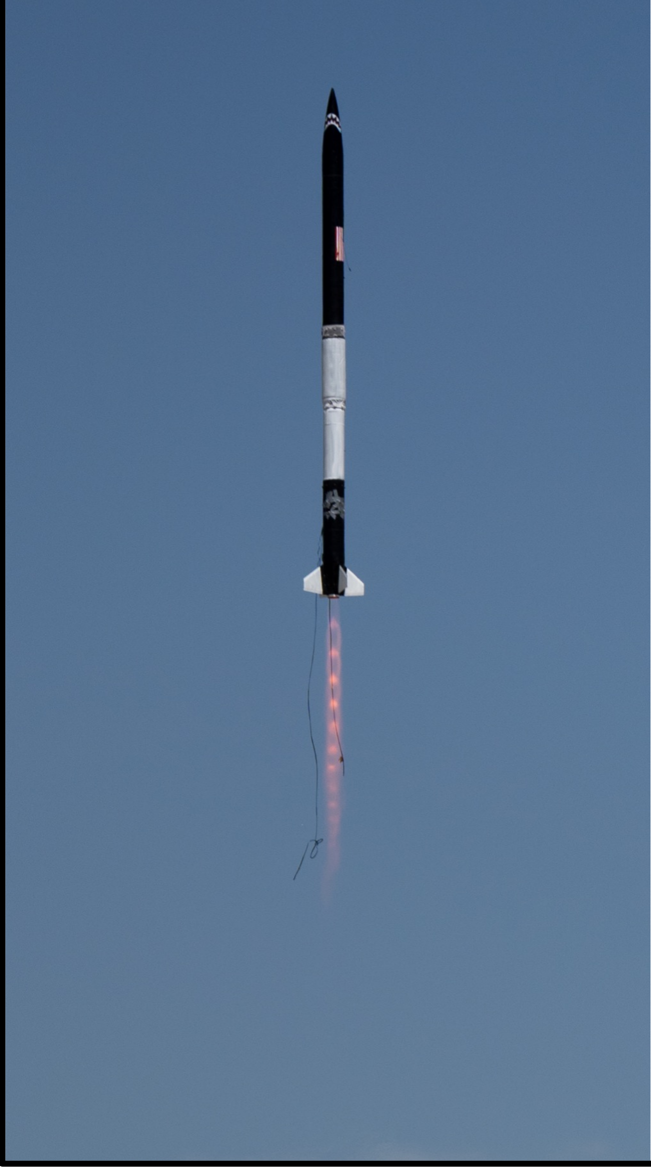


Project Ares 2024-25 Preliminary Design Review

October 17, 2024

Propulsion

Propulsion Contents

Propulsion Administration

Background on Last Year

- Focus:
  - Efficiency
  - Consistency
    - e.g not burning through or having combustion instability
- Engine Design:
  - Phenolic engines for test stand and dev valve validation
  - Develop throttle capability
- Testing:
  - 3 test stand static fires
  - 1 flight system static fire trip

Propulsion Goals

Main Goal: Advance propulsion technology and sophistication to decrease total flight system mass and optimize propulsion efficiency

Sub-goals:

- Prioritizing our testing cadence prior to static fires and launch through more coldflows and independent dev testing
- Work with electronics to enhance sensor count and placement, greatly improving data collection and optimization capabilities.
- Work closely with Vehicle Engineering to determine and optimize a thrust curve
- Develop more sophisticated throttle capability

Major Propulsion Dev Projects

- Develop regeneratively-cooled 2000 lbf engine
  - Ethanol-water mixture (fuel) as coolant
  - Ability to withstand throttle condition down to 75% power
- Develop new waterflow stand
  - Drastically improves test cadence and speed of part characterization
- Develop new valve mechanism
  - Provides massive decrease in flight prop system mass
- Work with Electronics to develop new throttle mechanism

Regen Engine Motivation

- Enables longer burn times in support of throttling
  - First static fire burnthrough issues with extended burn times, even with phenolic linen ablative material switch (from G10)
  - Heritage graphite-RTV hot gas seals cannot withstand >25s burn times
  - Longer burn time at throttled down state may enable better use of available impulse per FAR-Mars competition
- Optimized Design can save on mass
- Less sealing joints, more predictable manufacturing results and variations
- Education
  - Industry standard
  - Innovating forward from matured liquid engine design (current design)
- Club milestone

Budget & Allocations

- Sponsor donations have accounted for most (>90%) of current propulsion procurement
  - Will continue to heavily push company outreach to support greater capabilities
- Previous years have exceeded budgetary constraints, hopefully will maintain within limit despite ambitious projects

	Fall Quarter	Winter Quarter	Spring Quarter
Engine	$600	$1050 ($400)	$0
GSE	$600	$200	$0
TE	$800	$450	$0
Feed Systems	$500	$2000	$200
		Total Team Budget:	$7000

Fall/Winter Testing Campaign

Main Goals:

- Fire our regen engine on the test stand while flight system is still being built
- Qualify CMFV using ablative engines, then switch to testing on regen once reliability is confirmed
- Begin flight system testing

Fall										Winter										
1	2	3	4	5	6	7	8	9	10	0	1	2	3	4	5	6	7	8	9	10

= Test Stand Static Fire

= Manufacturing/Build/T

= Flight System Static Fire

Spring Testing Campaign

Main Goals:

- Qualify a finalized flight feed system with flight engine (minimum 2 fires)
- Verify flight variant of regen engine

Spring									
1	2	3	4	5	6	7	8	9	10

= Flight System Static Fire

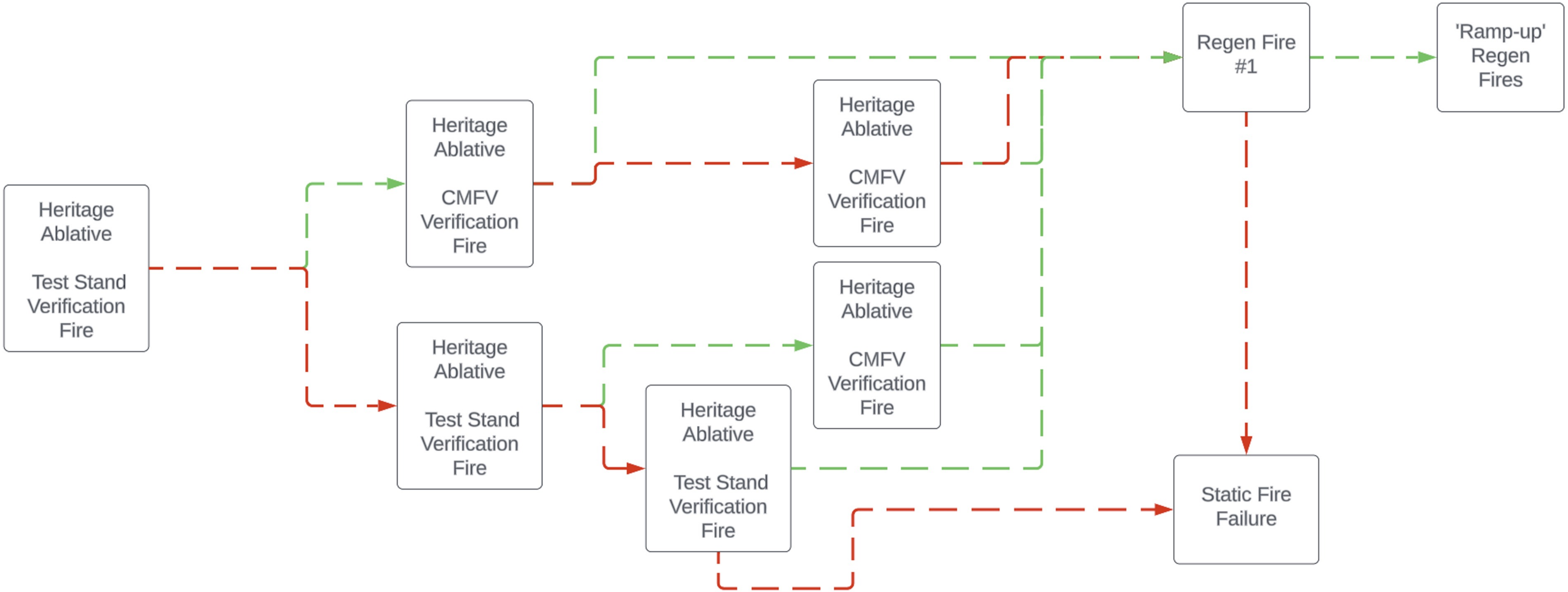
= Manufacturing/Build/T

= Launch

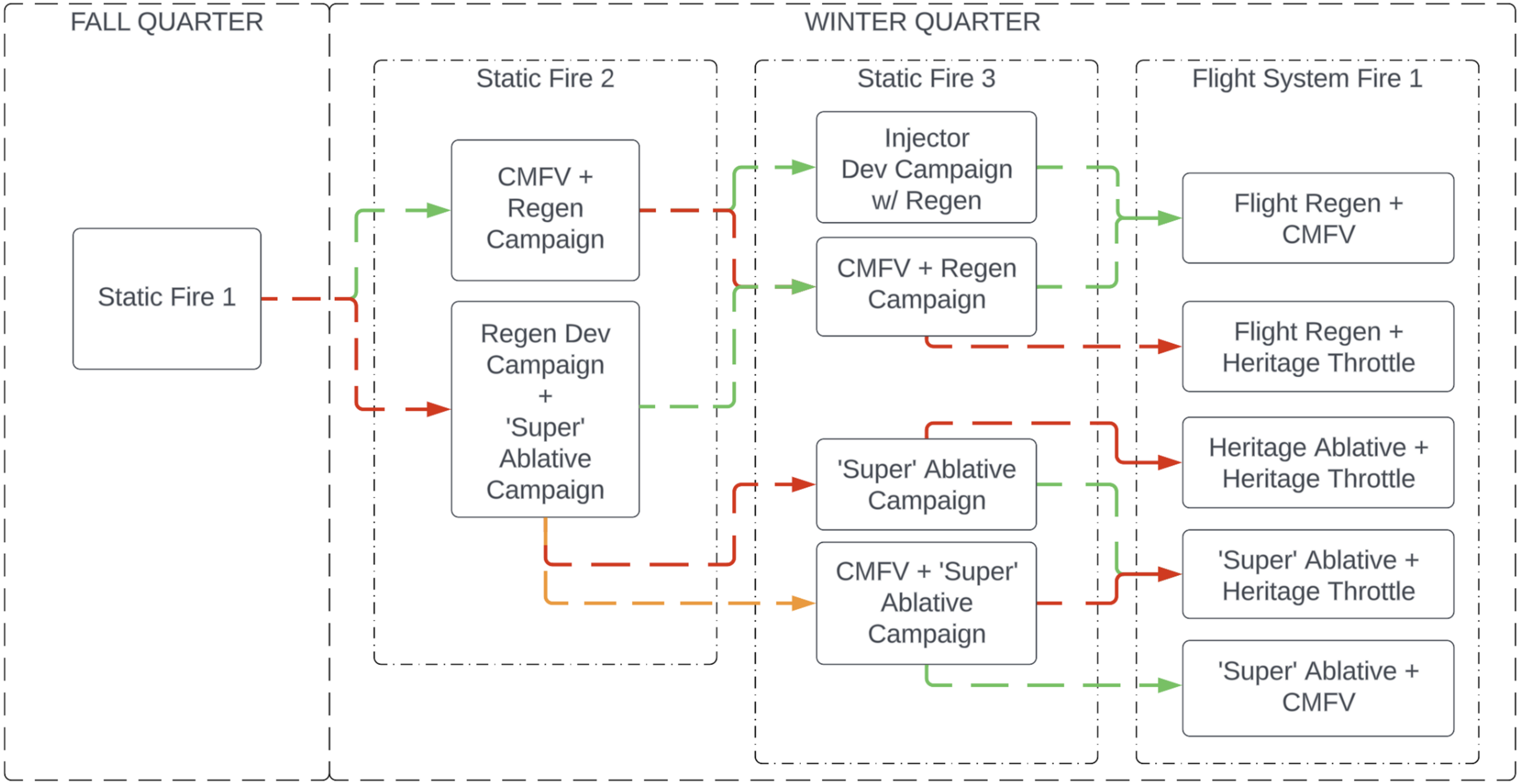
= Back-up Launch

Test Matrix - Fall

- Hotfire 1 (3x Ablative Engines, 1x Regen Engine)



Test Matrix - Winter



Current Prop Timeline

	Week 4							Week 5							Week 6						
	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S
Regen																					
Test Stand												C	C	C					C	C	C

	Week 7						
	M	T	W	T	F	S	S
Regen							
Test Stand	R	R					

= AM Printing

= Heat Treatment

= Thermal Coating App.

= Post-Machining

= Test Stand Refurb.

= Coldflow

= Regen Coldflow

= Static Fire

Brief Overview of Parameters

- Tasked with designing 2000 lbf engine utilizing ethanol-LOX propellants
  - Heritage use of 75% ethanol + 25% water
- Rocket intends to reach ~50,000 ft
- 4 planned static fire trips to Mojave Desert
  - With varying amount of engine tests during each trip

Material	Heat Treated Inconel 718
Chamber Pressure	413.7 psia
Target O/F Ratio	1.3
Thrust	2000 lbf
L*	30 in
Assumed C* Efficiency	94%
Assumed C_F Efficiency	99%

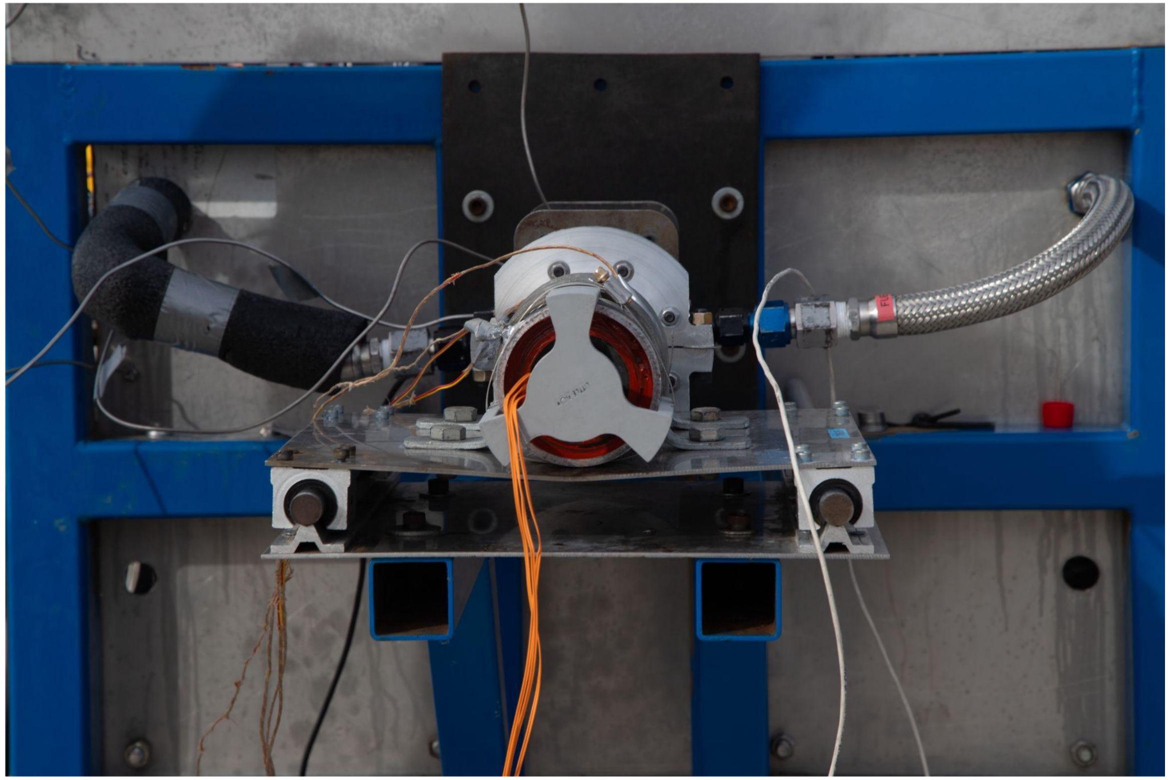
Ignition

- Currently planning to use solid rocket motor ignition braced in bracket with hose clamps
- Primary concerns are ignitor blowout as well as mistiming of propellants
- Aerotech composite propellant motor with ammonium perchlorate and aluminum has higher flame temperature (~3800 K)
- Heritage ignition system

Ablative Design

Purpose

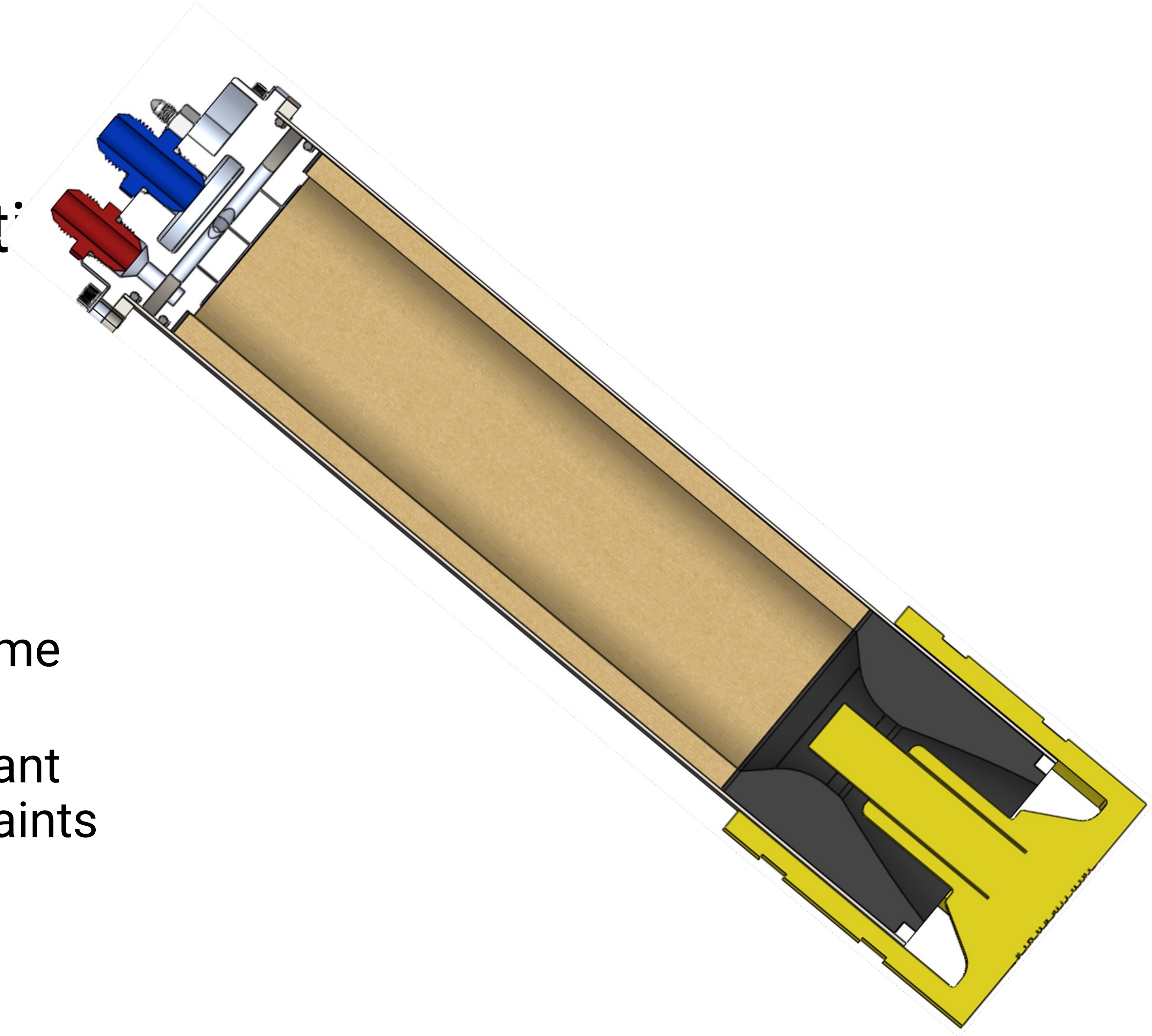
- Ablative engines will provide a fallback in the event of regen development failure
    - Will attempt to develop 2000 lbf ‘Super’ Ablative engines to mimic thrust profile expected with regen engine
    - Proven throttle capability on ablative engine
- High cost of upsized ablative engine makes it unfavorable for primary dev project



Ablative Engine Design

Heritage Engine Design:

