Structural System Design and Analysis for a Liquid Propellant Rocket

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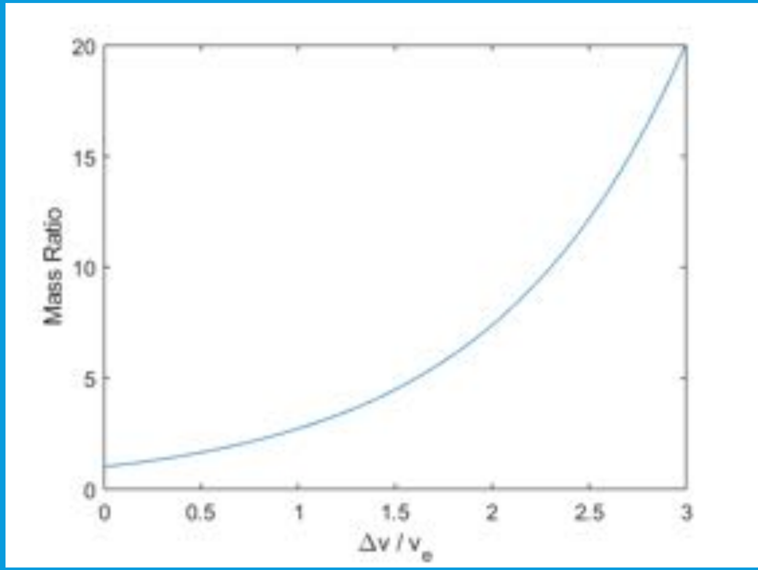
Home Institution: **UMBC** Host Institution: **MSU**

INTRODUCTION & BACKGROUND

- **Goal:** Design a liquid bi-propellant rocket capable of reaching an apogee of 13,000 ft. (MSU Base 11 Program)
- Liquid propellant launch vehicles are extremely relevant right now
- This project focuses on clean sheet structural design
- Structural design is a difficult problem
- "Tyranny of the rocket equation"

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln\left(\frac{m_0}{m_f}\right)$$

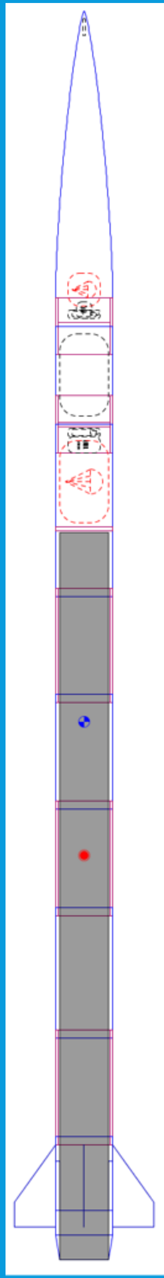


CONCEPTUAL DESIGN

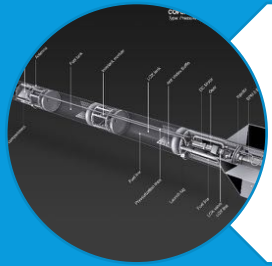
- Optimization goal: Maximize apogee
- Criteria:
  - Minimize gross liftoff weight (GLOW)
  - Increase mass ratio
  - Minimize drag
  - Simplicity

While ensuring structural integrity & aerodynamic stability

- Challenges:
  - Propulsion system in development
  - Minimal starting constraints and highly coupled variables
- Analytical solutions: **OpenRocket** design tool used for trajectory simulation



AIRFRAME DESIGN



Case Study

Preliminary Modelling

Propulsion Data

- Diameter: driven by propulsion system dimensions
  - Comparable rockets - 6-10 inches
- Length: driven by propulsion system and other mission system lengths
  - Comparable rockets - 10-18 ft
- A diameter of 7 inches was chosen for further development

