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Zenith Propulsion

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ZENITH PROPULSION

Final Presentation

April 24, 2020

Primary objective of Zenith Propulsion

The objective of Zenith Propulsion is to successfully launch and recover a liquid bi-propellant rocket.

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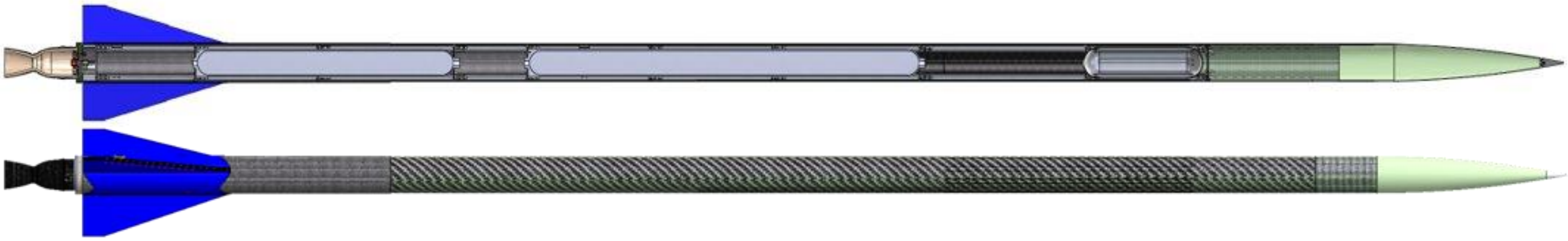
Top level design requirements

- Successful launch must leave the launch rail.
- Successful recovery must deploy the parachutes and lands with minimal damage.
- The team shall meet all safety requirements put forth by the Friends of Amateur Rocketry



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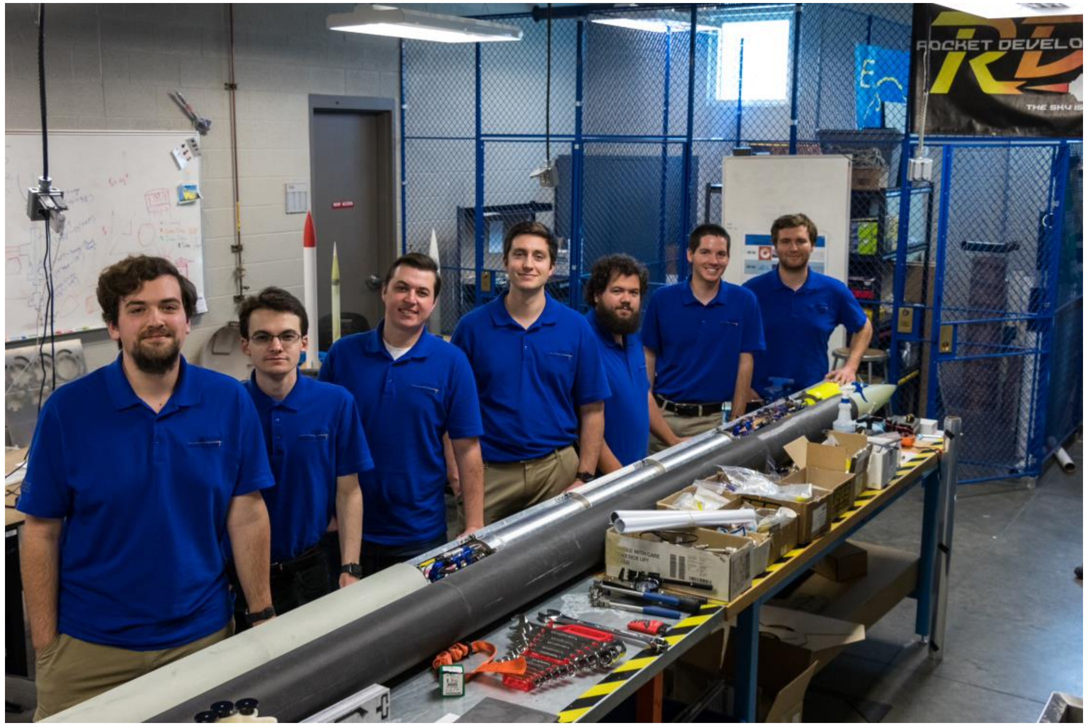
Team members & roles

Name	Primary Role
Bryce Smoldon	Design Team Lead, Structures RE
Matt Boban	Feed System RE
Jonathan Noble	Engine Redesign RE
Andrew Lucka	Propellant Tanks RE
Stefan Johnson	Avionics RE
Nicholas Wright	Aeroshell RE
Max Kauker	Ground Support Equipment RE

RE: Responsible Engineer



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Agenda

- Review project background
- Discuss design and predicted performance
- Provide vehicle status update
- Provide budget and timeline status update

Project Background

Stefan Johnson

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Friends of Amateur Rocketry (FAR)

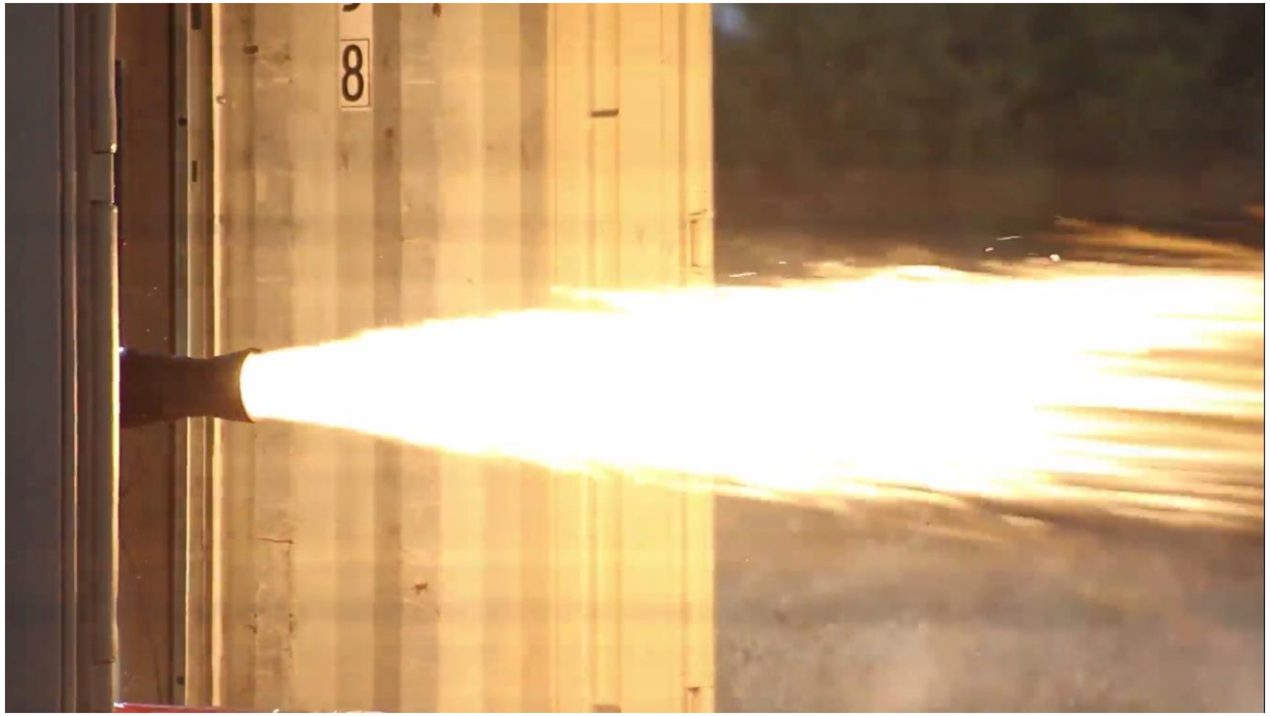
- Put forth a challenge to universities to develop and launch bi-propellant launch vehicles
  - FAR-Mars Competition (2017)
  - Dollar Per Foot (DPF) Challenge (2019)
- Offering substantial amounts of money to successful teams
  - FAR-Mars: $50,000-$100,000
  - DPF: $1 – $328,084

FAR-Mars qualification requirements

- **Target Apogee:** 30,000 feet above mean sea level (MSL).
- **Ground-hit velocity:** 20 ft/s or less with minimal damage.
- **Total impulse limit:** 9,208 lbf-s.
- The team shall meet all safety requirements put forth by the Friends of Amateur Rocketry

Tiber Designs (2018-2019)

- Developed ERAU-Prescott's first successful bi-propellant rocket engine in response to FAR-Mars challenge.



Altair Design Overview & Predicted Performance

Nicholas Wright

Design parameters to reach target altitude

Design Parameter	Value
Engine Thrust Curve	-9.04*t+900 lbf
Engine Burn Time	10 seconds
Propellant Mass	45.7 lbm
Altair's Diameter	6.2 inches
Nose Cone Length	30.7 inches
Altair's Length	250 inches
Engine Nozzle Exit Area	18.9 in^2
Fin Planform Area	200 in^2
Fin Sweep Angle	70 °
Inert Mass Limit	112.8 lbm
Max Acceleration	7 gees
Max Structural Loading	(See next slide)

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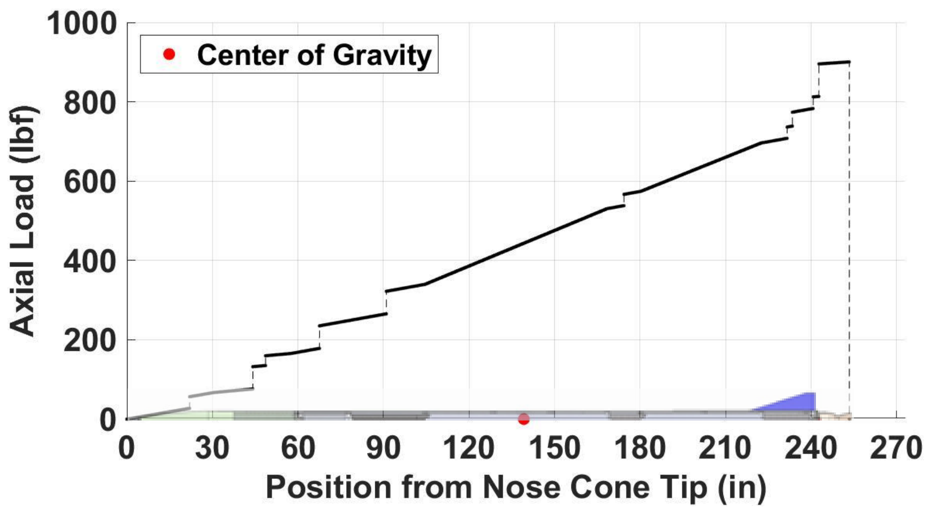
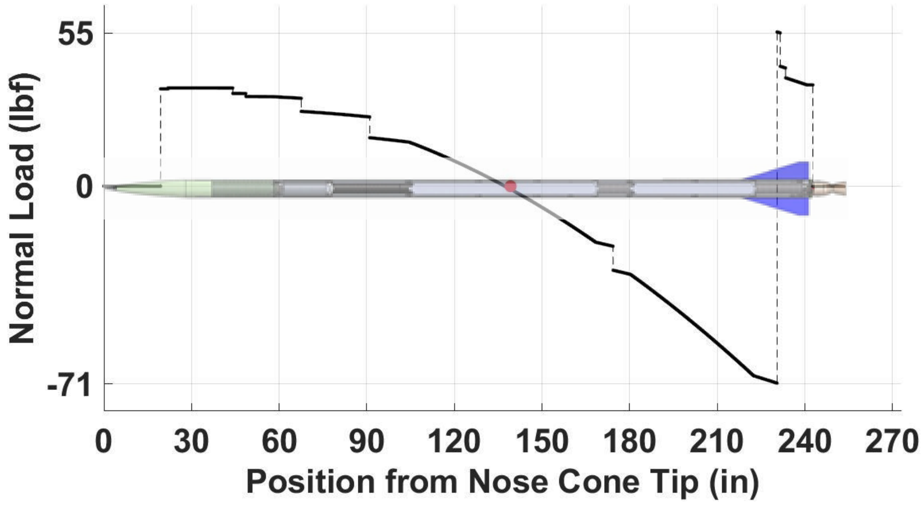
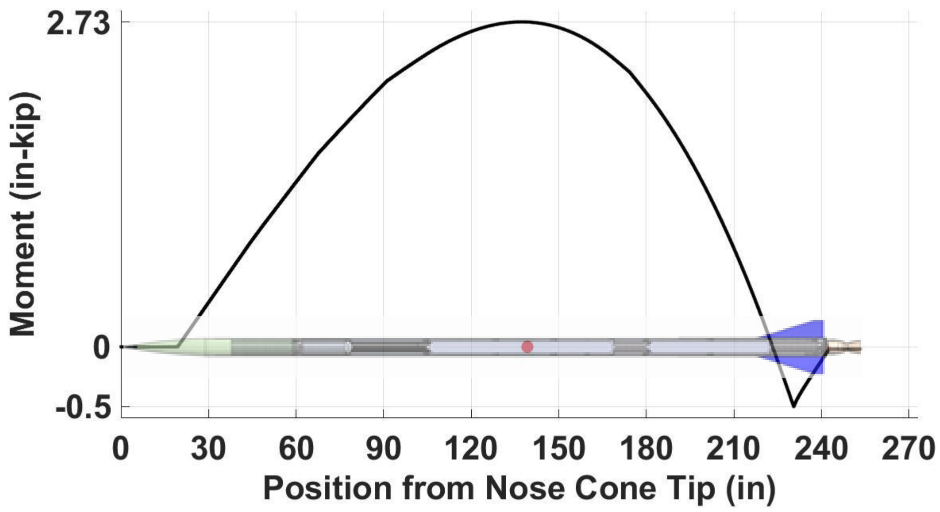
Max structural loading







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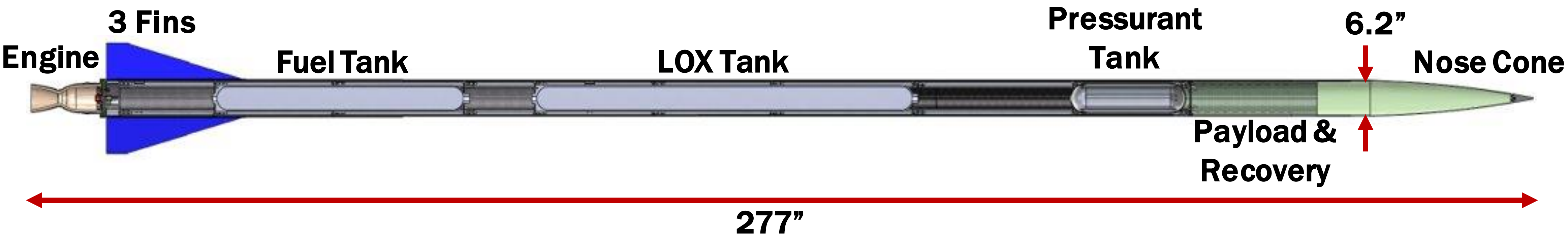
Altair design overview



Seven subsystems

- Engine – Propel the rocket
- Propellant tanks – Hold required propellant
- Feed system – Deliver required propellant to engine
- Structure – Support internal components during flight
- Aeroshell – Protect payload and improve aerodynamic performance
- Recovery system – Provide a safe descent and landing for rocket
- Ground support equipment (GSE) – Control prop loading, pressing, launch sequence

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Current mass rollup & engine performance

Component	Mass (lbm)
Engine	14.0*
Feed System	31.0**
Tanks	30.0*
Structure	20.0*
Aeroshell	17.3**
Recovery	11.6**
FAR Payload	2.2*
INERT MASS	**126.1****
Propellant	45.7**
TOTAL MASS	**171.8****

*** = Known Values**
**** = Estimated Values**

Mass rollup comments

- Current design 13.3 lbm of inert mass over budget
- Aggressive schedule limited redesigns to reduce mass

Current engine performance

- Average thrust curve of -21.45*t + 756.7 lbf
- Capable of 10 second burntime

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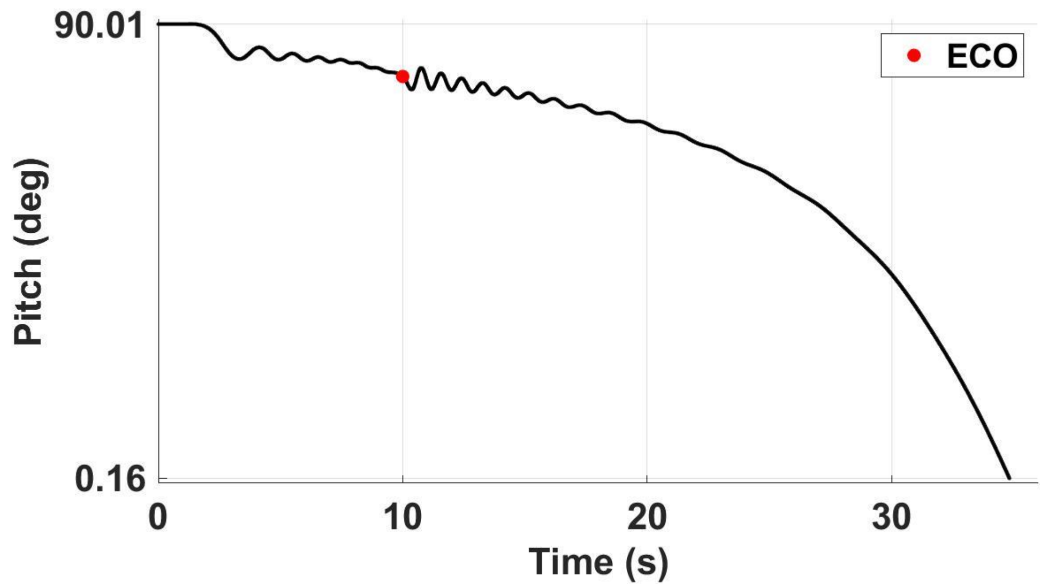
Predicted performance of Altair

Trajectory Model Inputs		Trajectory Model Outputs	
Inert Mass	126.1 lbm	**Total Engine Impulse**	6494 lbf-s
Propellant Mass	45.7 lbm	**Max Altitude (no wind)**	18.4 kft
Engine Thrust Curve	-21.45*t +756.7 lbf	**Max Altitude (worst-case wind scenario)**	18.1 kft
Engine Burntime	10 seconds	**Max Acceleration**	3.4 g's
Altair's Length	277 inches	**Max Mach Number**	0.92
Altair's Diameter	6.2 inches		
Nose Cone Length	30.7 inches		
Nozzle Exit Area	18.9 in^2		
Fin Planform Area	206 in^2		
Fin Sweep Angle	69.9°		



No tumbling despite performance decrease, thus primary objective is still achievable.