- Welded flanged steel combusti chamber
- Modified to be as simple as possible to produce and test
    - Heritage DC650 injector
    - Heritage G10 Liner
        - Only stock available to use in time
    - Conical Nozzle
        - Rao nozzle will present significant manufacturing and cost constraints
    - Heritage Solid motor ignition
    - Last year's sealing methods



Regen Model

Brief Overview of Model Assumptions

- Coolant flow is incompressible
- A rectangular channel geometry is assumed for ease of calculations
    - For fluid calculations, a fillet in each corner is accounted for
- Bartz Correlation holds true in all parts of the chamber
- Axial dimension is largely ignored and assumed to be negligible
- Nozzle experiences compressible isentropic flow

Engine Geometry

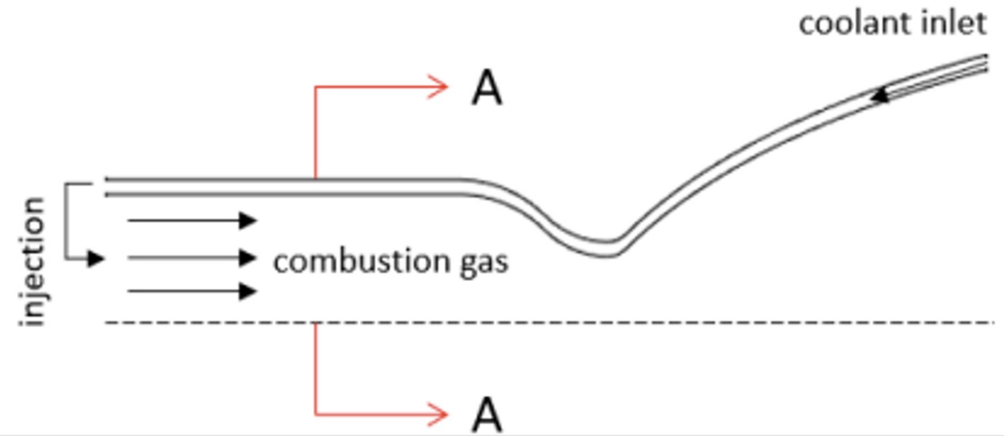
- Utilizes outputs from NASA CEA runner function to begin geometry initialization
  - Rao Nozzle is utilized with predefined optimal relations
  - CR and P_e are set manually by user
- Wall geometry is discretized into evenly spaced stations
  - Isentropic relations are run at each point to determine gas-side conditions
  - Certain properties of the gas are interpolated using NASA CEA data
  - Adiabatic wall temperature found through Huzel & Huang equation

$$\frac{P_t}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{A}{A*} = \frac{1}{M}\left(\frac{\frac{\gamma + 1}{2}}{1 + \frac{\gamma - 1}{2} M^2}\right)^{\frac{\gamma + 1}{2 - 2\gamma}}$$

$$\frac{T_t}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right)$$

$$T_{aw} = T_o \frac{1 + \sqrt[3]{\mathrm{Pr}} \frac{\gamma - 1}{2} M^2}{1 + \frac{\gamma - 1}{2} M^2}$$



Discretization

- Each station contains both coolant and gas properties that must either must be retrieved or calculated
  - CoolProp v6.6.0 used for coolant properties
  - Assuming mixture properties follow ideal mixing and mixture property equations
- Heat transfer and stress is then calculated at each station

$$T_w^j = T_{aw}^j - \frac{q^j}{u_g^j}$$

$$T_c^{j+1} = T_c^j + \frac{\pi d_i^j L^j q^j}{N \dot{m}_c c_{p,c}}$$

$$P_c^{j+1} = P_c^j - \frac{\rho_c^j v^{j2}}{2} \left(K_L^j + f^j \frac{L^j}{d_h^j} \right)$$

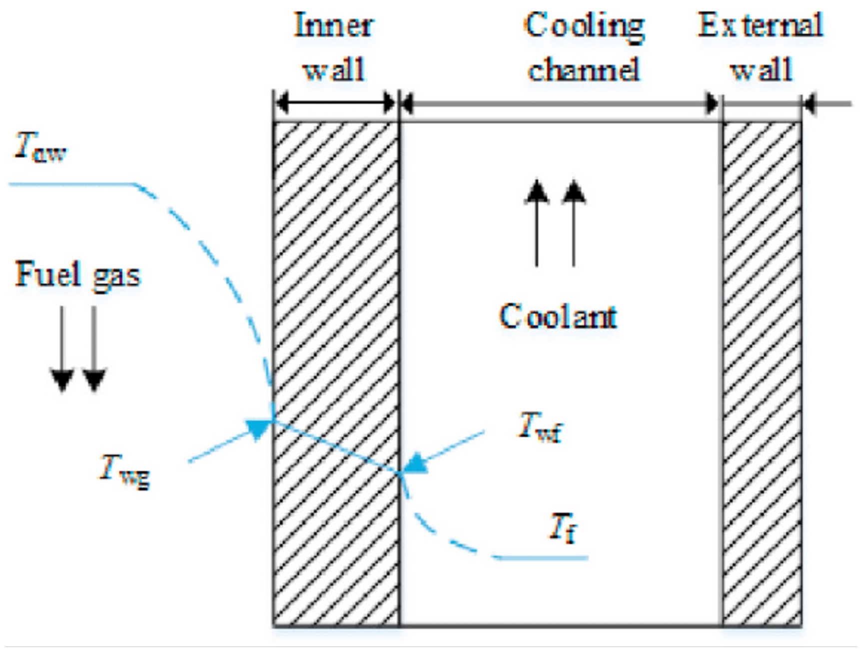
$$\frac{1}{\sqrt{f}} = -1.8 \log \left[\left(\frac{\epsilon / d_h}{3.7} + \frac{6.9}{\text{Re}} \right) \right]$$

1D Heat Transfer Analysis

- Constructed 1D thermal resistance circuit
  - Simple and fast solution to begin scoping the project out
  - Utilized Bartz Correlation for gas coefficient, Dittus-Boelter Correlation for coolant coefficient
- Rectangular geometry for simple geometry assumptions

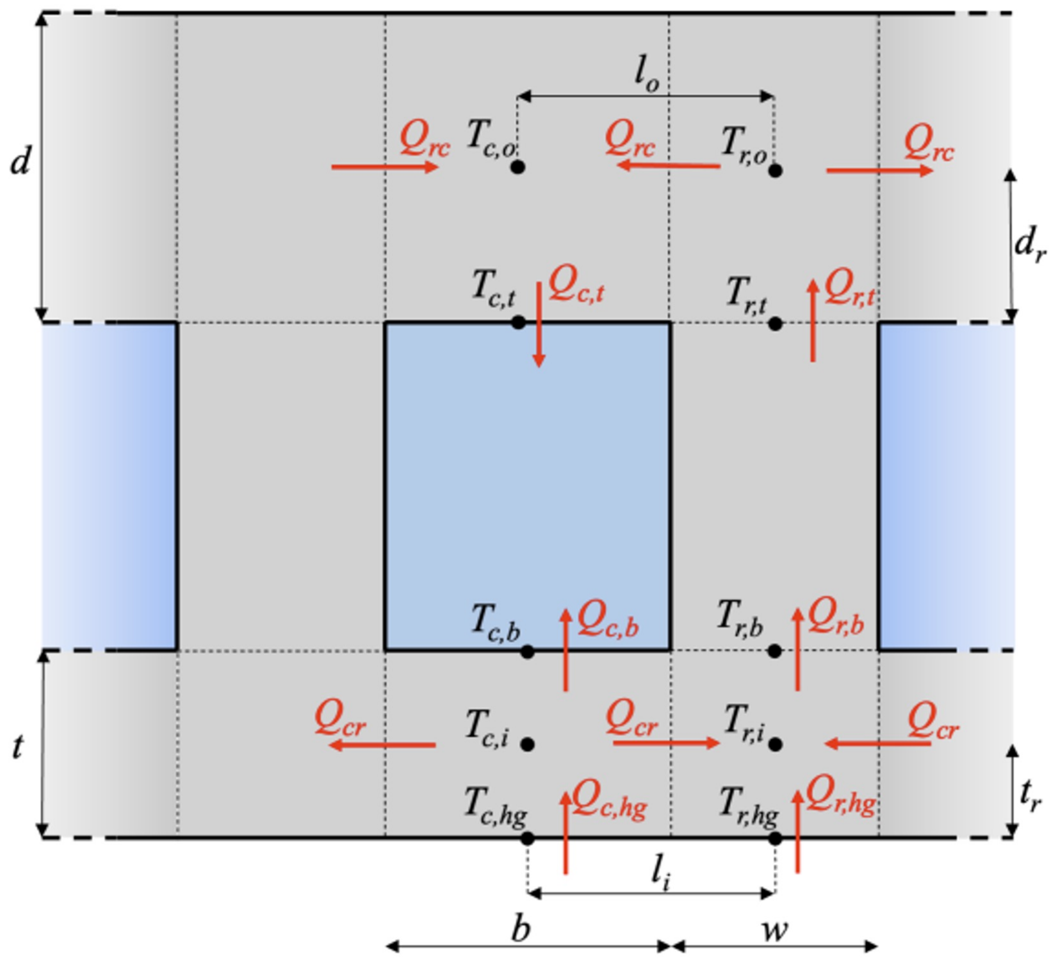
$$h_g = \left[\frac{0.026}{D_t^{0.2}} \left(\frac{\mu^{0.2} C_p}{Pr^{0.6}} \right)_{ns} \left(\frac{(p_c)_{ns} g}{c^*} \right)^{0.8} \left(\frac{D_t}{R} \right)^{0.1} \right] \times \left(\frac{A_t}{A} \right)^{0.9} \sigma$$

$$\sigma = \frac{1}{\left[\frac{1}{2} \frac{T_{wg}}{(T_c)_{ns}} \left(1 + \frac{\gamma - 1}{2} M^2 \right) + \frac{1}{2} \right]^{0.68} \left[1 + \frac{\gamma - 1}{2} M^2 \right]^{0.12}}$$



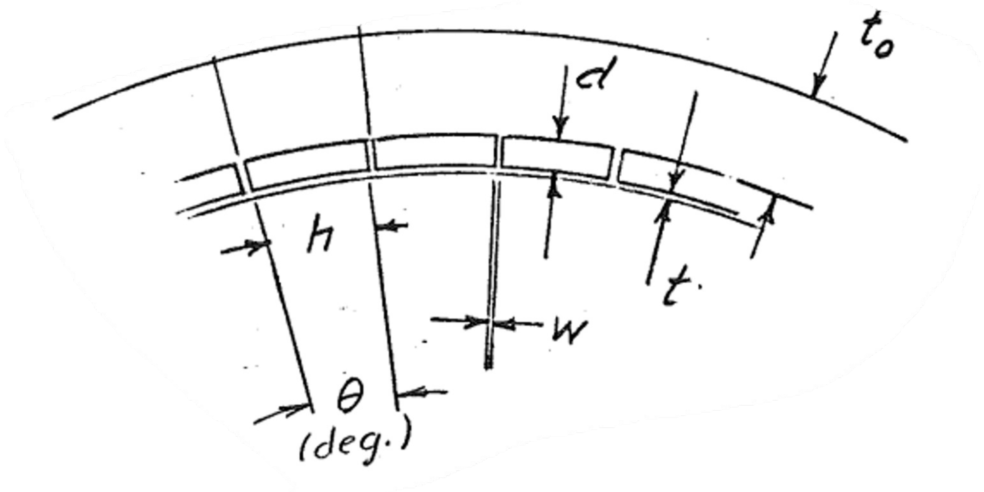
2D Heat Transfer Analysis

- Utilized control volume approach
  - Amplifies ability to view heat transfer effects of ribs
  - Coupled in a system of equations with convective correlation
  - k(T), and is calculated through convergence at each local position within the wall
- Higher resolution provides better ability to fine tune individual aspects of the wall



Engine Stress

- Calculated 4 primary cases
  - One 'hot' steady-state
    - The stress experienced during static fire testing with combustion
  - Three transient 'cold' cases
    - Engine startup
    - Engine shutdown
    - Channel hydrostatic test



MATLAB Limitations

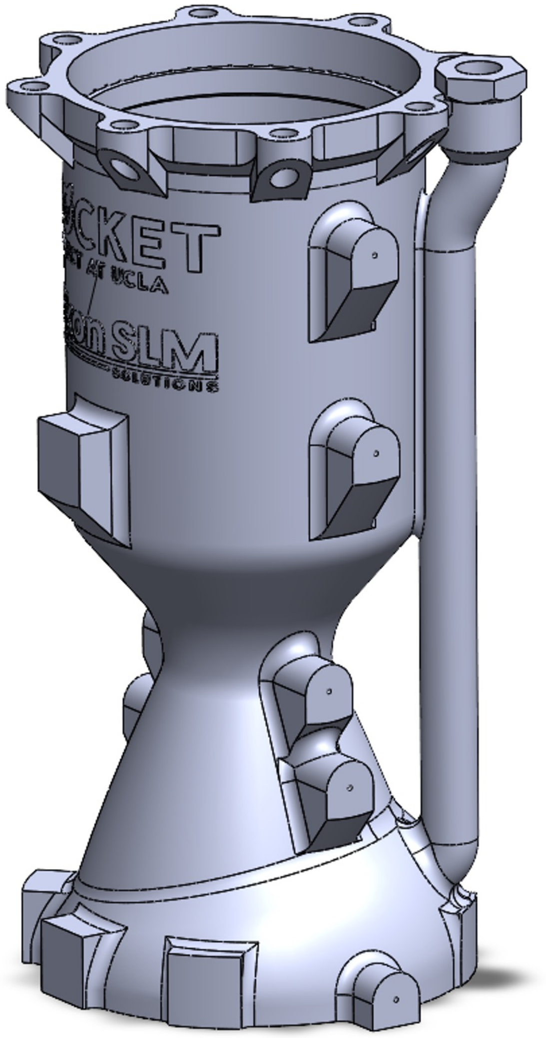
- Channel geometry is defined for ease of calculation
    - Rectangular geometry drastically simplifies problem
    - Heat transfer is evaluated in a similar way which is a notable inaccuracy
- Temperature dependent properties such as yield strength, E, CTE, K are evaluated at the temperature midpoint of each control volume

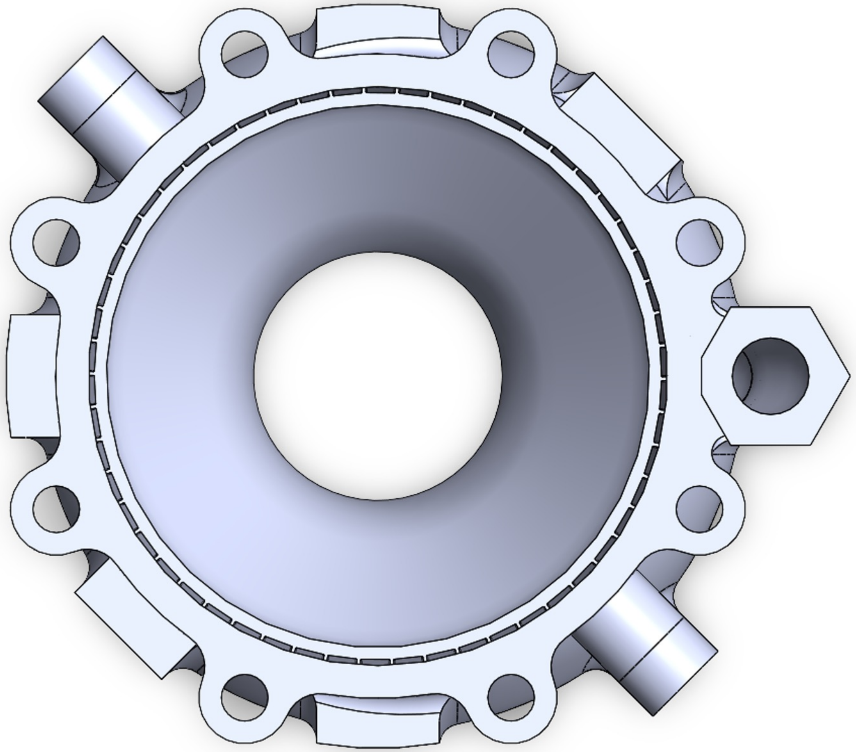
Regen Design

Manufacturing

- Opted for AM processes
  - Enables the fastest, most sophisticated means of engine manufacturing
  - Allows for easy sponsorship of engine, plenty of companies that provide commercial metal AM services
- Planned heat treatment of Inconel-718
  - Solution annealment + aging
  - Vacuum heat treatment procedures