ENGINE SIMULATION

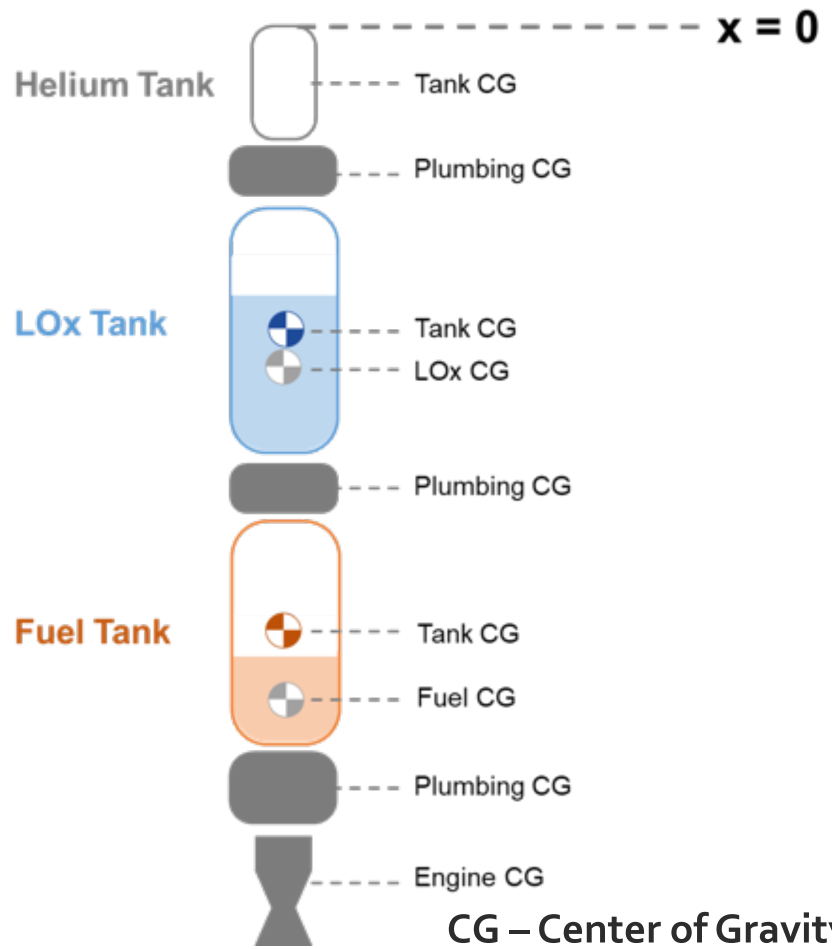
- Lack of complete propulsion system to base design around.
- EngineSim python script:
  - Allows batch testing for different fuel types and burn times.
  - Validation of diameter choice and estimation of propulsion system length

Input: Basic propulsion system parameters	
• I_{sp}	• O/F ratio
• ρ_{fuel}, ρ_{ox}	• Thrust
• Tank pressure	• radius

Output: Dimension data and Engine File
• Tank lengths and thickness
• $x_{CG}(t)$
• Engine File for OpenRocket