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Vehicle Status

Andrew Lucka

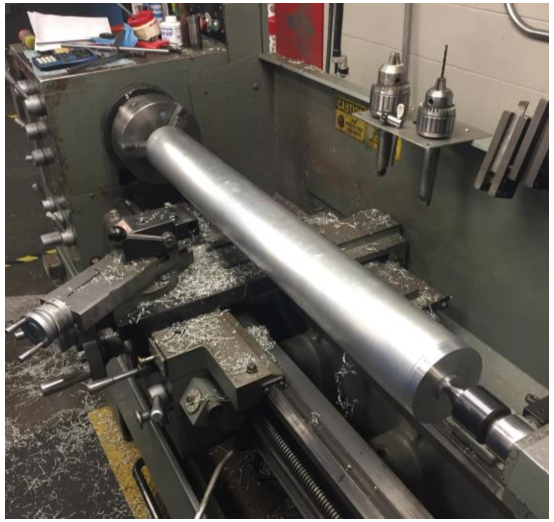
Vehicle integration

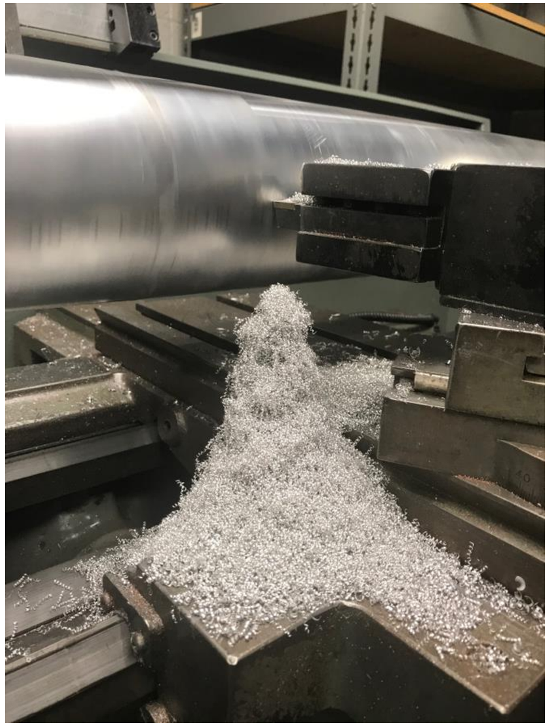
Subsystem	% Complete
Propellant Tanks	100%
Structure	95%
Feed System	95%
Ground Support Equipment	95%
Engine	90%
Aeroshell	60%
Recovery	40%
Total	**82%**

Propellant tank fabrication

Tank main bodies after being cut to length

LOX (top) & Fuel (bottom) tank main bodies on lathe





Turning OD of LOx Tank

CNC machining of a top endcap

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Propellant tank fabrication

Tensile test specimens

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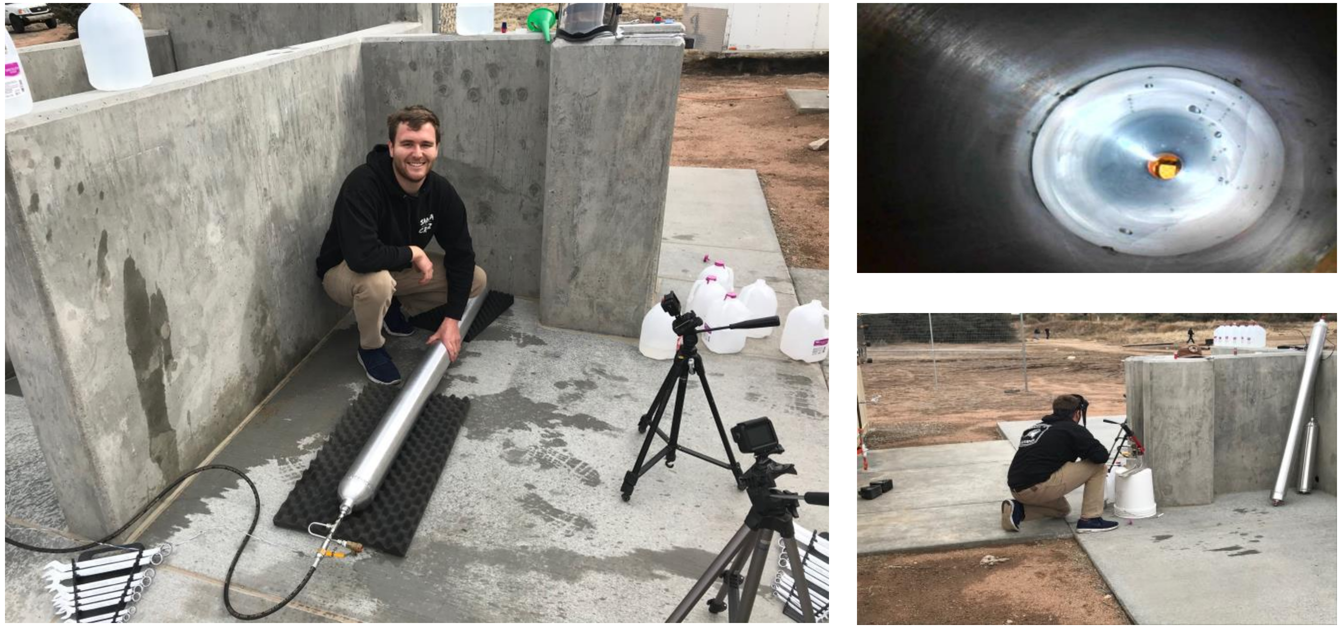
Hydrostatic pressure testing

- Analyzed welds internally using borescope
- Lox and Fuel tanks tested to 1.5MEOP (1.5 x 550 = 825 psi)
- Extra “boomie” tank fabricated and tested to 1900psi
  - Need to test to failure



Fuel and LOX tanks passed hydrostatic flight qualification testing

Propellant tanks – successes and downfalls

Successes:

- Structurally sound at 1.5x working pressure
- Simple design of components
- No risk of leaks at endcaps
- Under original weight projection
- Under budget

Downfalls:

- Overbuilt, weight penalty
- Unable to be opened for cleaning

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Structure fabrication

Raw Material

Waterjet Bulkheads

Milling C-channel

Post machining cleanup

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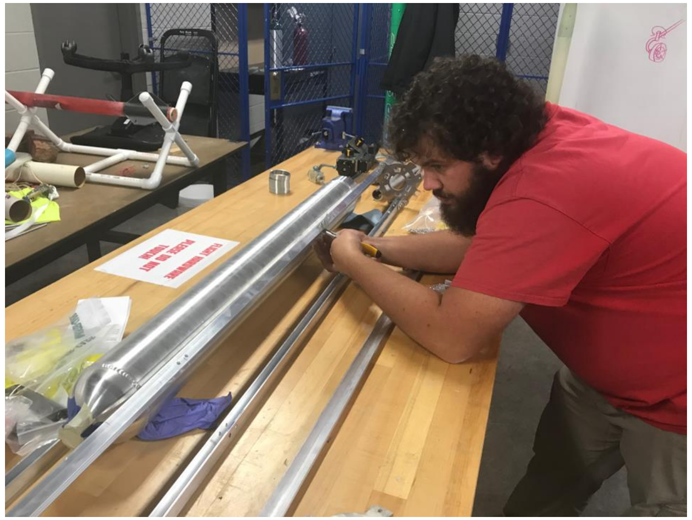
Structure assembly



First physical visualization of Altair

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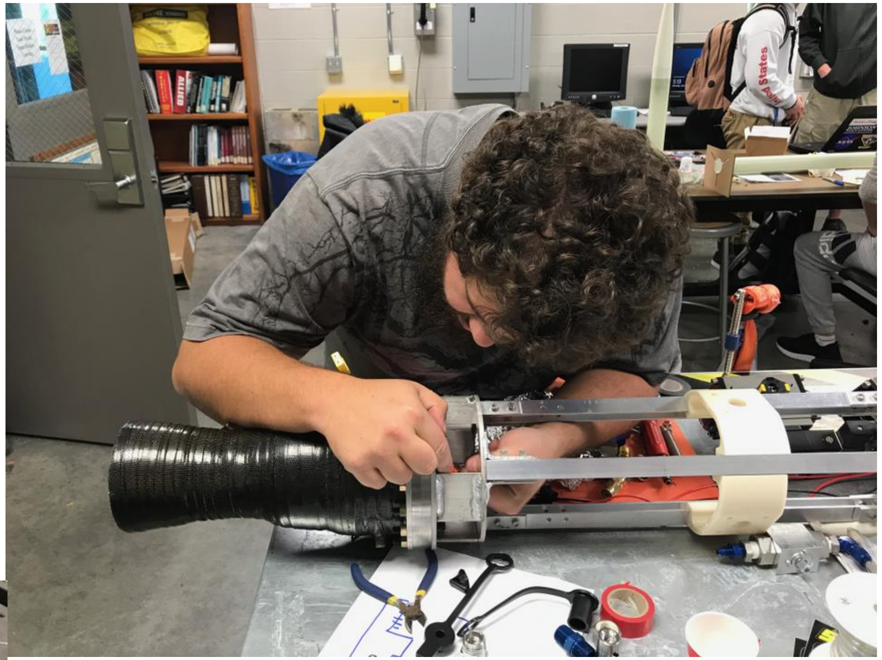
Engine mounting



Engine Mount - Post Weld

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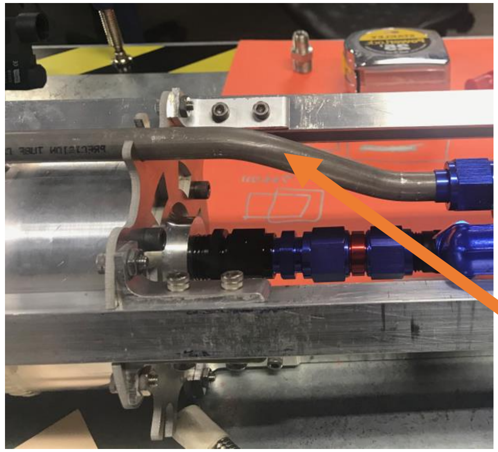
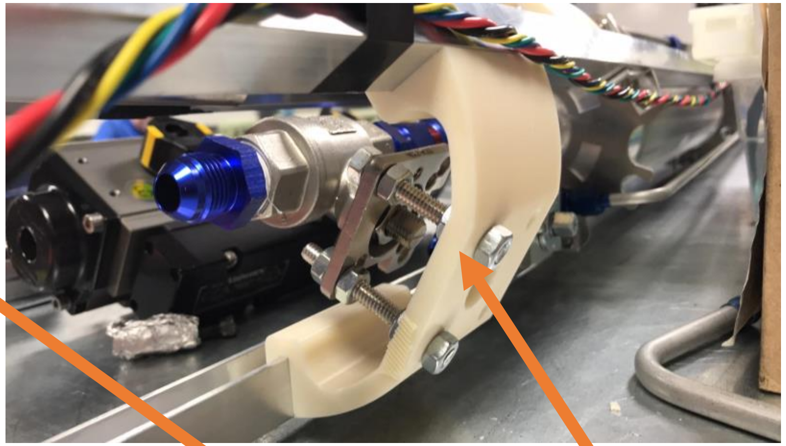
Structure - successes and downfalls

- Successes:
  - Simple design
  - Easy to assemble
- Downfalls:
  - Heavy
  - Overbuilt

Feed system fabrication

Pressurant Gas Storage



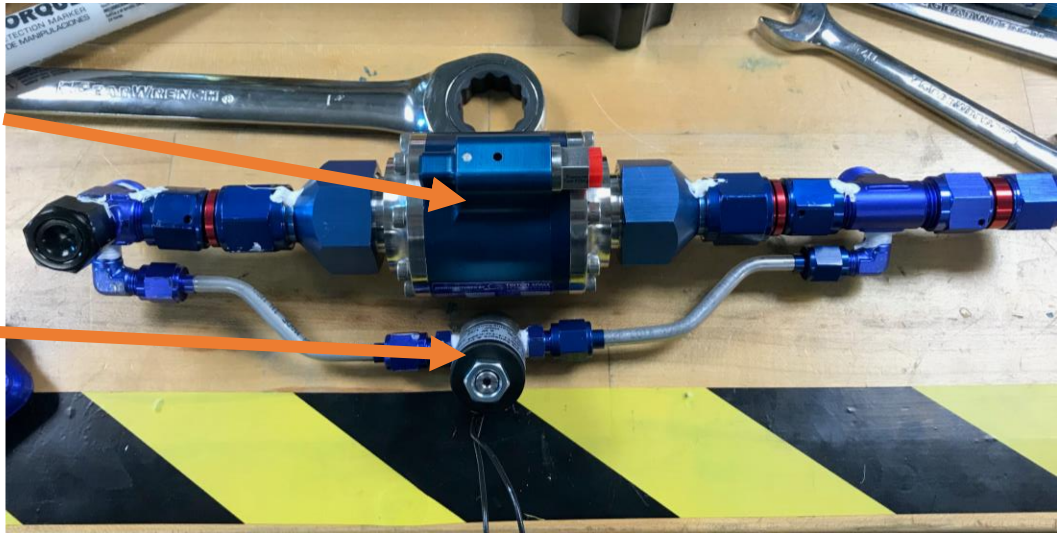


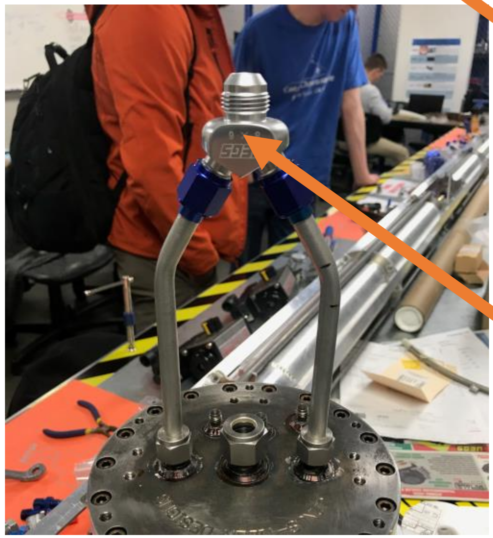
Liquid Oxygen Raceway

Main Propellant Valve Fixture

Pressurization Valve

Pre-Press Valve





Fuel Splitter

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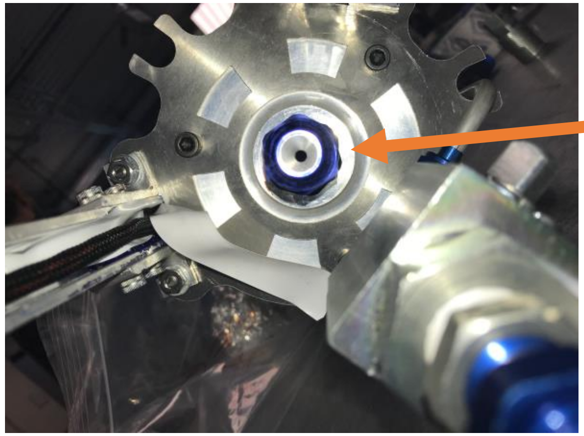
Cavitating venturi installation

Venturi fits inside flared fitting

Flared sealing surface is replaced by venturi flare

Left = Fuel Venturi
Right = LOx Venturi



Fuel venturi installed below fuel tank

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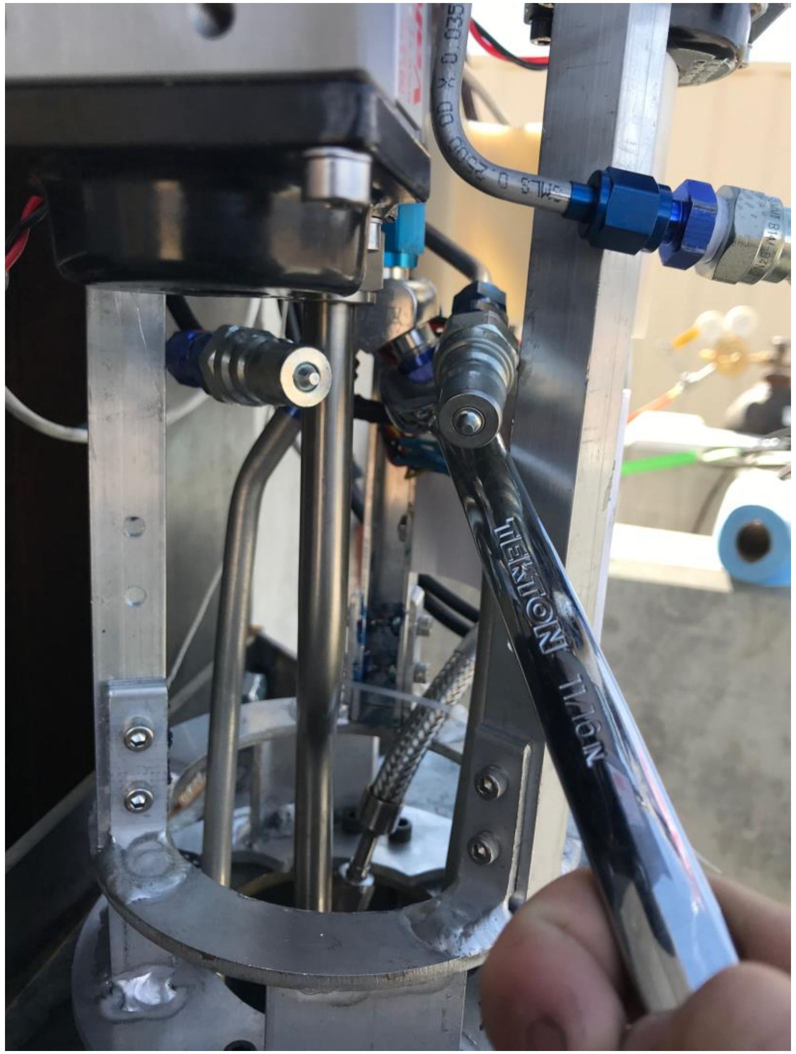
Feed system- successes and downfalls

- Successes:
  - Simple, functional design
  - Easy to change out or add parts as needed
- Downfalls:
  - Some oversight for last-minute changes
  - Sub-optimal layout
  - Better planning could have reduced some mass



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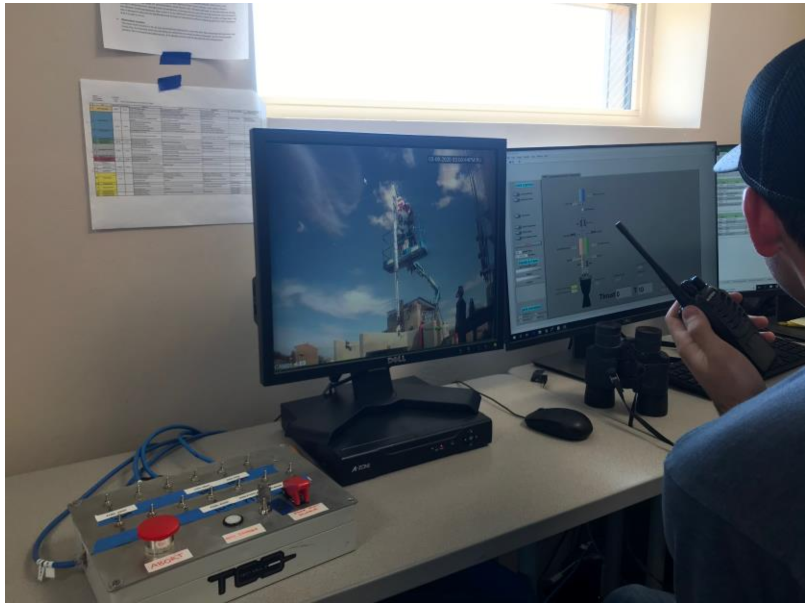
Ground support equipment



Console view of test article

Low pressure GN2 for pneumatics

GSE in test configuration

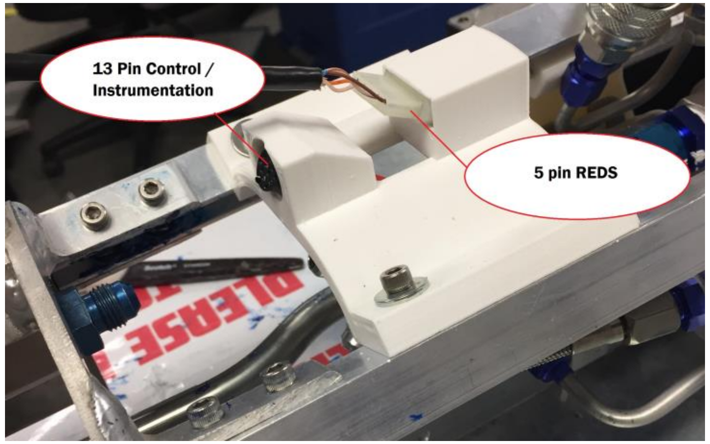
Ground support equipment

Success:

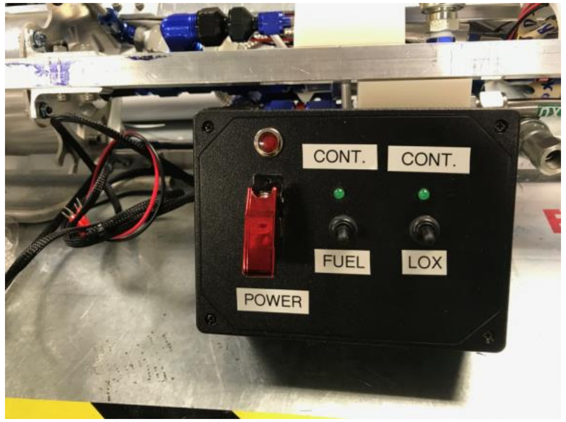
- Interface with vehicle smooth and consistent
- REDS system works beautifully
- Ground plumbing simple and quick

Difficulties:

- DAQ box documentation
  - Floating ground
  - Common positive terminals
  - Inputs / outputs not marked



Quick release connection



REDS box assembly


DAQ box mobile

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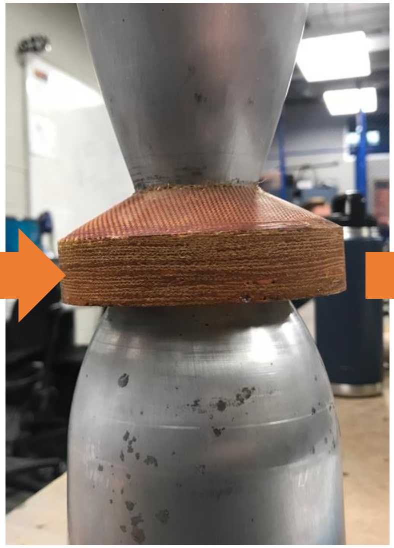
Combustion chamber fabrication

Blank silica-phenolic throat insert

Machining the throat contour

Throat insert ready for silica wrap



Throat insert on mandrel

Mandrel Extension

Completed chamber

Throat insert reduces thrust-loss rate by slowing erosion of the engine's throat.

