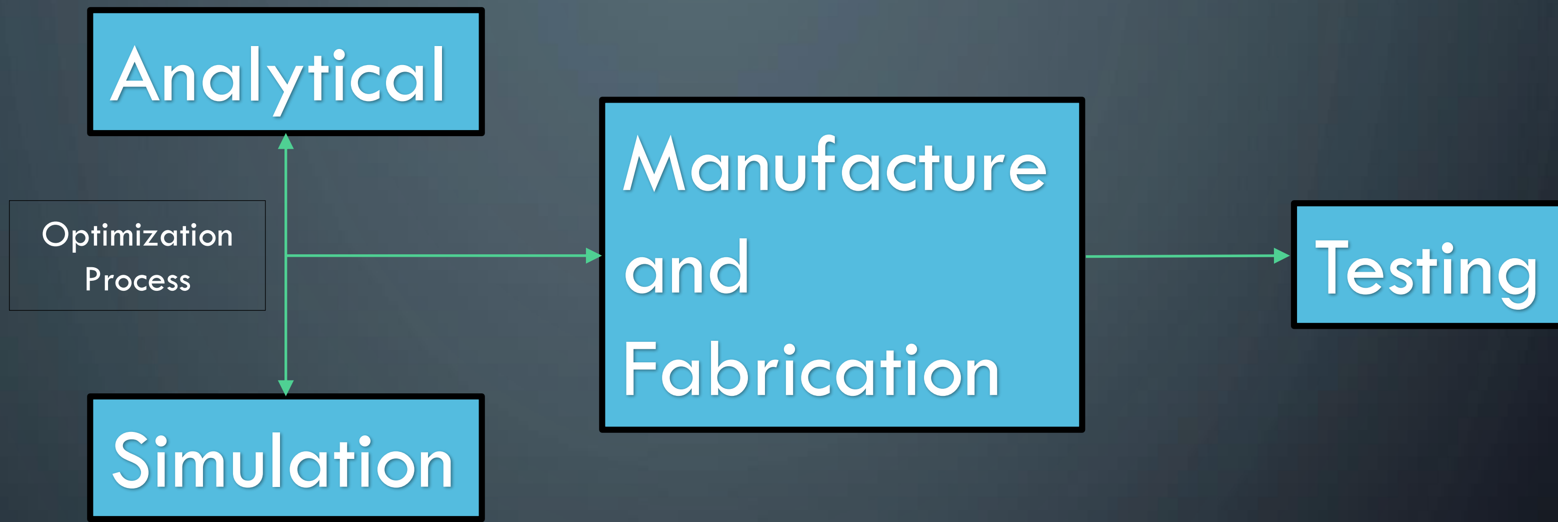
$$\frac{T_0}{T^*} = 1 + \frac{\gamma - 1}{2}(M)^2$$

Area Ratio: $$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1 + \frac{\gamma-1}{2}M^2\right)\right]^{\frac{\gamma+1}{\gamma-1}}$$

Prandtl-Meyer Expansion:

$$\theta = v(\mathrm{M2}) - v(\mathrm{M1})$$

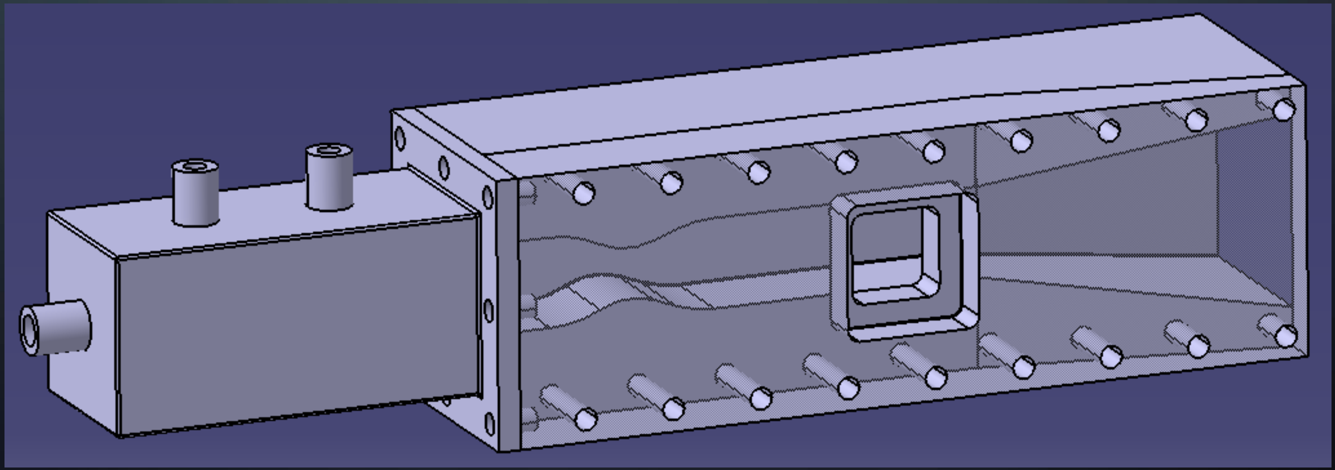
DESIGN PROCESS



- Analytical calculation can be altered based on Simulated results
- Currently in phase 3, manufacturing and fabrication

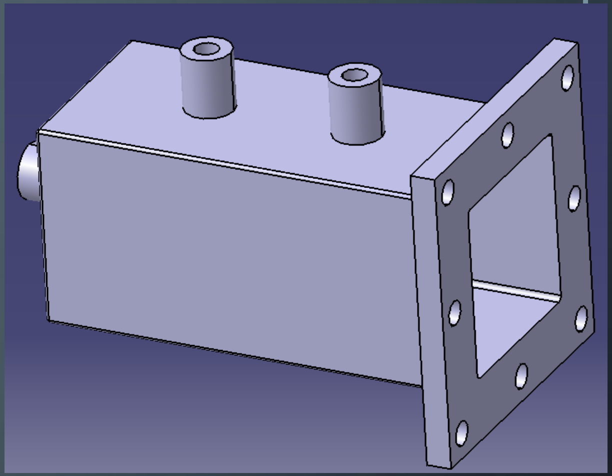
FACILITY SECTIONS

- Compression configuration
- Nozzle
- Testing Chamber
- Viewing Window
- Diffuser

