Design and Analysis of a Cold Gas Propulsion System for Stabilization and Maneuverability of a High Altitude Research Balloon

College of Engineering & Applied Sciences Senior Design Thesis

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Objective

Design a propulsion system to stabilize a high altitude research balloon and provide means of anti-rotation via yaw control

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Design Considerations

- FAA regulations
  - 2.72 kg limit for a single payload
  - 5.44 kg total
- Jet stream
- Temperatures and pressures at altitude
- Amount of thrust needed
- Time of system operation

Propulsion System Selection

- Propeller – low-density medium at high altitudes
- Solid Rocket Engines – inability for instantaneous control
- Chemical Combustion – volatile and high-density fuel
- **Cold Gas Propulsion – feasible**

Basics of Cold Gas Propulsion

- Releasing a compressed gas (N2, CO2, AIR, etc) through a nozzle
  - e.g, Exhausting fire extinguisher while sitting in a rolling chair.
- Nitrogen (N_2) gas was selected
- Nitrogen has an average specific heat
- Abundant, ethically validated
- Hydrogen has a specific heat almost 14x that of Nitrogen but is highly combustible

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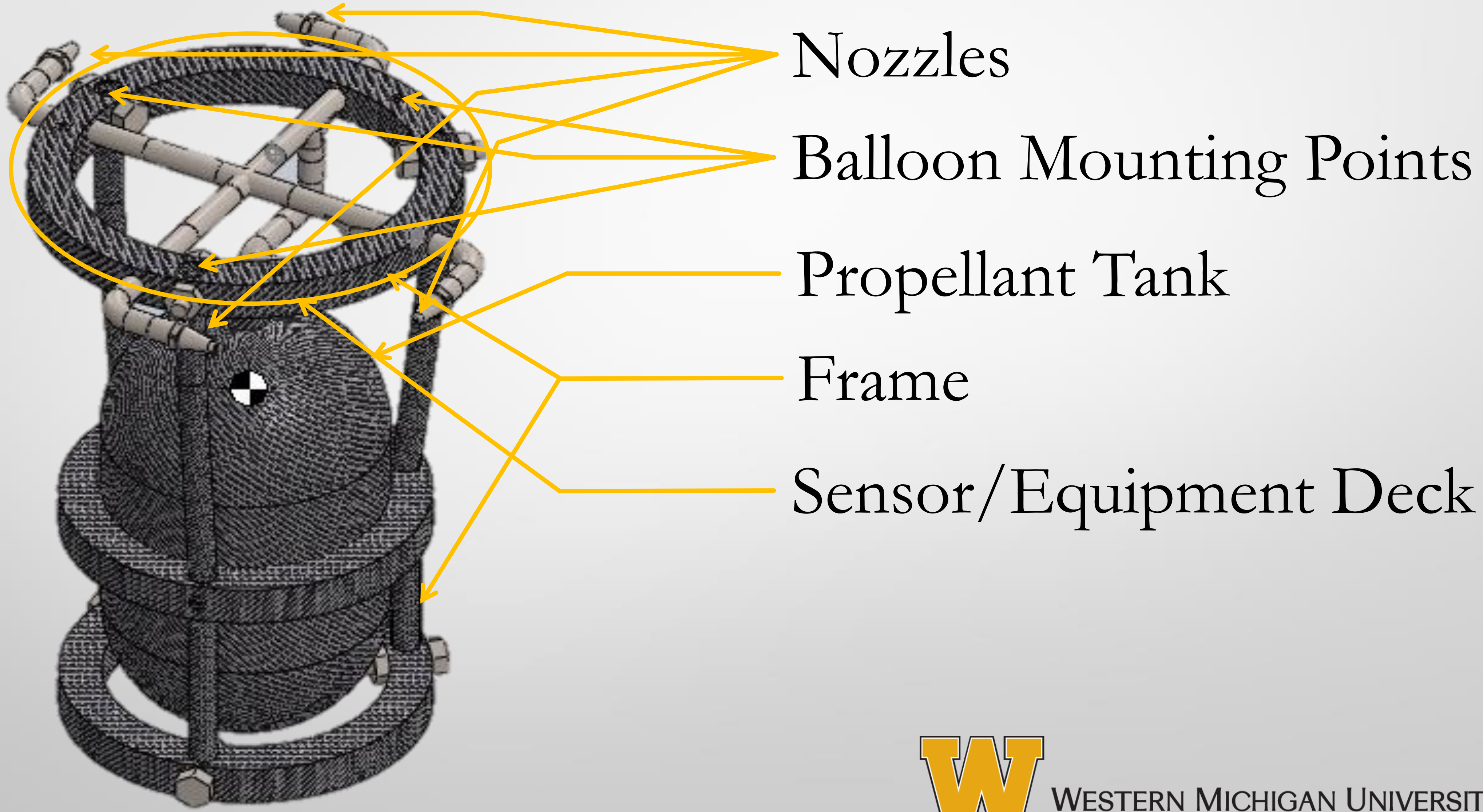
Concept Selection Evaluation Design for Cold Gas Propulsion System *Western Michigan University* *College of Engineering & Applied Sciences* Mitch Brownell Greg Neff Ryan Savard						
Design Concepts	Concept Reference Number		1.a	2.a	3.a	4.a
	Gas/Propellant		Nitrogen	Nitrogen	Nitrogen	Carbon Dioxide
	Thruster Material		410 Stainless Steel	410 Stainless Steel	410/NACE Stainless Steel	410/NACE Stainless Steel
	Other Design Notes		Converging Custom Propellant Tank	Subsonic, Converging/Diverging Custom Propellant Tank	Converging Modular Propellant Tank	High Pressure Converging Custom Tank
Rating Summary	**OVERALL DESIGN RATING**		**82.91**	**66.05**	**73.00**	**67.54**
	Geometric/Design Rating		85.06	65.08	70.52	61.52
	Cost/Quality Rating		79.68	67.51	76.73	76.58
Design Parameters/Conditons						
Ref No.	Description of Design Parameter	Importance Factor				
1	**Manufacturability/Producability**		**73.6**	**74.5**	**77.3**	**83.6**
1.1	Ease of material access	4	8.0	10.0	9.0	9.0
1.2	Part Complexity	7	7.0	6.0	7.0	8.0
2	**Thrust Maximization**		**83.2**	**68.8**	**58.4**	**70.4**
2.1	Optimization of gas flow	9	8.0	4.0	10.0	8.0
2.2	Overall Thrust Value	8	8.0	8.0	4.0	4.0
2.3	Head Loss	8	9.0	9.0	3.0	9.0
3	**Gas Delivery System**		**85.7**	**60.5**	**76.2**	**69.5**
3.1	Tank Design/Materials/Analysis	6	9.0	6.0	7.0	8.0
3.2	Gas Delivery System and Mass Flow	8	7.0	7.0	6.0	7.0
3.3	Material Properties	7	10.0	5.0	10.0	6.0
4	**Design Considerations**		**93.0**	**74.3**	**90.0**	**45.2**
4.1	Ability for CAD/ANSYS modeling	7	10.0	5.0	9.0	8.0
4.2	Maximization of laminar flow	8	8.0	9.0	10.0	5.0
4.3	Ideal gas properties for application	8	10.0	8.0	8.0	1.0
5	**Geometric Characteristics**		**78.9**	**52.1**	**63.2**	**68.9**
5.1	Size applicable to cube sat	6	10.0	8.0	7.0	8.0
5.2	Machinibility relative to size	7	6.0	3.0	6.0	5.0
5.3	Mountability on application	6	8.0	5.0	6.0	8.0