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Aeroshell body shell status & to-do items

Status update

- Necessary materials to fabricate acquired
- All 6 lower layer composite segments made
- Began joining the segments together

5 lower layer segments with nose cone, fins, & engine

3 lower layer segments joined

To-do items

- Bond upper composite layer to lower layer to complete body shell
- Validate that body shell will handle expected aerodynamic loads

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Aeroshell fin can status & to-do items

Status update

- All 3 fin cores fabricated

To-do items

- Attach fins to body shell once body shell design is validated
- Validate that the fin can will handle expected aerodynamic loads

3 fin cores of aft swept leading-edge trapezoid shape

Approximate layout of fins on aeroshell body

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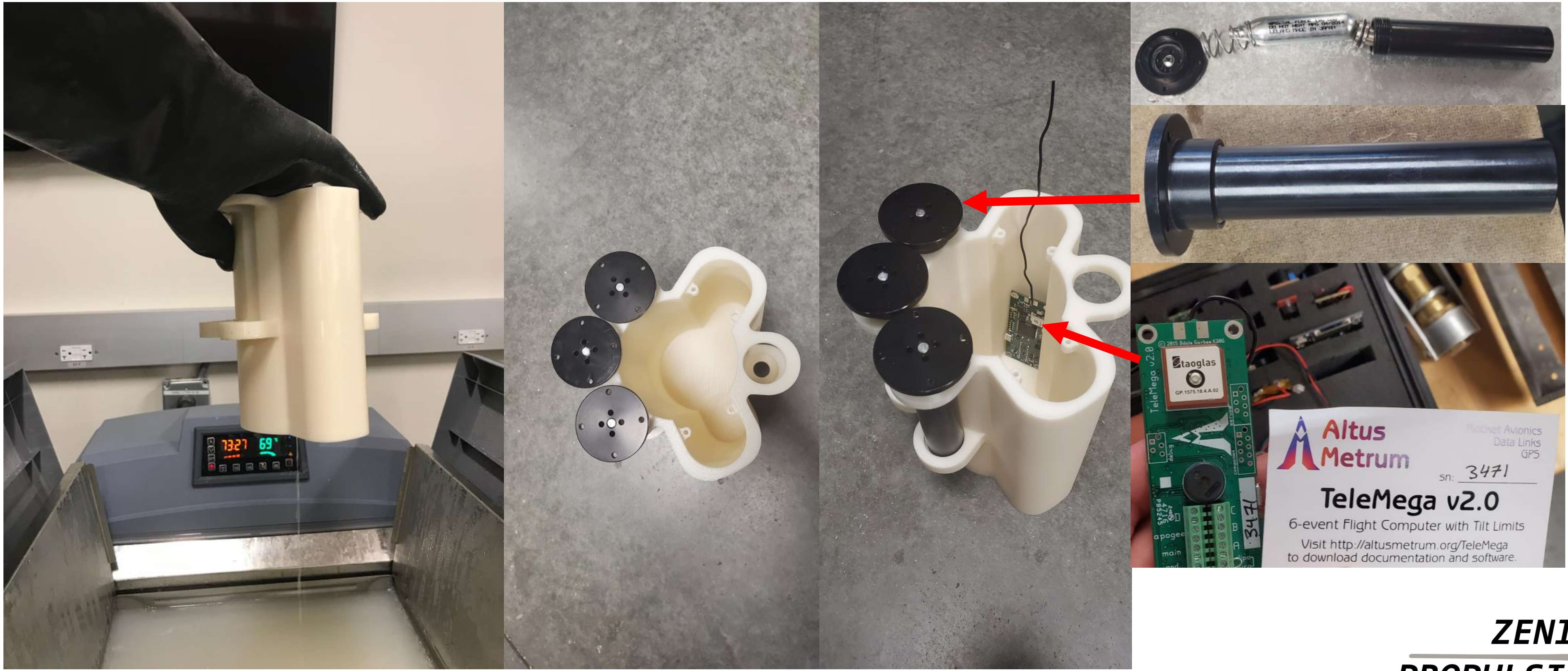
Recovery housing



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Recovery next steps

- **To-do items:**
  - Vacuum chamber test of microcontrollers
  - Finish cover on housing to accommodate CD3
  - On-ground test of recovery
    - Off-vehicle test of CO2 system
    - Fully integrated on vehicle test of just CO2 system
    - Cable cutter testing with parachute bundle
    - Fully integrated on vehicle test of harnessing and parachute deployment
      - Trial-and-error nature of packing

Vertical test stand fabrication


Thrust takeout after welding

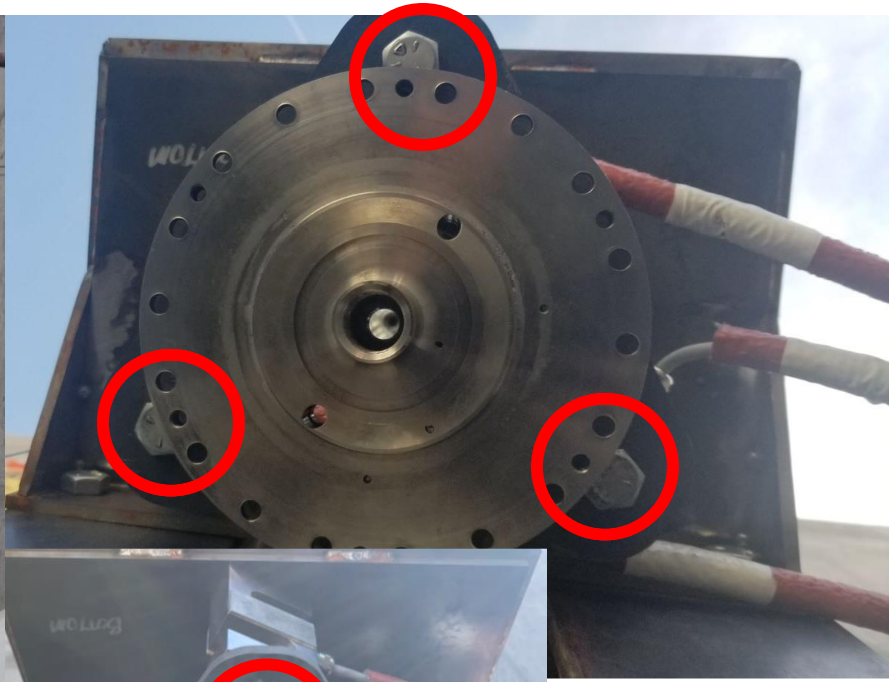

I-beam support holes being drilled

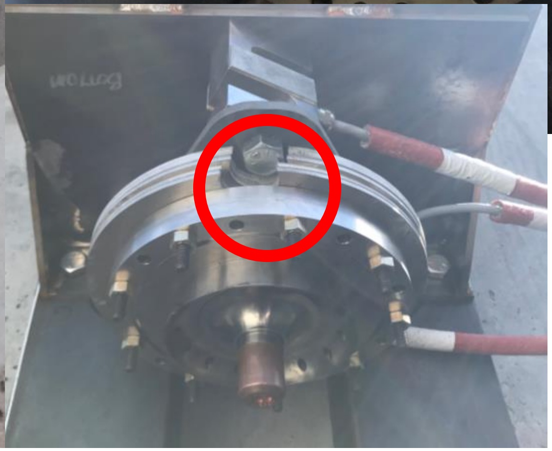

Assembly in Test Cell 2

Vertical test stand – shortcomings

Issues of design:

- Being designed based on Janus 2 feed line layout
- Blast pan





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Testing & Launch

Jonathan Noble

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Test cell 3 test campaign

Tests completed

- 1A – Low pressure GN2 activation
- 1B-1D – LN2 cold flow
- 1E-1F – Water cold flow
- 1G-1H – Snow flows
- 2A – 4 sec hotfire
- 2B – Chamber Failure
- 2C – Flight-duration attempt, manual abort
- 2D – Flight-duration hotfire

Chamber Failure

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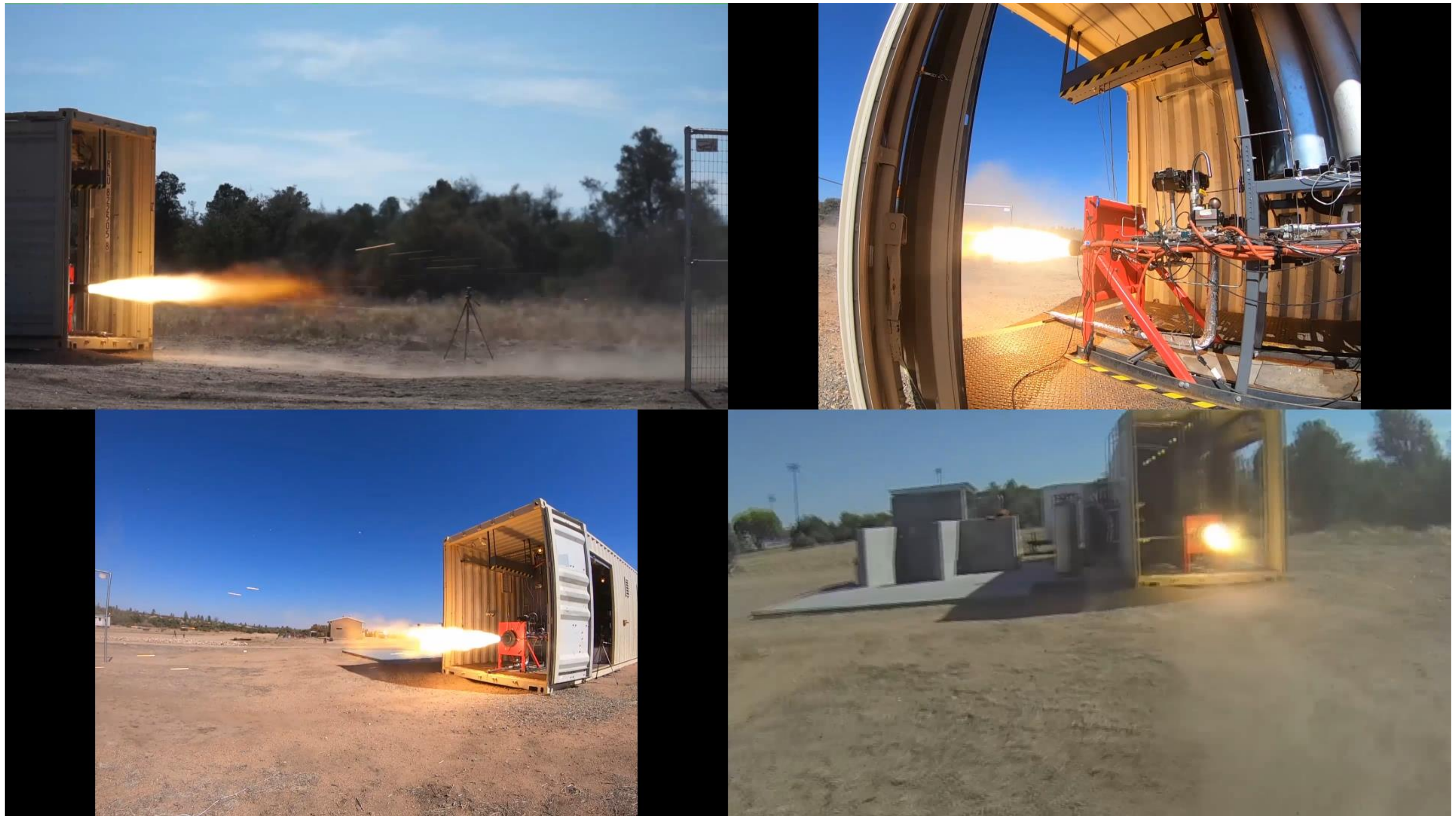
Flight Qualification

October 2019:

- Successful ten second burn leading to proven flight-readiness



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Vertical Lift Operation

Vertical lift rehearsal on 02/27/2020 lessons:

- Orientation of the vehicle for access to quick-disconnects.
- Placement of pneumatic actuators.
- Uninhibited positioning of guy wires.

Final vertical lift on 03/04/2020

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Vertical cold flows

Vehicle control	✓
Propellant loading and offloading	✓
Tank pressurization	✓
Valve sequencing	✓
Expected flowrates and pressures	✗

Film cooling flow rate is low due to pressure loss in elbow fittings.

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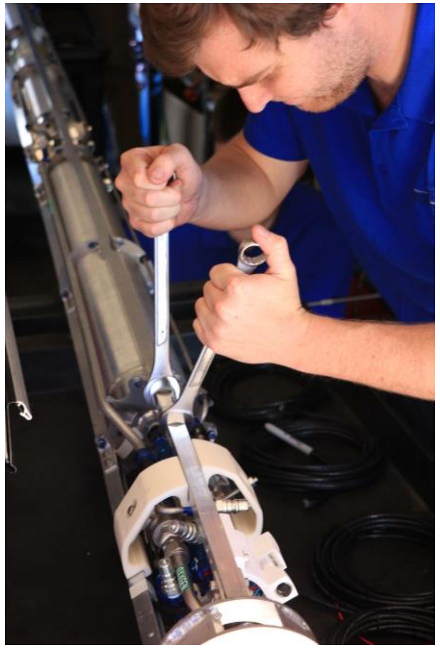
Plans for vertical hot fire

- After success of cold flows to prove film cooling a hot fire could follow
- One hot fire in Fall 2020 for a burn with full tanks, lasting approximately 10 seconds
  - Thrust vs time plot and video can be sent to FAR after a successful hot fire
  - After success of hot fire, 30 days until launch



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Plans for launch

- **Contingency plan for the fall**
  - Like the hot fire, launch delayed until Fall 2020 at the earliest
  - Knowledgeable students still at Embry-Riddle to complete the project
  - Back up all of the content on the team drive and putting on a portable hard drive so knowledge base of decisions on project are saved

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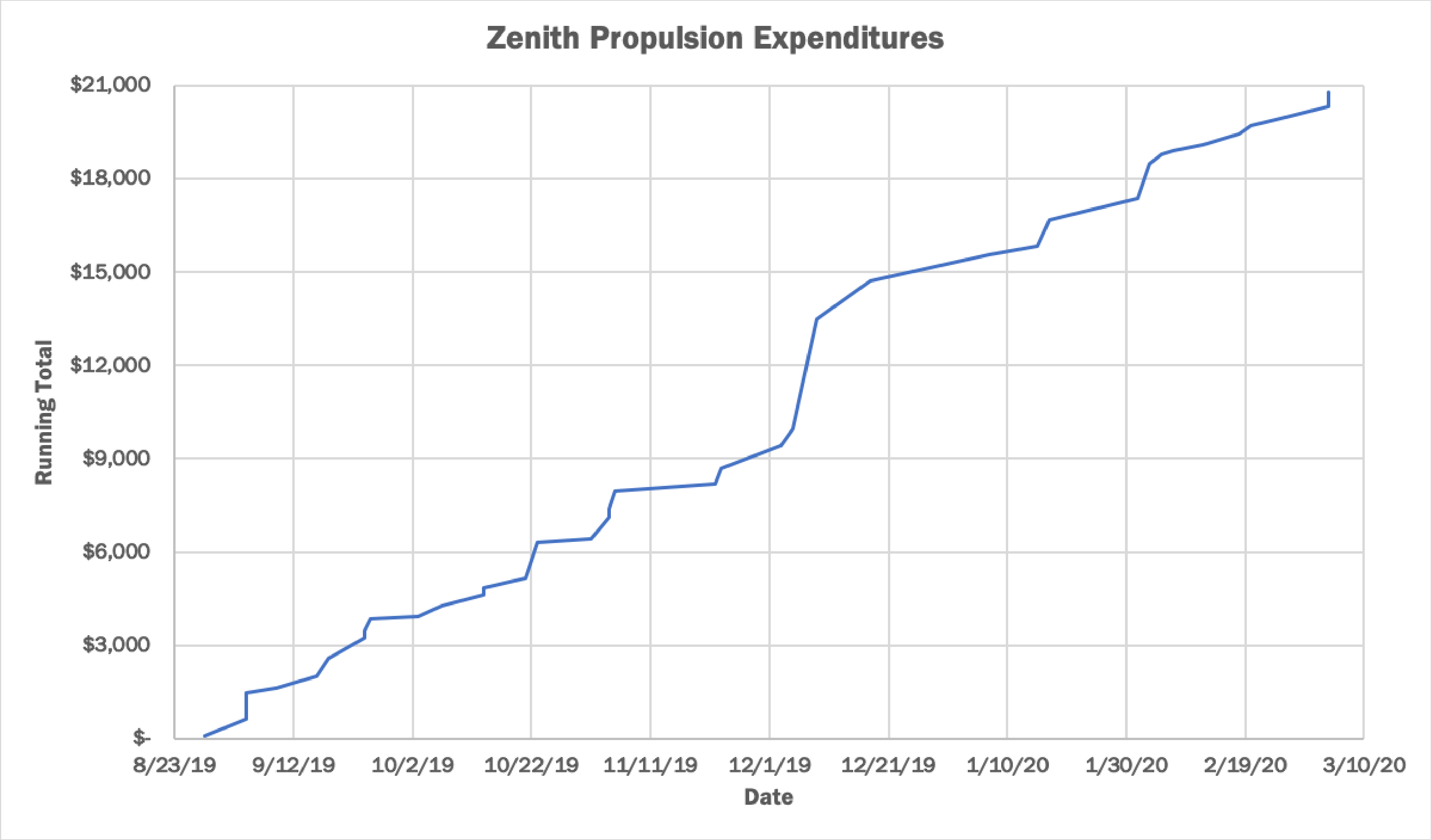
Budget & Timeline Update

Bryce Smoldon

Project budget & resources



Initial Project Cost Prediction:
$15,000

Total Project Expenses as of 3/4/2020:
$20,784

Average:
$113 per day for 184 days

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Pre-COVID-19 Timeline

Flight Duration Hotfire Test	Vehicle Design Completion	Vehicle Assembly Begins	Assembly Complete, Vertical Test	Recovery System Testing, Launch Prep	Launch
Oct 2019	**Nov 2019**	**Dec 2019**	**March 15 2020**	**March/April 2020**	**April 18 2020**

Testing Suspension

Testing was on-track to meet schedule before suspension

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Conclusions

Bryce Smoldon

Conclusions

- Confident that objective will be meet
- Most subsystems are validated with minor oversights that will be fixed
- We were on track to meet deadlines before pandemic.
- Due to the generosity from the URI and ME Department Chairperson all funding necessary was provided and used.