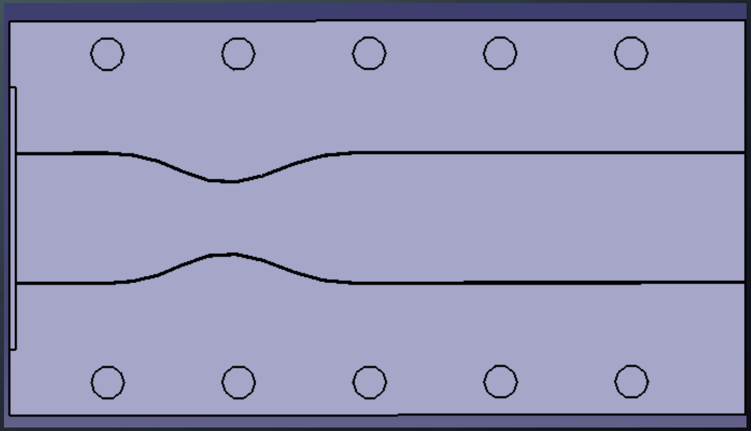


COMPONENTS

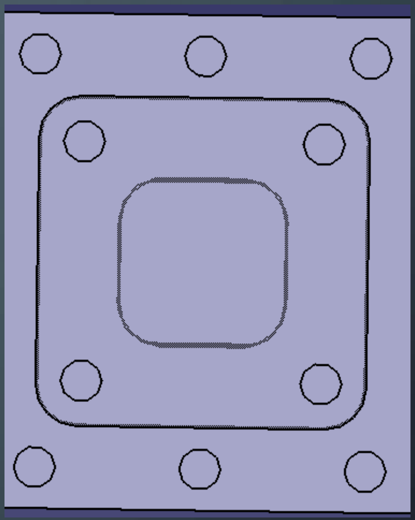
- Compression Configuration
  - Air Regulator
  - Safety Vale and Pressure Gauge
  - Mylar Diaphragm
  - Flange and Gasket



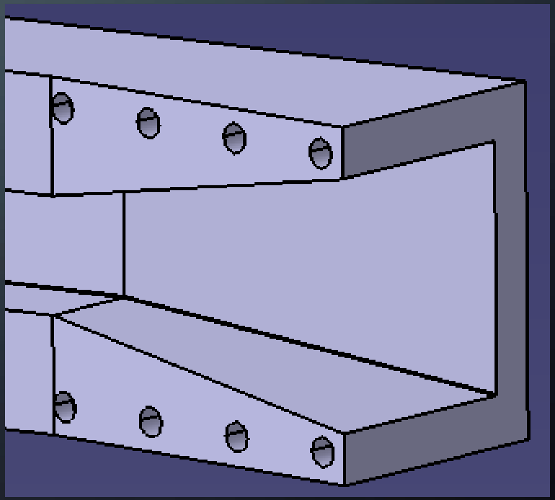
- Nozzle
  - Fixed Design
  - Area Ratio



COMPONENTS CONTINUED…



- Testing Chamber/Viewing Window
  - Desired Mach Value
  - Plexiglass
  - 1” X 1” cross-sectional area

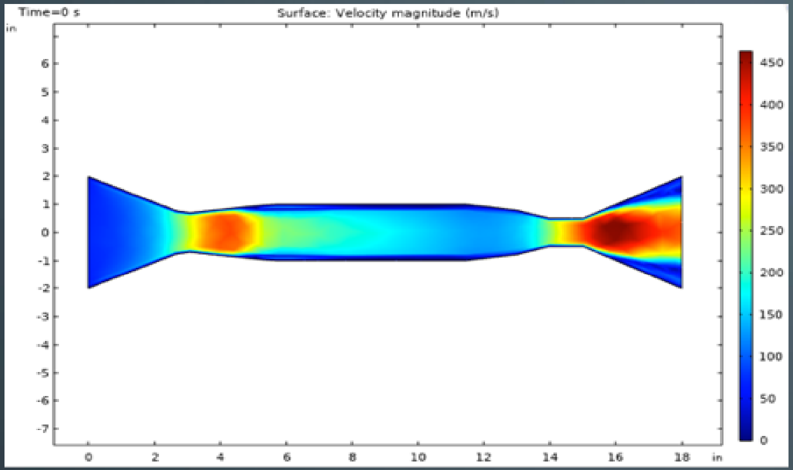


- Diffuser
  - Diverging Outlet
  - 19 degree angle in Y and Z direction
  - Creating an expansion wave

COMSOL MODEL

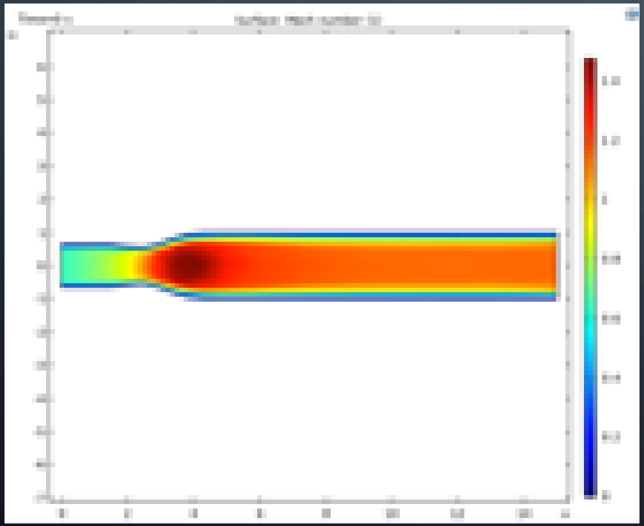
- COMSOL Modules
  - High Mach Number Flow
  - Laminar Flow
  - Turbulent Flow
- Study Condition
  - Transient and Stationary Study
- Post processing
  - Velocity vs Mach
  - Temp vs Area
  - Pressure vs Area