Overall Design



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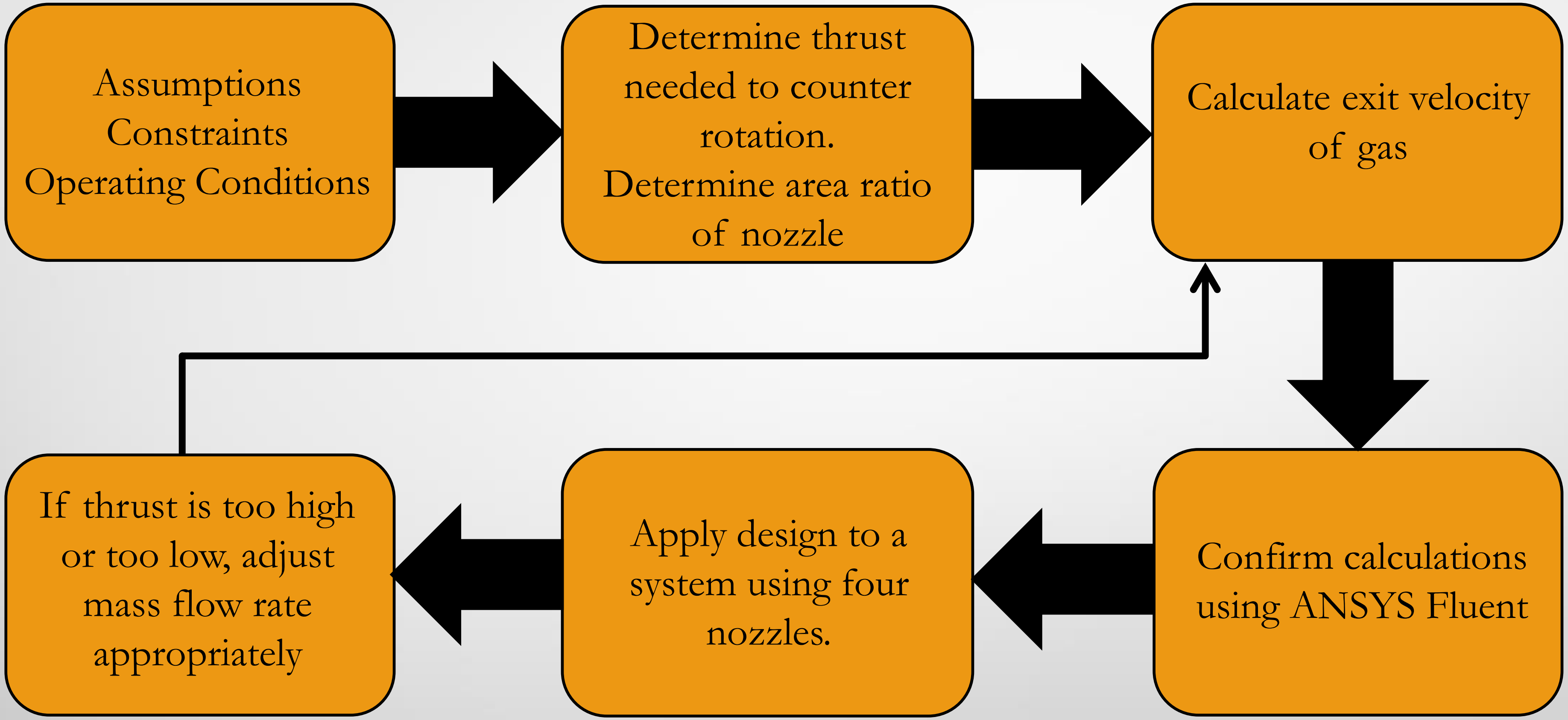
Nozzle Design Process