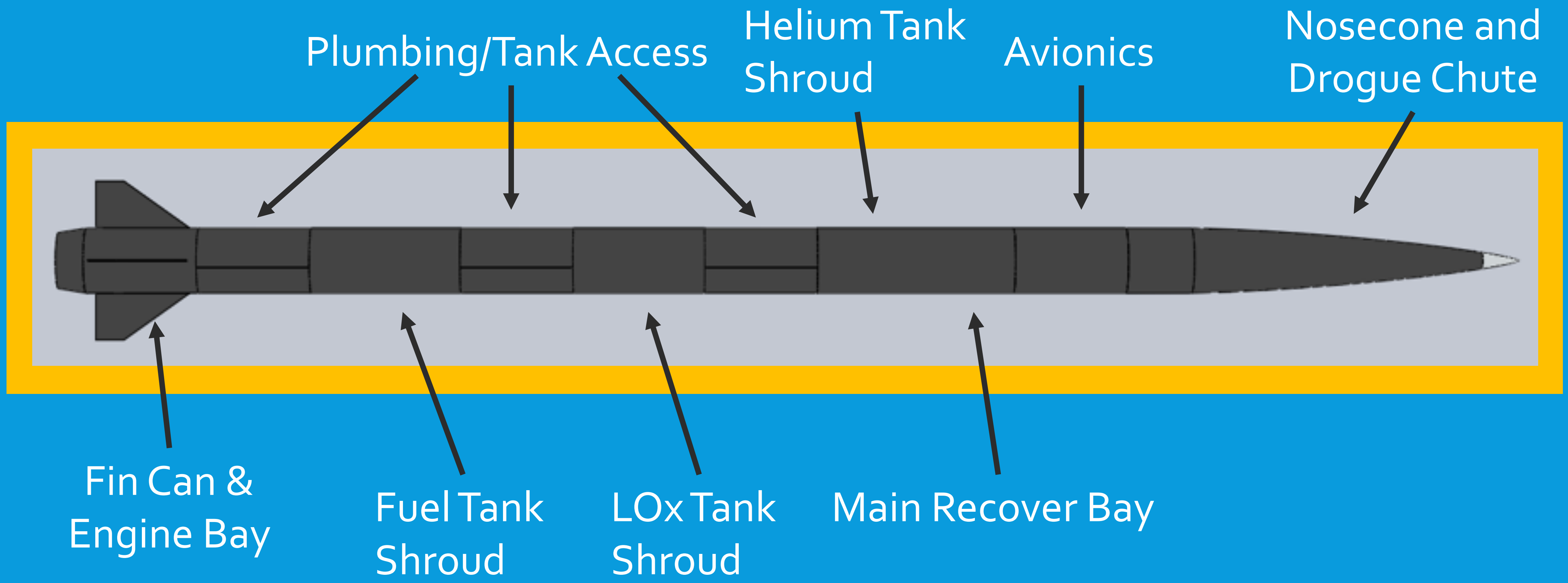
- Proceed with LOx-Ethanol propellant combination with 10s burn time
  - System Length: ~ 80 inches

Liquid Engine mass model:



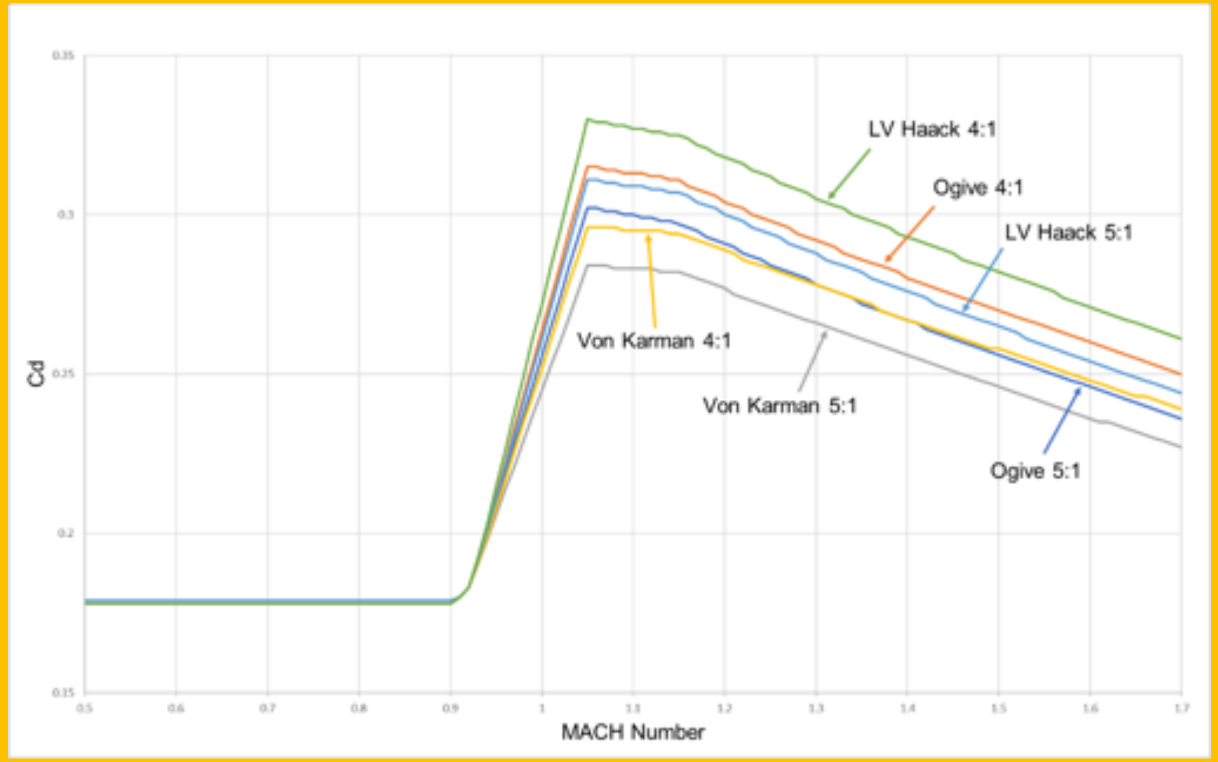
CG – Center of Gravity

CONFIGURATION

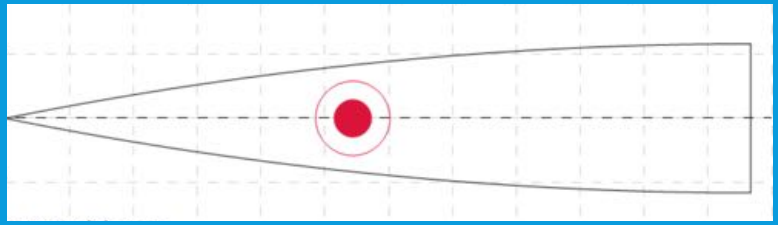


AERODYNAMICS - NOSECONE

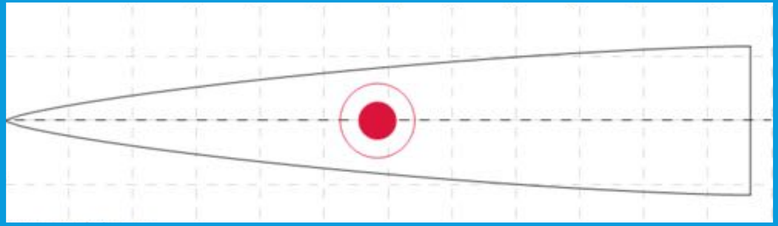
- Purpose: minimize aerodynamic drag of the rocket
- Design Parameters: Shape and Fineness ratio
- Ideal nosecone shape is dependent on operational speed of the rocket
- CFD Testing in RASAero II used for selection
- Von Karman with 5:1 fineness ratio chosen