INLET FLOW SIMULATION PROCESS

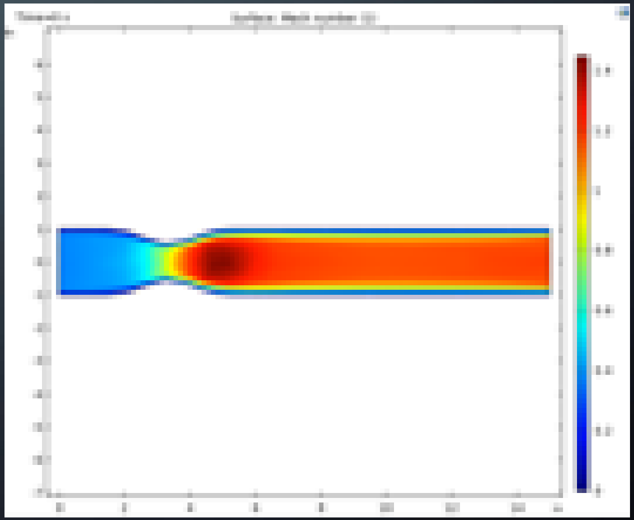


Initial Flow Simulation

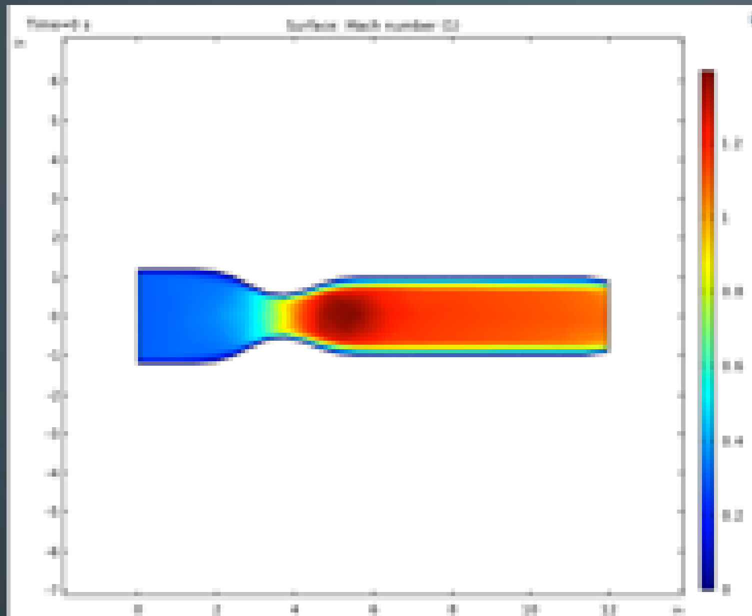
Small area inlet



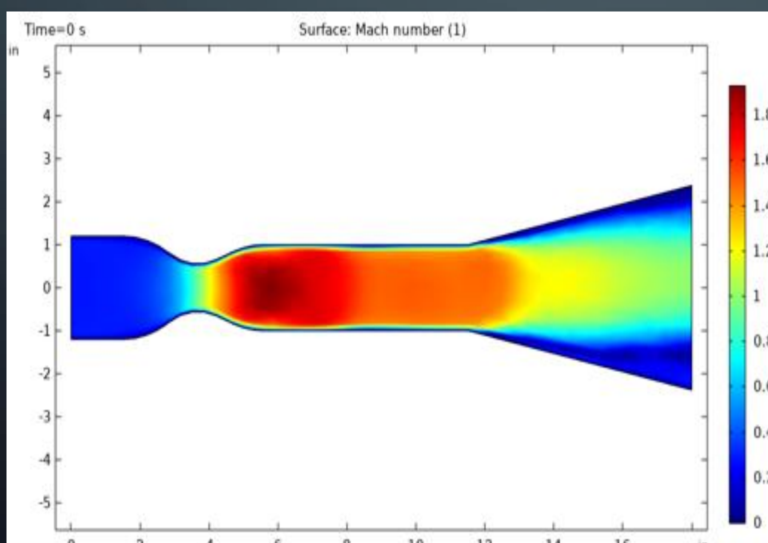
Large area inlet



DIFFUSER FLOW SIMULATION PROCESS



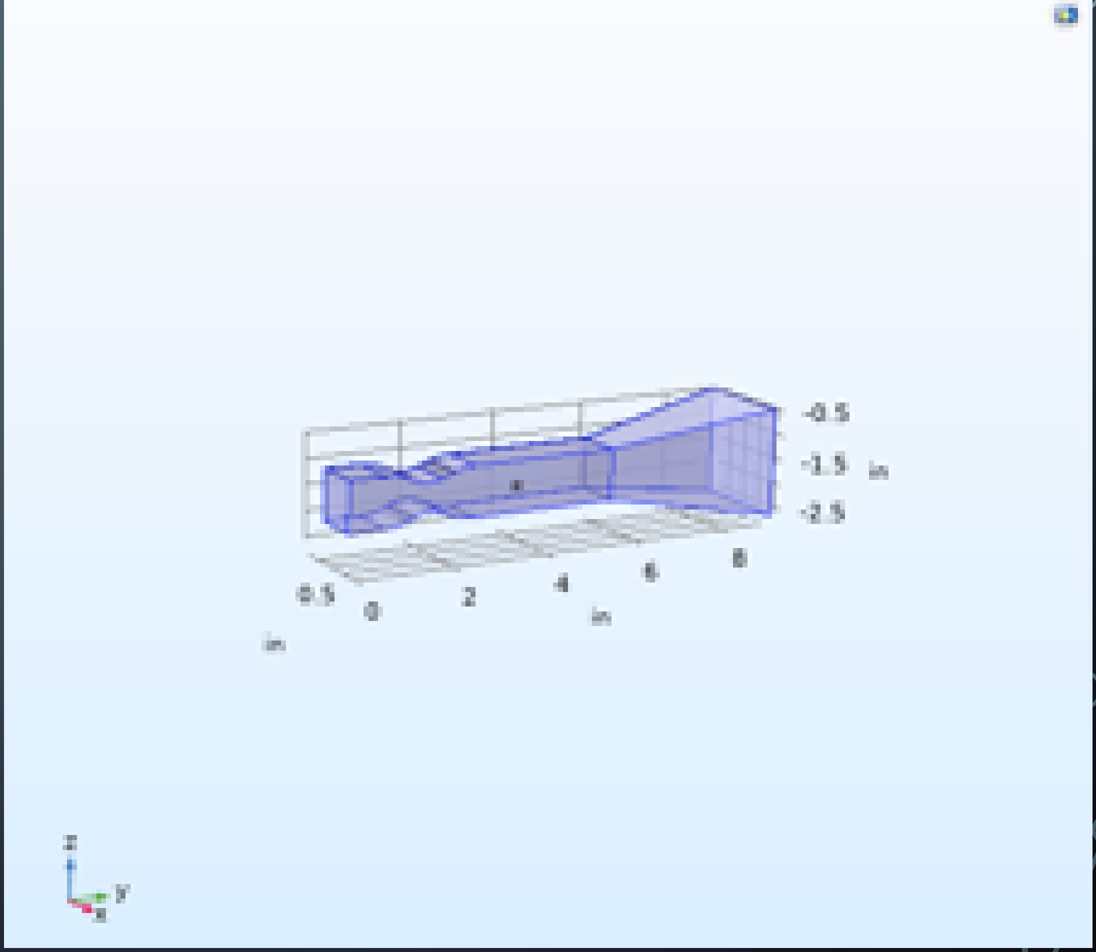
Convergent Duct



Divergent Duct

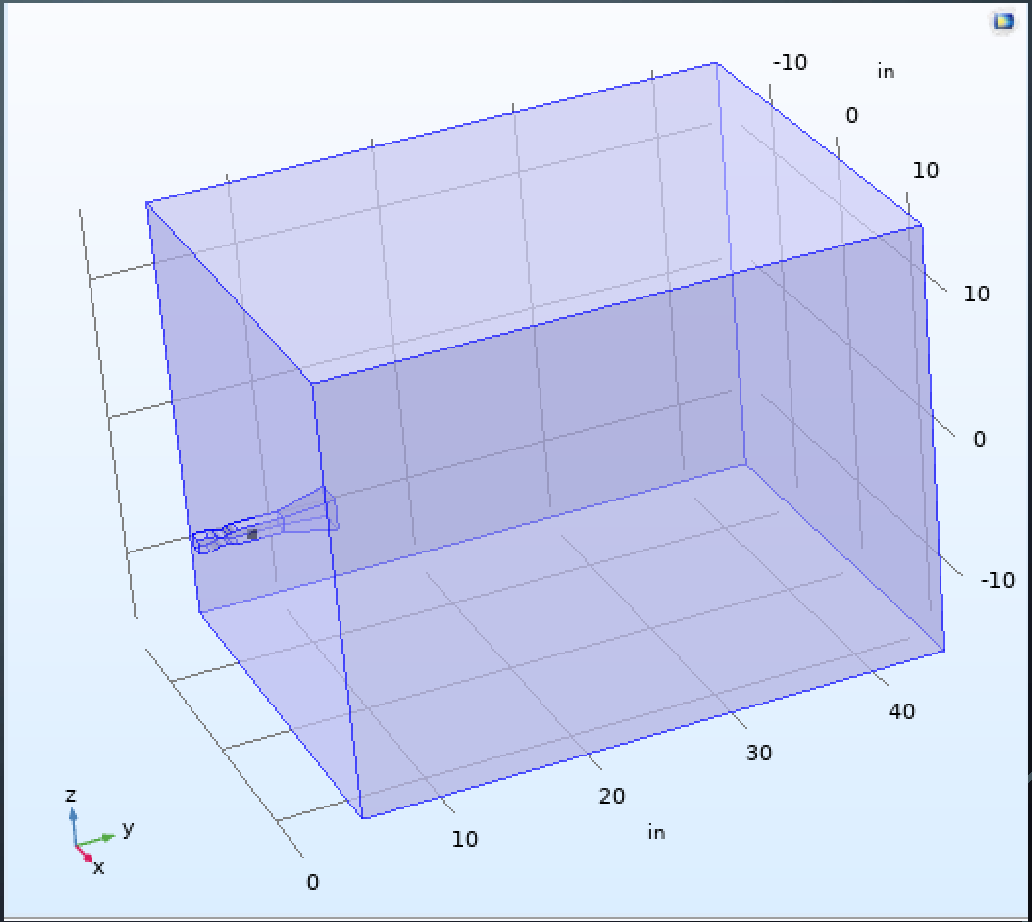