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Nozzle Design

- Required thrust – 0.0476 N total, 0.0238 N per Nozzle.
- Velocity calculation – based on a set mass flow rate, the geometry of the nozzle, and the state of the gas.
- ANSYS simulation – modeled the geometry and specified inlet and outlet conditions
- If the velocity being produced did not produce enough thrust, either the mass flow rate was increased or the nozzle area ratio was increased
- Initial assumption of incompressible flow was confirmed through fluid flow analysis in ANSYS

$$F_{air} = \rho_{air} {V_{air}}^2 A$$

$$V = \frac{\dot{m}}{\rho A}$$

$$T = \dot{m} V$$

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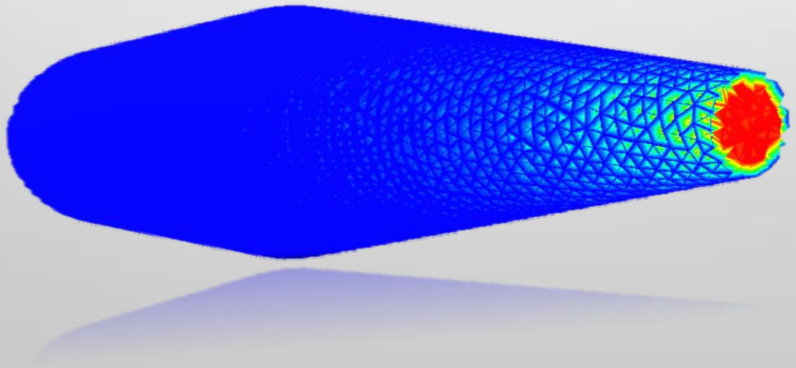
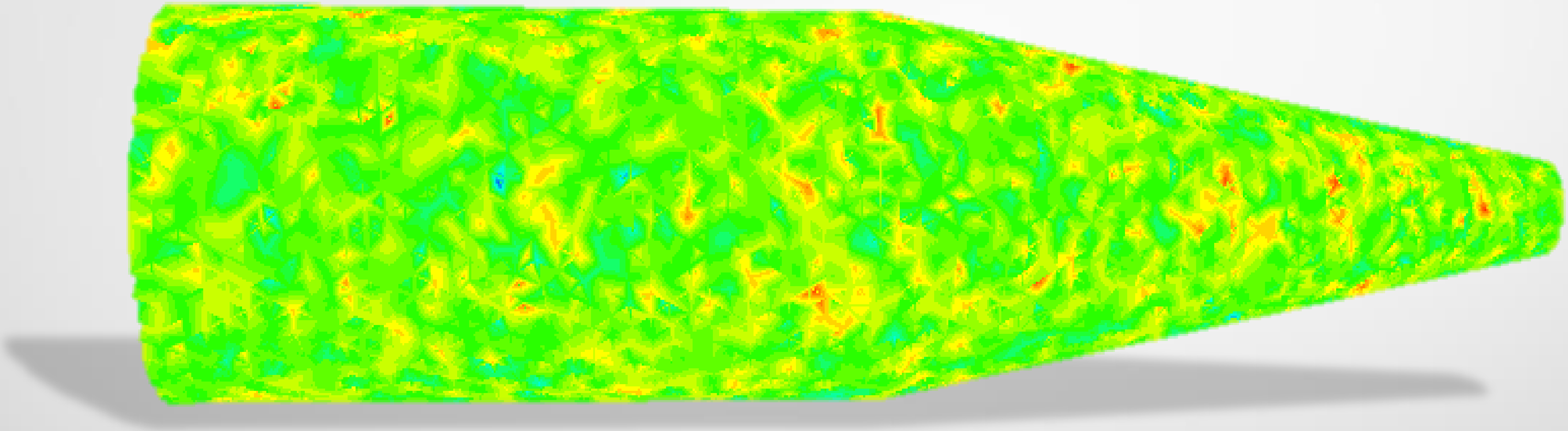
RESULTS

	Hand Equations	Ansys
Velocity (m/s)	35.3	36.1
Thrust (N)	0.024	0.0256
Inlet Diameter (mm)	6.35	
Outlet Diameter (mm)	1.5875	

	Inlet	Outet
Pressure (Pa)	689475	1185
Temperature (K)	231	231
Density (kg/m³)	10.17	10.17



Graphical Nozzle Profiles



Density

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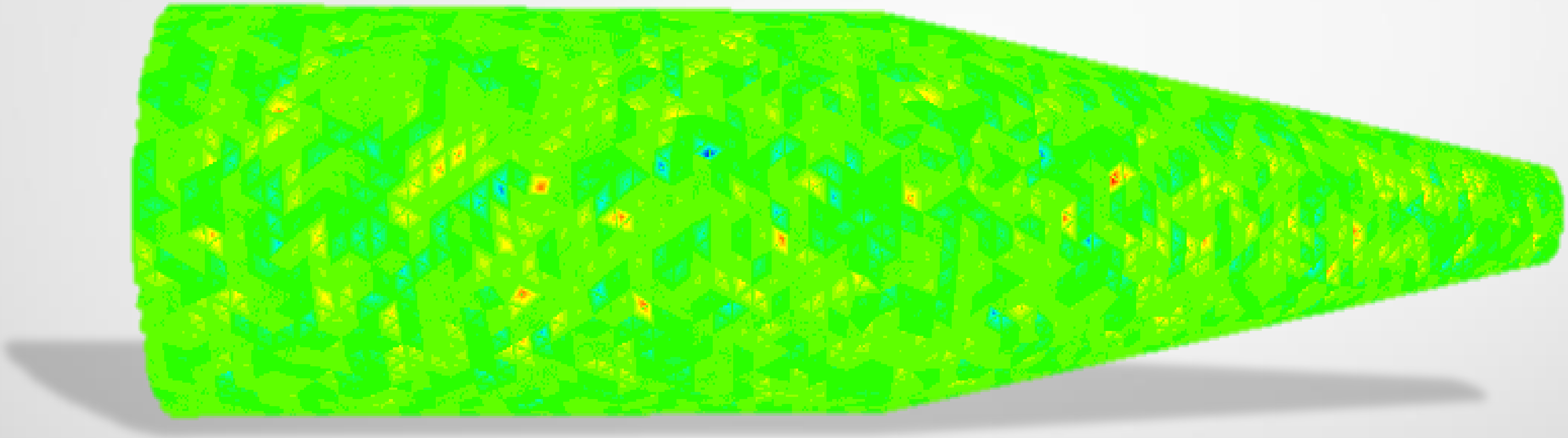
Graphical Nozzle Profiles