Special Thanks / Acknowledgements

- Professor Gerrick
- Dr. Haslam
- Dr. Dannelley
- Dr. Boettcher
- Dr. Bryner
- Dr. Fabian
- Dr. Haven
- Virginia MacGowan
- Jared Vanatta
- Jeff Hyatt
- Patrick Lavelle
- Director Michael Brady
- Stellar Exploration
- Triton Space Technologies

Questions?

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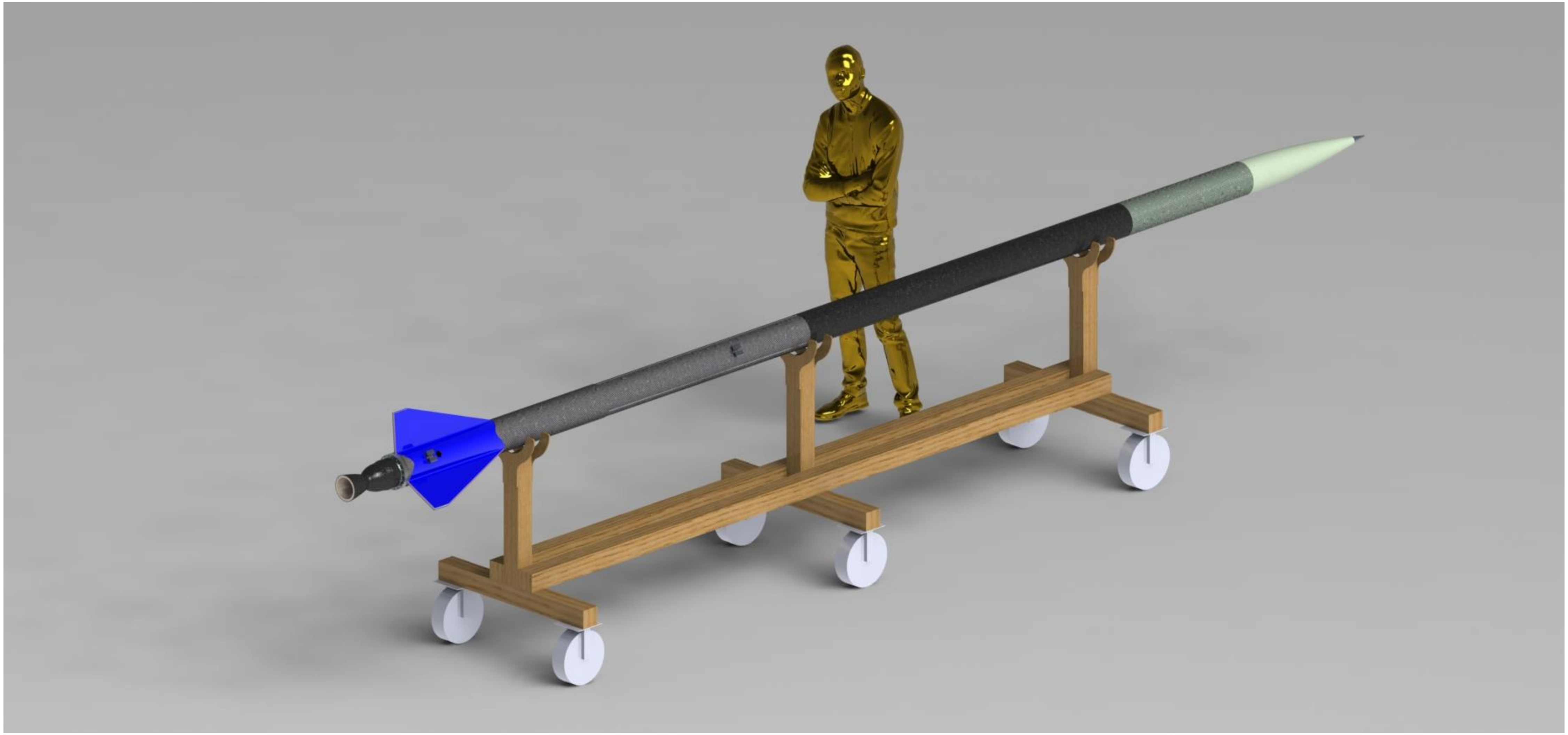
Supplemental Slides

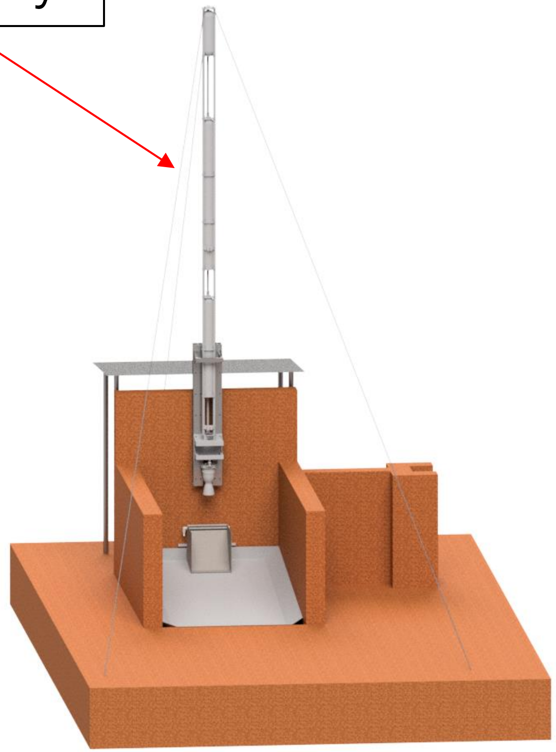


Vertical test stand (VTS)

- FAR-Mars competition requires a test of the vehicle in the flight configuration.
- Test cell 2 allows testing on campus
- Currently no thrust takeout or flame deflector is installed
- I-Beam structure with vehicle cradle and thrust takeout
- Winch structure supports from above
- Three load cells measure thrust

Test Cell 2

Vehicle supported vertically



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Level 1.0 requirements - vehicle design

1.1	The launch vehicle shall use a bi-propellant rocket engine.
1.2	The launch vehicle shall utilize dual-deployment parachute recovery with a drogue parachute deployed at apogee and main parachute deployment below 1,000 feet.
1.3	The launch vehicle shall not have active guidance.
1.4	The launch vehicle shall have fixed fins.
1.5	The launch vehicle shall carry a payload provided by FAR that will monitor the launch vehicle's altitude at apogee. (see Level 3.0 Requirements – Payload)
1.6	The payload compartment shall be radio transparent.
1.7	The payload compartment shall be vented to the atmosphere.
1.8	The payload compartment shall be attached to the main body of the launch vehicle.
1.9	The payload shall be attached to the main body of the launch vehicle.

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Level 1.0 requirements - vehicle design

1.10	Relief valves on tanks shall be rated at 1.25 times the maximum operating pressure.
1.11	Propellants shall be filled and drained from the bottom of the launch vehicle.
1.12	Propellant fill and drain valves shall be accessible from ground level.
1.13	Manual vent valves shall be accessible from ground level.
1.14	Propellant tanks shall have the Rocket Emergency Depressurization System (REDS).
1.15	Tanks shall have remote electronic pressure instrumentation for tank pressures.
1.16	Fluid umbilicals shall release from the launch vehicle through electromechanical, pneumatic, or lift-off release mechanisms.
1.17	Electrical umbilicals for remote vent controls and pressure instrumentation shall have lift-off or pull-release mechanisms.
1.18	The electrical ignition shall have a key lock-out on the pad with the same key lock-out at the main launch controller.

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Level 2.0 requirements - competition

2.1	The team shall submit a video recording of the static firing by February 1, 2020.
2.2	The team shall submit a thrust-versus-time plot of the engine system by February 1, 2020.
2.3	The launch vehicle shall be assembled for the on-site safety inspection on the launch date.
2.4	The launch vehicle shall pass a safety inspection conducted by FAR before launch.
2.5	The launch vehicle shall be mounted on the launch rail, loaded with propellants, and successfully flown within a 2-hour time limit.
2.6	The team shall complete the Safety Form on the FAR website.
2.7	The team shall complete the Qualification Form on the FAR website.
2.8	The team shall register for the competition by February 1, 2020 on the FAR website.
2.9	The team shall confirm intent to launch and select a launch day by March 20, 2020 on the FAR website.

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Level 3.0 requirements - payload

3.1	The launch vehicle shall accommodate a payload with a weight of 2.2 lbf (1 kg).
3.2	The launch vehicle shall accommodate a payload with a diameter of 3 inches and a length of 5 inches.
3.3	The launch vehicle shall accommodate a payload that utilizes a GPS and an altimeter that are powered by an internal battery.

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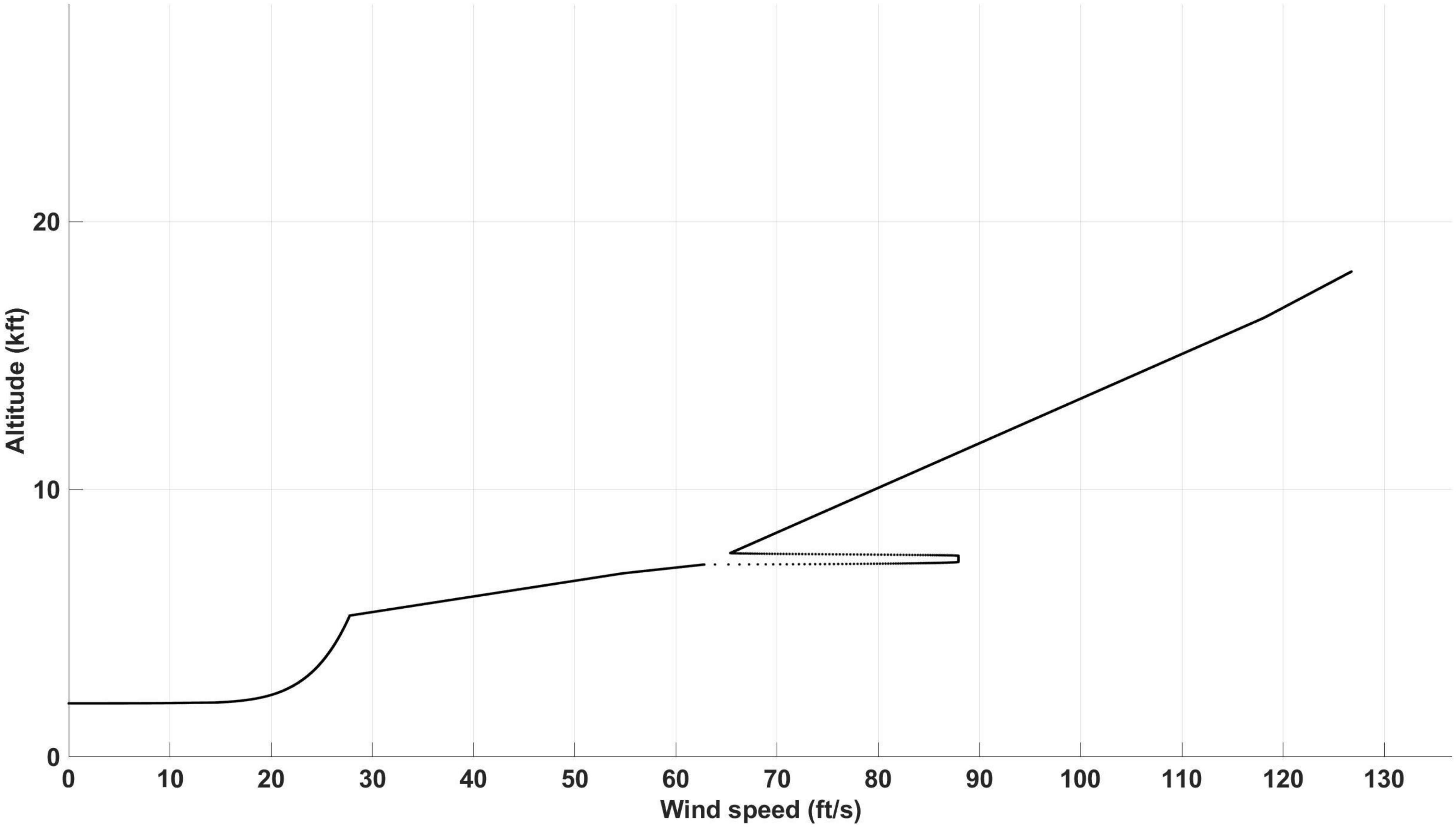
Predicted Performance Graphs

Matt Boban

Worst case wind scenario



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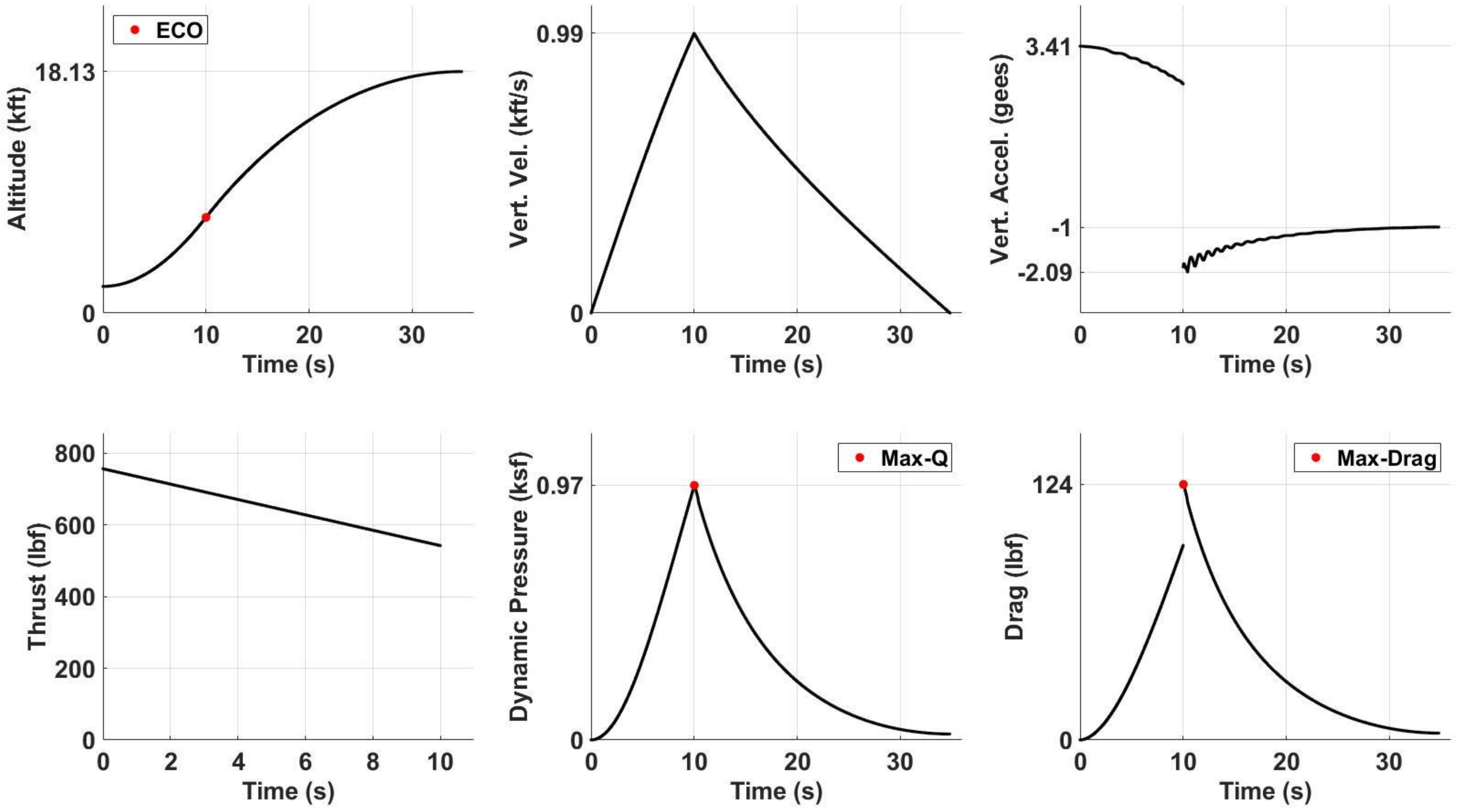
Predicted flight condition plots