INITIAL SIMULATION ENVIRONMENT

- CFD analysis using 100 psi resulted in high exhaust values.
- A reduction in inlet pressure produced subsonic values around 0.9 Mach in the exhaust



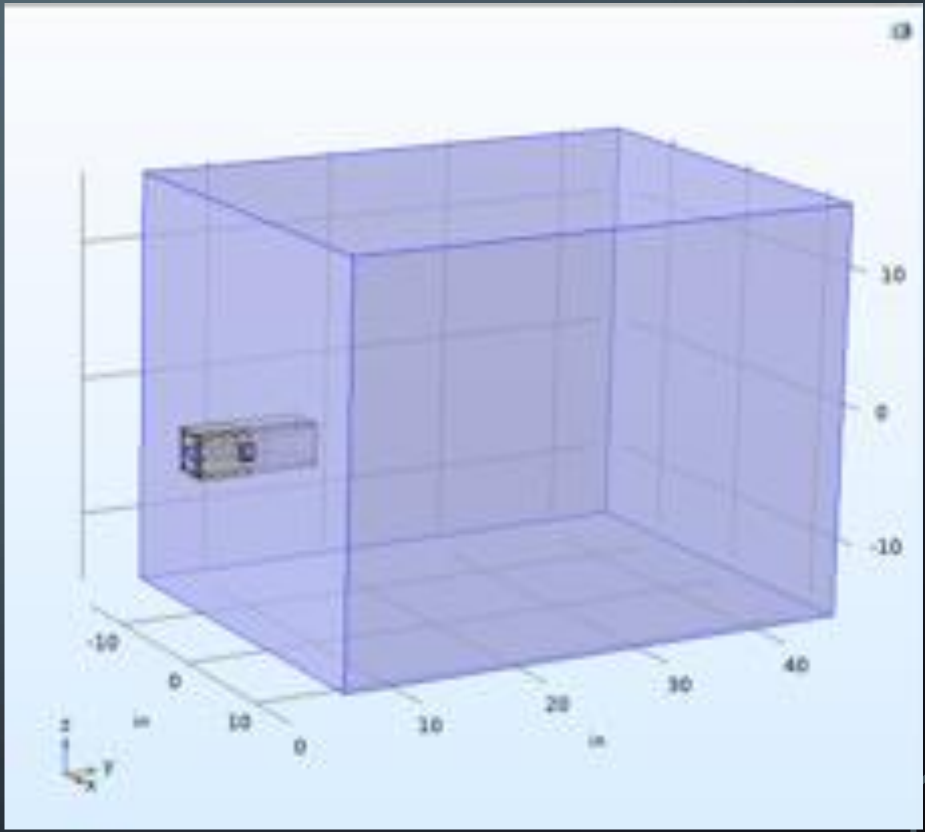
2ND SIMULATION ENVIRONMENT

- An enclosure simulates a better atmosphere, therefore producing more accurate results
- Flow is diffusing at 0.8 Mach at the exhaust