Temperature

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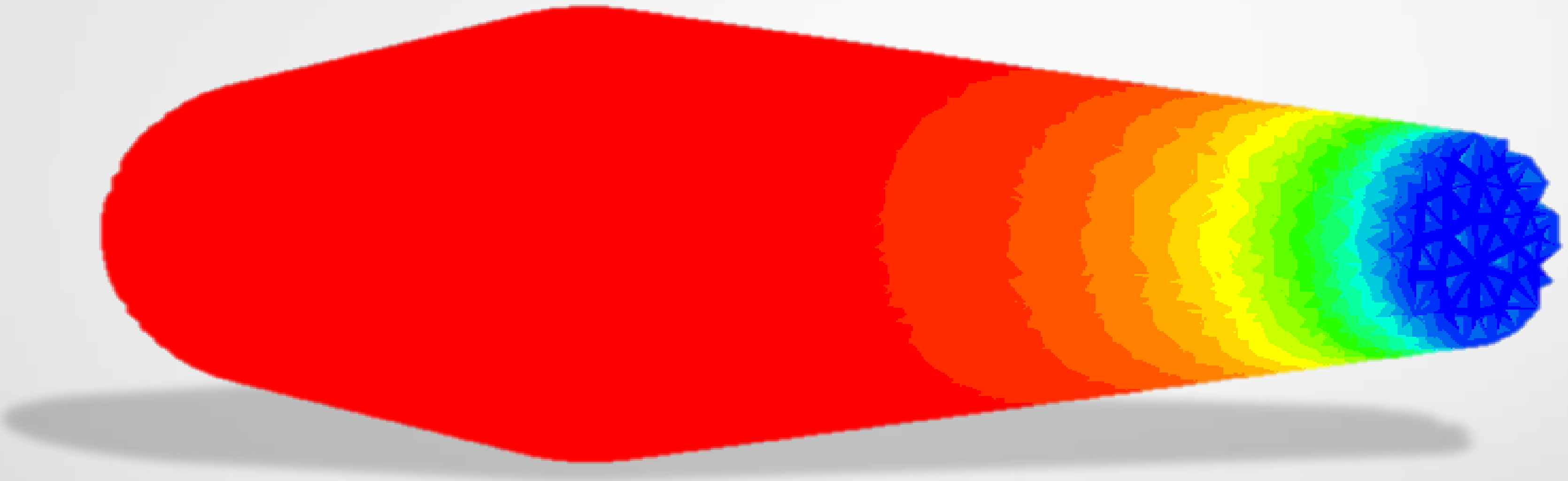
Graphical Nozzle Profiles



Pressure

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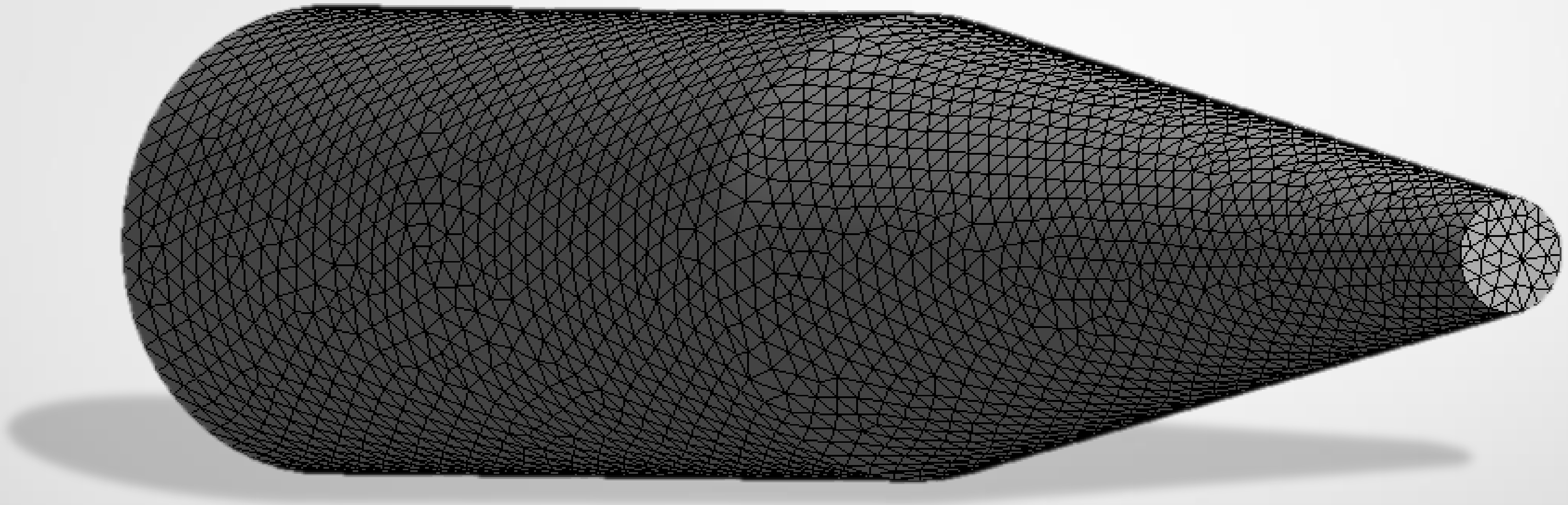
Graphical Nozzle Profiles