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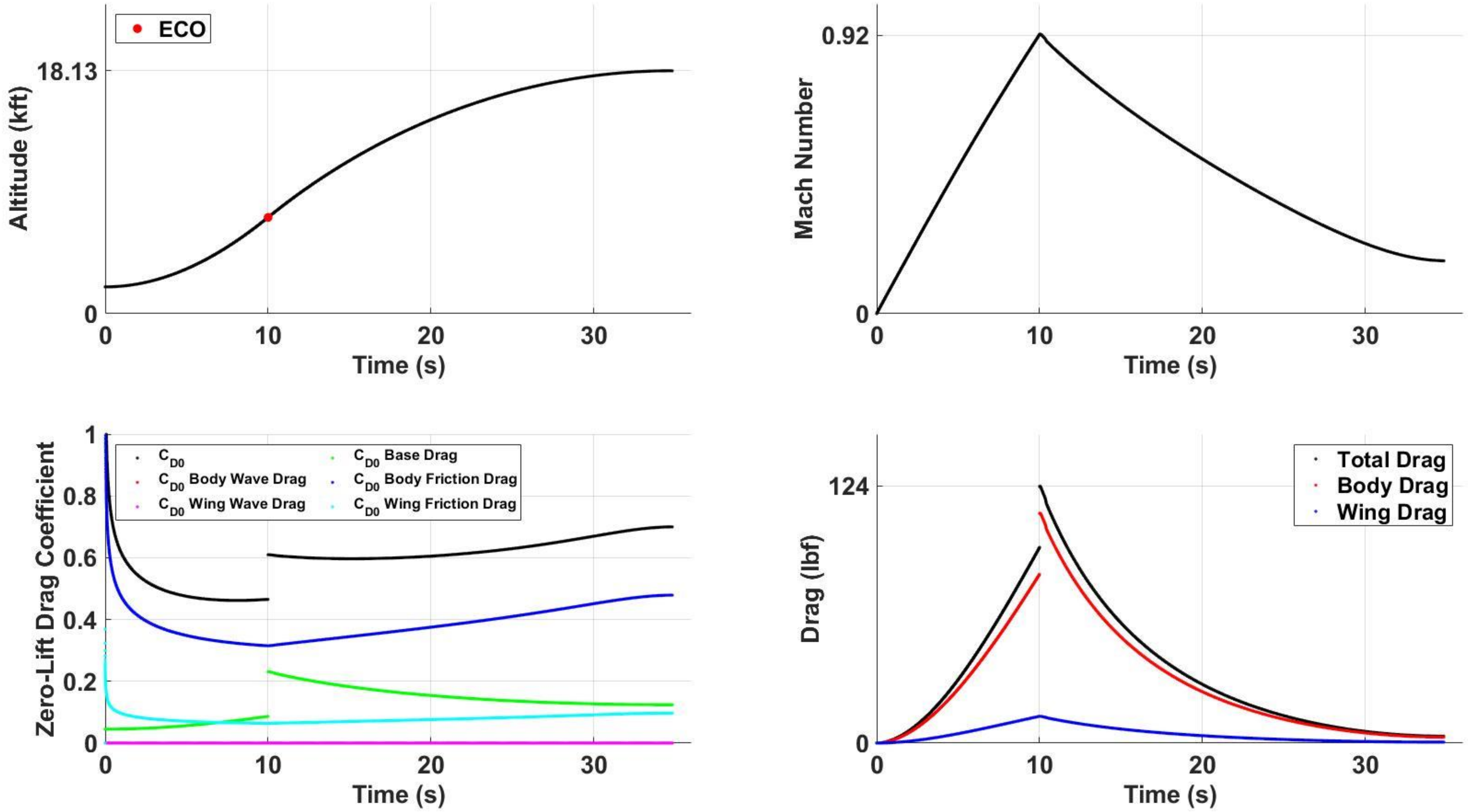
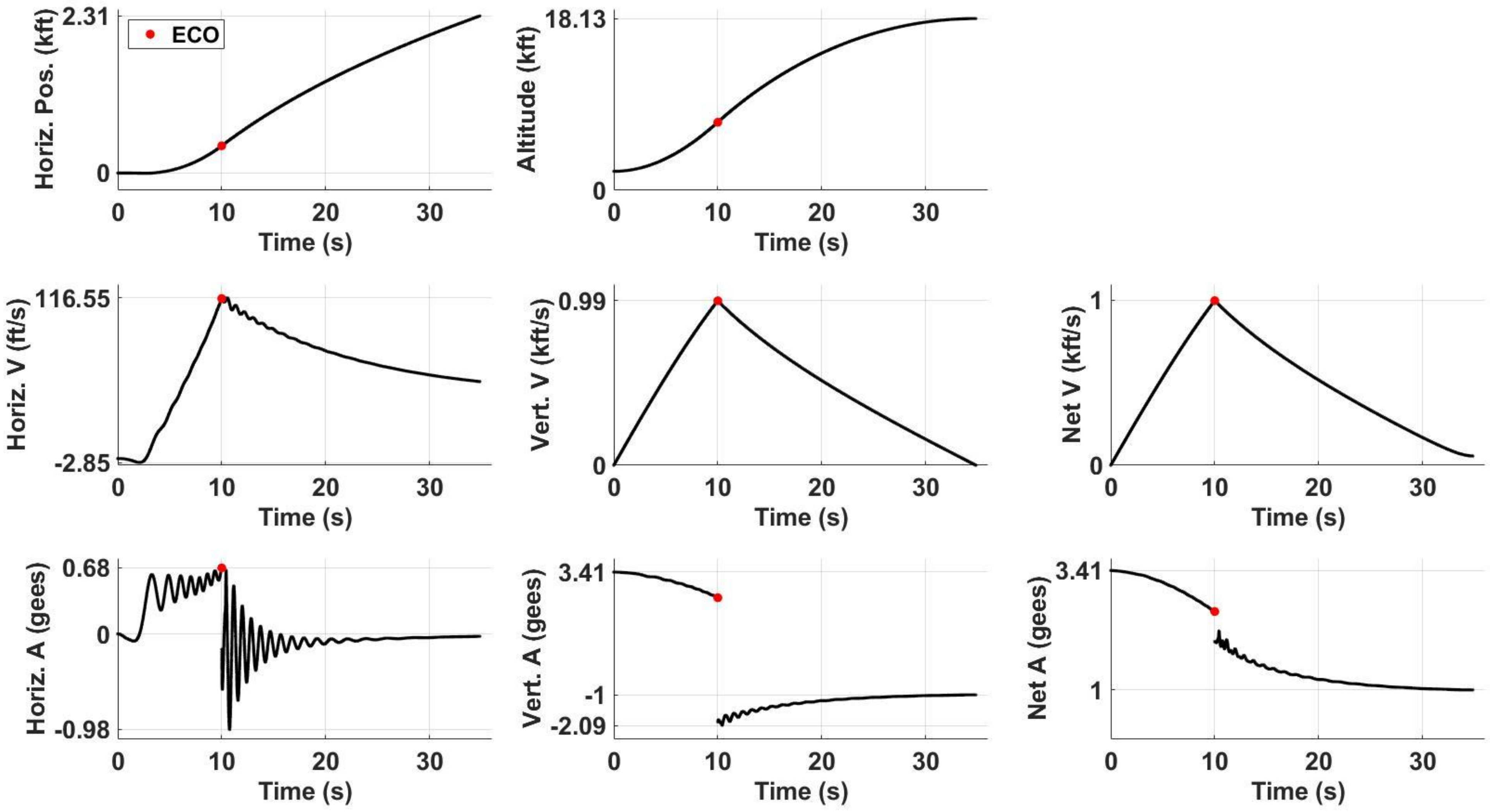
Predicted drag plots

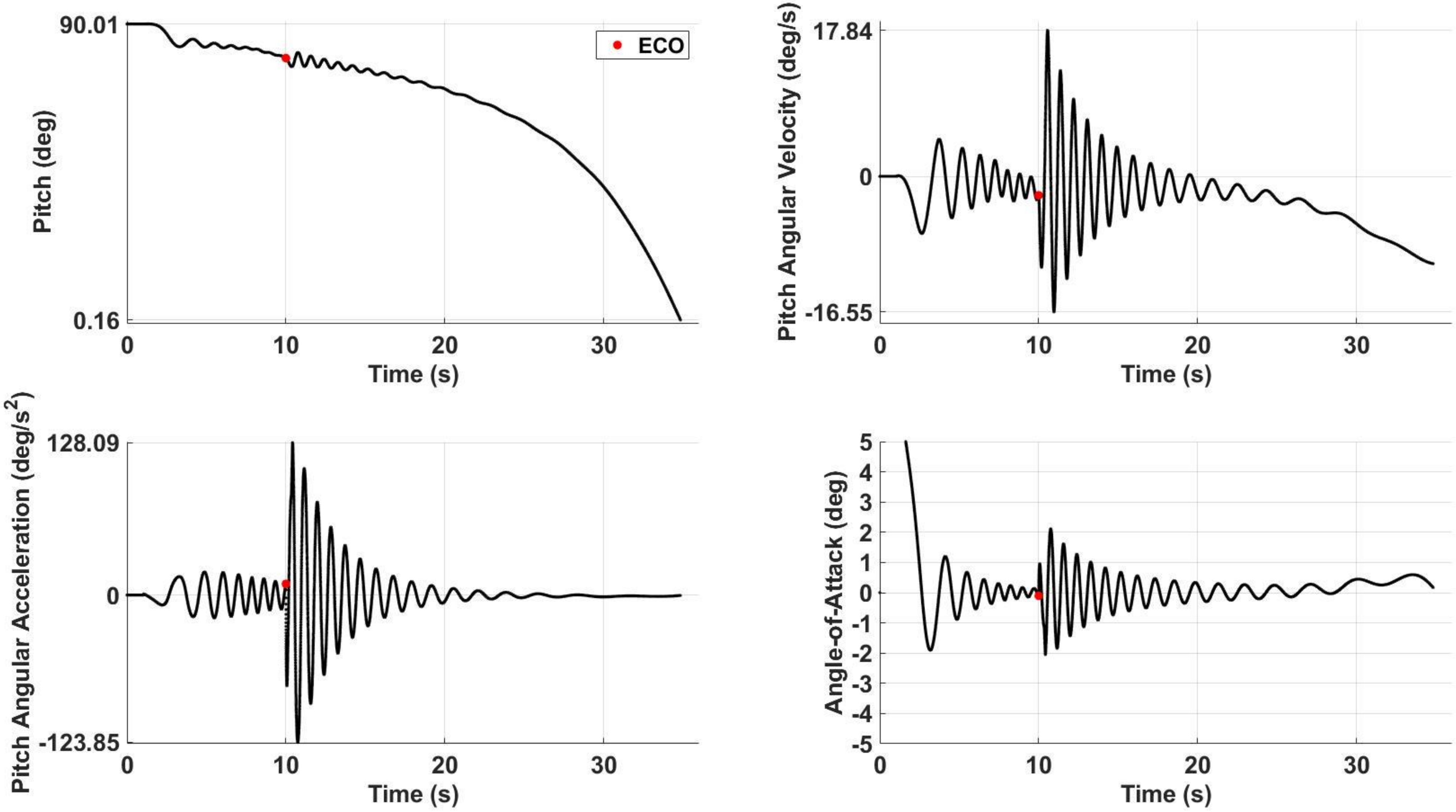


ZENITH PROPULSION

Position, velocity, & acceleration plots



Pitch & angle of attack plots



ZENITH PROPULSION

Risk Reduction

Matt Boban

Project contingencies

- Janus 2
  - Meeting project objective of flight
  - Integrate Janus 1 into design
  - Proceed with Janus 2 fabrication
- Vertical Test Stand
  - FAR-MARS vertical test requirement
  - Deadline of 2/1/20
  - Point of no return: end of November
    - Decision: hot fire at FAR

GSE extended BOM

Item	Vendor	Descriptio	Cost	QTY	EXT Cost
CPC 37 Pin connector FMLE	Digikey	PT / VLVE	6.20	2	$ 12.40
SD-130 Connector MALE	Digikey	quick rls	3.15	2	$ 6.30
SD-130 Connector FMLE	Digikey	vhcl side	5.20	2	$ 10.40
Diode 1kv 1a	Digikey	DIODE	0.10	16	$ 1.60
20awg wire 16ft spools	Digikey	PT / VLVE	28.42	1	$ 28.42
Key Lockout	Digikey	Lockout	3.46	2	$ 6.92
Cat 6 MOLEX	Digikey	Connect	1.57	2	$ 3.14
Cat 6 Boot	Digikey	strn releif	0.37	10	$ 3.70
CONN RCPT MALE 2POS SOLDER CUP	Digikey	Ig sens ig volt	3.66	1	$ 3.66
CONN PLUG FMALE 2POS SOLDER CUP	Digikey	Ig sens ig volt	5.96	1	$ 5.96
Wire for base valves	Digikey	Gnd valves	12.15	1	$ 12.15
SD-130 Inline connect	Digikey	Quick rls	5.47	2	$ 10.94
REDS ConnecTOR pins	Mcmaster	Crimp pins	10.76	1	$ 10.76
REDS Connector MALE	Mcmaster	REDS	1.75	1	$ 1.75
REDS Connector FMLE	Mcmaster	REDS	3.5	1	$ 3.50
			TOTALS		$ 121.60
			Allocated Budget		$ 200.00
			% Budget Used		61%

ZENITH PROPULSION

Buckling equations

- $P_{CR} = \frac{\pi^2 * E * I_{yy}}{l_e^2}$
- $\sigma_{CR} = \frac{\pi^2 * E}{\left({}^{l_e}/_{r}\right)^2}$
- $r = \sqrt{\frac{I_{yy}}{A}}$

- P_{CR} = Critical Load
- σ_{CR} = Critical Stress
- l_e = Effective Length
- r = Radial Gyration

ZENITH PROPULSION

Bolt sizing equations

Shear in Bolt:

- $\tau_{max} = \frac{P*F.S.}{2*A_{Fastener}}$

Bearing:

- $\sigma_{Br} = \frac{P*F.S.}{A_{Hole}}$

Shear in Plate:

- $\tau_T = \frac{P*F.S.}{2*C*t}$

Tear Out:

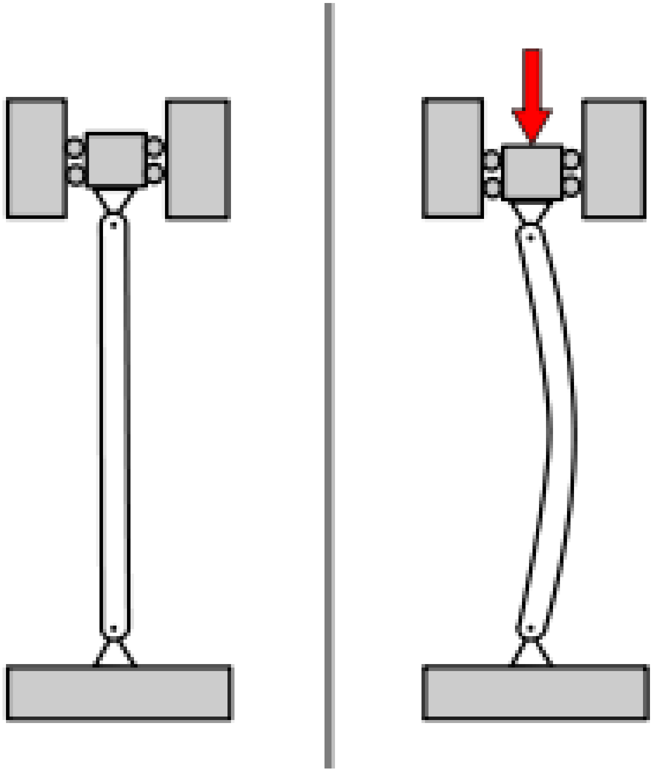
- $\tau_{TO} = \frac{P*F.S.}{(w-d)*t}$

- τ = Shear Strain
- σ = Shear Stress
- P = Loading
- A = Cross Sectional Area of Fastener
- F.S. = Factor of Safety
- C = Distance From hole to edge of plate
- t = Plate Thickness
- w = Width of Plate
- d = Diameter of hole

ZENITH PROPULSION

Buckling calculations

- Pin-pin support
- Effective Length (Le) = 36 in
- Critical Stress = 29.49 ksi
- Applied Stress = 3.357 ksi



Bolt sizing

	Ribs	Margin of Safety	Rail Guides	Margin of Safety
Bolt Dia (in.)	10-32		8-32	
Shear of Bolt (ksi)	10.485	6.630	22.159	2.159
Bearing Stress (ksi)	12.912	5.351	23.599	1.839
Tear Out (ksi)	2.531	14.015	4.000	9.500
Shear of Plate (ksi)	8.325	2.123	6.051	4.784

ZENITH PROPULSION

Extruded part selection

Standard Dimensions Used:

- Width: 1 in
- Height: 1 in
- Length: 15 ft

Parameter	T-Bar	I-Beam	C-Channel
Moment of Inertia (in^4)	0.011	0.0526	0.0526
Total Weight (lb)	3.4277	5.027	5.027
Cost Per Foot	$2.84	N/A	$3.57

- C-Channel was chosen

Material selection

Parameter	6061-T6 Aluminum	6063-T5 Aluminum	304 Stainless Steel
Ultimate Strength (ksi)	42	27	73.2
Density (lbm/in^2)	0.0975	0.0975	0.285

- 6061-T6 Aluminum was chosen for the rib supports
- 6063-T6 Aluminum was chosen for the extruded parts

ZENITH PROPULSION

Stress calculations

Buckling Calcs:

- Effective Length (Le) = 36 in
- Critical Stress = 29.49 ksi
- Applied Stress = 3.357 ksi

Bending of Plate:

- Max Displacement: 0.000154 in
- Max Stress: 158 psi

Bolt Sizing:

- Size: 10-32
- Driving M.S. = 2.123 (Shear of Plate)

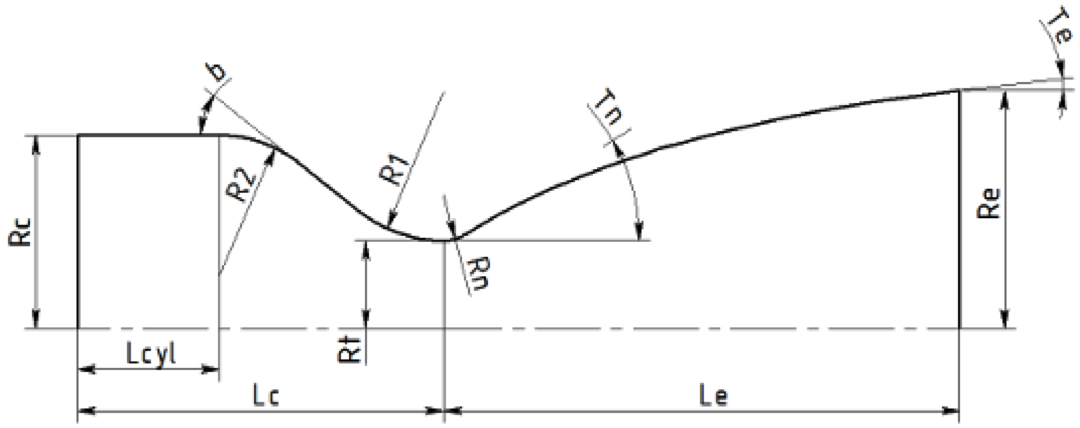
- Size: 8-32
- Driving M.S. = 1.839 (Bearing)

ZENITH PROPULSION

Rocket propulsion analysis program outputs

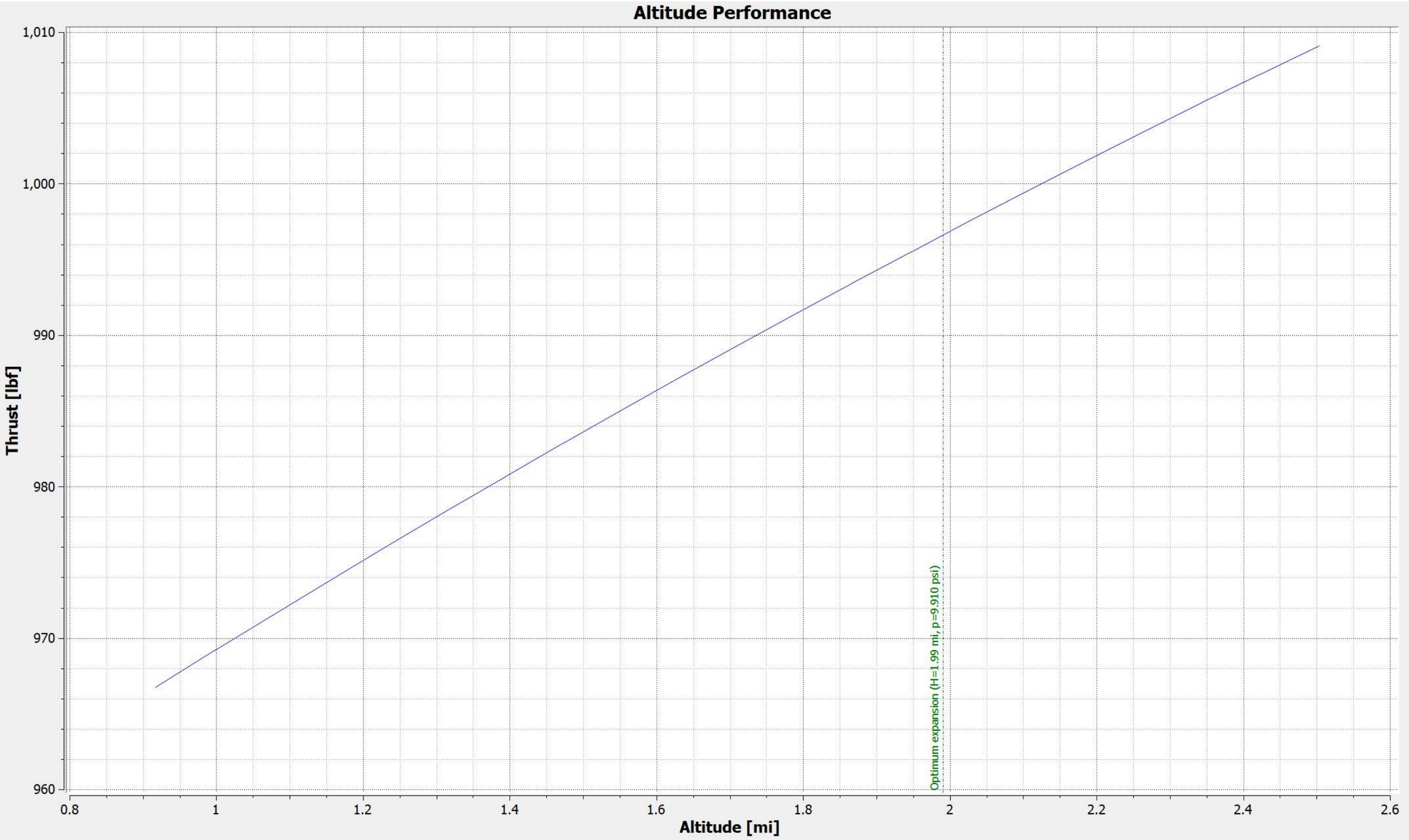
```
Thrust and mass flow rates
-------------------------------------------
   Chamber thrust (opt):  996.59627    lbf
 Specific impulse (vac):  289.94109      s
   Chamber thrust (vac): 1120.45935    lbf
 Specific impulse (opt):  257.88906      s
   Total mass flow rate:    3.86444  lbm/s
Oxidizer mass flow rate:    2.72449  lbm/s
    Fuel mass flow rate:    1.13995  lbm/s

Geometry of thrust chamber with parabolic nozzle
-------------------------------------------
    Dc =     3.63  in        b =   30.00 deg
    R2 =     2.94  in       R1 =    1.28  in
    L* =    35.00  in
    Lc =     8.85  in     Lcyl =    6.05  in
    Dt =     1.71  in
    Rn =     0.33  in       Tn =   19.99 deg
    Le =     4.53  in       Te =    8.00 deg
    De =     3.93  in
 Ae/At =     5.28
 Le/Dt =     2.65
Le/c15   =  108.12 % (relative to length of cone nozzle with Te=15 deg)
```