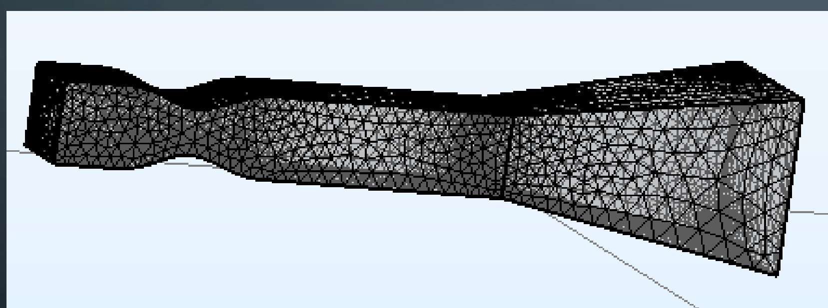
FINAL SIMULATION ENVIRONMENT

- Material applied to negative space, helped to refine results
- Diffusing at 0.25 Mach in the exhaust

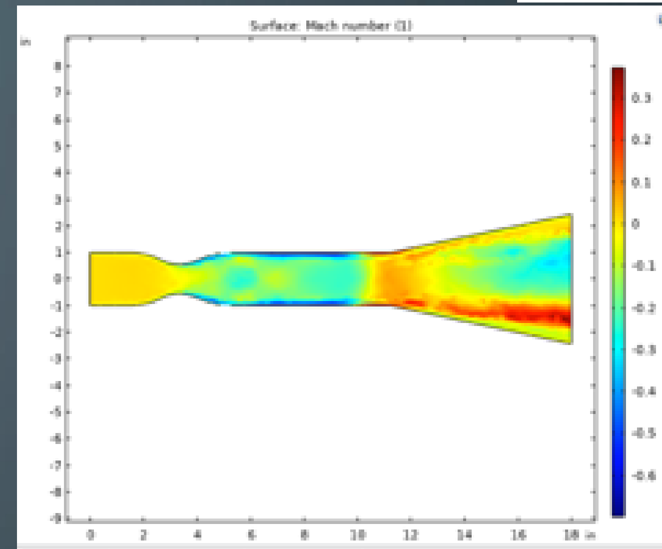


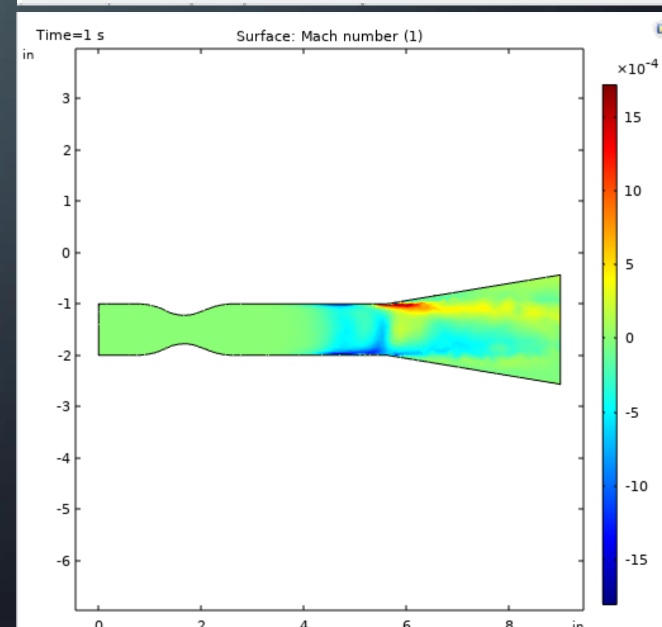
CFD MESH STUDY

- Mesh analysis produces similar results
- The 2nd environment solutions were compared using a mesh analysis ranging from a mesh with 78,713 elements to 1,613,751 elements.
- The final environment were compared consisting of a maximum of 187,613 elements.



(Visual of Meshed CAD model)



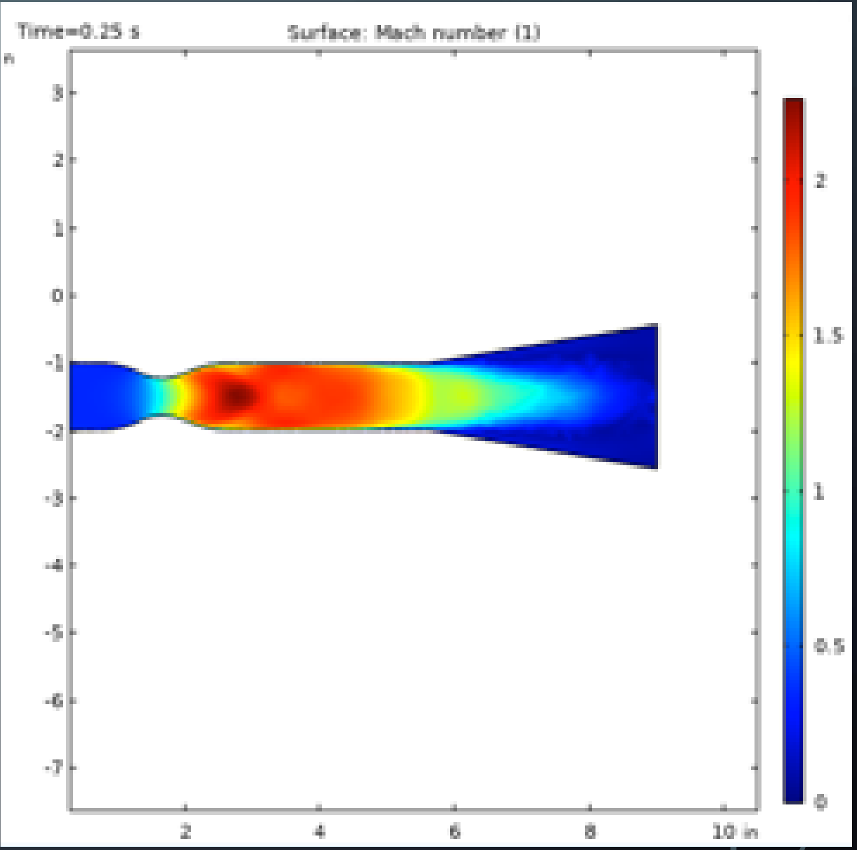


Difference in mesh results from fine to finer, negative space alone (Pictured top right)