Mesh

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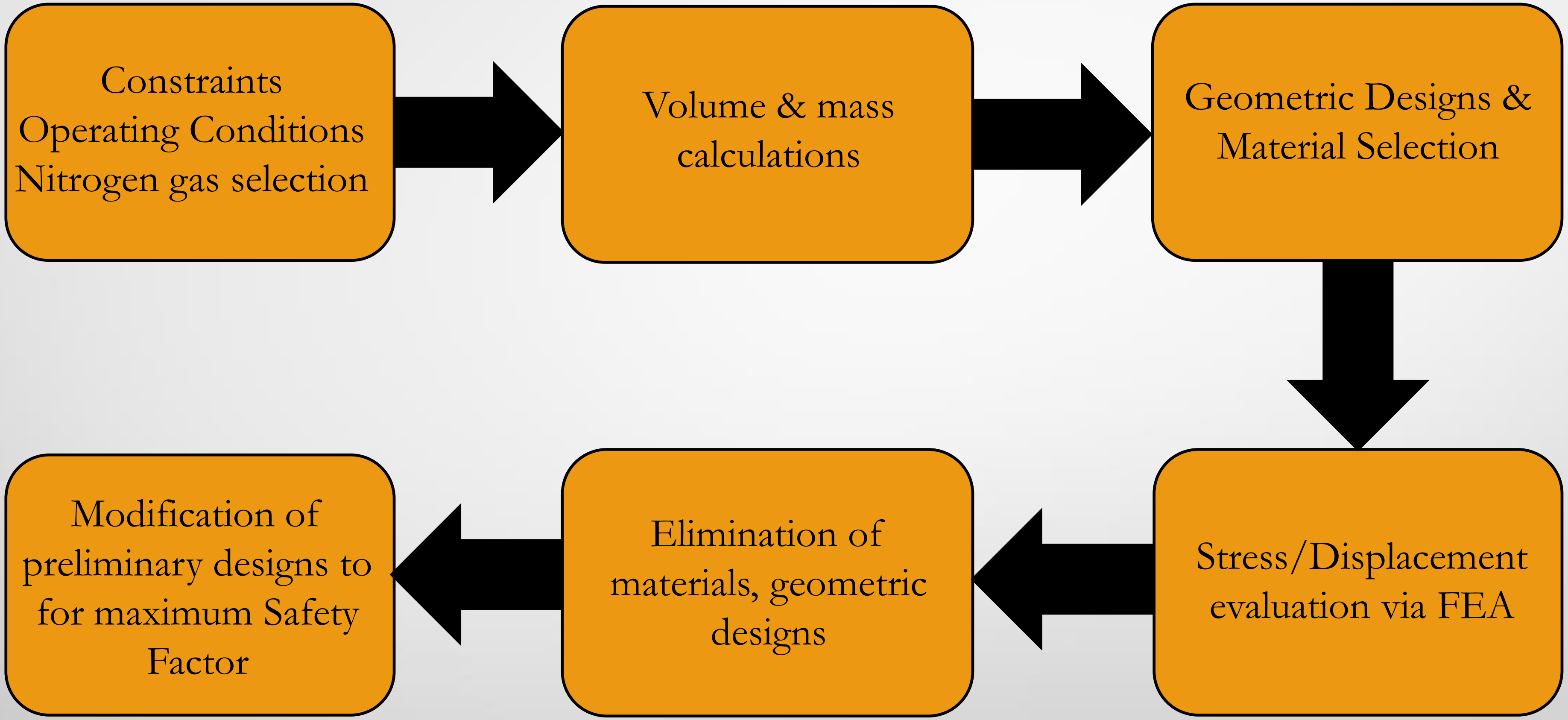
PROPELLANT TANK DESIGN PROCESS



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Tank Design Requirements

- Lightweight material
- High Strength (i.e, high strength to weight ratio)
- Compatibility of pressure vessel manufacturability
- Low stress concentration (geometric factor)
- Compact, non-robust design
- High safety factor due to application

Baseline Vessel Properties

- Density of nitrogen propellant at operating conditions
  - 275.8 bar (4000 psi, 27.6 MPa), -60 ° C (Ideal Gas)
- Nozzle mass flow rate: 0.0014 kg/s, 5 minutes continuous thrust
- 0.336 kg of N_2 gas (design mass)
- Using density relationship, vessel volume of 0.00088 m^3 (0.88 L)
- Rough geometric boundary: (10 cm diameter, 18 cm length)

Concept Summary

	Concept 1	**Concept 2**	Concept 3	Concept 4
Overall Length (cm)	16.54	**17.78**	14.22	15.24
Overall Diameter (cm)	10.16	**10.16**	10.16	10.16
Displacement Volume (cm^3)	1139	**1065**	1145	1056
Volume of Material (cm^3)	115.5	**140.2**	140.1	141.4
Volume Inefficiency (%)	13.65	**13.16**	12.23	13.39
Tank Material	Carbon Fiber	**Carbon Fiber**	304 Stainless Steel	Titanium
Wall Thickness (cm)	0.25	**0.13**	0.25	0.25
Density (kg/m^3)	1630	**1630**	8050	4430
Mass, excluding gas (kg)	0.28	**0.25**	1.13	0.64

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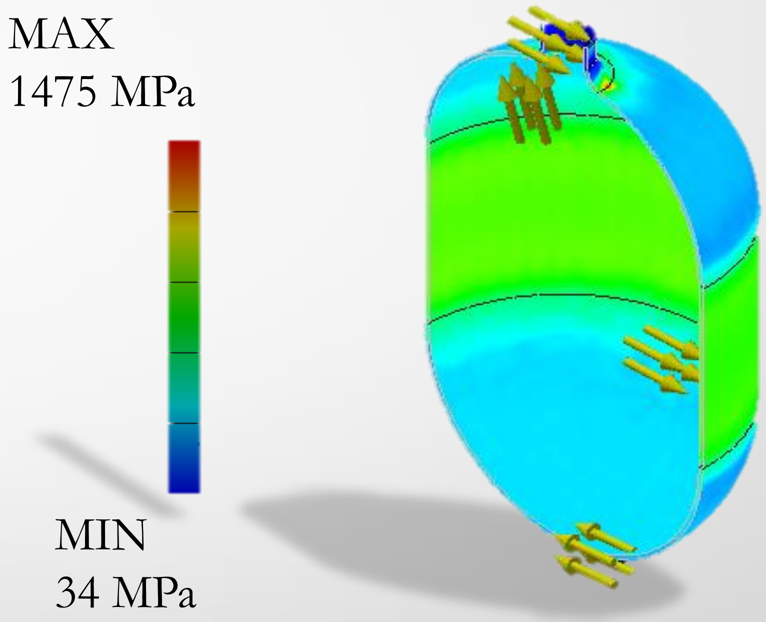
CHOSEN TANK CONCEPT