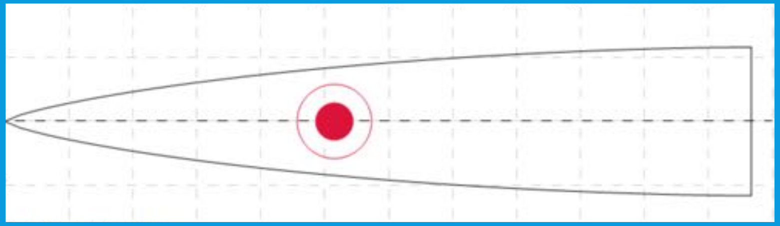
Ogive



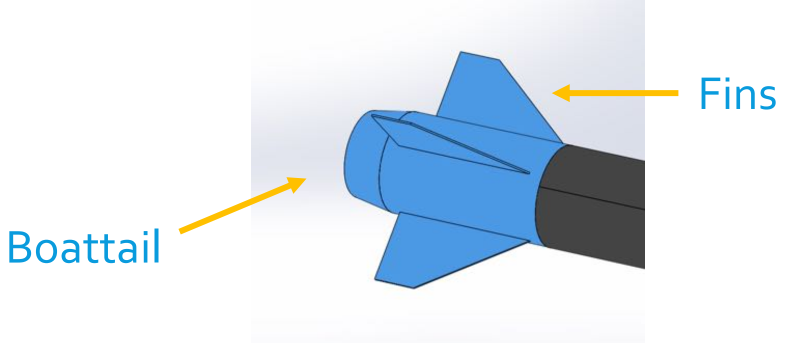
Von Karman



LV Haack

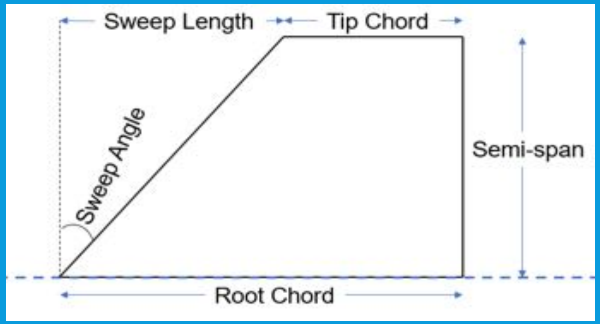


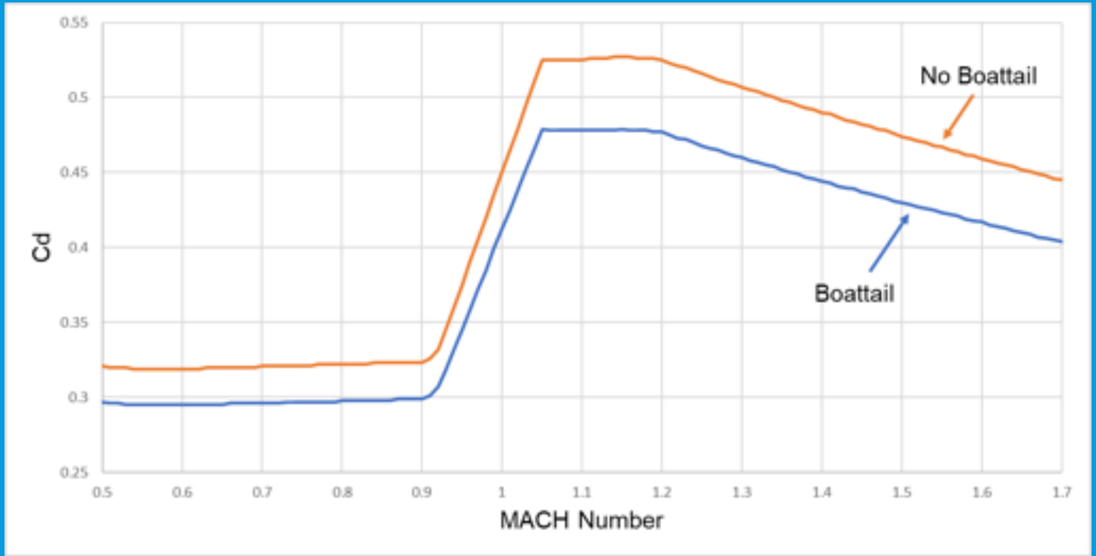
FINS AND BOATTAIL



- Fins size driven by stability vs. drag tradeoff
  - 1.5+ calipers of stability requirement
- 4 fin clipped delta design selected
  - Allows smaller fins and ease of installation at cost of increased interference and skin drag.
  - ideal shape for drag reduction in operational speed range
- Specific fin shape chosen using design “rules of thumb” with iterative OpenRocket simulations
- Boattail – reduces base drag
  - Estimated over 1,000 ft apogee increase through drag reduction