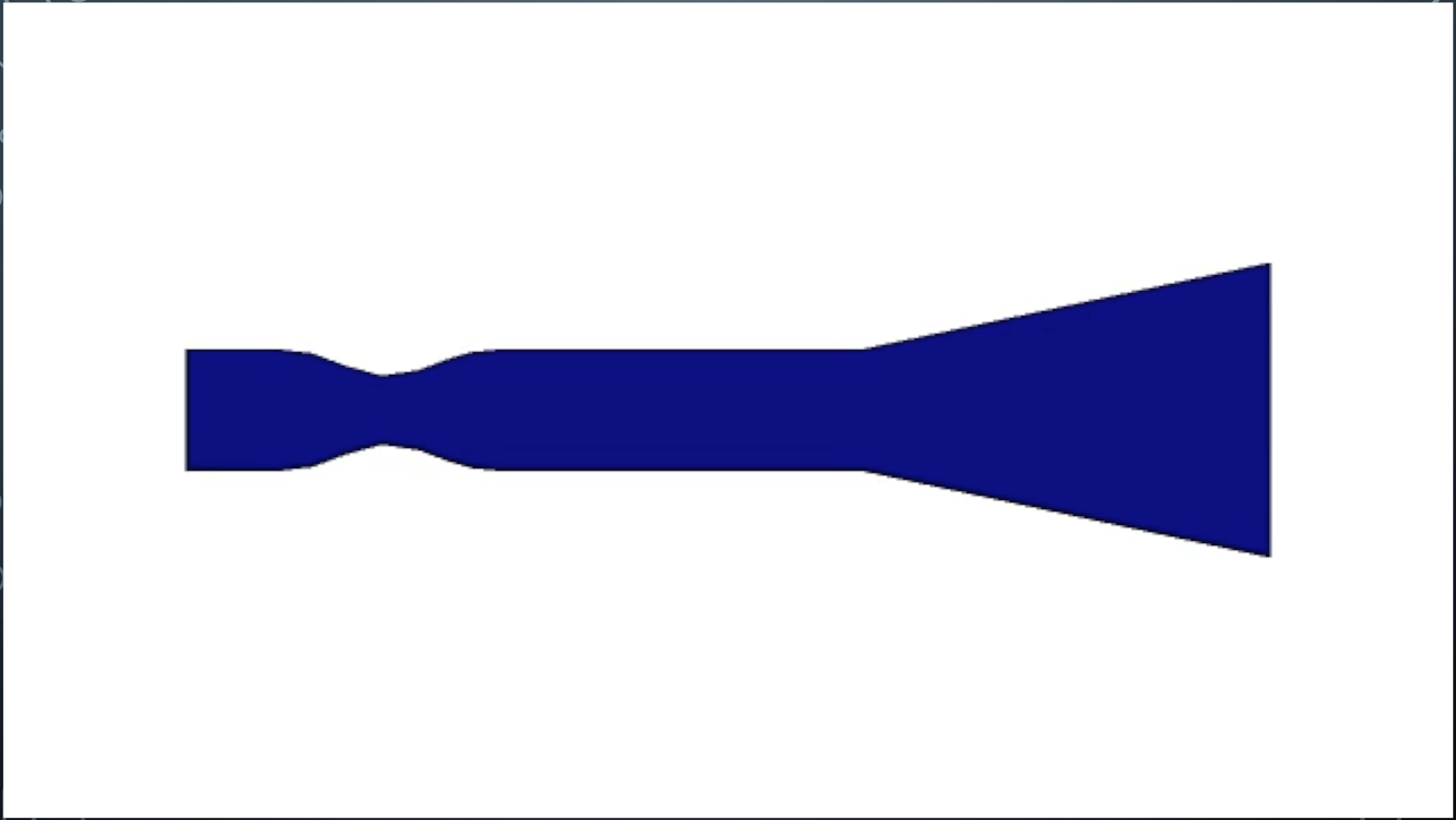
Difference in mesh results from course and normal, material included as well as enclosure (Pictured bottom right)

CFD SIMULATION RESULTS

- Using an enclosure to simulate the environment produced realistic values
- The inlet conditions were set to 70 psi at the inlet and 1 atm at the exhaust.
- Supersonic flow was achieved past the throat of the C-D Nozzle, resulting in a Mach flow of 1.82 at the testing section.

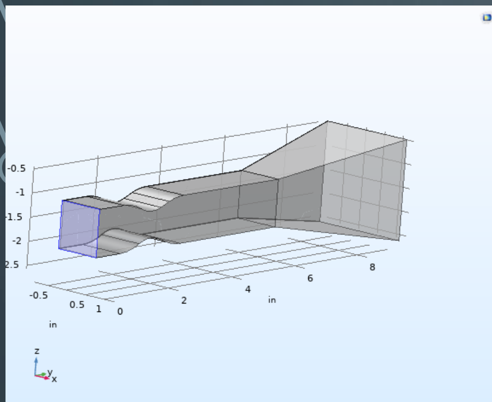


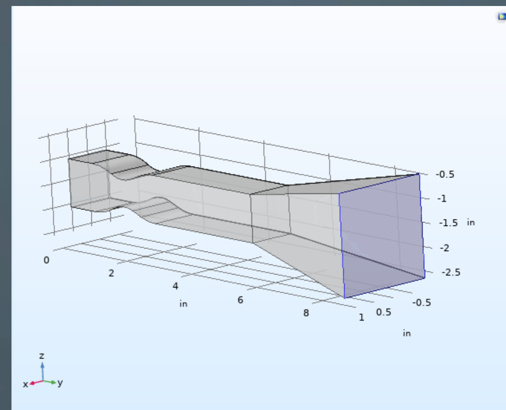
Simulation Video

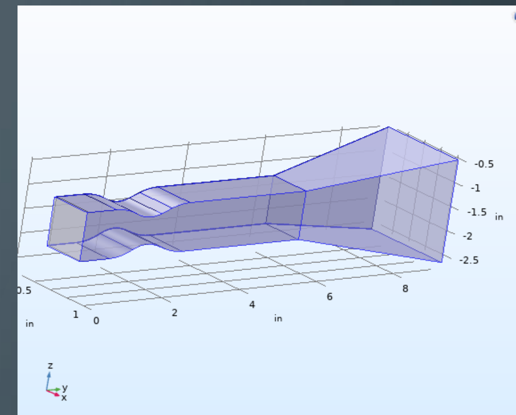


From 0 to 50 milliseconds

FLOW FORCES







- Inlet Force due to Pressure: 198.27N or 44.57 lbf
- Momentum due to inlet: 30.019 N

- Outlet Force due to Pressure: 296.76N or 66.71 lbf
- Momentum due to Outlet: 86.44 N