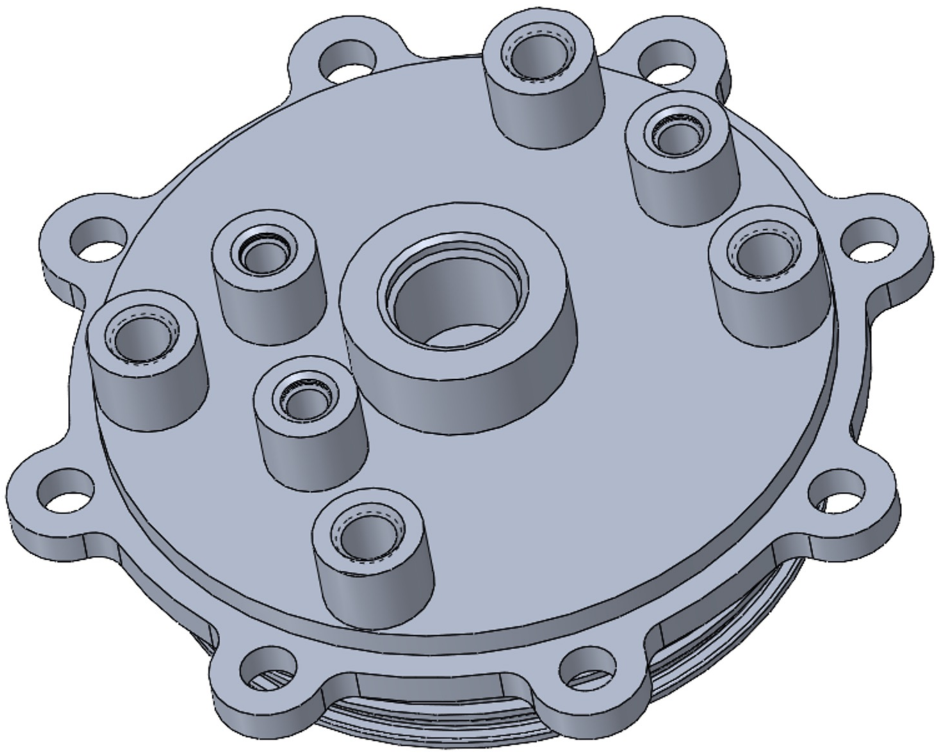
CAD



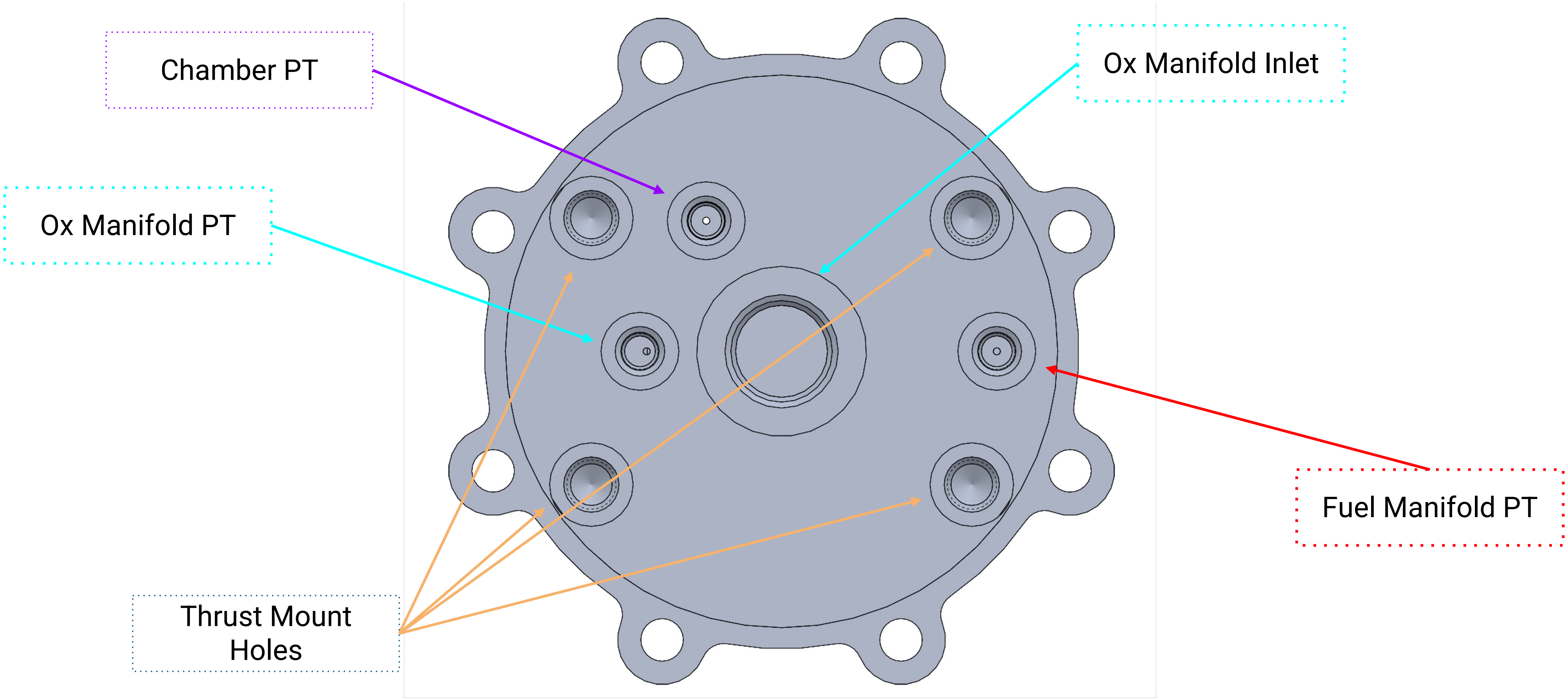


Modified Regen Injector

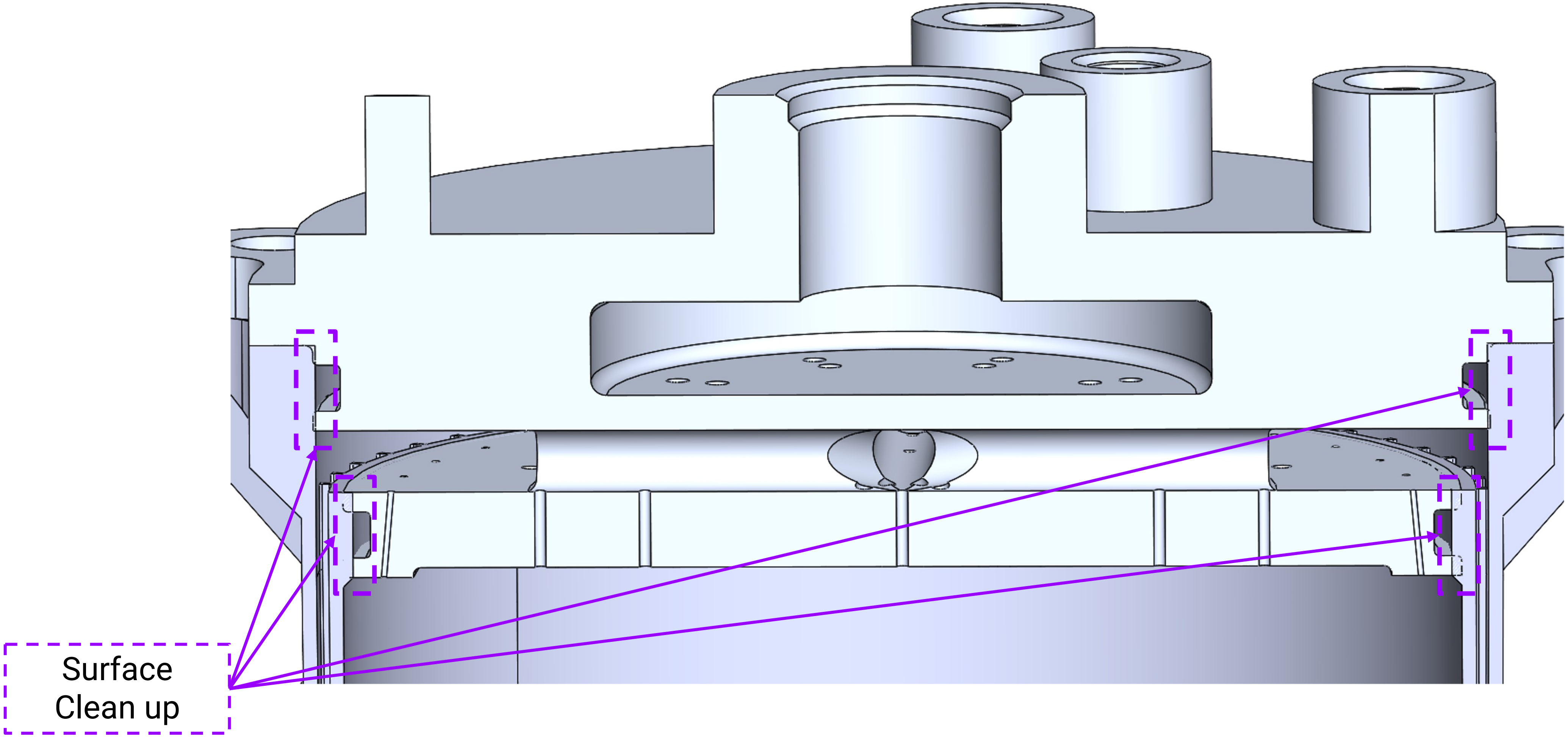
- Utilizes heritage DC650 architecture
    - Adjusted to be compatible with the optimal regen channel outlet geometry
- Scaled up to work for 2000 lbf
- Will be purchasing several injectors with varying orifice sizings
    - For the “ramp-up” campaign



Modified Regen Injector

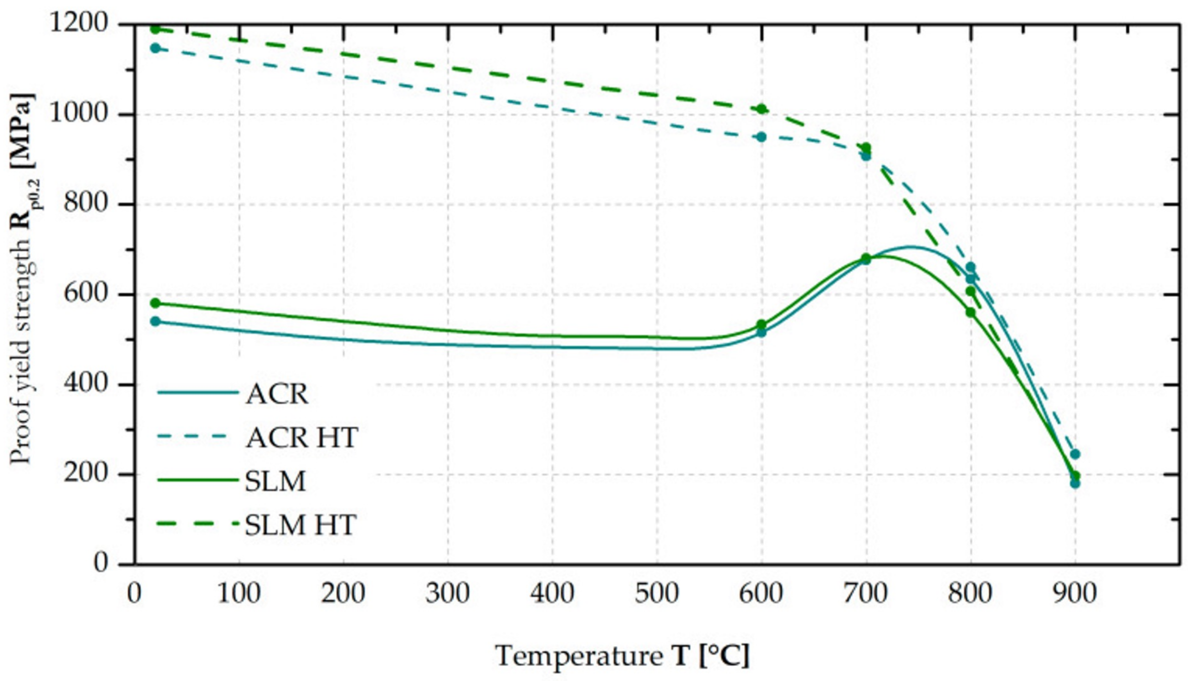


Modified Regen Injector



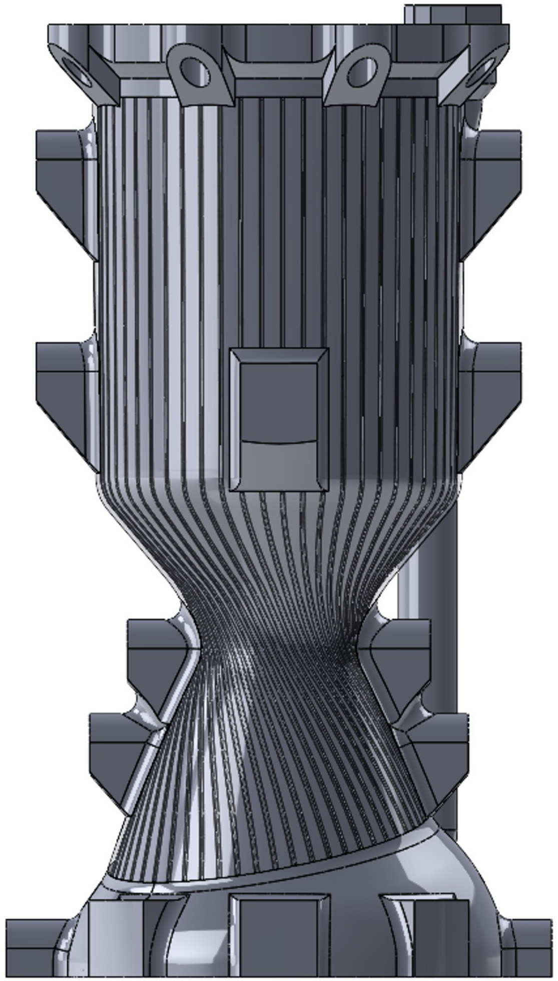
Material Selection

- Primarily guided by two factors:
  - Mechanical properties
    - High thermal stability + high melting temperature
    - High yield strength
    - Thermal conductivity
    - AM manufacturability
  - Secondary: Sponsor material availability
- Material selected: Inconel 718
  - Post-HT, YS of about 140 ksi



Regen Overview

- Additive manufacturing sponsor (Nikon SLM) providing free print services for one regen engine out of Inconel-718
    - heat treatment + depowdering services included
- In-house MATLAB script verified by RPA software and ANSYS 3D thermal models
    - PDMS fuel additive for reduced heat transfer
- Utilizes helical channels at 25 degree pitch in the 40 degree converging section



Regen - ‘Ramp Up’ Campaign

- Goal is to attempt reaching an optimal O/F through consecutively ramping up chamber conditions to more extreme temperatures

	Fire 1	Fire 2	Fire 3	Fire 4	Fire 5	Fire 6
O/F	1	1.1	1.2	1.3	1.3	1.3
FC %	21%	21%	21%	21%	15%	10%

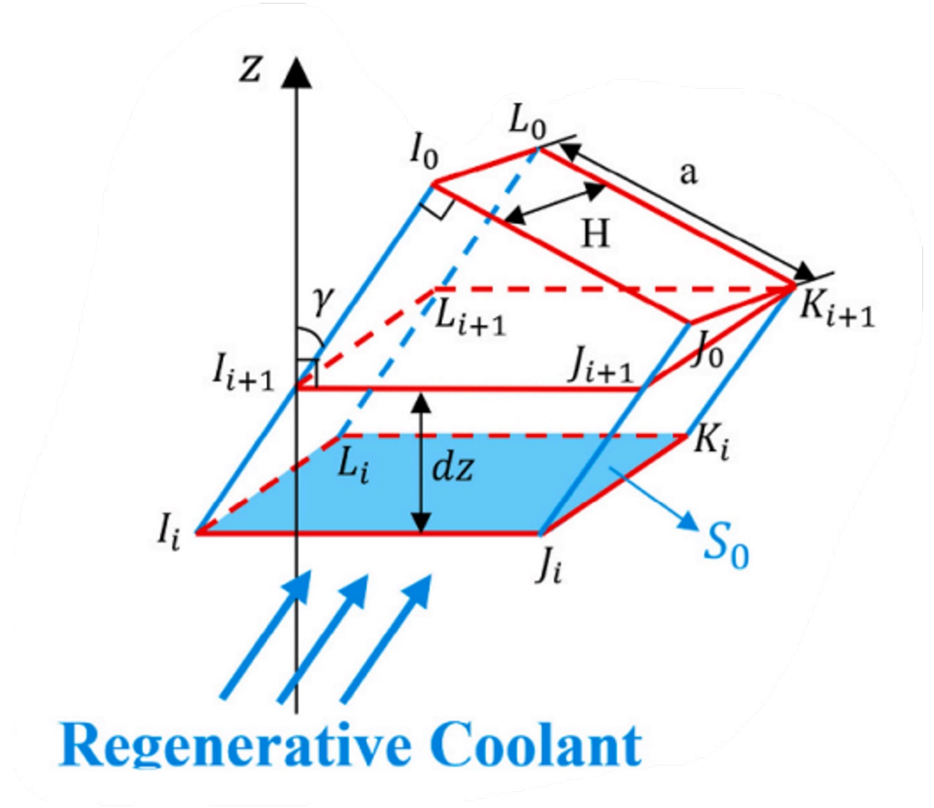
Chamber Pressure	400 PSI
Exit Pressure	10.3 PSI
Thrust	2000 lbf
Total Mass Flow	3.96 kg/s

Regen Testing - Failure Criterion

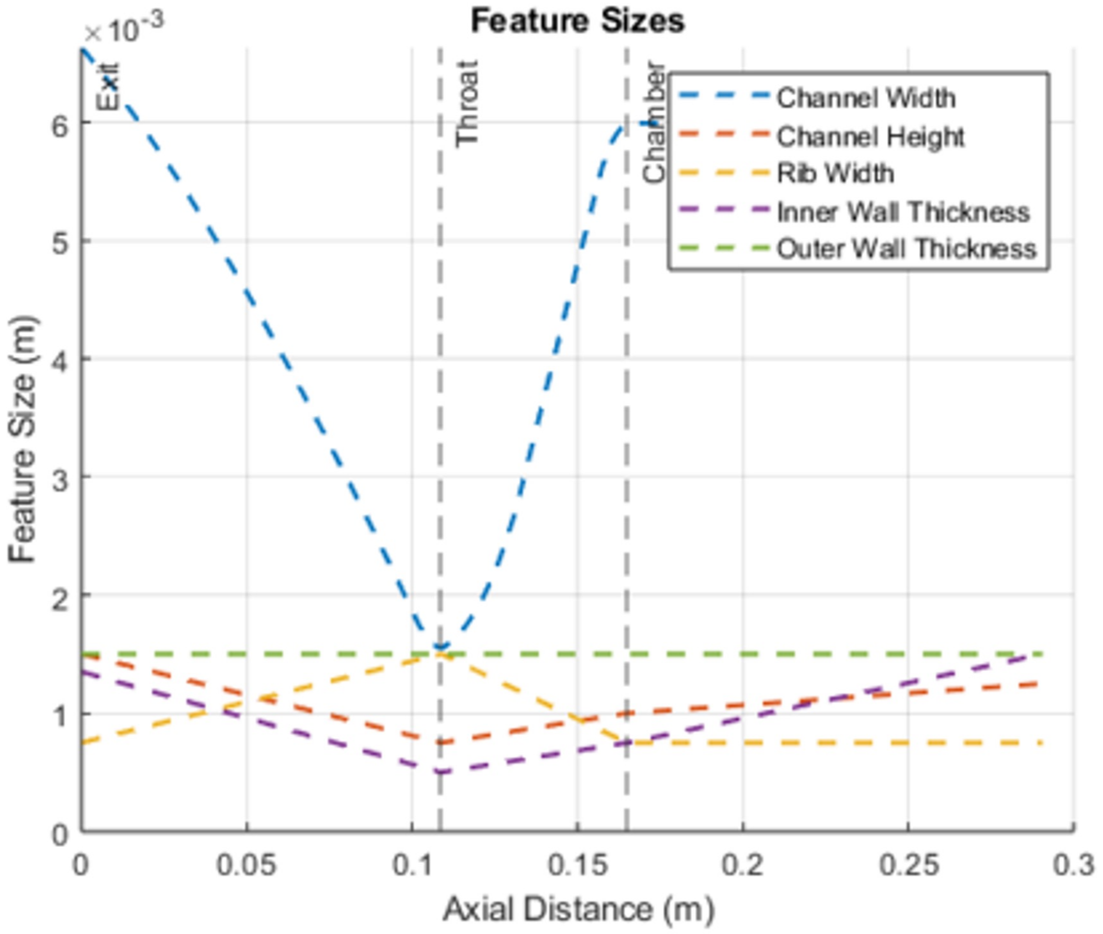
- Dimensional Changes or Distortion
  - Post-fire, the engine will be thoroughly inspected for any deformations in the wall
  - If warping is detected, the team will assess and cancel future static firing on the part
- Thermocouple Data
  - Post-fire, TC data will provide better clarity on whether the part yielded or not
  - Will be able to calculate a preliminary heat flux value
  - If TCs show that coolant/wall is getting hotter than acceptable, the static fire will conclude

Why Helical Channels?

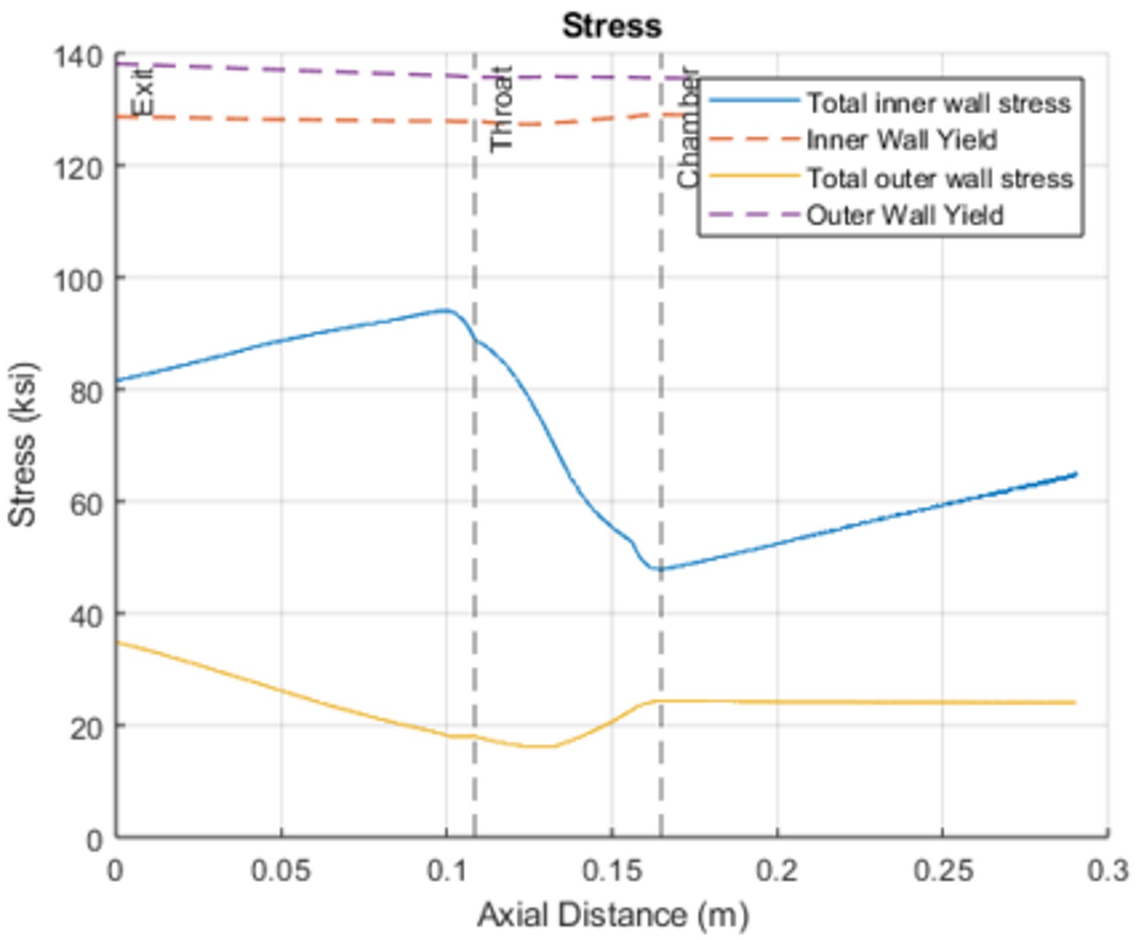
- Faster velocity for equal amount of required mass flow
  - Surface area remains constant, but longer channels requires they get smaller or fewer in number
- Pushes AM limits
  - The ILKJ plane will be limited to AM minimum negative feature size
  - Flow is actually constrained by the area formed normal to the flow direction