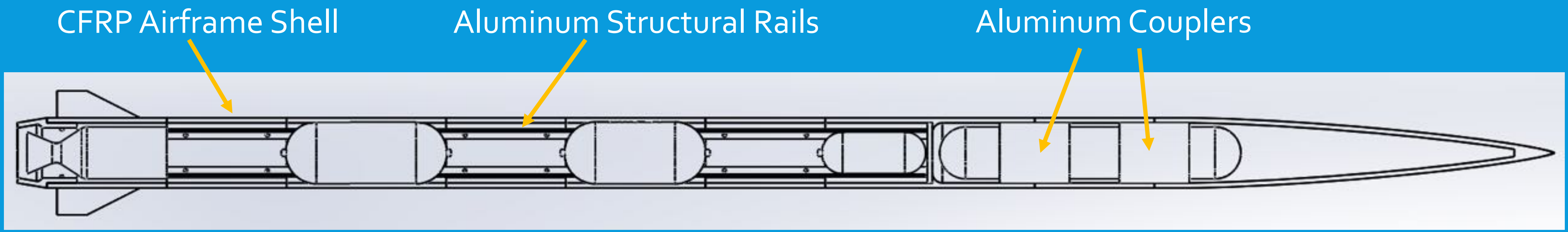
Root Chord	10 inches
Tip Chord	3 inches
Semi-Span	5 inches
Sweep Length	7 inches
Sweep Angle	54.5º





STRUCTURES - METHOD

- Goal: Ensure structural integrity of system, while minimizing weight
- Number of airframe sections
  - Increased modularity and access to missions systems vs. increased airframe stiffness
- Large number of airframe sections needed for liquid propulsion system
  - Tank and plumbing access
- Semi-Monocoque method selected

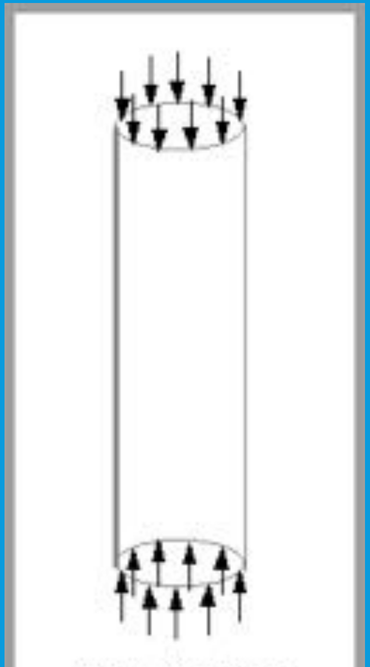


AIRFRAME AND BULKHEAD ANALYSIS

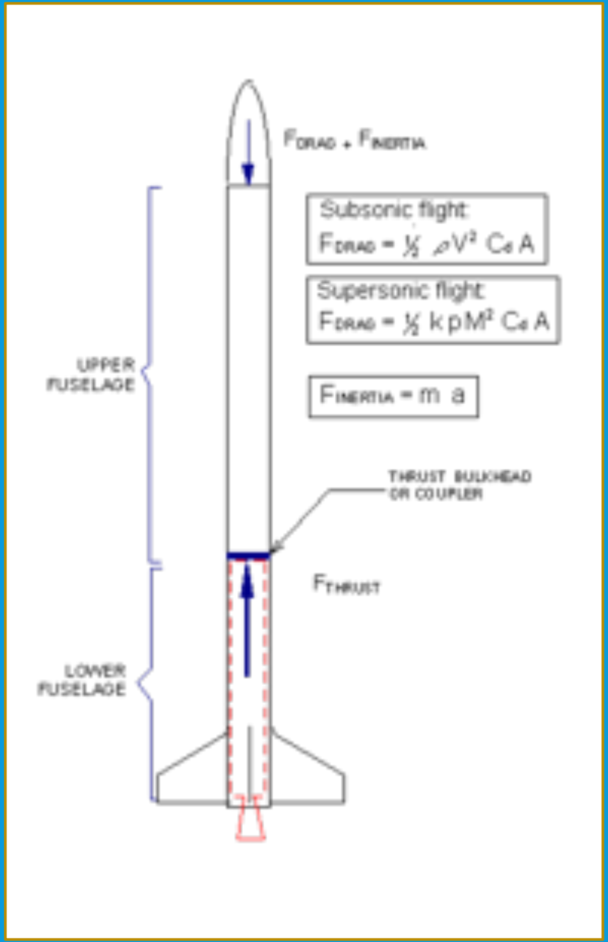
- Forces on the rocket: thrust, drag, gravity
- Airframe sections and structural rails in axial compression at $\alpha = 0$
- At nonzero angle of attack, bending moment becomes important