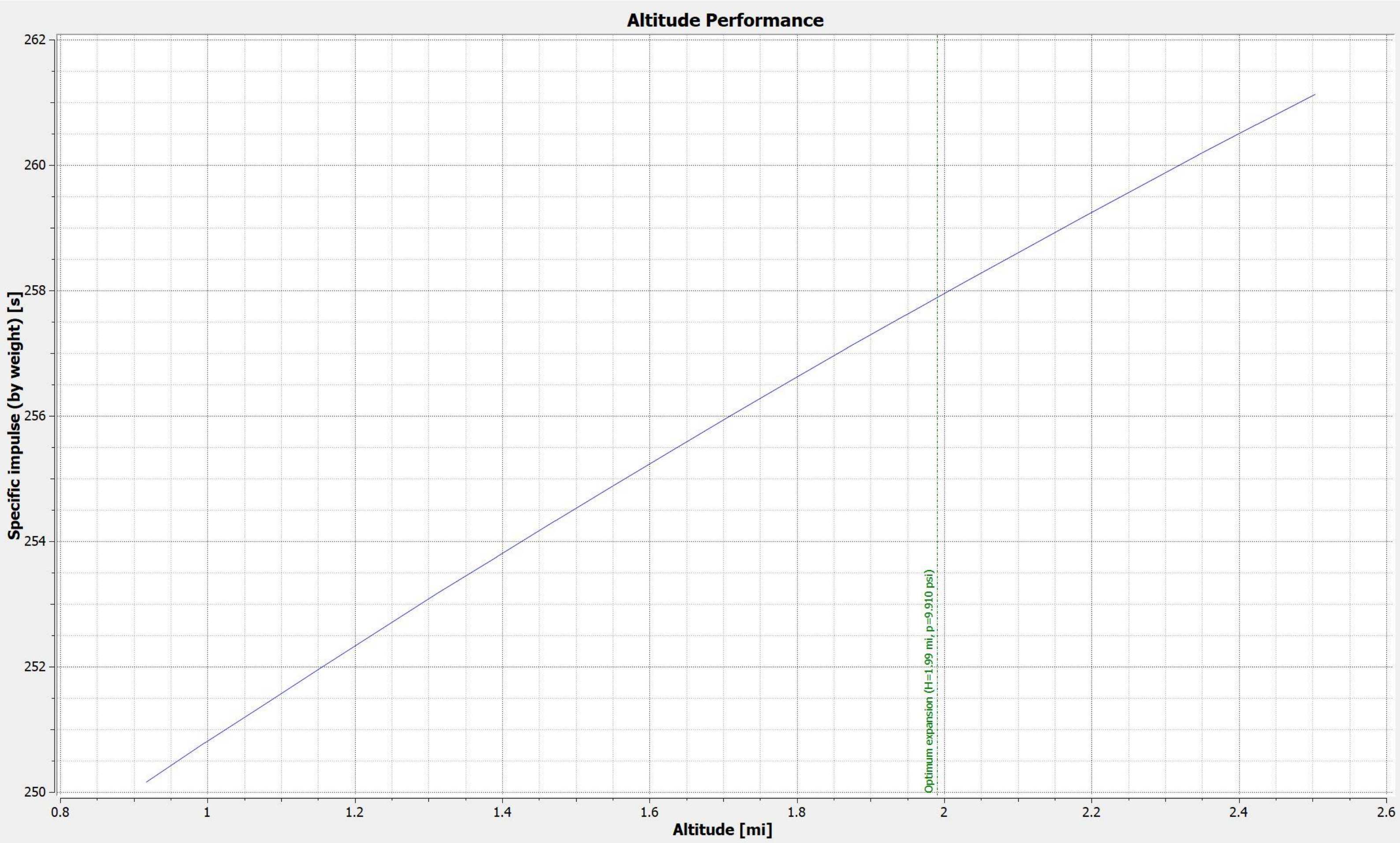
ZENITH PROPULSION

Janus 2.0 thrust vs. altitude



ZENITH PROPULSION

Janus 2.0 I_{SP} vs. altitude



ZENITH PROPULSION

Pressurant gas selection

	GN2	GHe
Cost ($/ft^3)	0.015	0.086
Reqd Tank Vol (ft^3)	0.1778	0.2065
Density (lbm/ft^3)	0.078	0.011
Total Mass Reqd	2.578	0.4278

ZENITH PROPULSION

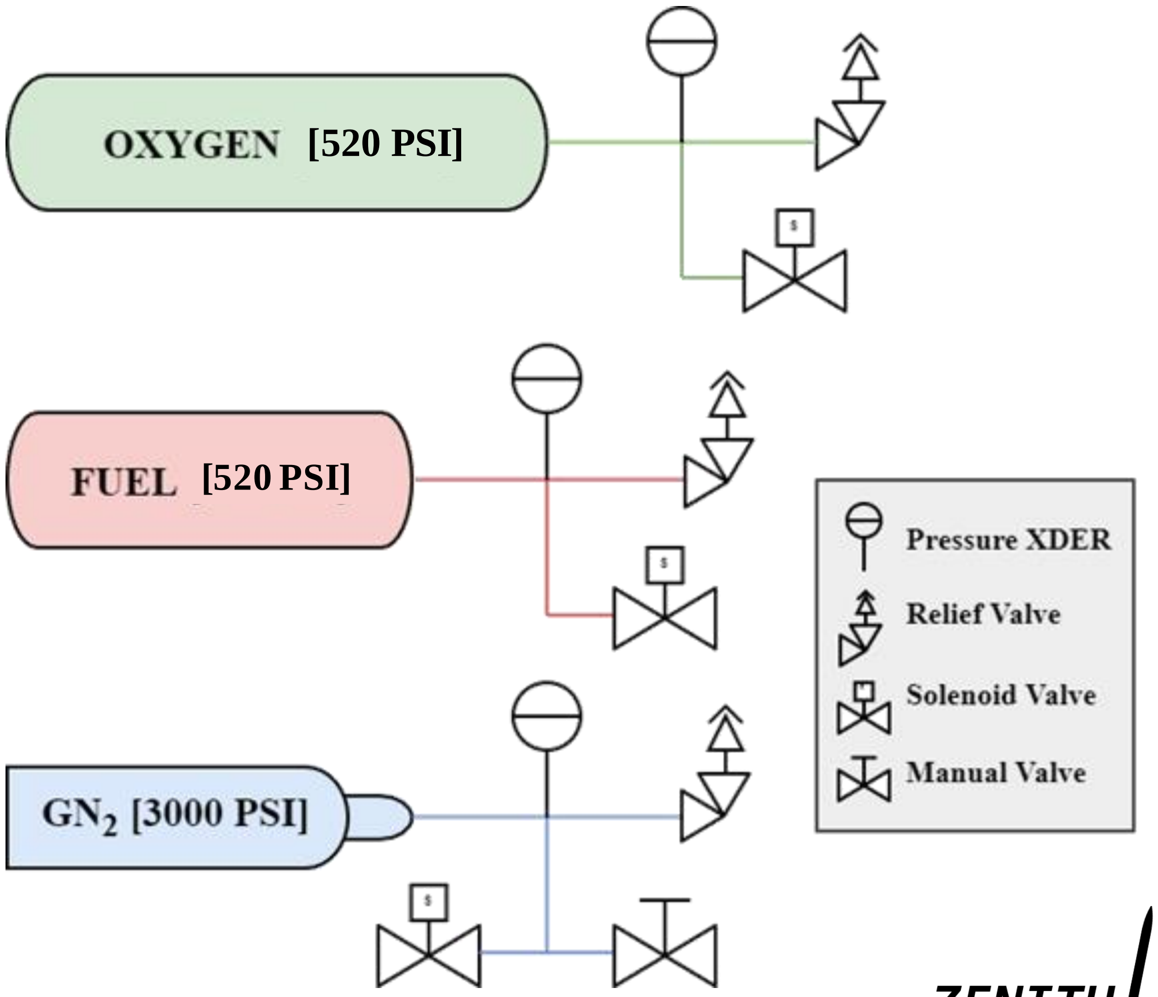
Cavitating venturis for mass flow regulation

Parameter	Value
Total Fuel Flow Rate	1.54 lbm/s
Fuel Film Cooling Flow Rate	0.21 lbm/s
Oxygen Flow Rate	3.21 lbm/s
Pressurant Flow Rate	175.9 scfm
Injector Pressure	360 psi
Venturi Inlet Pressure	520 psi

Important pressures

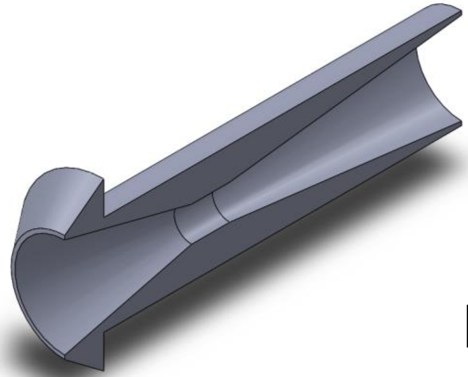
Location	Pressure
Combustion Chamber	300 psi
Propellant Tanks	550 psi
Pressurant Tank (initial)	3000 psi
Propellant Tank Relief Valve	700 psi
Pressurant Tank Relief Valve	4000 psi

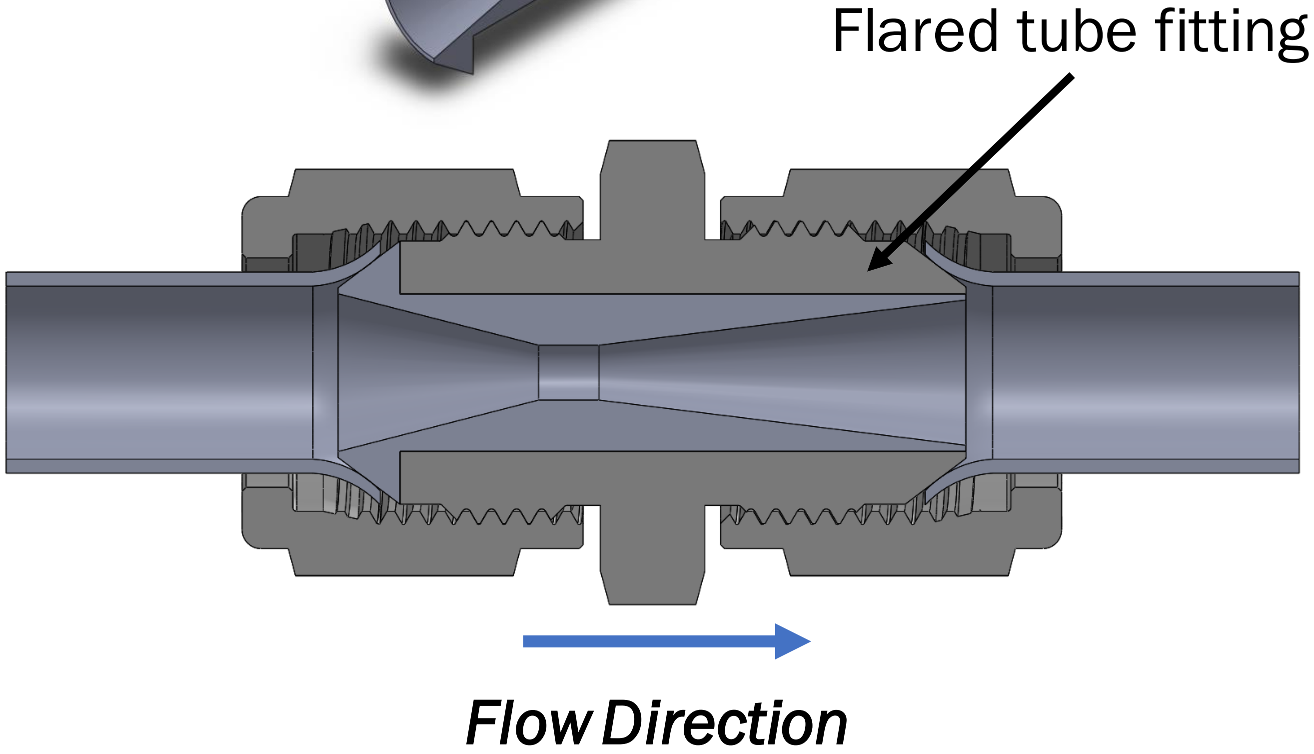
Pressure vessel safety mechanisms



ZENITH PROPULSION

Cavitating venturis for mass flow regulation





Specifications	
Cost (QTY 2)	$0
Mass flow rate (fuel)	1.54 lbm/s
Mass flow rate (lox)	3.21 lbm/s

ZENITH PROPULSION

Ball valves

¼” Man Valve for GN2 Fill

½” Man Valves for Prop Fill

½” Pneumatic Valves for Mains

Specifications	
Cost (QTY 5)	$261.6
Vendor	Valworx
Mass	~1.1 lbm each
Cv (1/4”)	8
Cv (1/2”)	15

ZENITH PROPULSION

Feed system mass

Item	Mass
Pressurant Tank	12.3 lbm
Regulator	2.87 lbm
Pyro Valve	2.23 lbm
Main Valves	2.2 lbm
Relief Valves	2.1 lbm
Vent Valves	1.5 lbm
Fittings & Tubing	7.8 lbm
TOTAL	**31.0 lbm**
BUDGET	**29.1 lbm**

GN2 tank sizing equations

Vol flow rate reqd	0.07374759	ft^3/s	$\dot{V}_{GN2} = \dot{V}_{fuel} + \dot{V}_{lox}$
Mass flow rate reqd	0.1982205	lbm/s	$\dot{m}_{GN2} = \dot{V}_{GN2} * \rho_{GN2@550}$
Reg set pressure	550	psi	
	79200	psf	
Burn time	10	seconds	
Usable mass reqd	1.98220498	lbm	$m_{GN2} = \dot{m}_{GN2} * t_{burn}$
	0.06160881	slug	
GN2 tank pressure	3000	psi	
	432000	psf	
Residual mass	0.01383055	slug	$m_{res} = m_{GN2}/(p_{tank}/p_{reg} - 1)$
Total mass reqd	0.07543936	slug	$m_{tot} = m_{GN2} + m_{res}$
Tank vol reqd	0.16738109	ft^3	$V_{tank} = m_{tot} R_{GN2} T / p_{tank}$
D	5.25	in	
H	19.48	in	
Vol approx	421.694018	in^3	$V_{tank} = \pi \frac{D^2}{4} H$
	0.24403589	ft^3	

ZENITH PROPULSION

Effect of acceleration on cavitating venturis

Fuel

Parameter	**Calculation**
Max acceleration	7 g_E
Delta inlet pressure	262 psf
Excess mass flow	0.028 lbm/s
Excess mass total	0.254 lbm

LOX

Parameter	**Calculation**
Max acceleration	7 g_E
Delta inlet pressure	3572 psf
Excess mass flow	0.066 lbm/s
Excess mass total	0.610 lbm

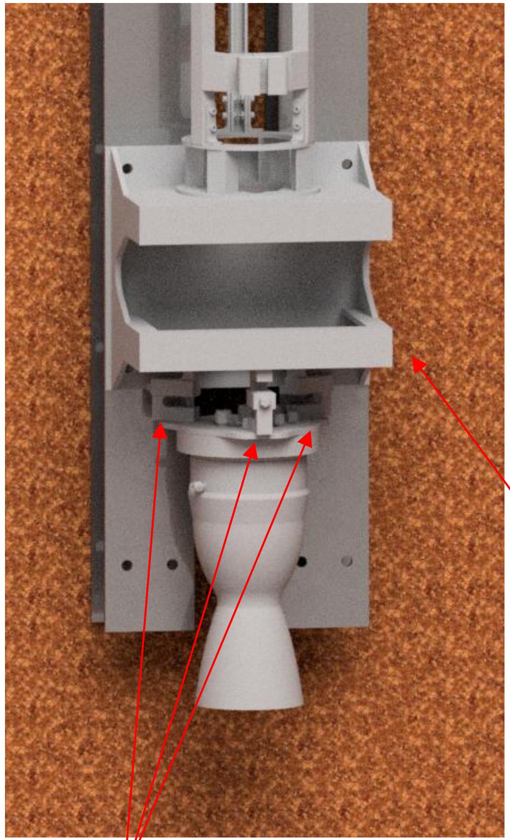
Excess thrust: ~20 lbf

Vertical test stand (VTS) requirements

System Requirements

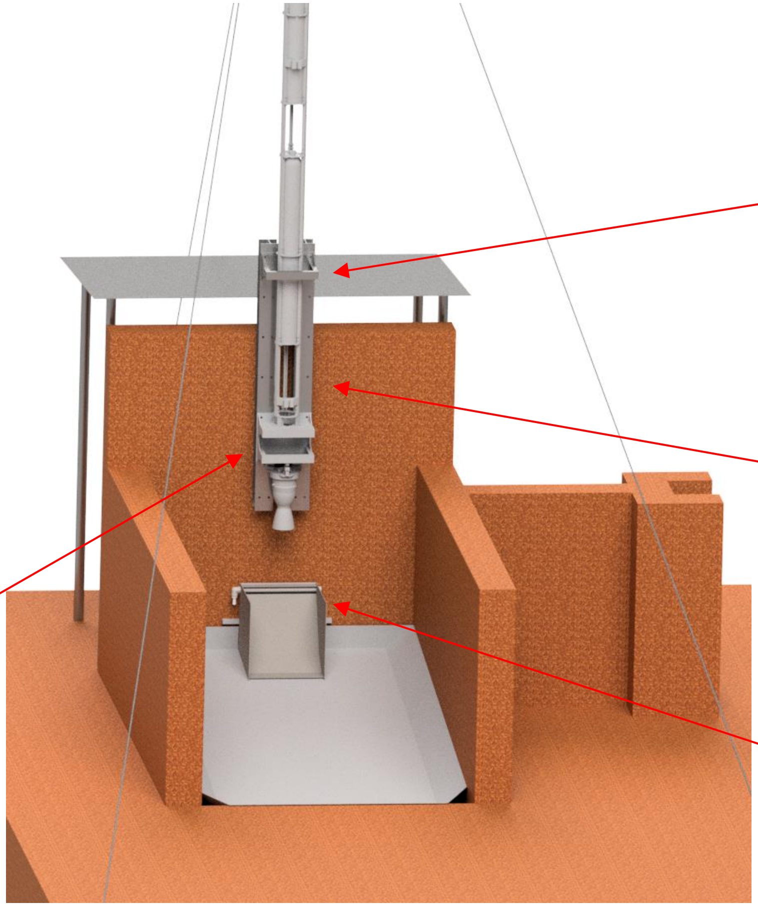
- Support full-duration vertical test fire (Requirement 2.1)
- Measure engine thrust during test fire (Requirement 2.2)
- Integrate with ground support equipment

Vertical test stand (VTS)