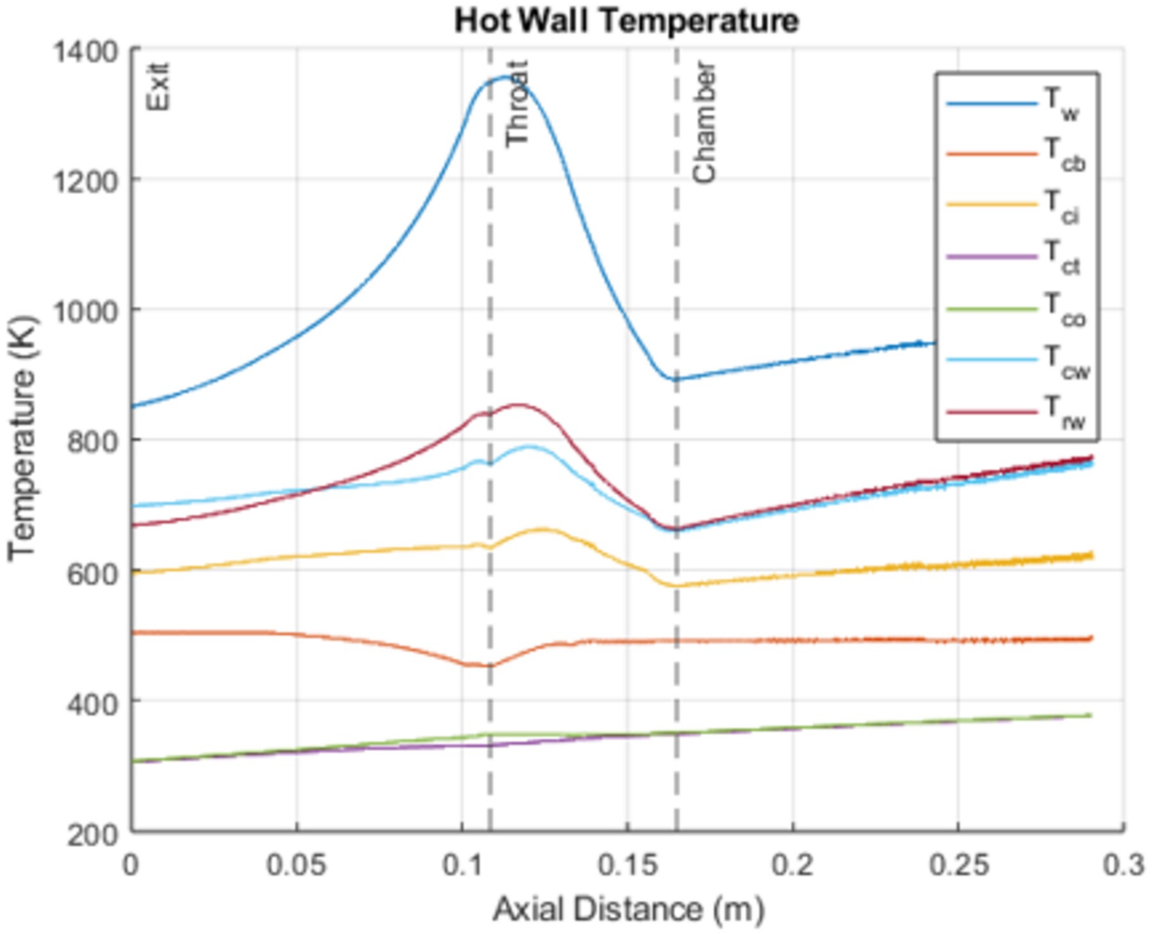
Model Output - Feature Size



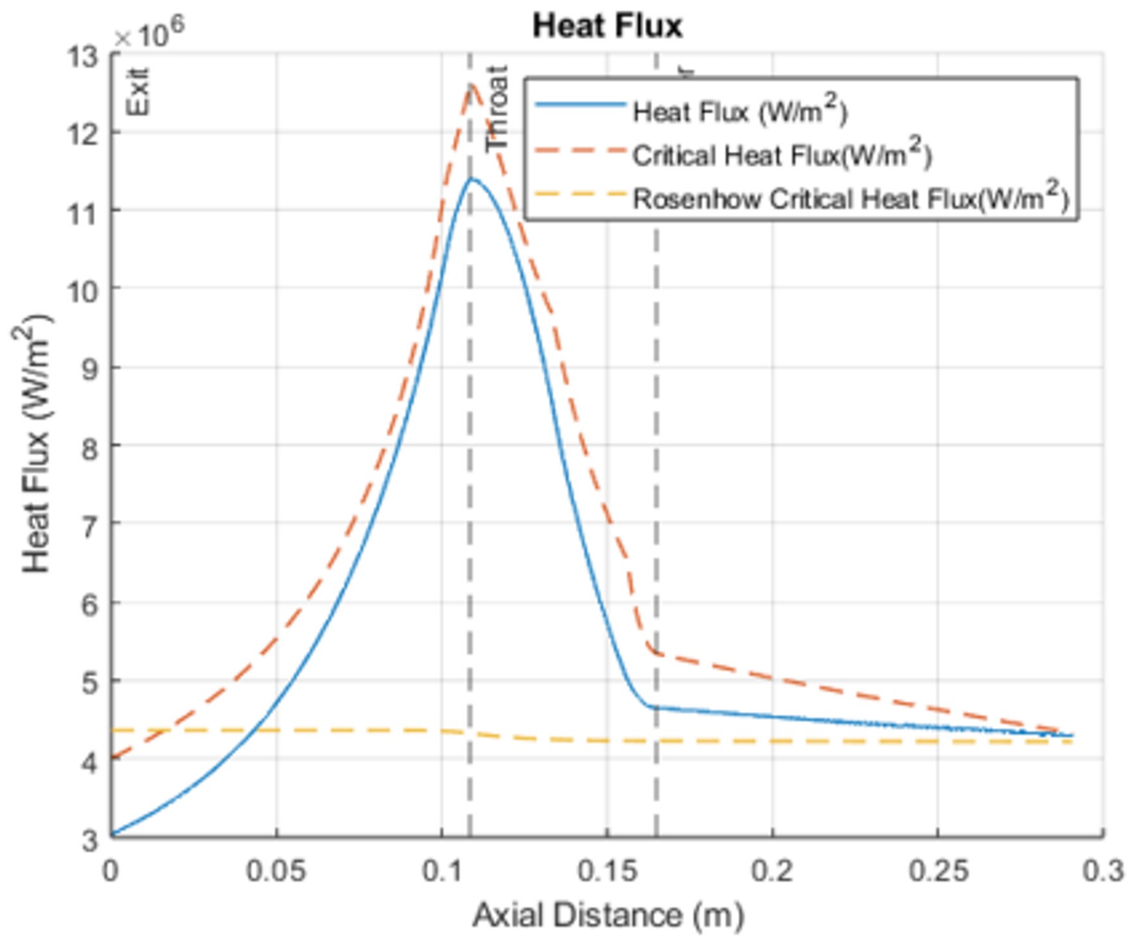
Model Output - Engine Stress



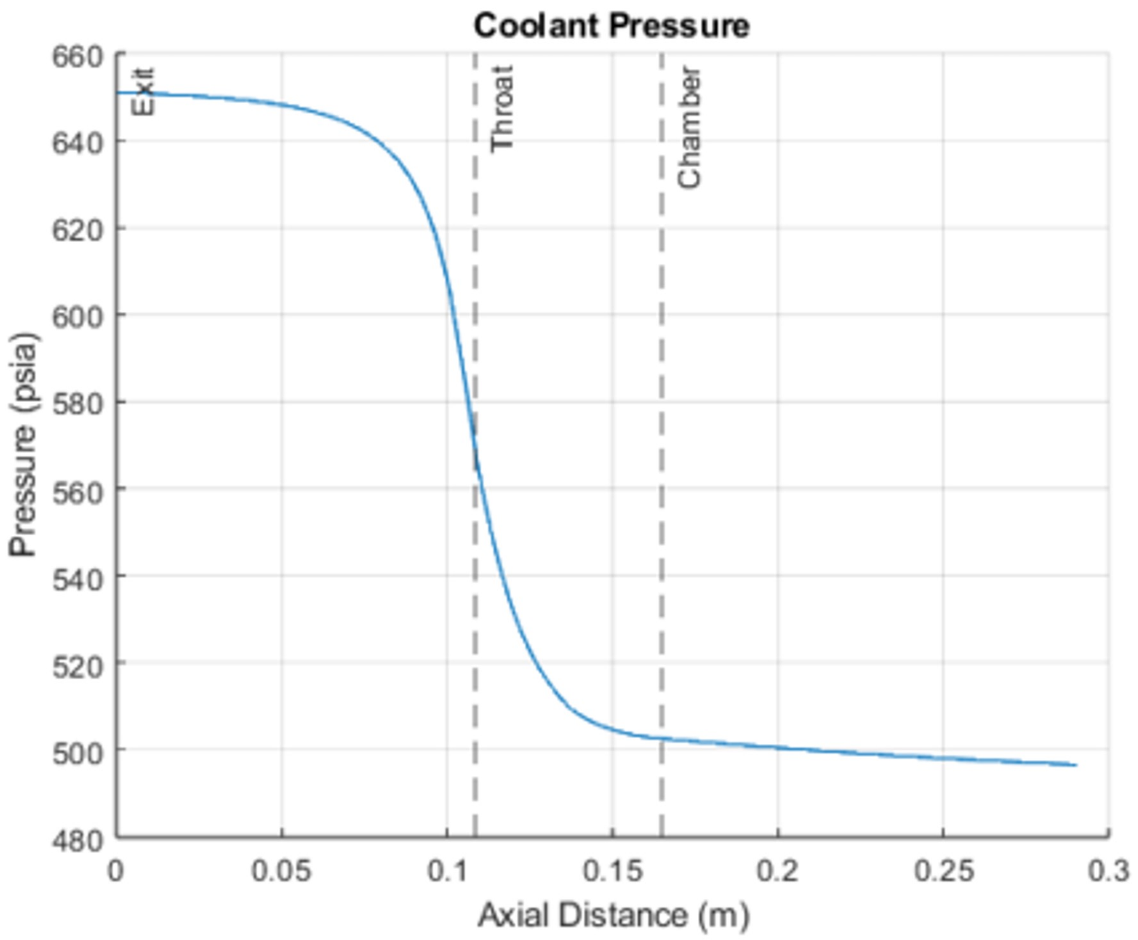
Model Output - Temperature Distribution



Model Output - Heat Flux

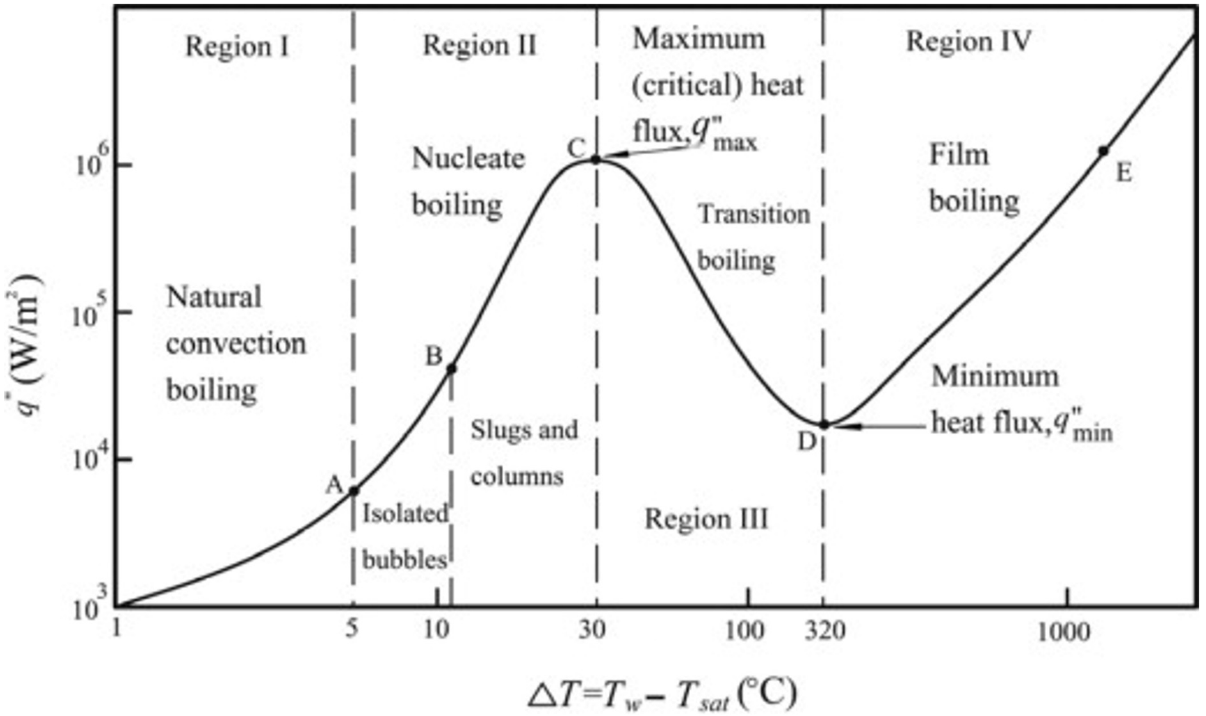


Model Output - Coolant Pressure



Why Nucleate Boiling?

- Latent heat absorption provides significant boost to heat transfer
  - Bubble formation and departure and carry heat away from the wall
  - High rate of heat transfer can be achieved with relatively low temperature difference
  - Reduces thermal stress on the inner wall

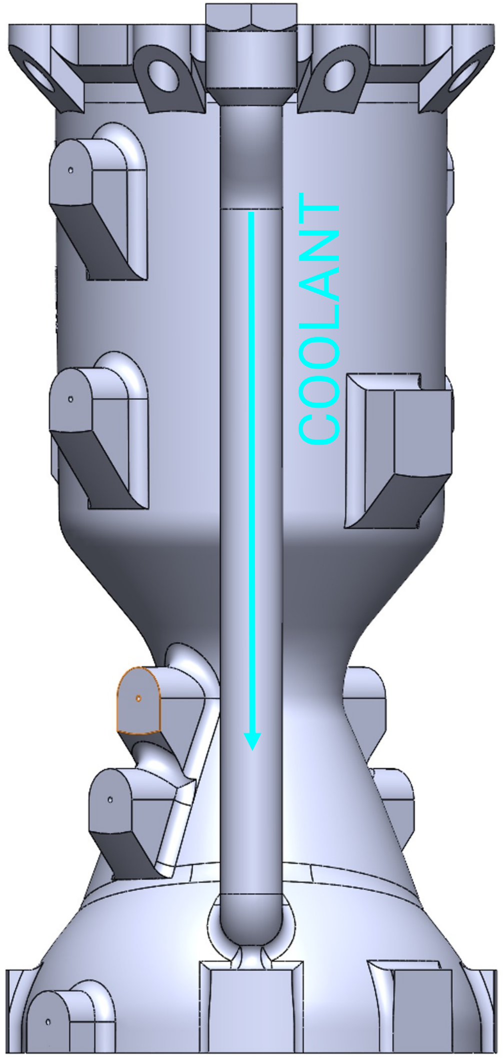


Additional Cooling Measures

- Thermal coating: Type YSZ Coating
  - Thermal conductivity: 1 W/m K
  - Applicable thickness: 0.05mm
  - Operating temperature: >2300 K
- Film Cooling: 21%
  - Will provide layer of fuel on the internal wall which will act as an insulator layer
  - Planning to decrease during “ramp-up” campaign
  - Hard to model given lack of correlations that model liquid-gas boundary layers and entrainment effects
- PDMS fuel additive
  - Decreases expected heat flux by 20-50%

Why Integrated Coolant Pipe?

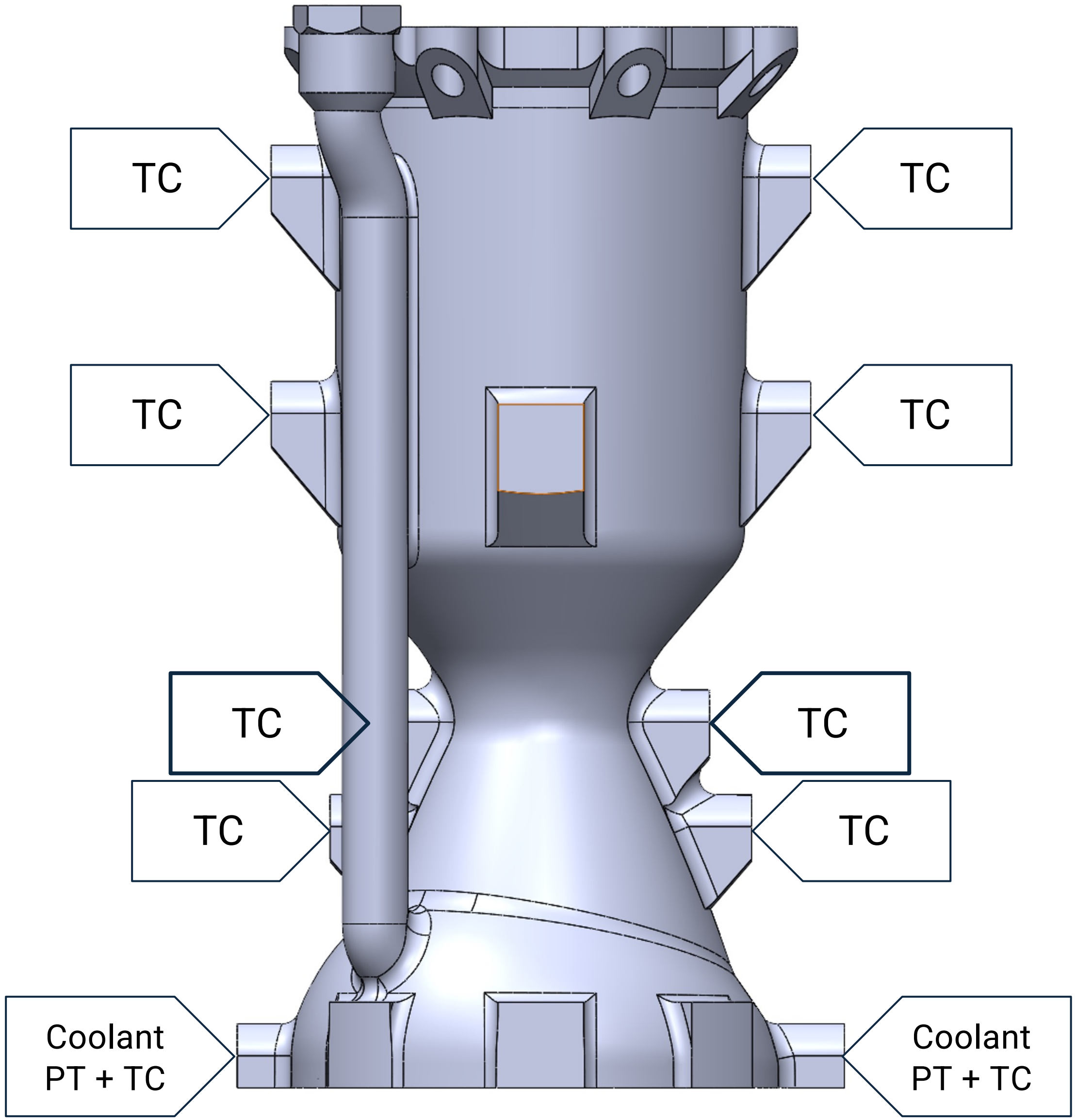
- At the cost of dP, makes manufacturability significantly easier
  - We are able to tap all holes in three operations
  - Does not require a 5 axis mill
- Significantly improves final rocket integration plans
  - Allows for boattail to more easily slide overtop