Overall Geometric Layout

FEA Loading



FEA Von-Mises Stress Results

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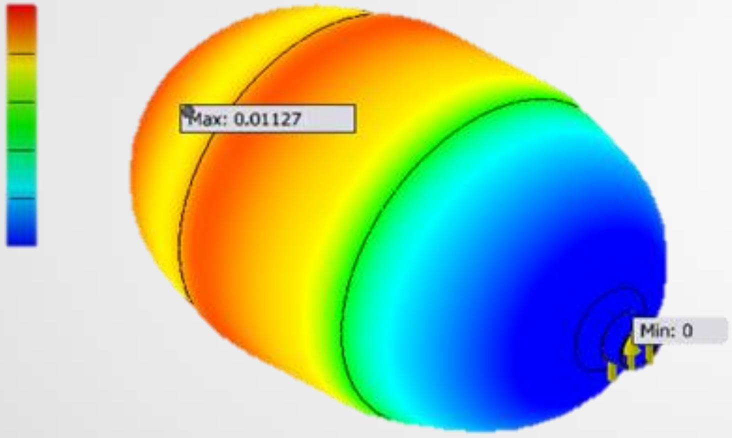
CHOSEN TANK CONCEPT

MAX
0.01127 mm

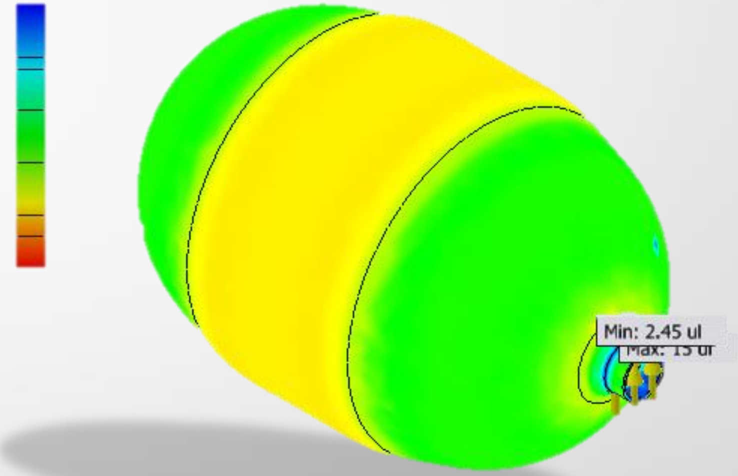
MIN
0.0000 mm



FEA Displacement Results

MAX
15

MIN
2.45



FEA Safety Factor Results

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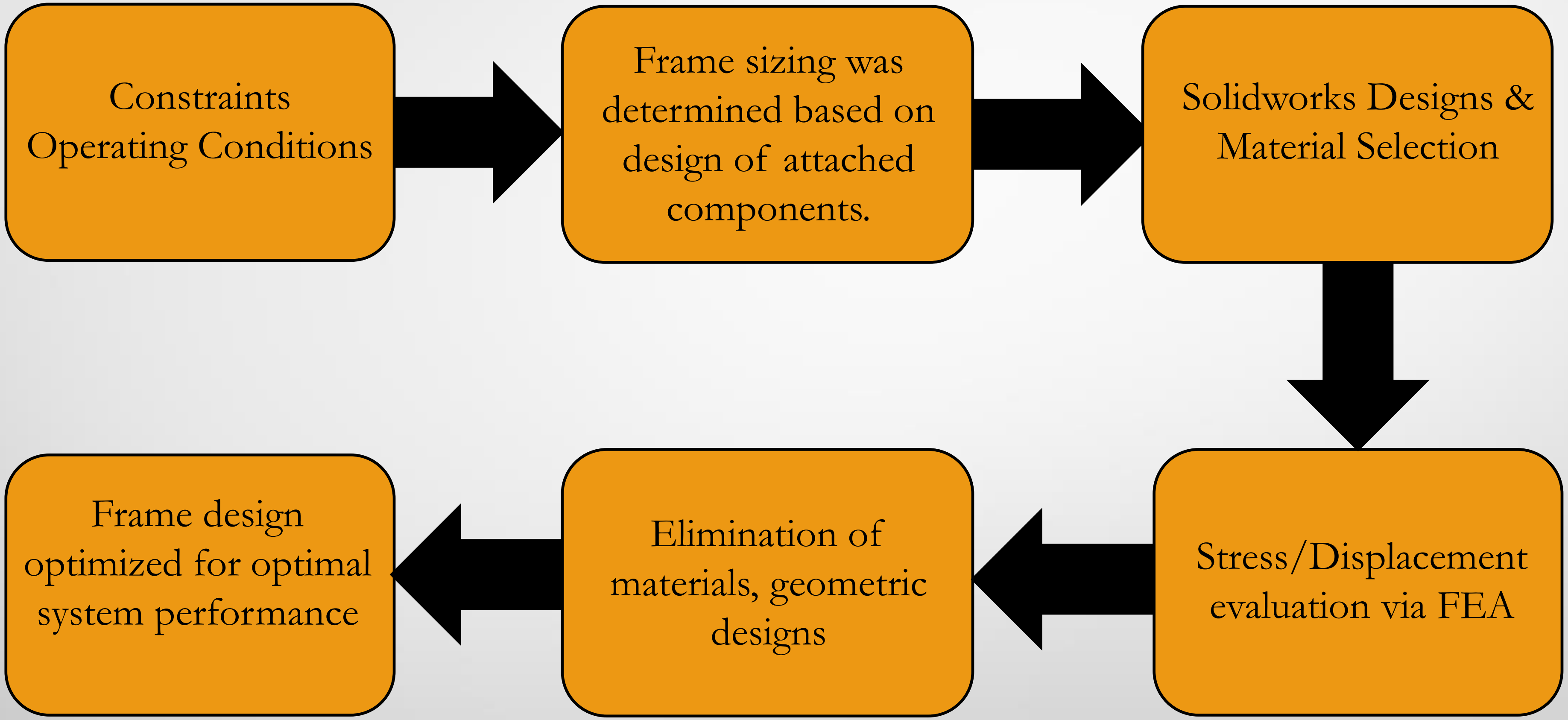
FRAME DESIGN PROCESS