- Shear Force: 230N or 51.71 lbf
- Difference in Momentum: 56.421 N

	Force (lbf)	Force per bolt (lbf)
Compression Chamber	44.572	5.57
Window	3.63	0.9075
Entire Assembly	225.369	12.52
Total Force	60	

PRESSURE AND TEMP VALUES

	Analytical (Ideal)		Simulated	
Section	Pressure (psi)	Temperature C	Pressure (psi)	Temperature C
Inlet	13.299	12.71	3	-15.487
Throat	7.759	-28.025	2.13	-45.8
Testing Section	2.557	-94.66	0.508	-115.61
Exhaust	7.862	-26.38	0.99	-71.636

SAFETY

- Max temp experiencing in tunnel: 20C
- Min Temp experiencing in tunnel:

-130.6C

- Designed factor of safety is greater than 10
- Critical Mach number associated with oxygen: 3.3637
- Critical Mach number associated with nitrogen: 3.75
- Shear strength of aluminum: 207MPA, 30,000psi
- Melting point of Aluminum: 582-652C

GASKET

- High Density
- Non-Asbestos Fiber
- Gasket max psi rating: 750-1500 psi

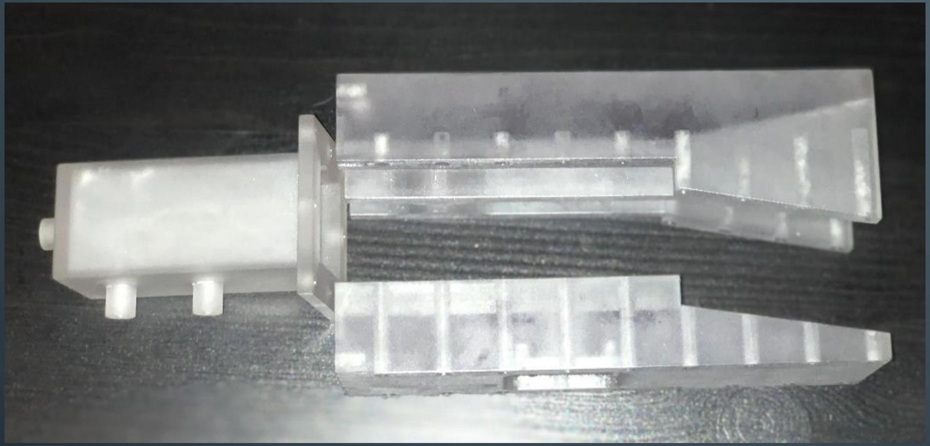
Bolts

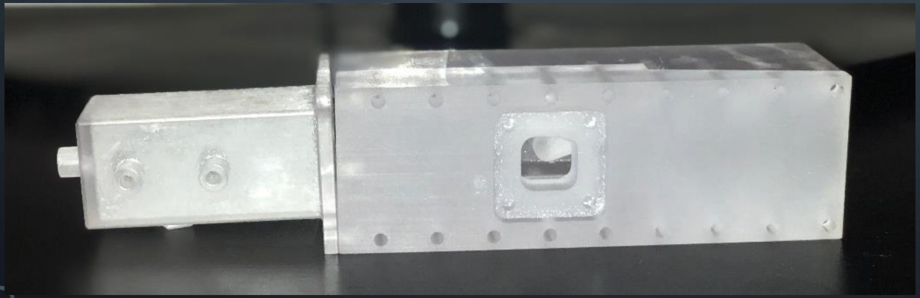
- Steel zinc coated
- Grade 5 rating
- Proof Load 85,000 psi

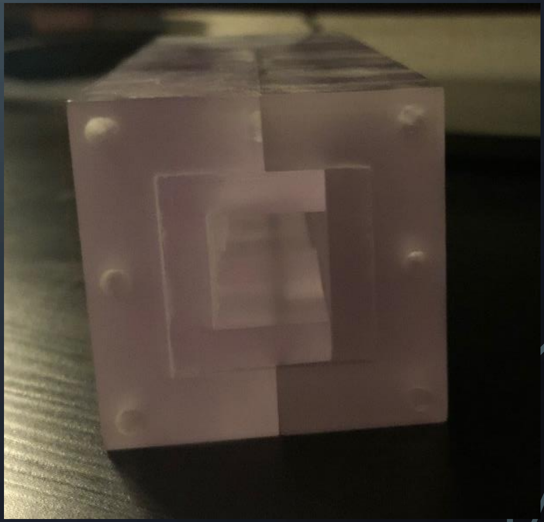
CHALLENGES

- Design Process
- Dehumidification
- Uniform Inlet Flow
- Convergent-Divergent Nozzle
- Diffusing the Flow
- Sealing the Tunnel (In Progress)
- Rupture Diaphragm (In Progress)