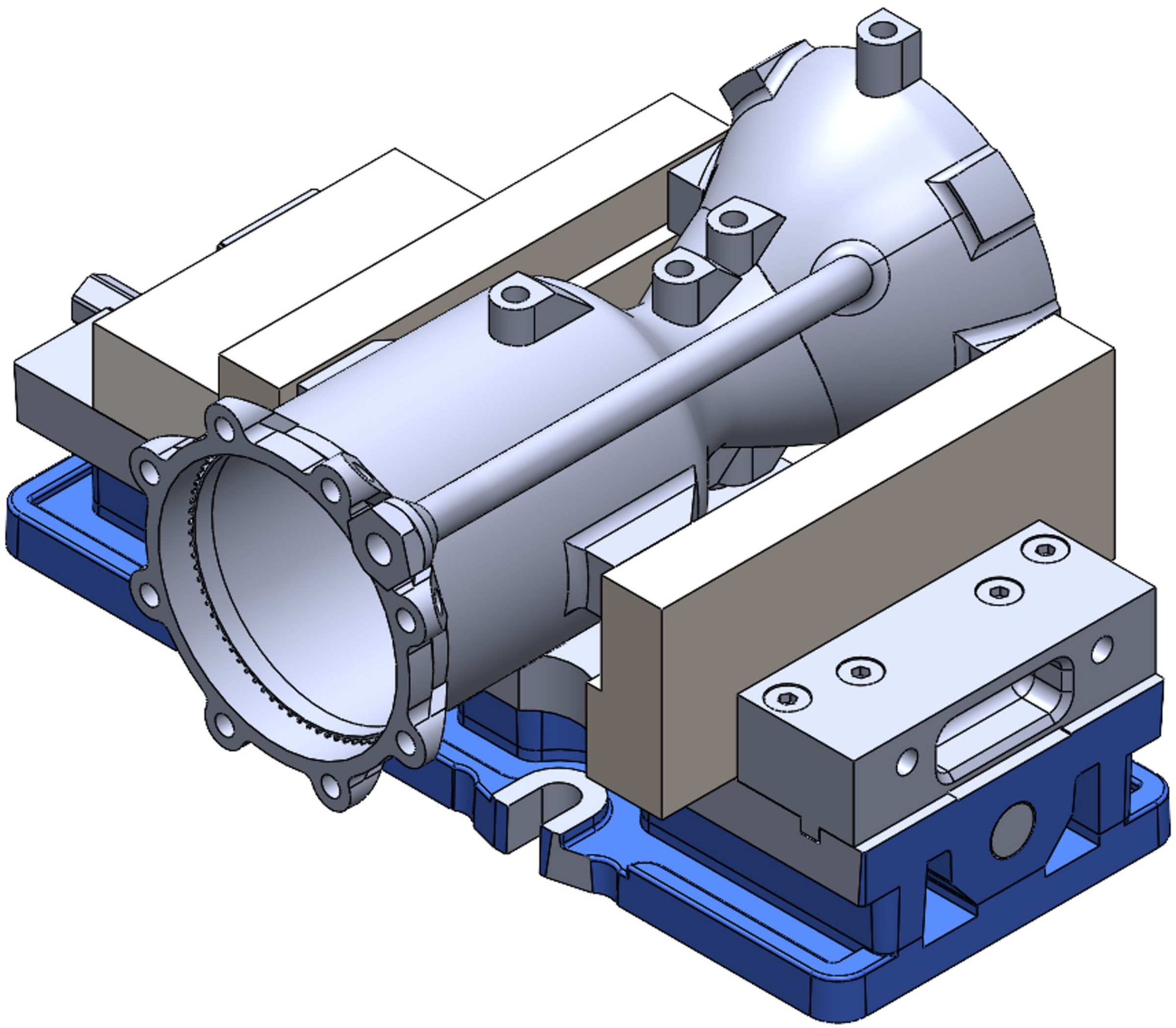
CAD - Sensor Placement

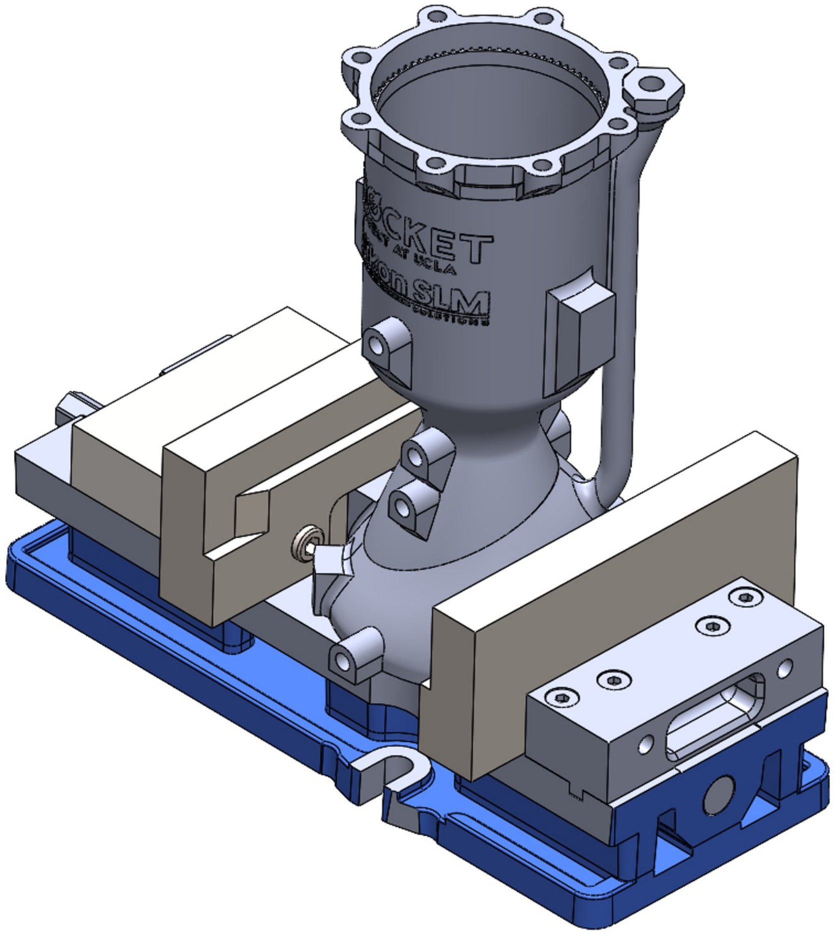
- 11 TCs total, 4 PTs total
  - 8 TCs measuring the outer wall temperature
  - 2 TCs and 2 PTs measuring the manifold temperature and pressure on opposed sides of the manifold
- Placement of PTs and TCs was to ensure any detection of flow bias and resultant cooling bias
- Might use FLIR thermal camera

Not modeled here:
- 1 Chamber PT
- 2 propellant injector manifold PTs
- 1 fuel injector manifold TC



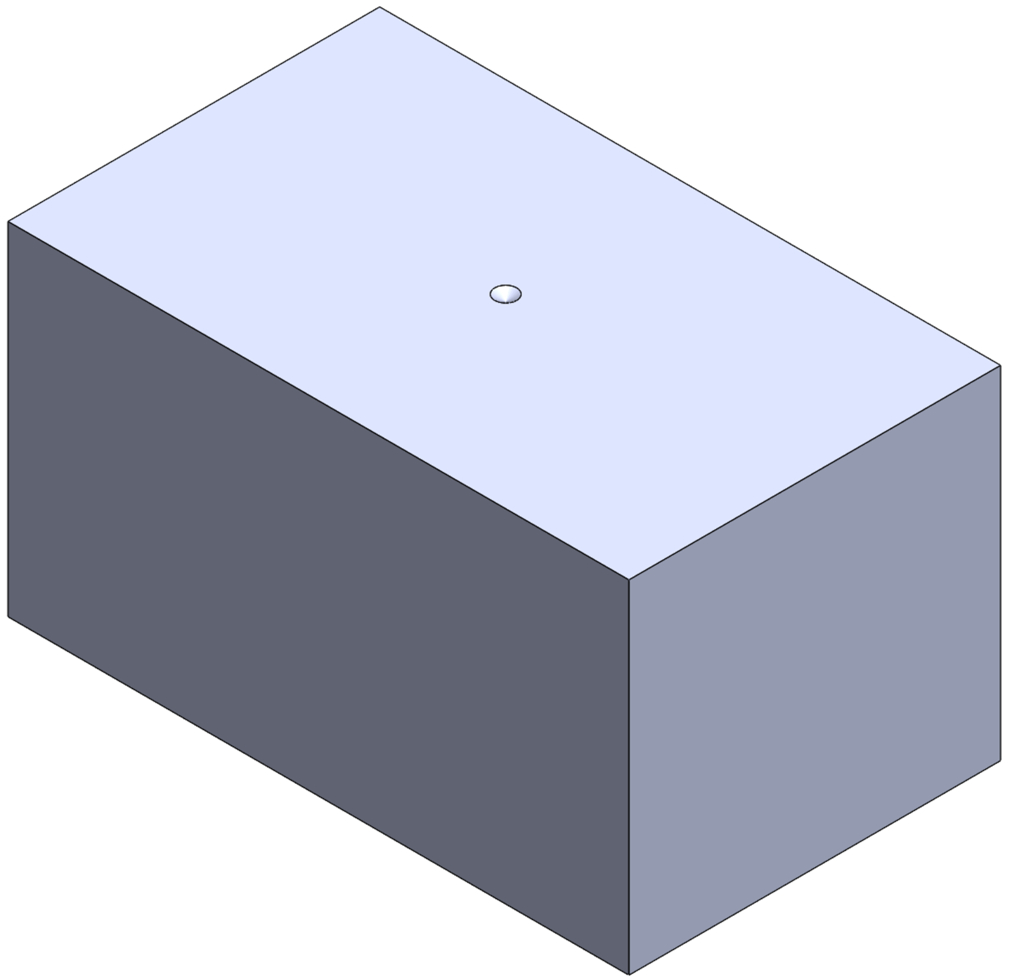
Post-Machining Ops



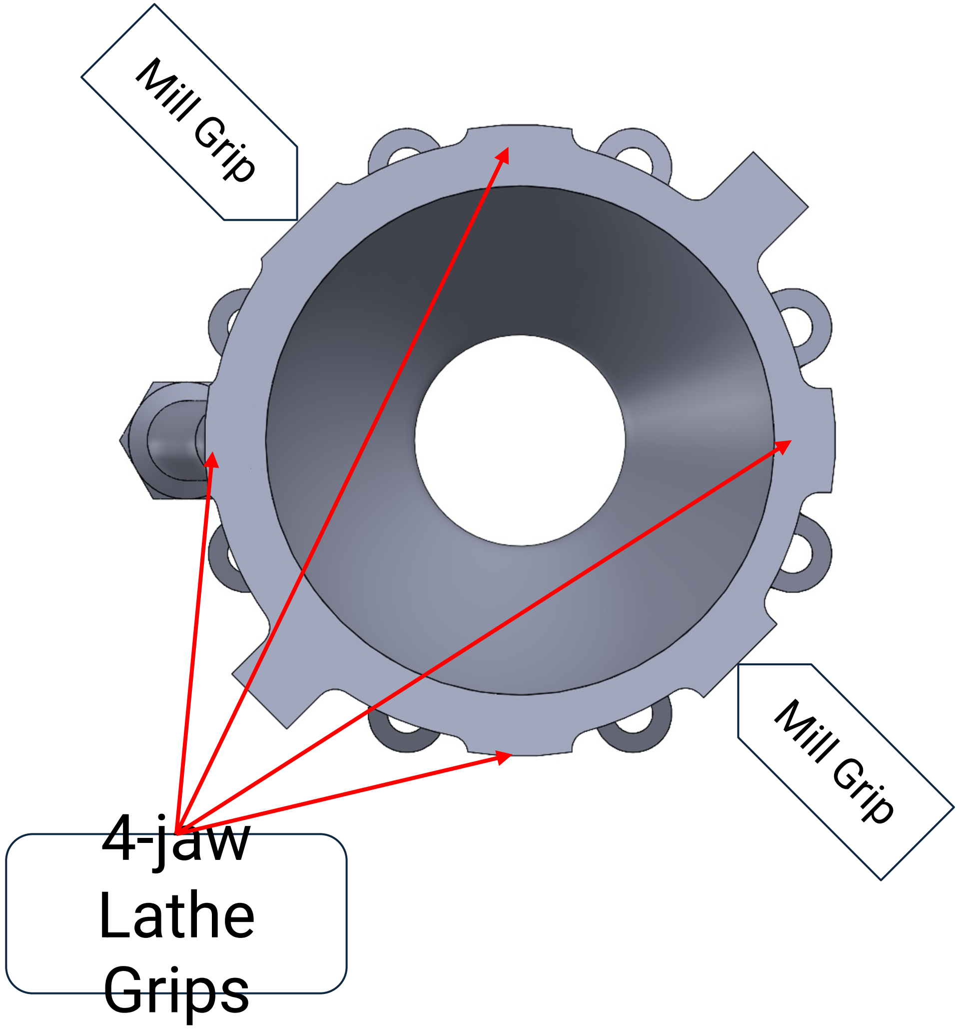


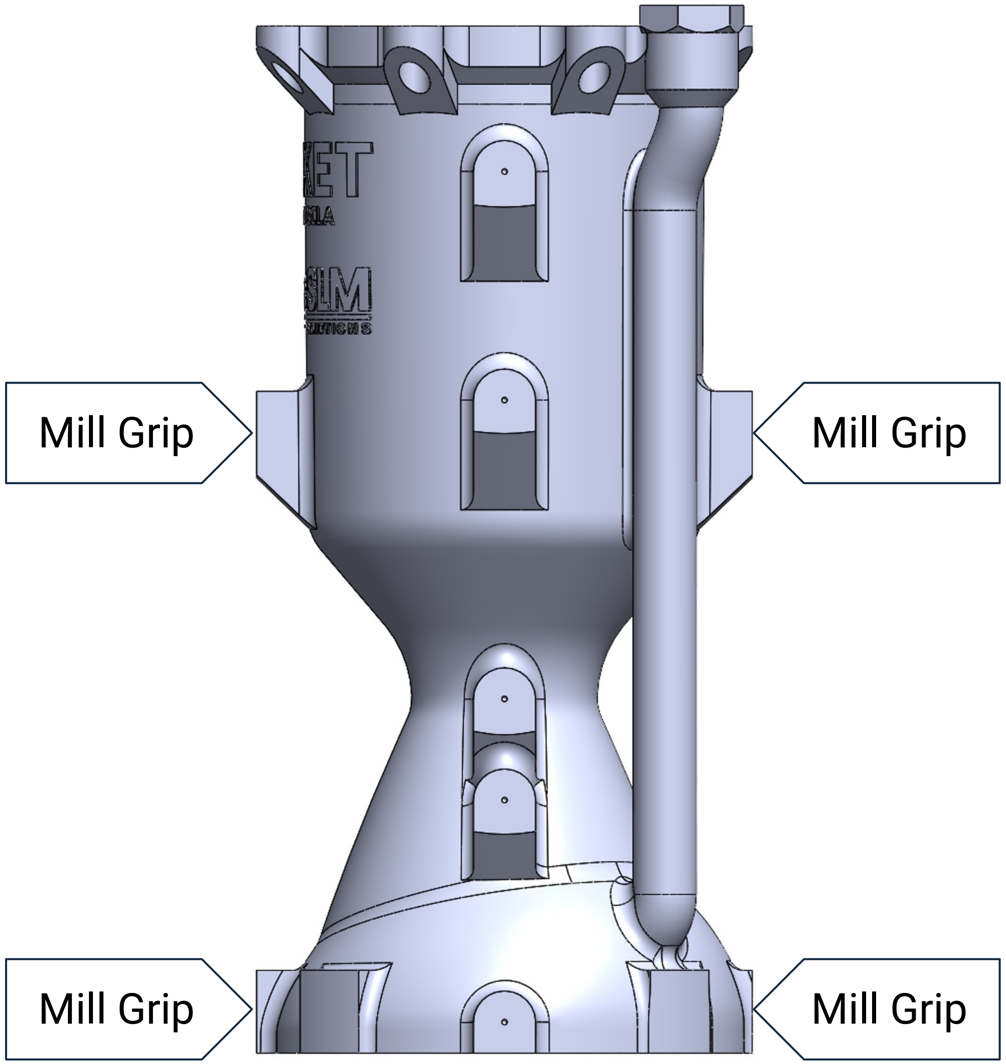
Post-Machining Ops

- Will create several tapping/drilling test articles
  - Ensures that we practice tapping and drilling into inconel prior to doing so on the engine
  - Tests out our planned machining ops on the engine on low-cost articles
  - Raises quality of final engine holes
- Planned machining tooling:
  - Drilling using carbide, TiAlN coated
  - Tapping using multi-stage carbide taps



CAD - Machining Supports

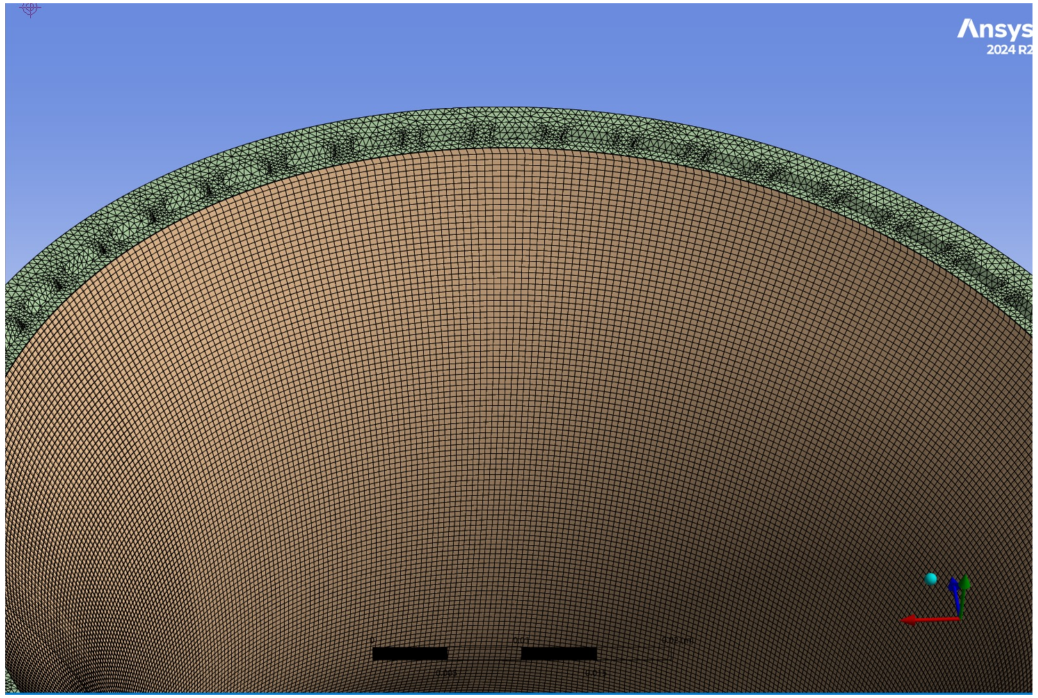




Regen Throat Thermal Analysis

Section near the throat is analyzed due to max temp and stress

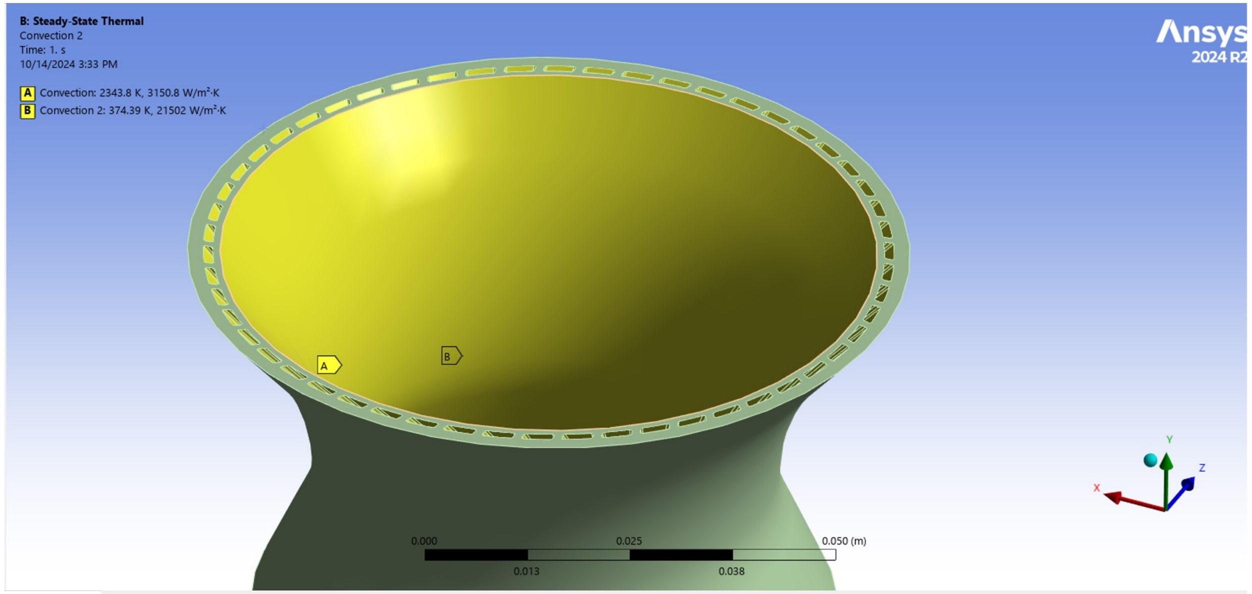
- Thermal coating is simulated using 50 um thick, k = 1 W/mK layer bonded with conformal mesh for thermal analysis only
- 0.5mm mesh was used with 1 layer of solid elements applied to the coating to determine temperature gradient through the thickness