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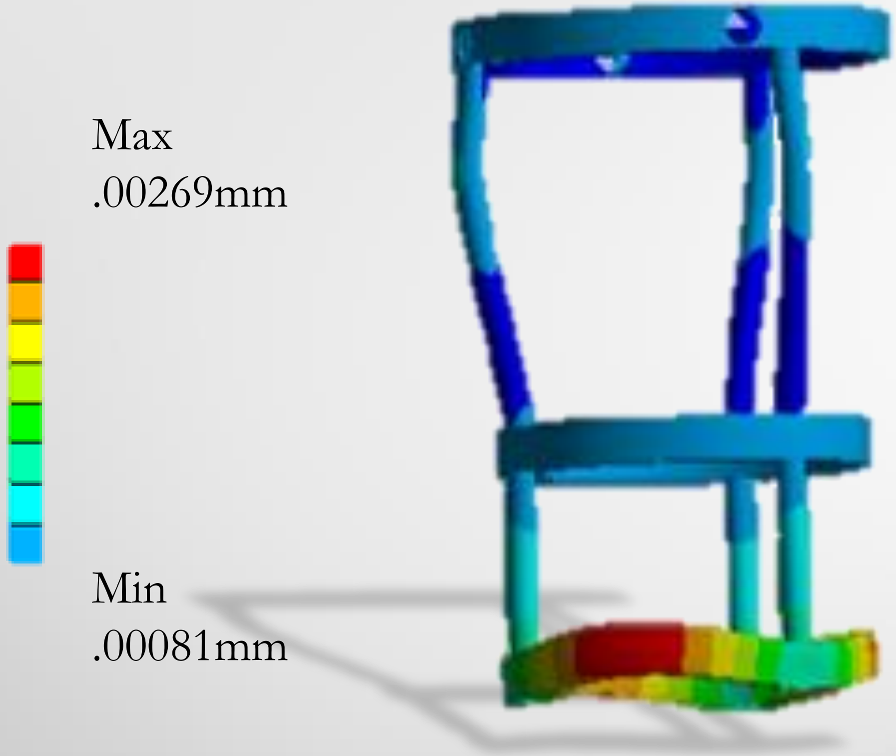
Material Selection

	AL 6061-T6	Ti-6AL-4V	17-7 Stainless Steel	**High Modulus Carbon Fiber**
Density (g/cc)	2.7	4.43	7.8	**1.63**
Rockwell Hardness	40	36	38	**10.16**
Tensile Strength, Ultimate(MPa)	310	950	1240	**1056**
Tensile Strength, Yield(MPa)	276	880	1030	**141.4**
Elongation at Break (%)	17	14	3-7	**N/A**
Modulus of Elasticity(GPa)	68.9	113.8	204	**215**
Modulus/weight ratio	2.6	2.53	2.54	**13.44**
Mass of Frame (grams)	398.72	572.71	1818.4	**380**