Load Cells

Thrust takeout



Vehicle cradle resists off-axis thrust

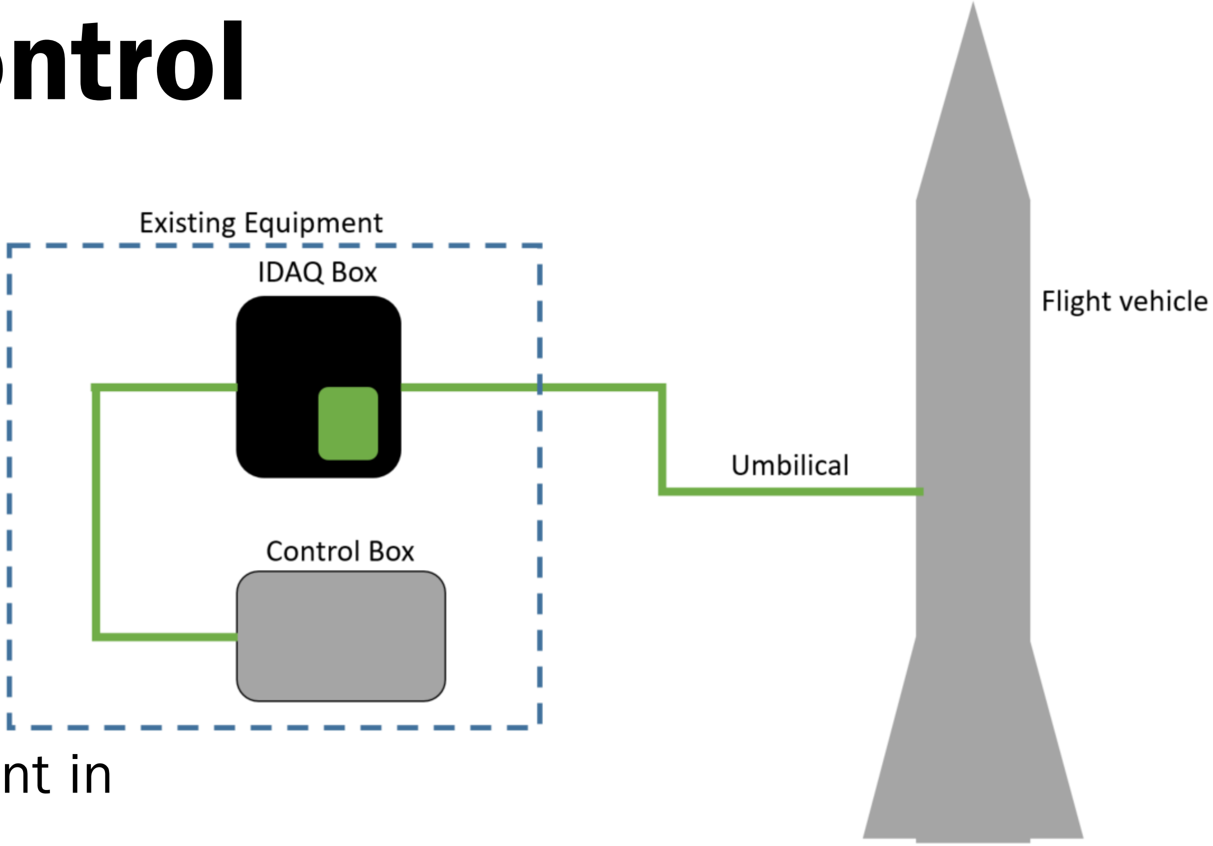
I-beams transfer load to concrete structure

Water-cooled flame diverter

Overview of vehicle control

Capability

- C++ in Arduino integrated development environment (IDE)
- Auto sequence and Labview-powered abort



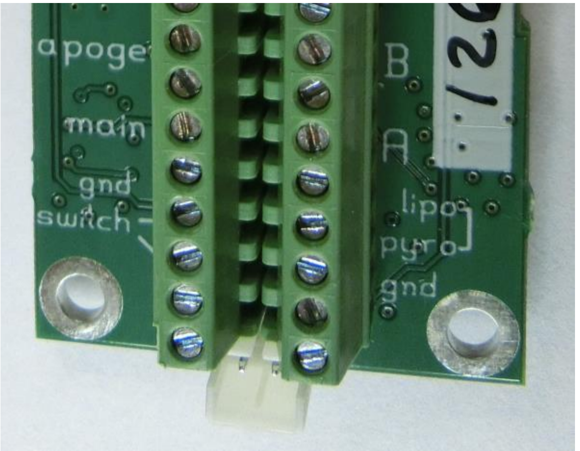
Utilization

- Modular when used with the IDAQ box present in Test Cell 3
- Modifications to original code make use in Vertical Testing and launch vehicle possible

Vehicle recovery system selection

Parachute recovery

- Drogue deployment at apogee
- Main deployment at 1000 ft AGL
- Data logging
- Running off a 9V battery

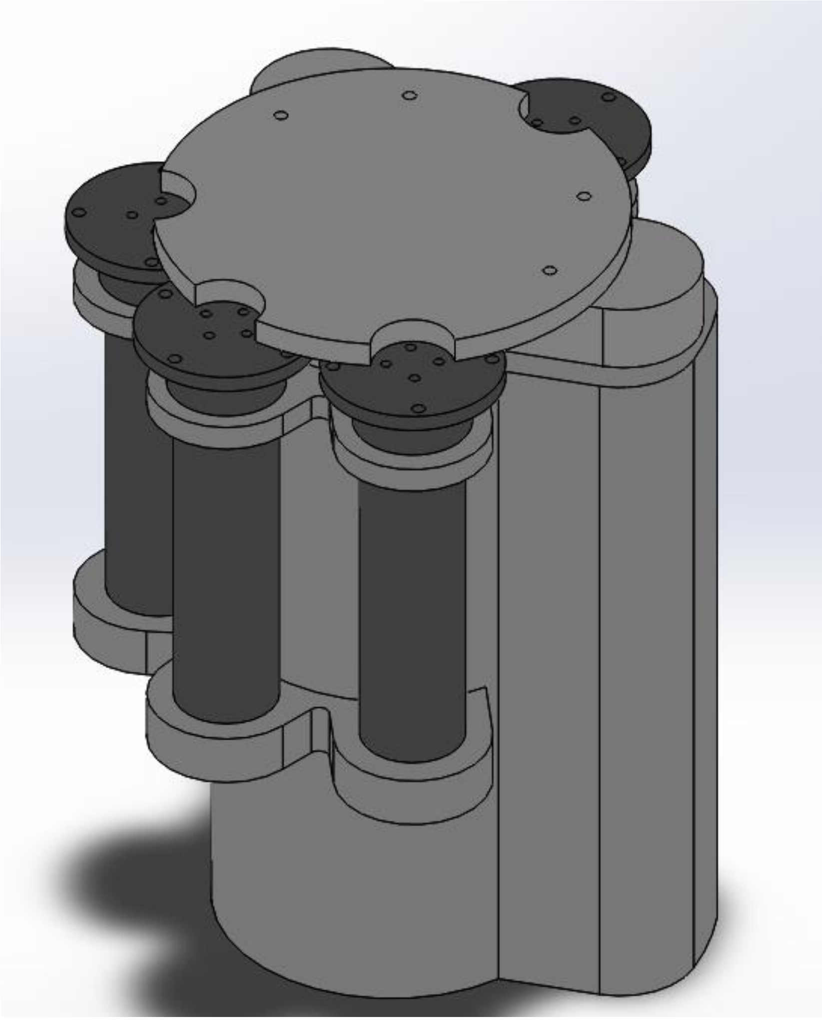


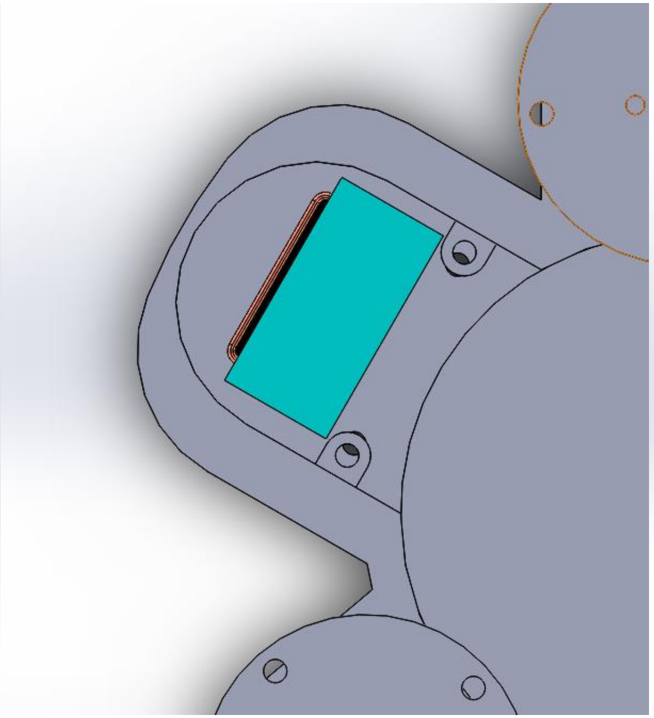
[12]

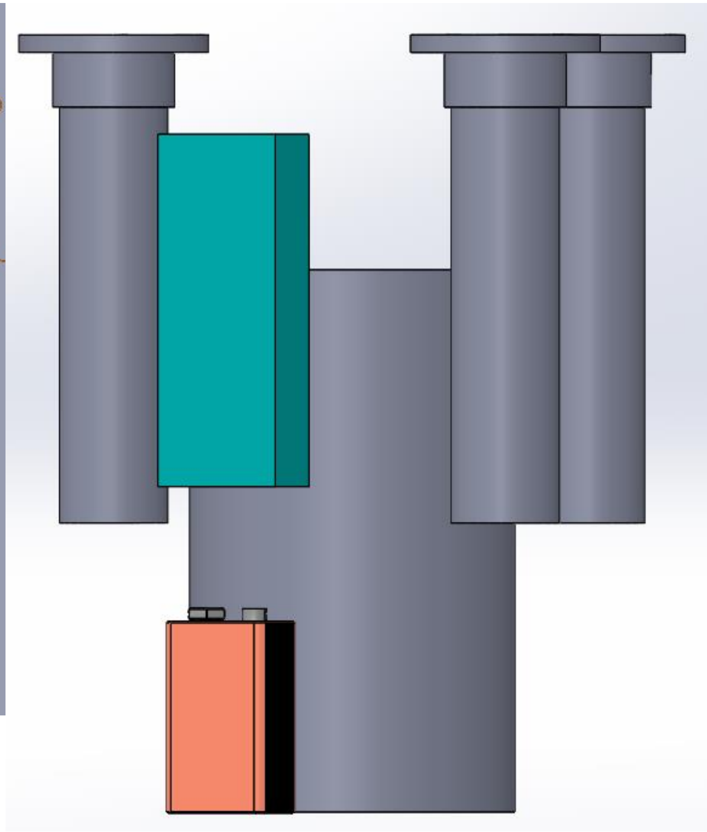
	Telemega	Telemini	Stratologger CF
Max. Altitude (MSL)	**100,000 ft**	100,000 ft	100,000 ft
Built-in telemetry?	**Yes**	No	No

- Telemega chosen as primary

Avionics housing views







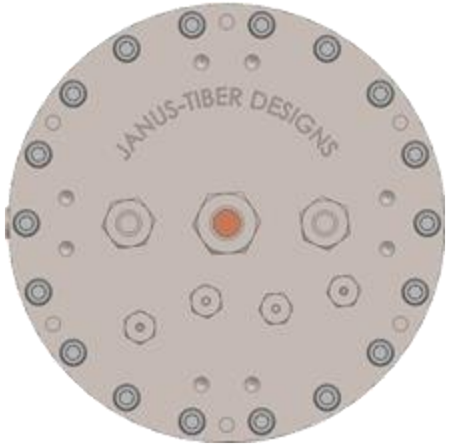
ZENITH PROPULSION

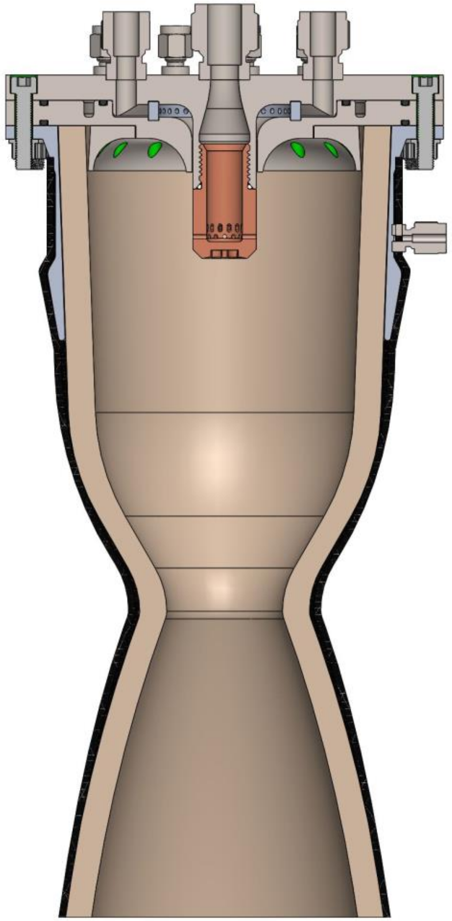
Engine Redesign

Jonathan Noble

Engine design requirements

- 6" Maximum Overall Diameter
- Maintain Janus 1.0 performance





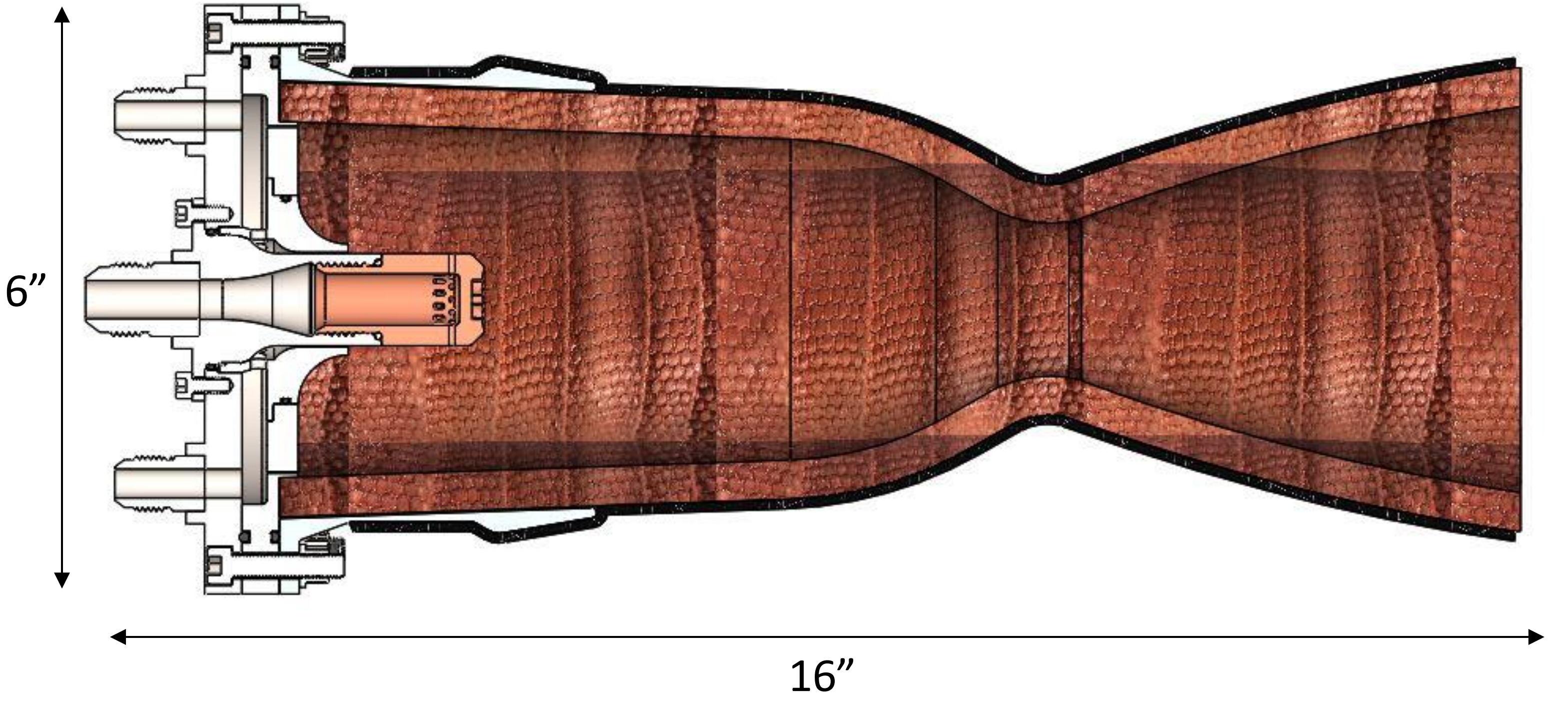
Janus 1.0

Janus 2.0

ZENITH PROPULSION

Engine design overview

Thrust	1000 lbf
Specific Impulse	257 s
O/F	2.39
Chamber Pressure	300 psi
Injector Pressure	360 psi
Total $\dot{M}$	3.71 lbm/s
L*	40in



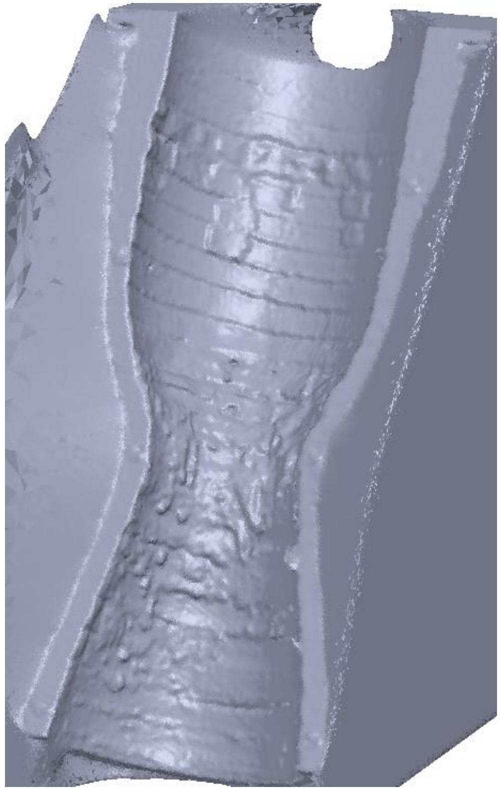
ZENITH PROPULSION

Ablative chamber design

- Rocket Propulsion Analysis (RPA)
- Increased L*
- Undersized contour
- High temp epoxy & silica strips