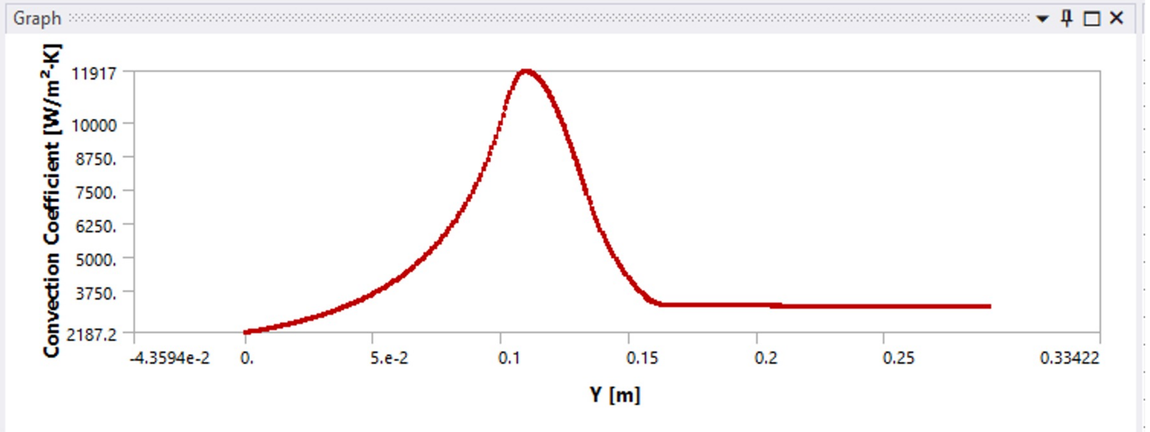


Regen Throat Thermal

Convection Loads

1. Tabular data for Bartz HTC and adiabatic wall temp applied as gradient to surface of coating
2. Tabular data for Dittus-Boelter + Chen nucleate boiling HTC and coolant temp applied to inside of all channels

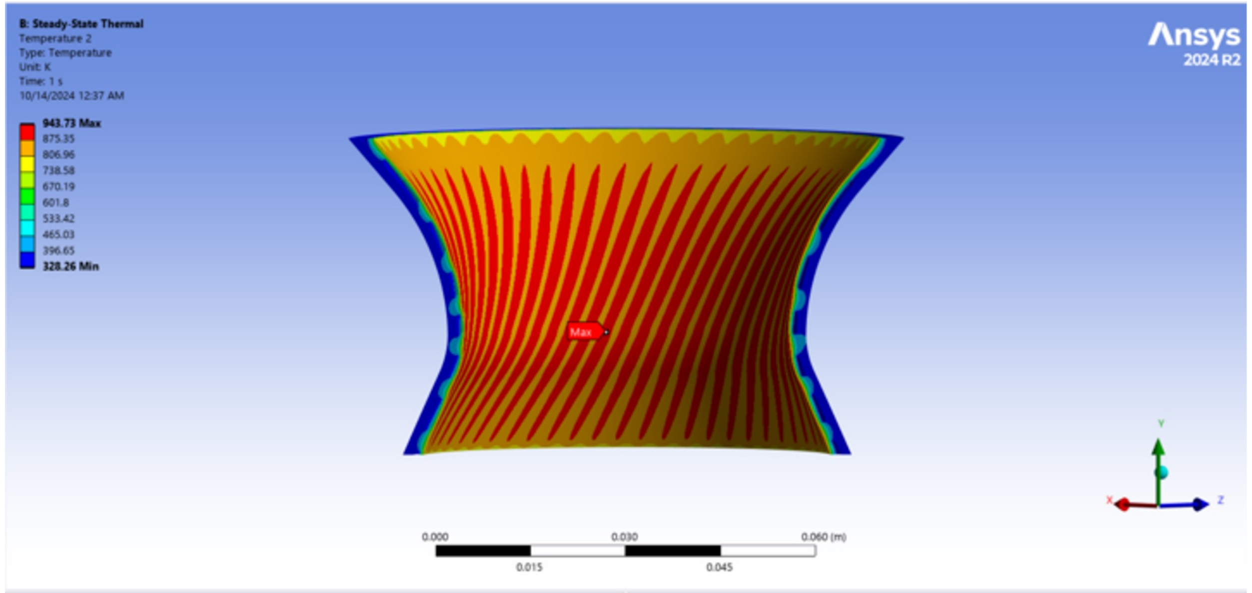




Regen Throat Thermal

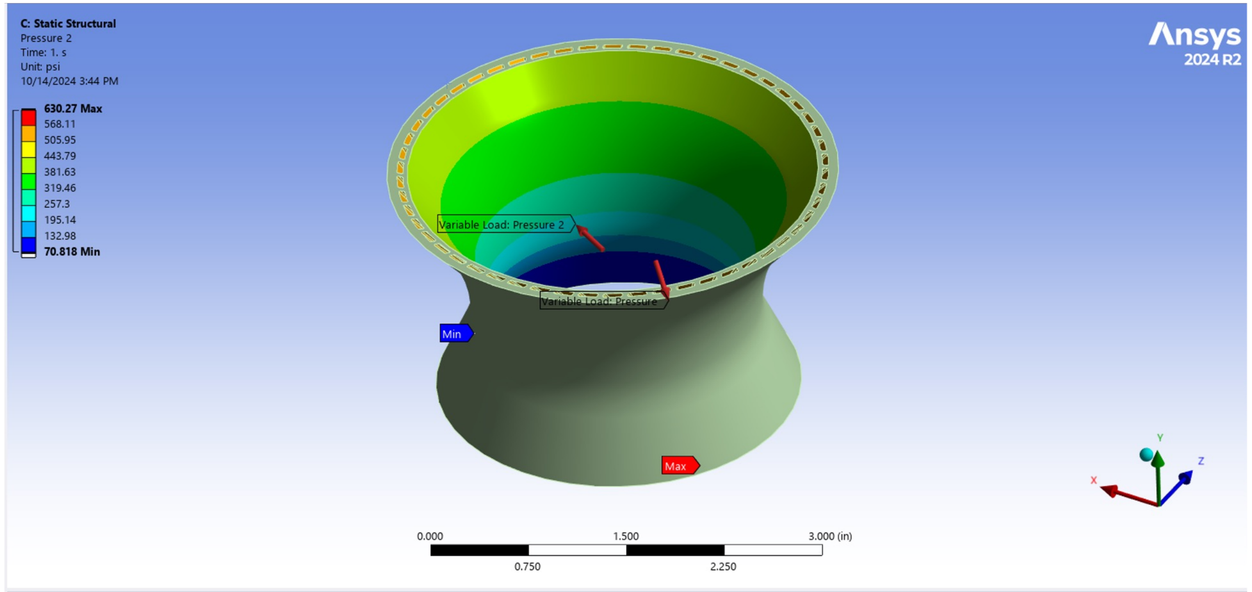
Body temperature is slightly higher than matlab script is predicting, especially at the ribs, but well below the melting point

Temp distribution on engine (coating not shown)



Regen Throat Structural

Body temperature of engine exported to txt file, reloaded into static structural case with the coating suppressed (it’s not load bearing)

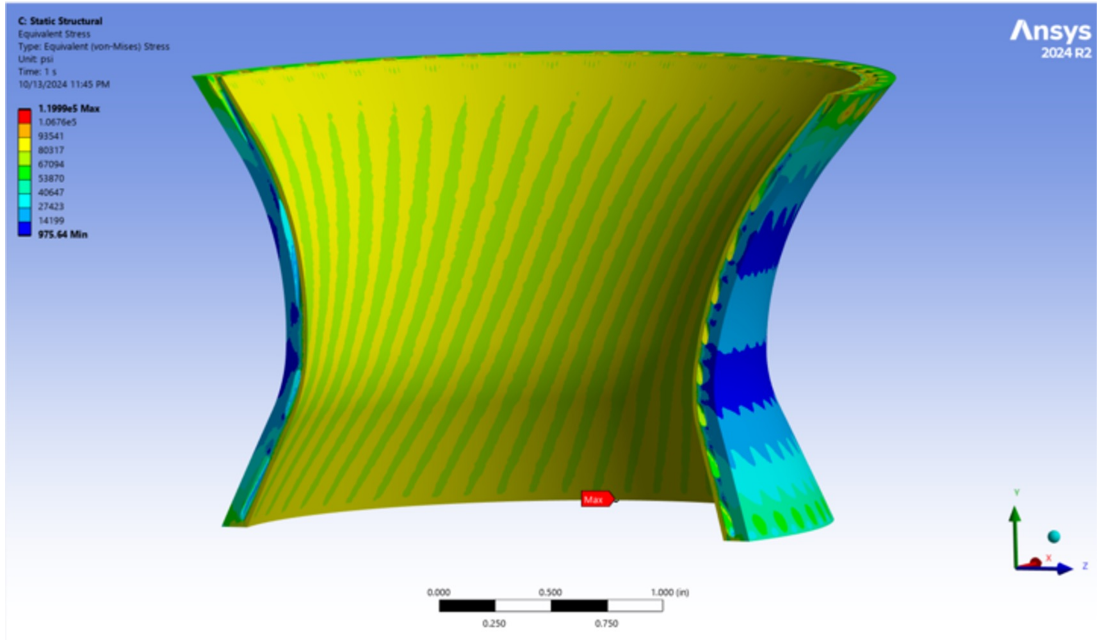


Pressure Loads

1. Gas side pressure gradient taken from MATLAB applied to hot wall
2. Coolant pressure gradient applied to inside of channels in a similar fashion

Regen Throat Thermal + Structural Analysis

Expected Chamber Pressure	400 psig
Yield Factor of Safety	1.3
Ultimate Factor of Safety	N/A
Material	HT Inconel 718 + Arbitrary Coating
Max Stress	83 ksi

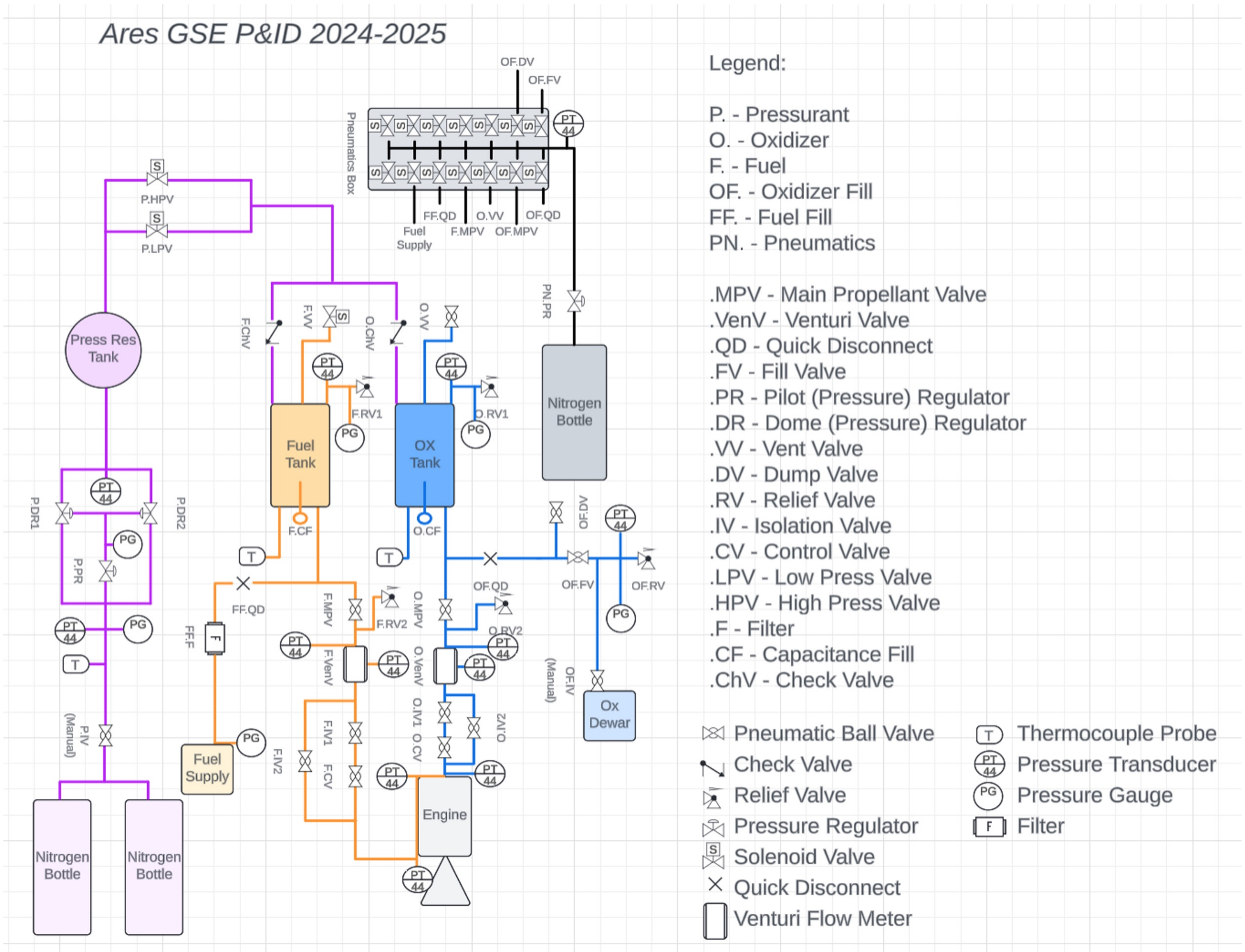


*Stress peaks at constraints ignored due to being non-physical

Test Stand Refurbishment

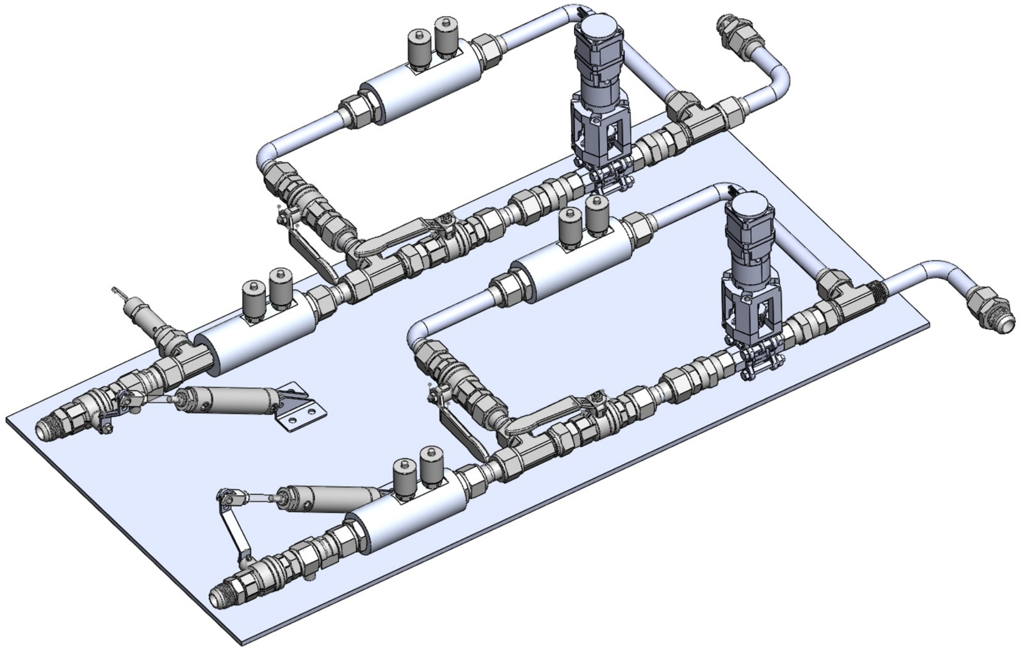
- Goals:
  - Configure the test stand to provide a method of validation for dev projects
  - Decouple all dev projects to allow for parallel design and testing
    - CMFV
    - Dev Feed Valves
    - Regeneratively Cooled Engine
  - Validate as much of the flight system as possible on the test stand