3D PRINTED MODEL

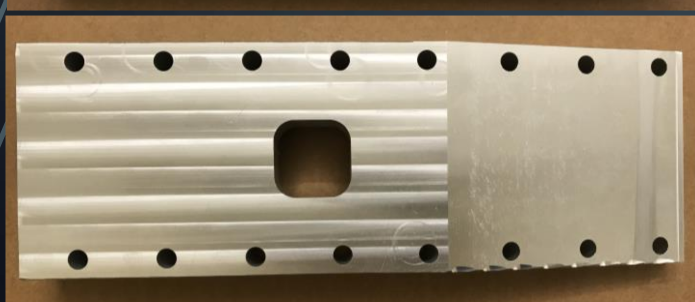


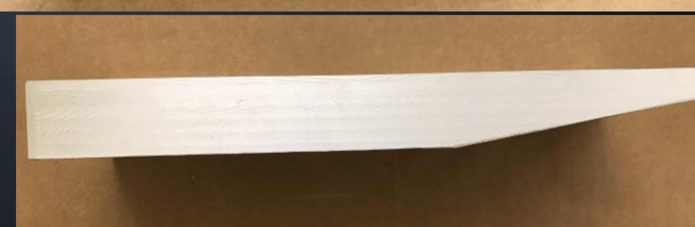




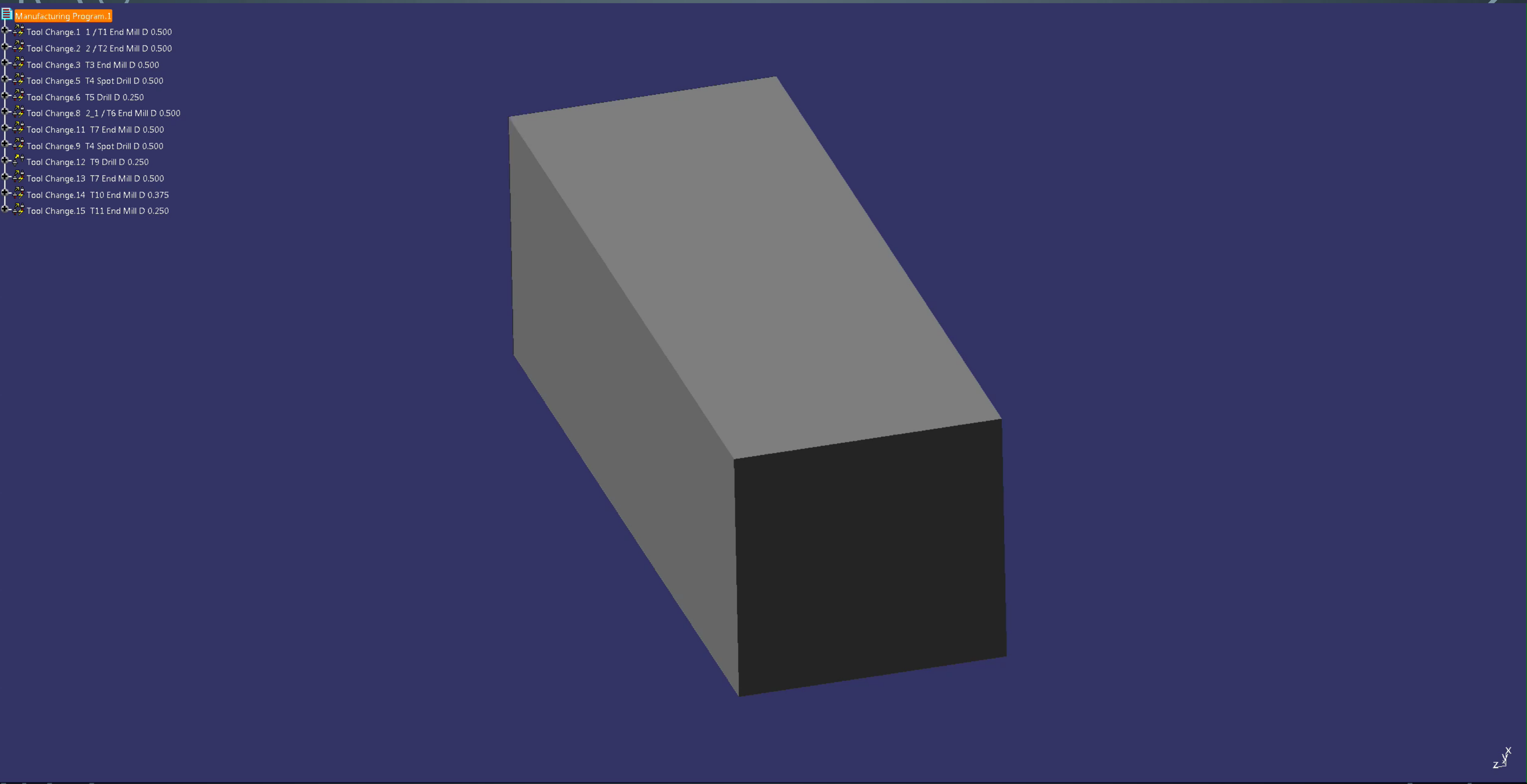
FABRICATION

VaughnCollege





CAM Video


Manufacturing Program.1
Tool Change.1 1 / T1 End Mill D 0.500
Tool Change.2 2 / T2 End Mill D 0.500
Tool Change.3 T3 End Mill D 0.500
Tool Change.5 T4 Spot Drill D 0.500
Tool Change.6 T5 Drill D 0.250
Tool Change.8 2_1 / T6 End Mill D 0.500
Tool Change.11 T7 End Mill D 0.500
Tool Change.9 T4 Spot Drill D 0.500
Tool Change.12 T9 Drill D 0.250
Tool Change.13 T7 End Mill D 0.500
Tool Change.14 T10 End Mill D 0.375
Tool Change.15 T11 End Mill D 0.250

FUTURE WORK

- Testing thickness of Mylar
- System that includes a test object and changes the angle of attack
- System that records the velocity - such as PIV
- System that captures the behavior of the flow – such as Schlieren Photography
- Development of anchoring system for the tunnel

CONCLUSION

- The analysis of the Supersonic Wind tunnel is conducted using COMSOL Multiphysics, along with analytical calculation for the geometry configuration, and a mesh conversion study to produce more accurate results.
- A Small-Scale Supersonic wind tunnel is designed for an inlet pressure of 70 psi which produces supersonic flow at speeds of Mach 1.82 in the testing chamber while diffusing the flow to subsonic at Mach 0.25 in the exhaust.

QUESTIONS?

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REFERENCES

- [1] Chang, Wilbur. Design and development of a rectangular supersonic wind tunnel facility for the study of shock/boundary layer interactions.2011, pp. 1–140
- [2] Anderson, John D. Fundamentals of Aerodynamics. McGraw Hill Education, 2017.
- [3] “Application Gallery.” COMSOL, www.comsol.com/models.
- [4] Diep, Francie. “Why Having A Liquid Nitrogen Pool Party Is A Bad Idea.” Popular Science, 20 June 2013, www.popsci.com/science/article/2013-06/why-having-liquid-nitrogen-pool-party-bad-idea.
- [5] Frank M. White. (2009). Fluid Mechanics 7th edition. New York: McGraw-Hill.
- [6] K. Butler, D. Cancel, B. Earley, S. Morin, E. Morrison, M. Sangenario (2010). Design and Construction of a Supersonic Wind Tunnel- WPI
- [7]“Atmosphere of Earth.” Wikipedia, Wikimedia Foundation, 2 Mar. 2019, en.wikipedia.org/wiki/Atmosphere_of_Earth.
- [8] NASA Online Resource (2019) – https://www.grc.nasa.gov/www/k-12/airplane/tunnozd.html
- [9] Bhavin K Bharath, Design and Fabrication of a Supersonic Wind Tunnel (IJEAS), ISSN: 2394-3661, Volume-2, Issue-5, May 2015
- [10] F. Ommi, V. Farajpour Khanaposhtani, M. Agha Seyed Mirzabozorg, K. Nekoufar, A New Approach for Supersonic Diffuser Design (Journal of Applied Sciences Research, 6(5): 401-414, 2010)