  Max Q $\quad Q = \frac{\rho v^2}{2}$

- Special Cases:
  - Thrust Bulkhead – circular plate centrally loaded
  - Recovery Couplers
  - Airframe Pressurization



Thin-walled cylinder loaded in axial compression



FUTURE WORK

- More robust structural analysis using MATLAB
- Fin flutter analysis
- Integration
  - Propulsion system
  - Recovery hardware
  - Structural rail attachments on tanks couplers
- Structural analysis for composites

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ENGINE SIMULATION DETAILS

Tank Thickness Calculation:

$$\sigma_{design} = \frac{\sigma_{yield}}{FOS}, \qquad t_{tank} = \frac{P \cdot r_{tank}}{\sigma_{design}}, \qquad r_{tank} > 10 \cdot t_{tank}\ for\ thin\ walled\ pressure\ vessel\ assumption$$

Propellant Mass Calculation:

$$\dot{m} = \frac{Thrust}{g_0 \cdot I_{sp}} \rightarrow \dot{m}_{ox} = \frac{\dot{m}}{1 + \left(\frac{1}{OF}\right)}, \dot{m}_{fuel} = \frac{\dot{m}}{1 + OF} \rightarrow \boldsymbol{m_{ox}} = \dot{m}_{ox} \cdot (Burn\ Time), \boldsymbol{m_{fuel}} = \dot{m}_{fuel} \cdot (Burn\ Time)$$

$Use\ oxidizer\ and\ fuel\ masses\ to\ calculate\ respective\ tank\ lengths\ using\ cylinder\ volume$

$Assume\ Ullage\ tank\ volume\ is\ 10\%\ of\ total\ propellant\ tank\ volume$

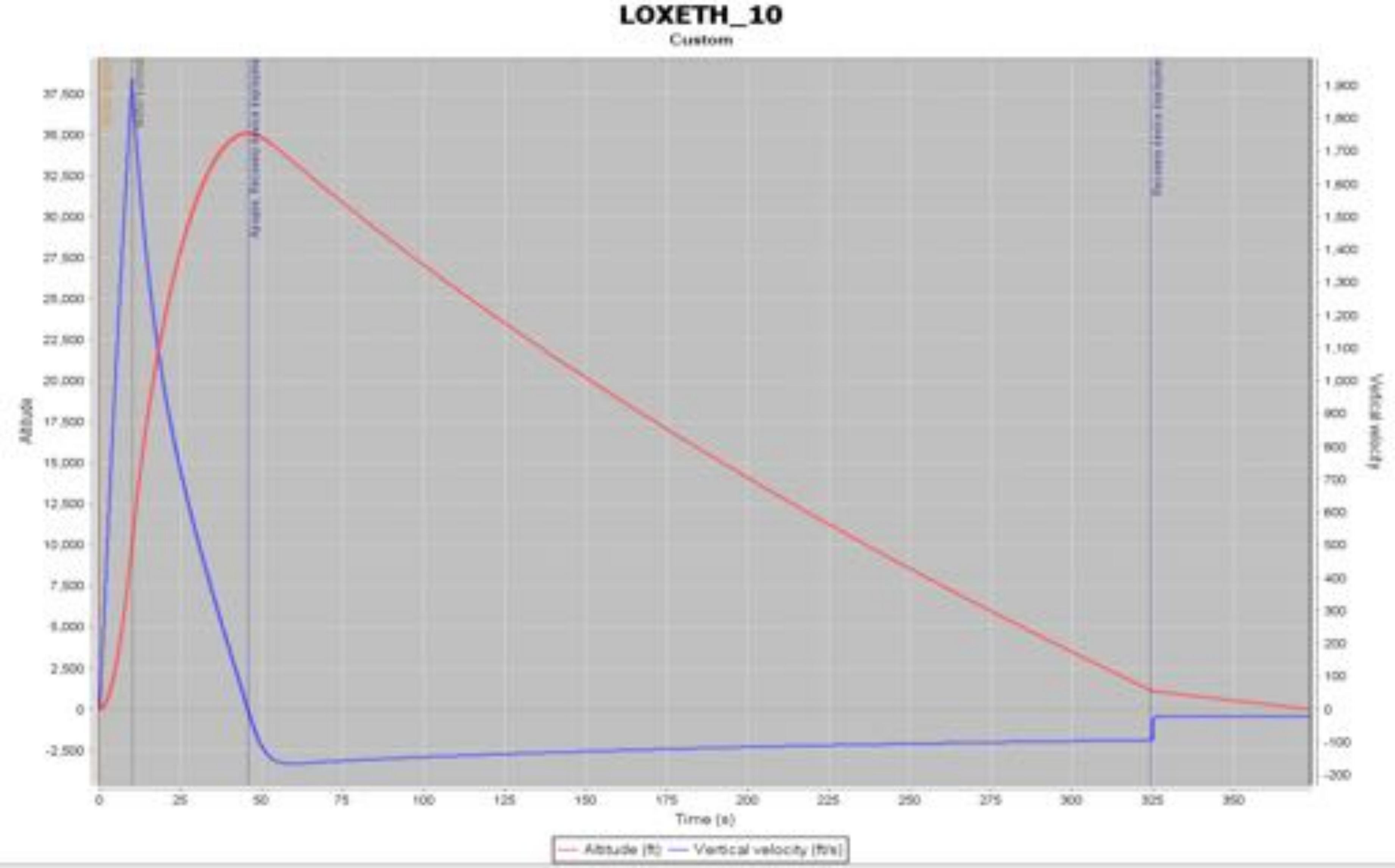
$$l_{propulsion} = l_{Ullage} + l_{plumb1} + l_{LOx\ Tank} + l_{plumb2} + l_{Fuel\ Tank} + l_{plumb3} + l_{Engine}$$