Test Stand PID

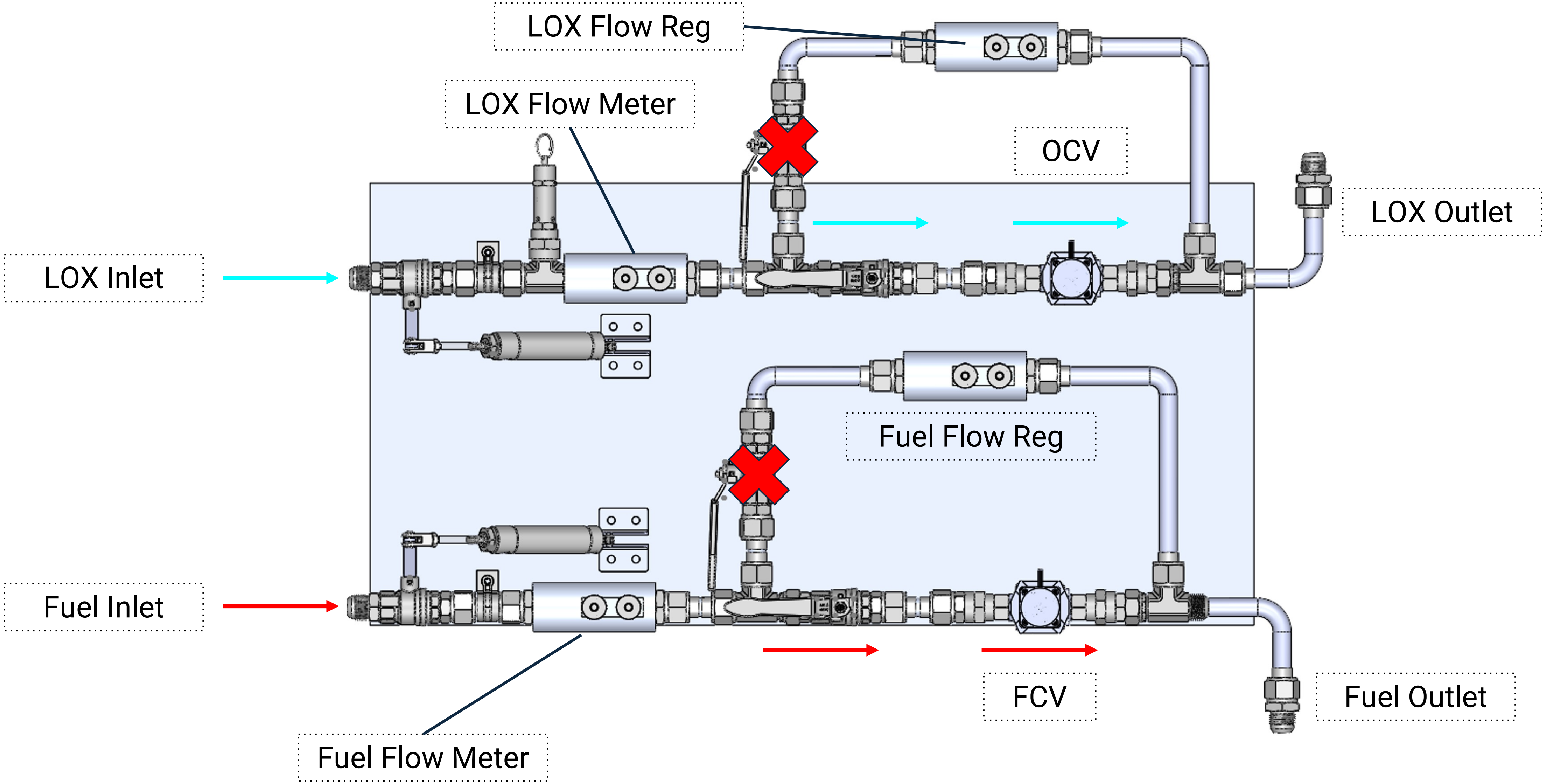


MPV Table

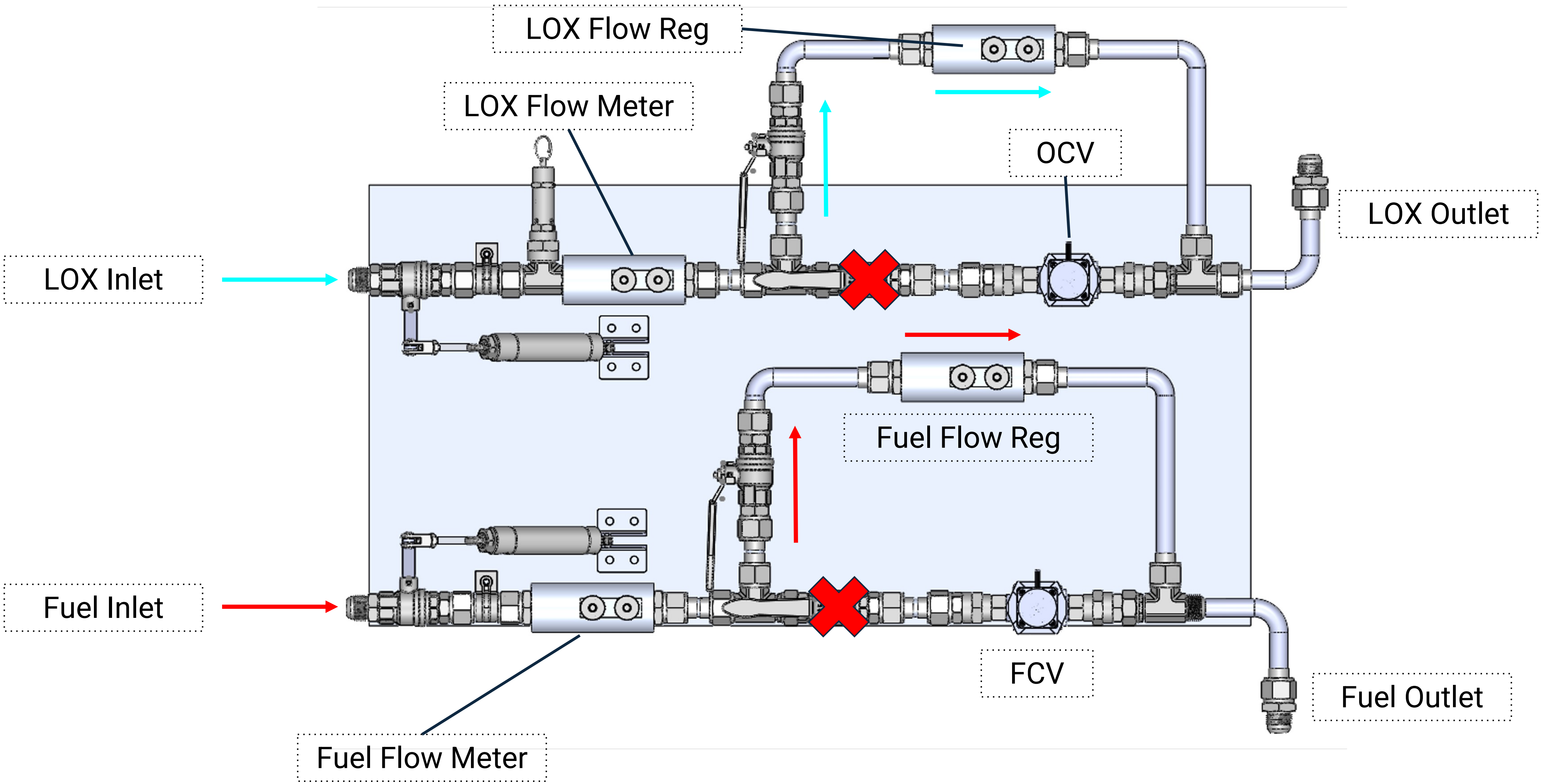
- Upsized to -12 to accommodate higher flow rates
- Parallel lines for each propellant fitted with isolation valves
  - One parallel line runs the electronically controlled valve
  - Other parallel line contains the backup method of varying the mdot with a cavitating venturi
- Non-cavitating Venturi Flow Meters used to measure flow rate
  - Creates a performance metric for the electronic valve and will be a critical datapoint for static fire analyses



MPV Table - Electronic Valve Config

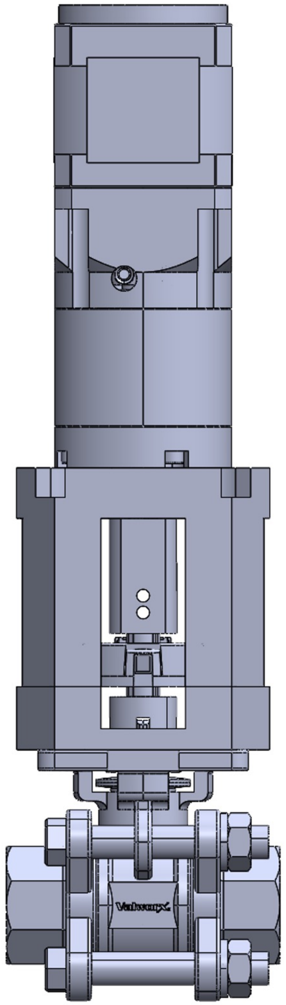


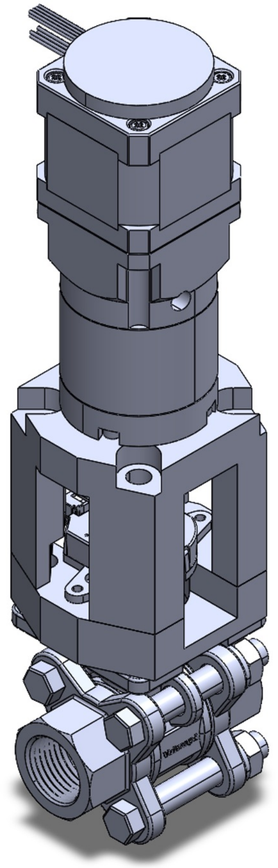
MPV Table - Venturi Config



Electronic Valve (CMFV)

- Controlled Mass Flow Valve (CMFV)
  - Electronically controlled ball valve
  - Will allow independent mass flow control over fuel and ox
  - One ‘valve’ to be placed on either propellant side
- Will be used to characterize the regen engine at static fires
  - Allows variation of O/F and mdot between fires
- If it is validated through reliability and consistency, it will allow us to throttle during a fire and for flight
- More about the design, control, and testing to be discussed in Electronics!

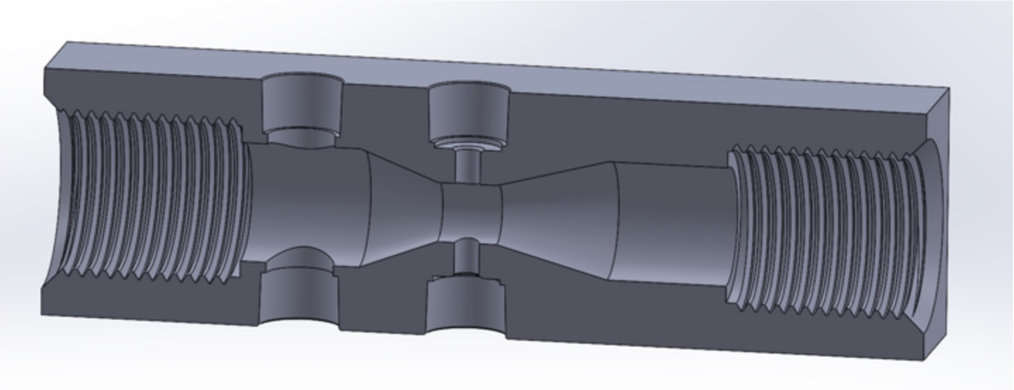


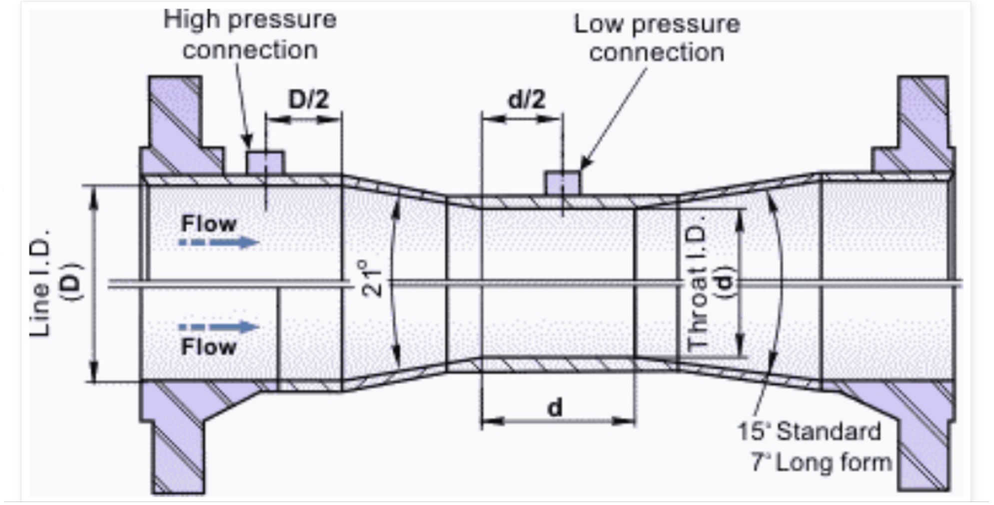


Non-cavitating Venturi Flowmeters

- Design Goal: Accurately measure our mdot with minimal dP
- Approach: Differential pressure flowmeters that extract mdot by measuring the dP at two different points of a pipe
  - dP created by constricting the diameter of the pipe at the second point
- Pressure transducers installed at the inlet and throat of the Venturi
- Uses incompressible flow relations:
- Goal is to maximize our recovery factor while minimizing the dP required between the inlet and throat to obtain accurate readings
- Converging/Diverging angle set to 21 degrees
- Throat Diameter set to ⅓ of an inch to obtain accurate measurements

$$mdot = CdA\sqrt{2p * dP}$$





Cavitating Venturi Flow Regulators

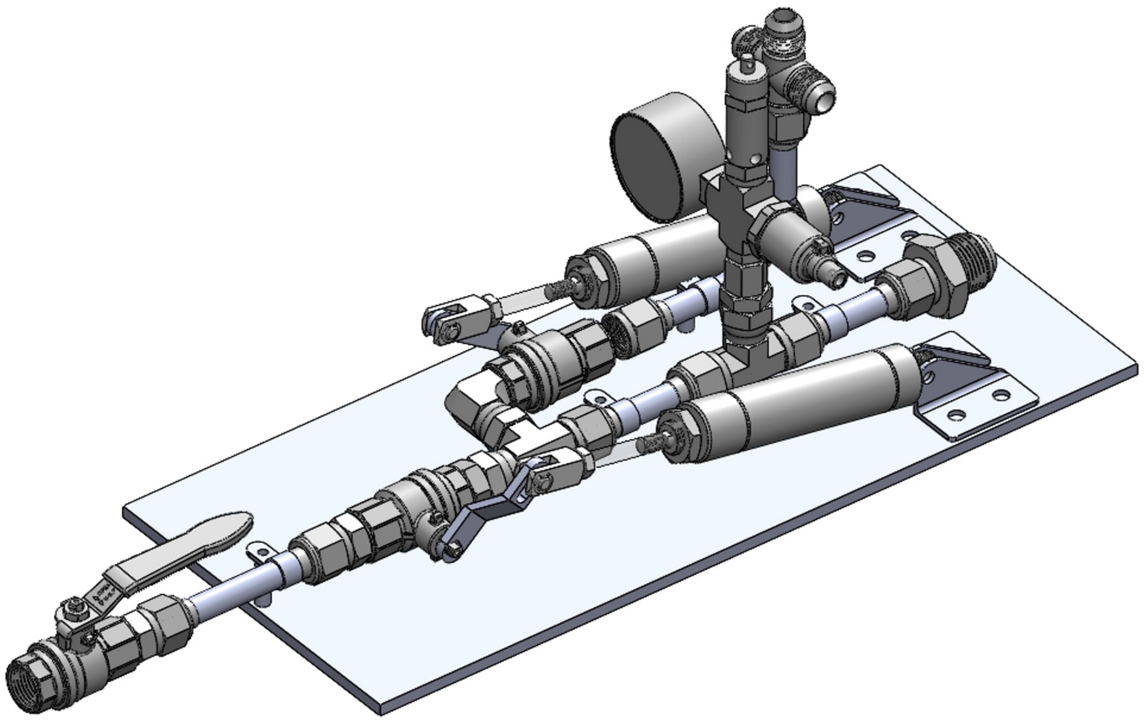
- Design Goal: Regulate our mdot with minimal pressure losses
- Approach: Venturi valves that choke the flow at our throat, then expand at the diverging section to recover the pressure
- Choking the flow will decouple the mdot from downstream conditions, hence the requirement of using cavitating venturis instead of non-cavitating
    - Traditional orifices have a relatively higher dP to achieve the same mdot, requiring us to pressurize our tanks higher to deliver a target mdot and pressure to the engine
- Uses compressible choked flow relations accounting for the phase change at the throat

$$\dot{m} = C_d A \sqrt{\gamma p_1 \rho_1 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

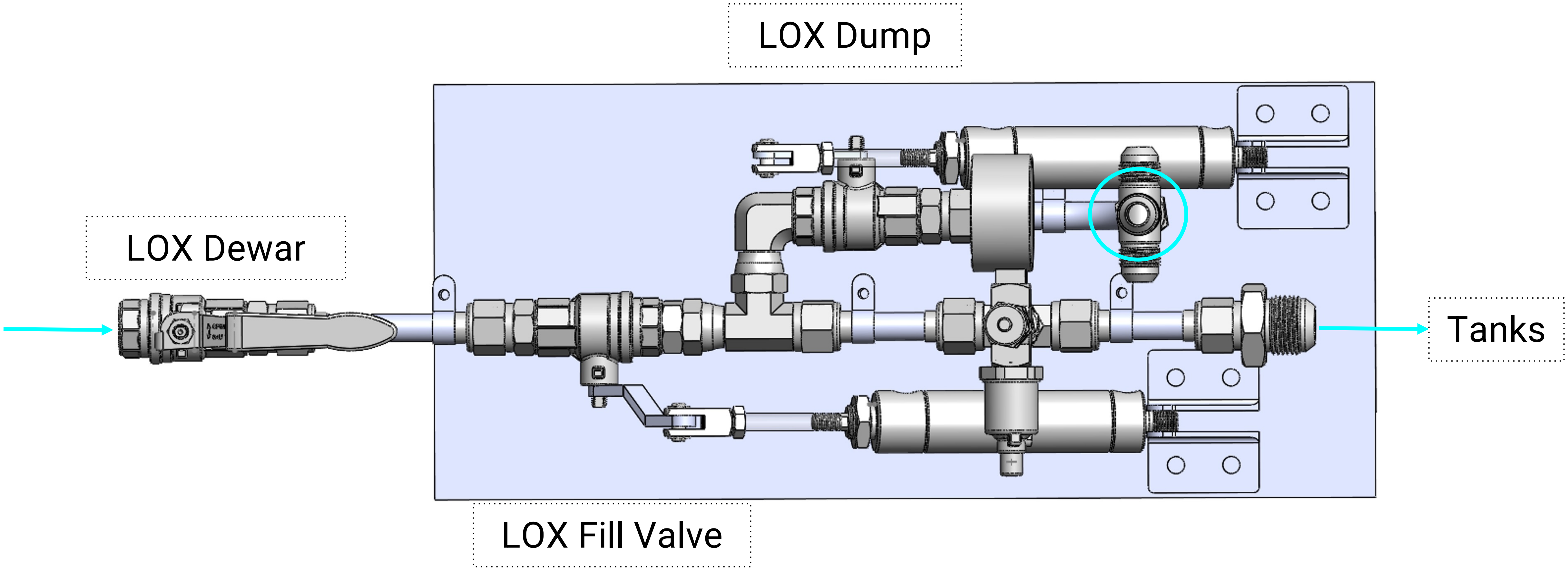
    - Implementing a MATLA given mdot

LOX Fill Table

- Designed to accommodate remote LOX fill
  - Fuel fill procedures will remain manual
- Similar design as last year, but made significantly smaller
- Potentially mounted to the test stand pending other test stand refurbishments

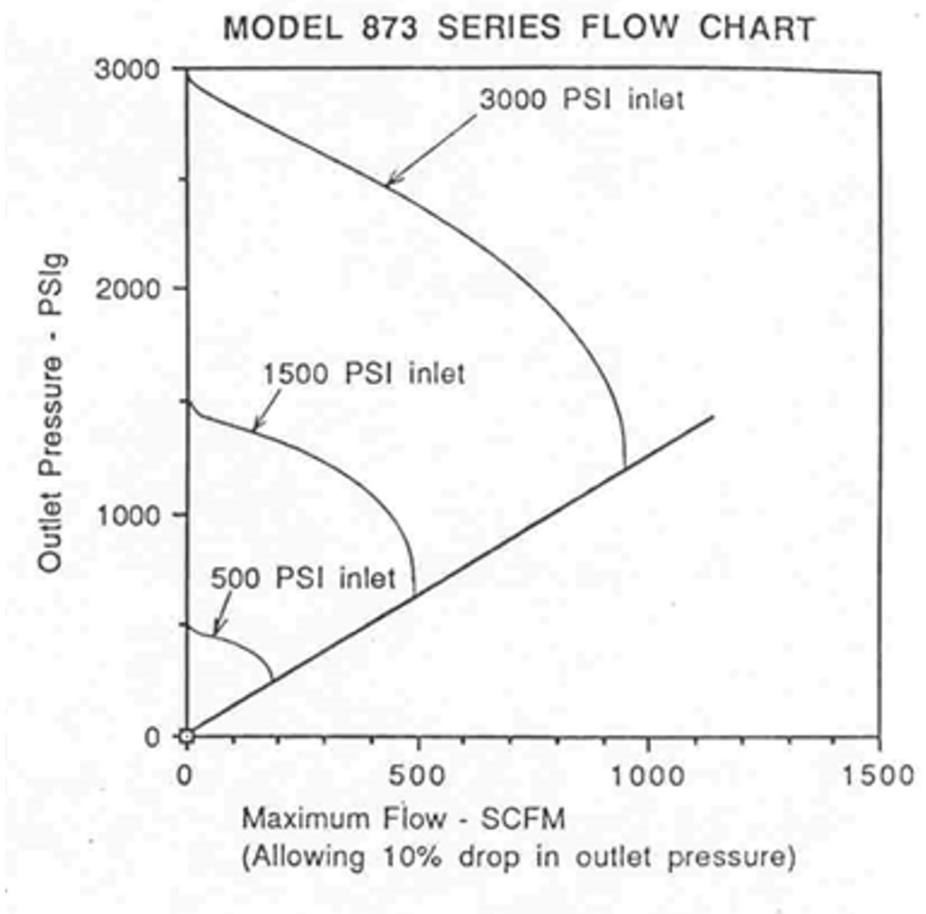


LOX Fill Table



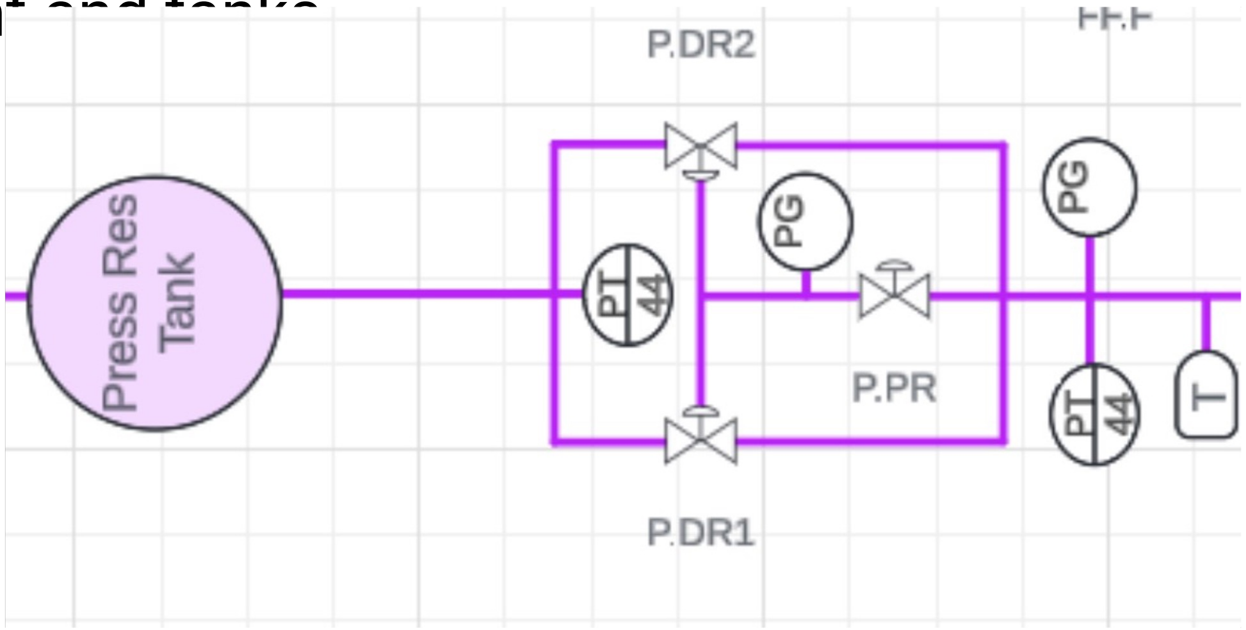
Test Stand Pressurant Requirements

- With a much greater mdot than last year, our ullage volume needs to be filled faster
- Pressurant for most test stand static fires is 2K GN2
- Requirement is now a higher SCFM at higher tank pressures while having the same inlet pressure as last year
- Heritage data, SCFM calcs, and Aqua Environment 873 Regulator curves indicate that the current setup cannot accommodate this without going into blowdown during the burn