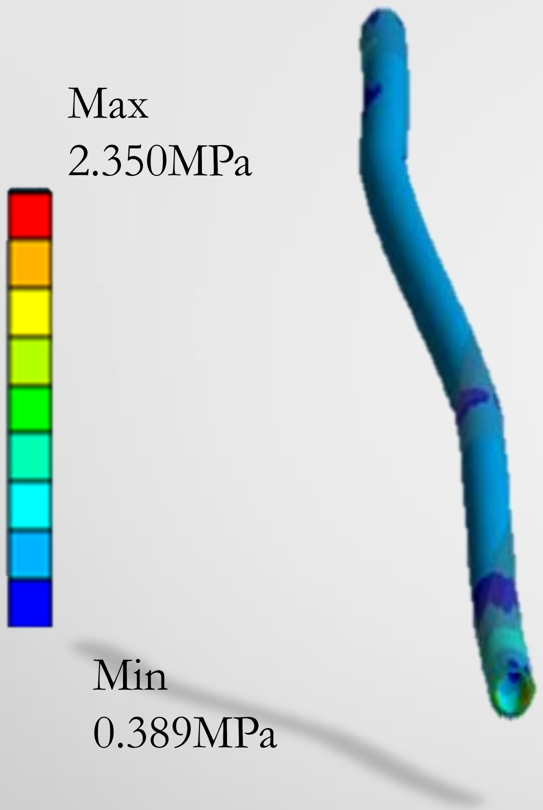
Frame FEA Results



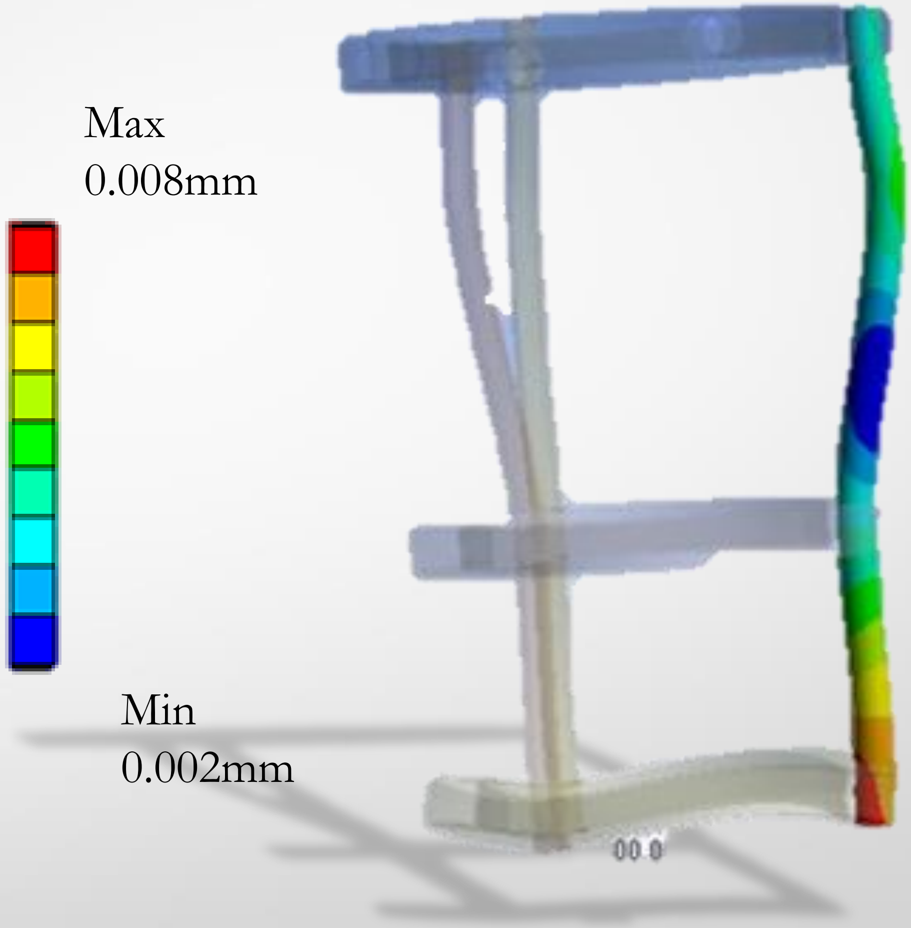
Total Deformation (mm)

Frame Assembly

Frame FEA Results



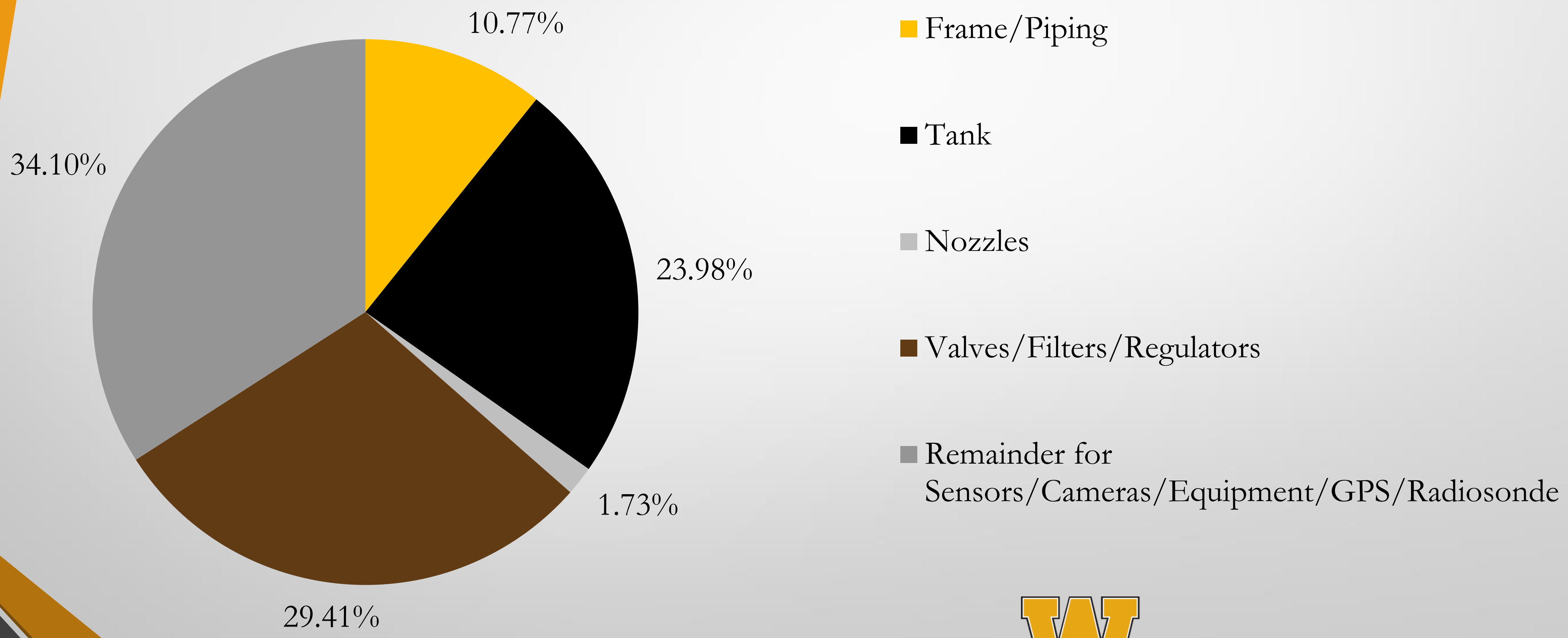
Maximum Principal Stresses on struts(MPa)



Total Deformation of Strut (corner impact 35N) (mm)

Component Mass Contribution

- Overall mass of system – 1.79 kg, design goal of 2.26 kg



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Design Results & Recommendations

- Total design mass is 79% of target mass
- Nozzle, frame and pressure vessel component design valid for application

- Testing/prototyping of propulsion system
- Remote control system design
- Simulate/analyze system within vacuum chamber to measure thrust characteristics

Questions & Comments

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