Center of Gravity Calculation:

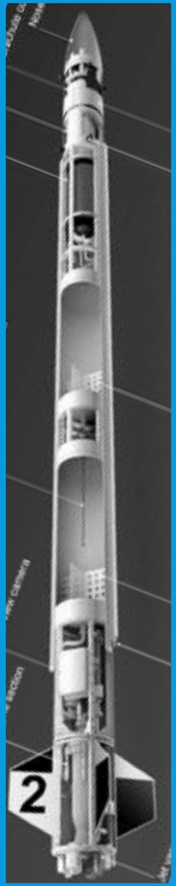
$$x_{CG,dry} = \frac{1}{m_{dry}}(m_{ullage} \cdot x_{CG,ullage} + m_{plumb1} \cdot x_{CG,plumb1} + m_{LOx\ Tank} \cdot x_{CG,LOx\ Tank} + m_{plumb2} \cdot x_{CG,plumb2} + m_{Fuel\ Tank} \cdot x_{CG,Fuel\ Tank} + m_{plumb3} \cdot x_{CG,plumb3} + m_{Engine} \cdot x_{CG,Engine}$$

$$\boldsymbol{x_{CG}(t) = \frac{1}{m(t)}(m_{dry} \cdot x_{CG,dry} + m_{LOx}(t) \cdot x_{CG,LOx}(t) + m_{Fuel}(t) \cdot x_{CG,Fuel}(t)}$$

FLIGHT SIMULATION



CASE STUDY SAMPLE



Copenhagen SO
NEXO II
Length: 22 ft
Diameter: 11.8 in
Propellants: LOx/Eth
Apogee: 46 kft

UCSD
Vulcan I
Length: 19 ft
Diameter: 8 in
Propellants: LOx/RP-1
Apogee: 4 kft

UCSD
Vulcan II
Length: unknown
Diameter: 8 in
Propellants: LOx/RP-1
Apogee: 40 kft (goal)

UCLA
Vulcan II
Length: 15.2 ft
Diameter: 7 in
Propellants: LOx/Eth
Apogee: 14.6 kft

3D PRINTING ROCKET LAYOUT – TANGIBLE DESIGN