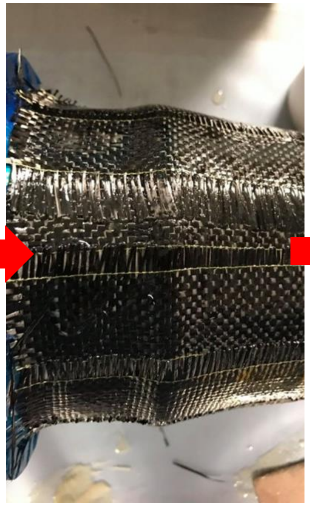
Ablative chamber performance

- Success: Full Duration Test
- Post Analysis
- Ablative improvements



Composite overwrap evolution

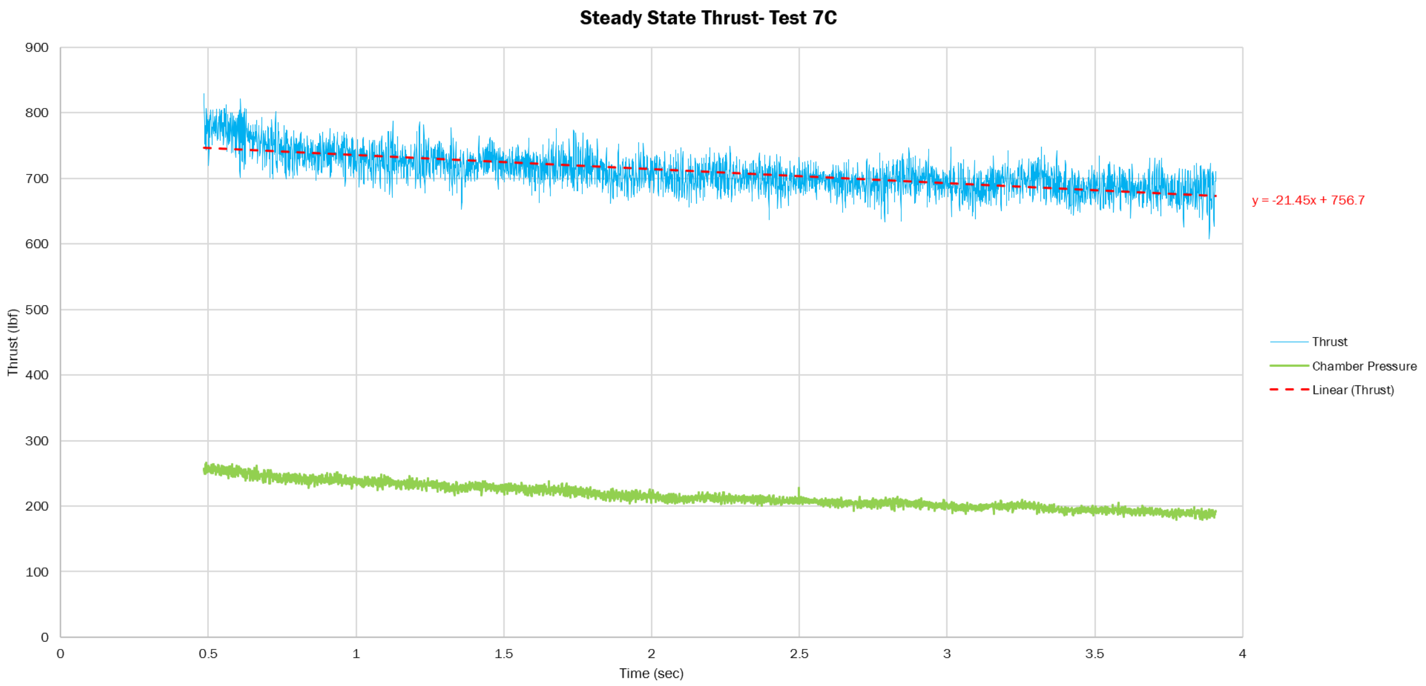
- Chamber Failures
- Quality Control
- Bi-directional fibers
  - Axial & circumferential retention



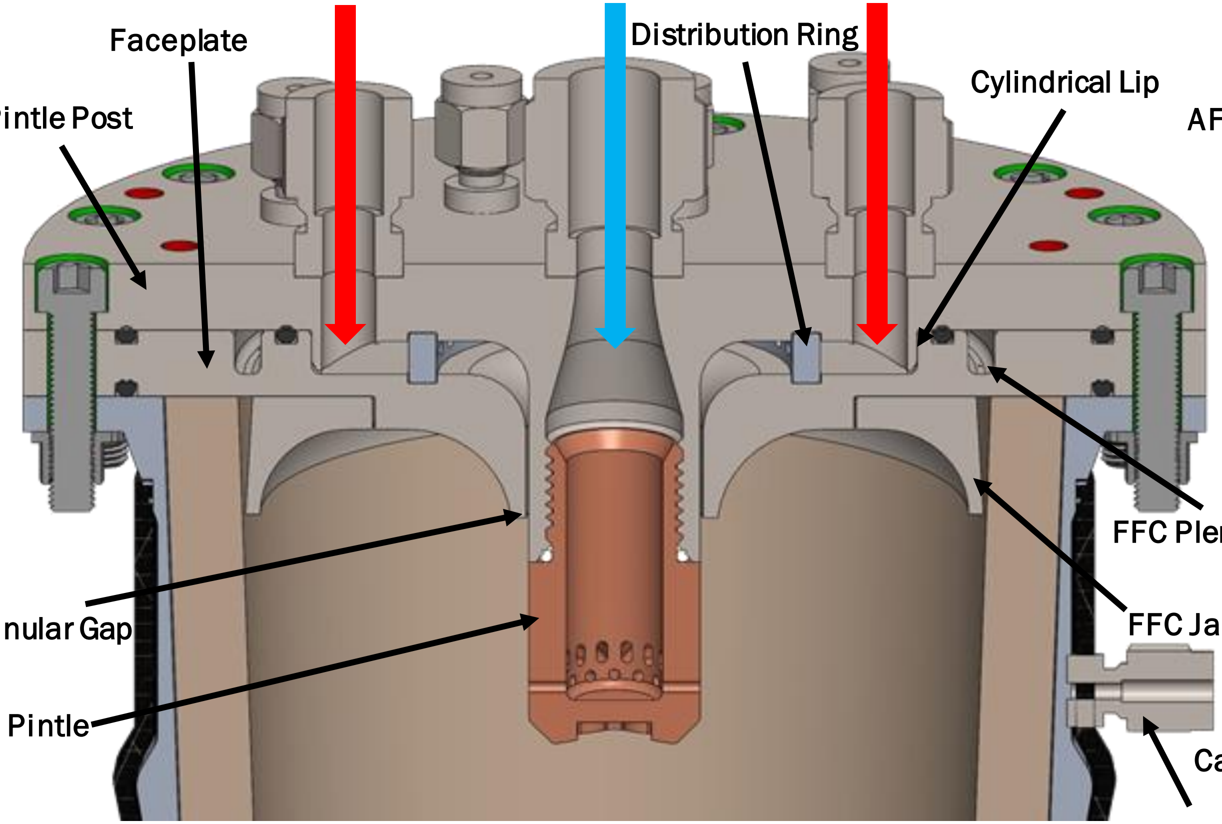
ZENITH PROPULSION

Janus 1 test data

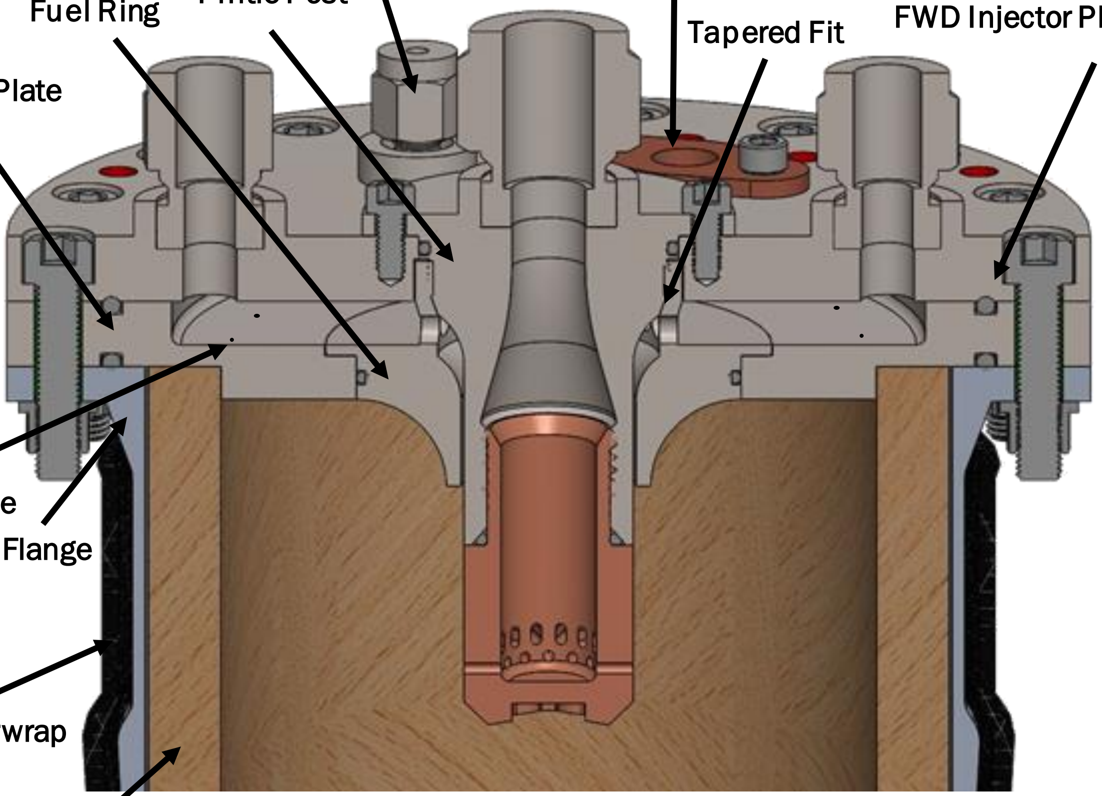
- Not meeting design performance
- 750lbf @ 250psi
- Projected 200lbf loss (20lbf/s)
- Full thrust curve (11/24)



Comparison of Janus 1.0 & Janus 2.0



Janus 1.0

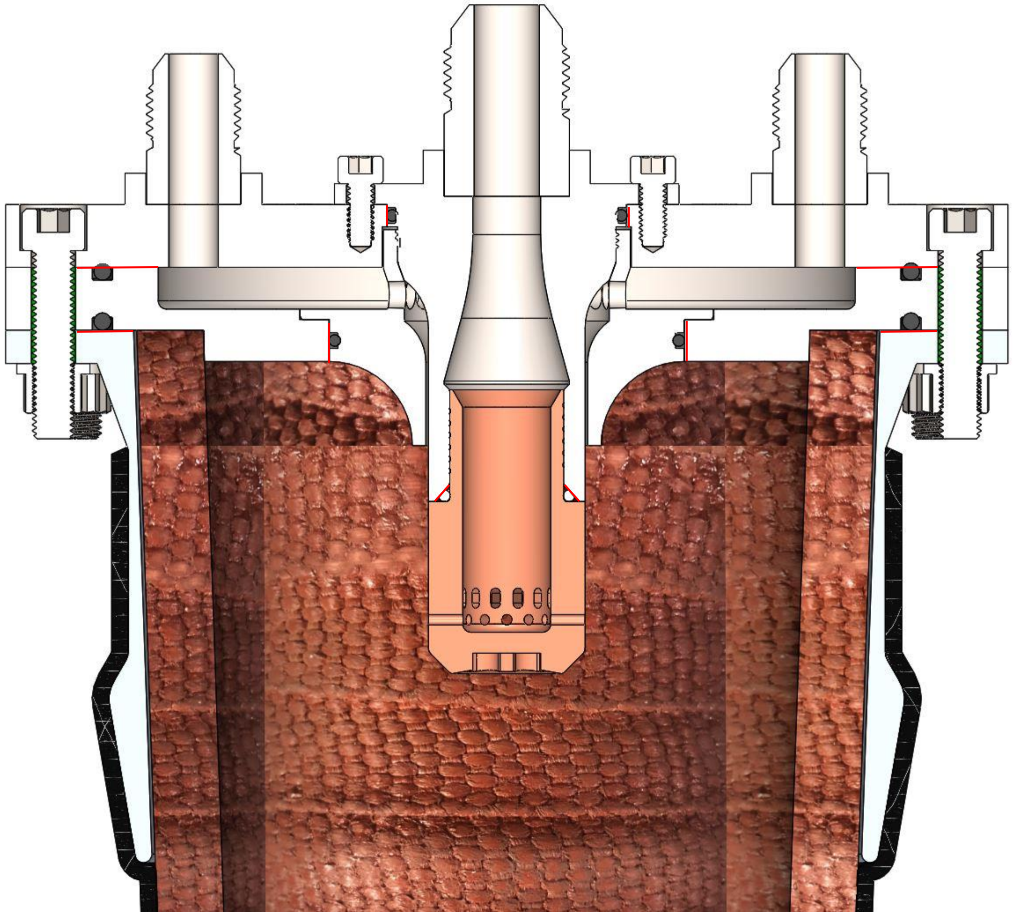


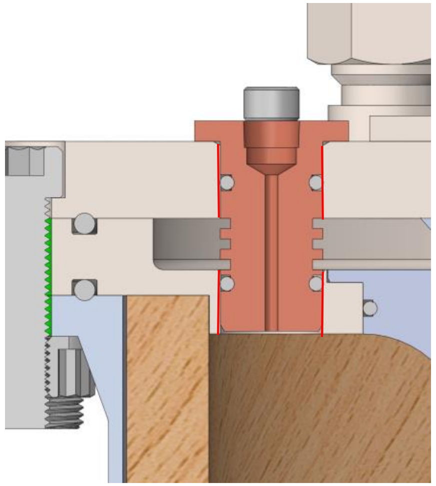
Janus 2.0

ZENITH PROPULSION

Seals

- 7 sealing surfaces
- 2 face & 5 radial seals
- (1) Teflon O-rings (¾")
- (6) Viton O-rings (3/8”, 1 5/16”, 2", 4 ¾”)

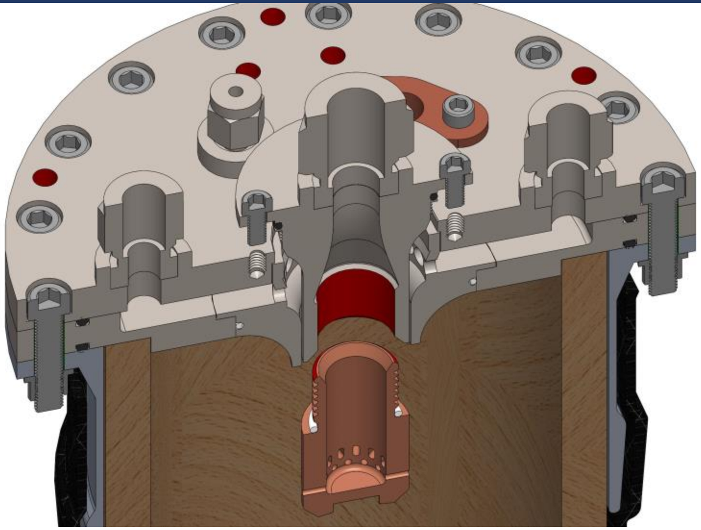


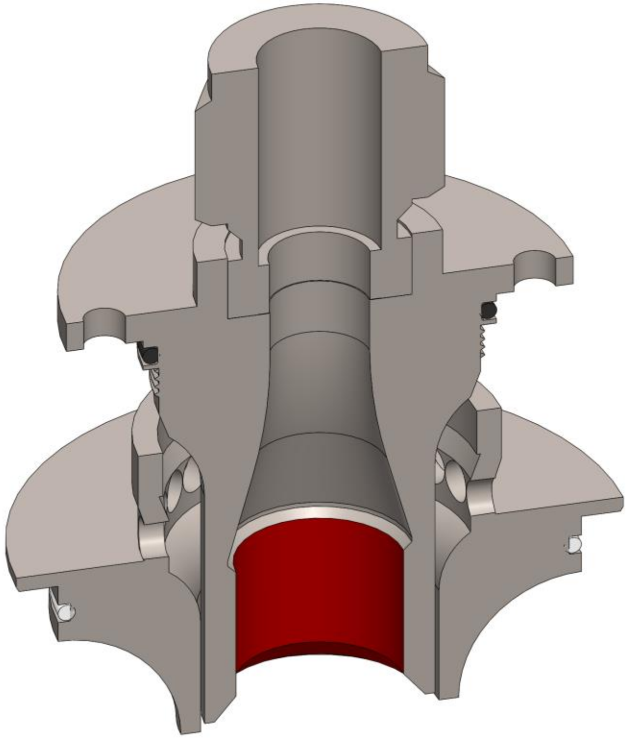


ZENITH PROPULSION

Critical fit

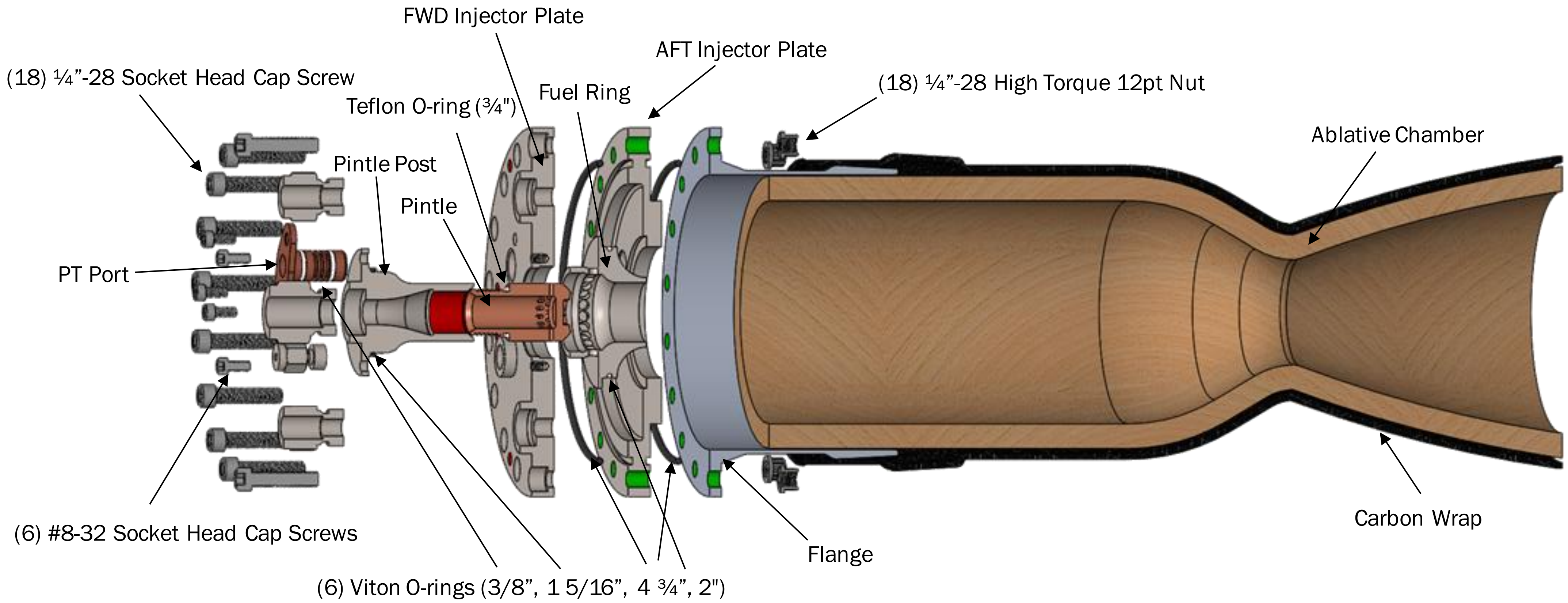
- Maintain .016” (±.0005”) concentric annular gap
- Cryogen Compatible
- Tapered Fit
- 1 5/16” – 28 Class 2 UN Threads





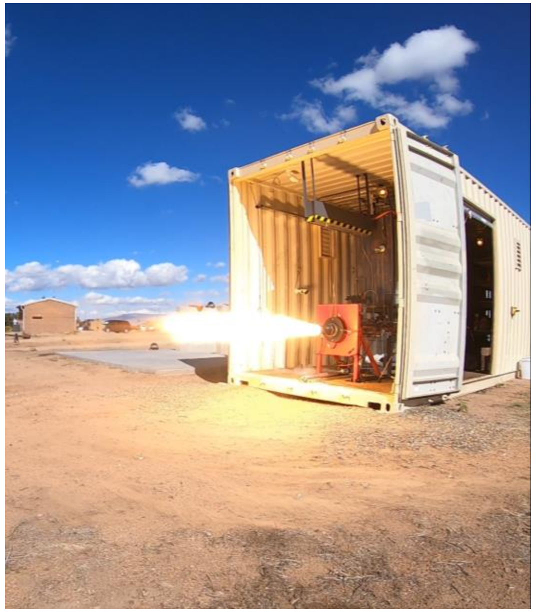
ZENITH PROPULSION

Assembly of Janus 2.0



ZENITH PROPULSION

Test 2B still frames of chamber failure



https://www.youtube.com/watch?v=XuWL5tYr21A

Preliminary weld testing

Filler Rod Material	Avg Yield Strength (PSI)	Avg Ult Strength (PSI)
4043, un-aged	11,000	12,435
4047, un-aged	10,837	11,110
5356, un-aged	10,838	13,622
4043, aged	11,660	12,367
4047, aged	14,900	16,247
5356, aged	13,130	14,201