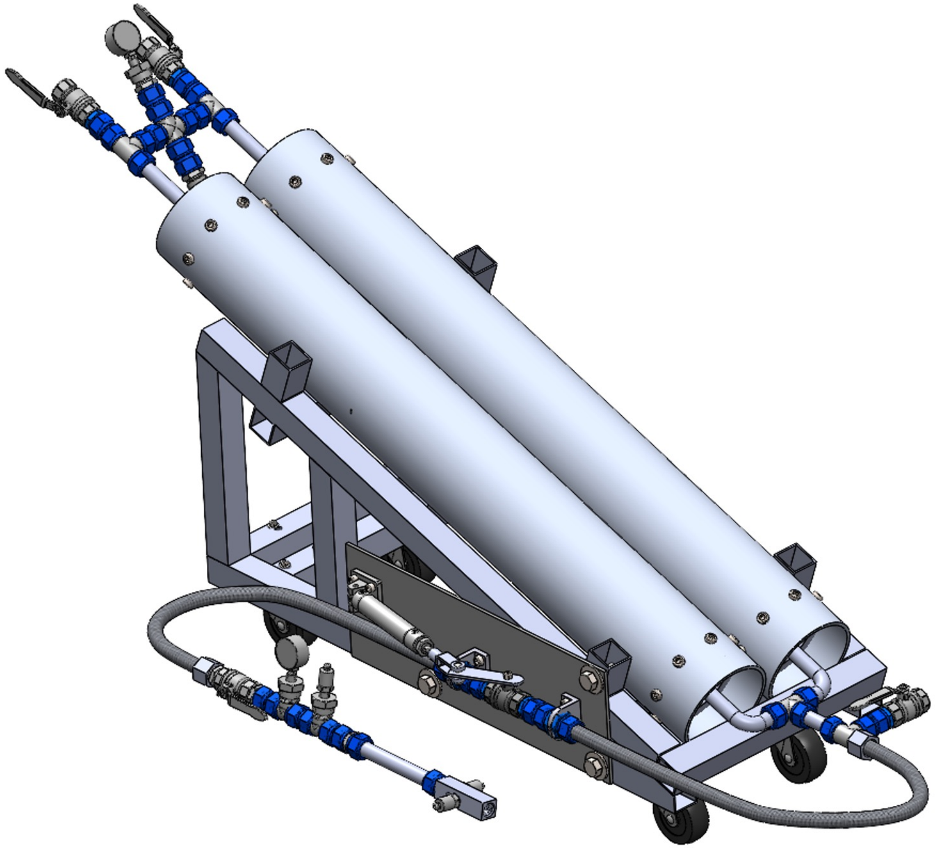
Gas Upgrades

1. Installation of a second Aqua Environment 873 Dome-Loaded Regulator in parallel with the current regulator
    a. Most feasible option as opposed to purchasing a new regulator because there are extras available in the lab
2. Replacement of the high-flow solenoid with one that has almost double the flow coefficient (Cv)
    a. High Flow Solenoid: Responsible for opening the path between the pressurant and tanks



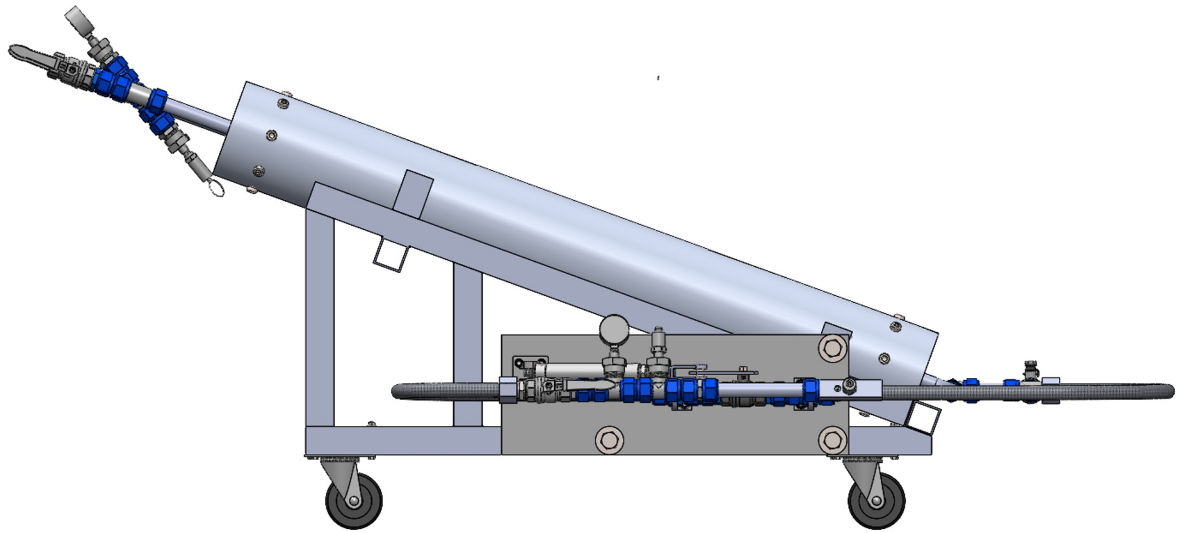
Waterflow Stand

- A separate testing setup to be used for all dev waterflowing
- Previously, water flows were primarily done using the static fire test stand, requiring frequent temporary modifications to the plumbing
- This stand accommodates the increasing demand of water flows
    - CMFV characterization
    - Venturi Valve throat sizing
    - Dev feed system valves



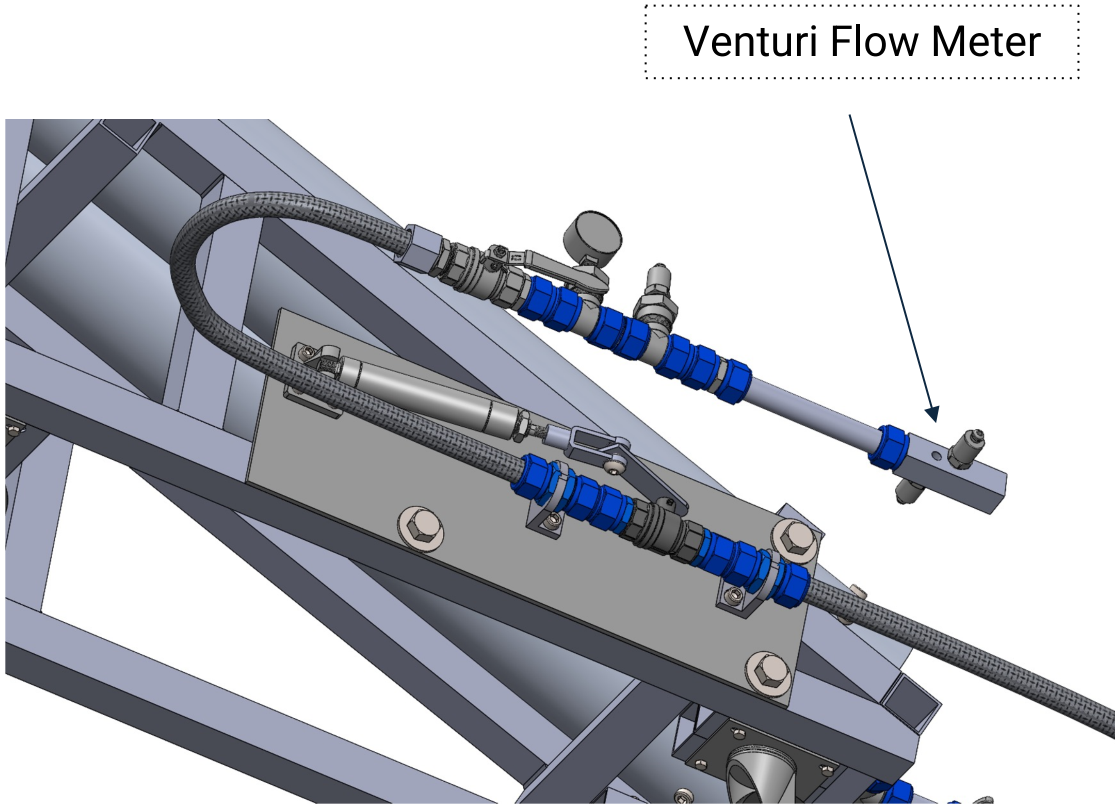
Waterflow Stand Design

- Supply is an in-house machined tank with radially bolted end caps (similar to Prometheus heritage tank)
- Tanks sized to handle water flows up to 200 PSI
- High pressure water flows done with remotely actuated system and pressure transducers
- Pressurized with GN2
- Non-cavitating Venturi Flow Meter used to capture mdot



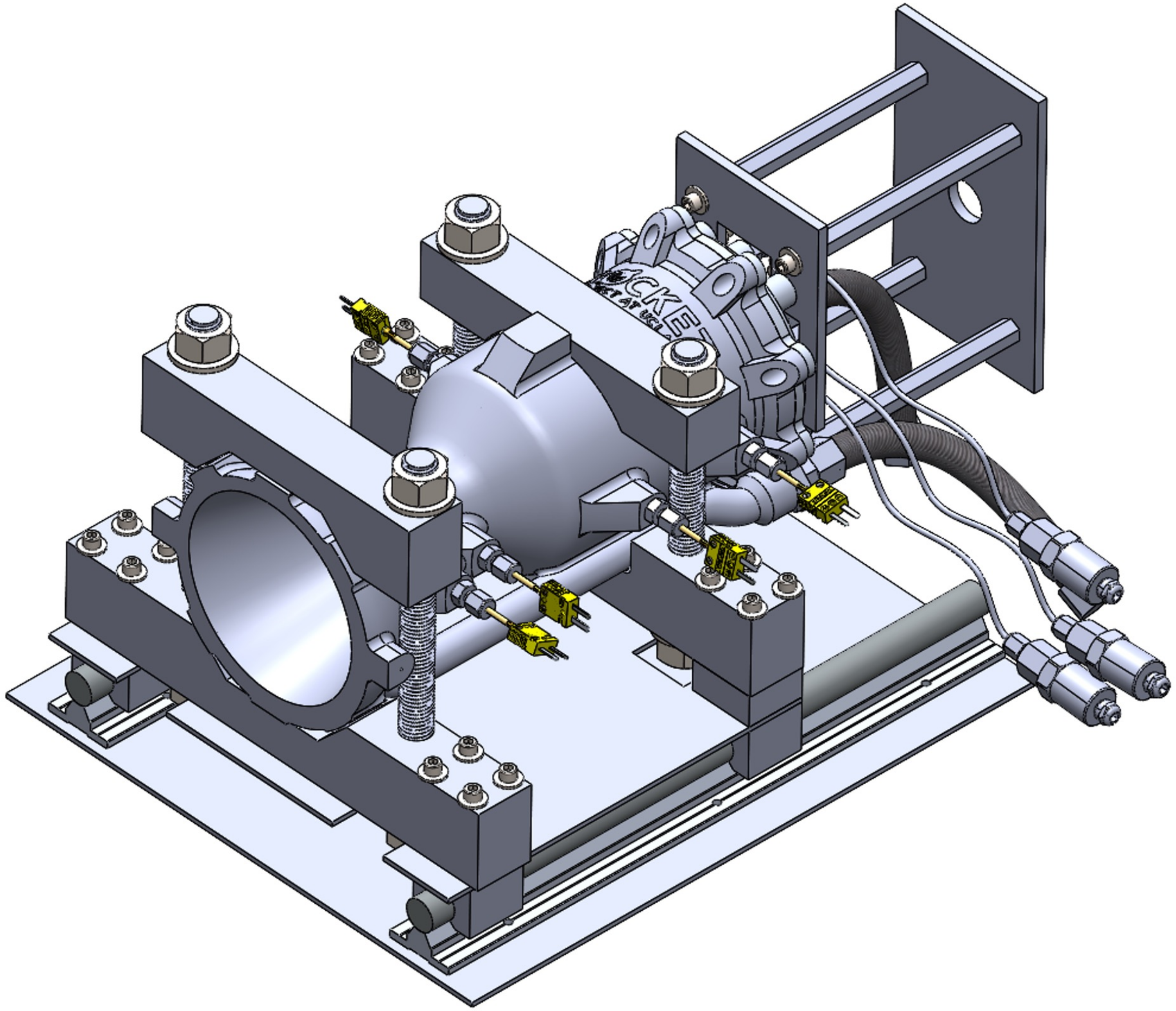
Waterflow Stand

- Pneumatically actuated valves and pressure transducers to allow for remote testing with more accuracy at higher pressures
- Venturi Flow Meter attached to measure flow through pressure/area instead of manual bucket filling
- Manual control with pressure gauges installed to accommodate low pressure manual testing
    - Additional gauges will be swapped in for manual testing
- Flex hose allows for custom mounting setups for varying parts



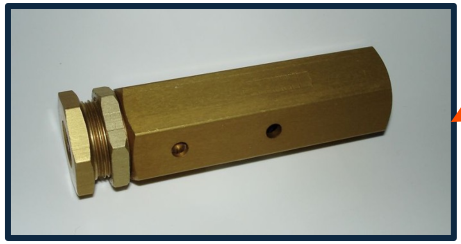
Regen Thrust Mount

- Need a method of mounting the engine to the test stand's thrust mount
- Ablative Engines will follow the heritage technique of mounting with U-clamps
- Regen Engine requires a custom mount to accommodate the geometry of the body, flats, fuel pipe, etc



Pressure Regulation Scheme

- Legacy dome-pilot regulator setup from Aqua Environment
- 873-D Dome-Loaded Regulator
- 1247 Inline Reducing Regulator
- Tried and true setup:
  - Same as previous years
  - Been used on the test stand throughout fall quarter
- Does not require the same upgrades as the test stand because inlet pressure begins at 4500+ PSI, flight system will use Helium, and the pressurant tank is sized and pressurized to avoid blowdown until the end of the burn



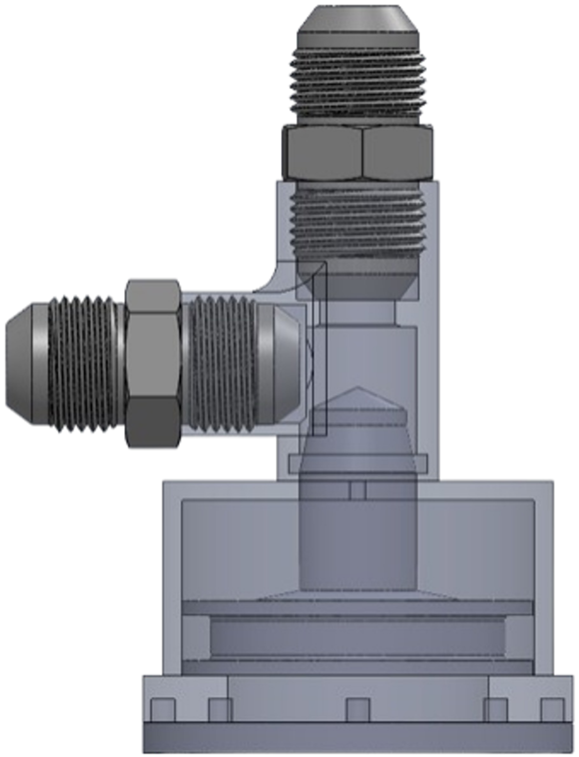
Pressurant Tank

Main Idea: Upsizing commercial pressurant tank from 6.8 L to 9 L

- Blowdown must be mitigated to achieve desired thrust curve. With a larger ullage volume to fill this year, a larger pressurant tank is necessary
- Pressurant tank shall carry 4500 psi helium gas
    - Commercially rated limit of pressurant tank
- Calculations/Script available in the appendix

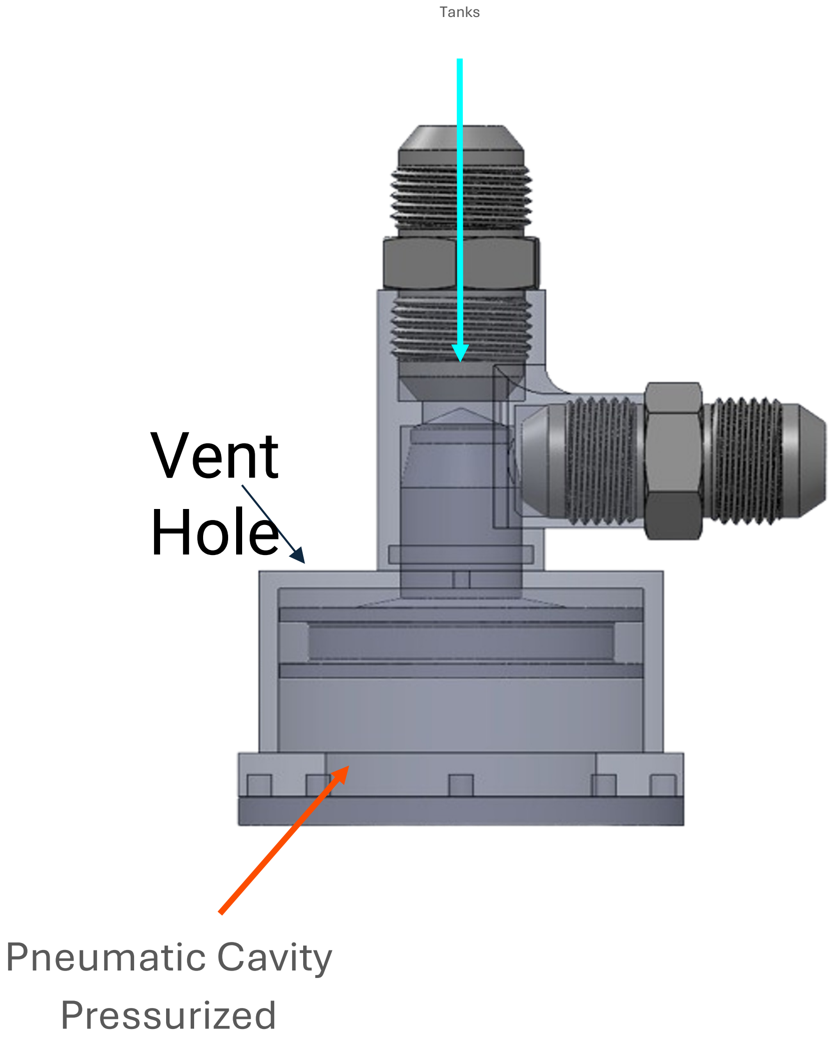
Dev Main Propellant Valves

- Goal: Maximize mass and volume savings for each valve without losing reliability, consistency, and mitigating losses
- Current Dev Project: SRAD Pneumatically Actuated Poppet Valve
- Pneumatic Cavity integrated into valve body
  - Does not require the same open volume that a pneumatic actuator's arm needs
    - Combats the failure mode of Heritage integration problems where an actuator's arm got stuck on neighboring insulation during flight
- Current design only weighs 0.5 pounds
  - Heritage Ball valve + pneumatic assembly weighs about 2 pounds each
    - With regen requiring decoupled MPV actuation timings, the complete heritage assembly is 4 pounds

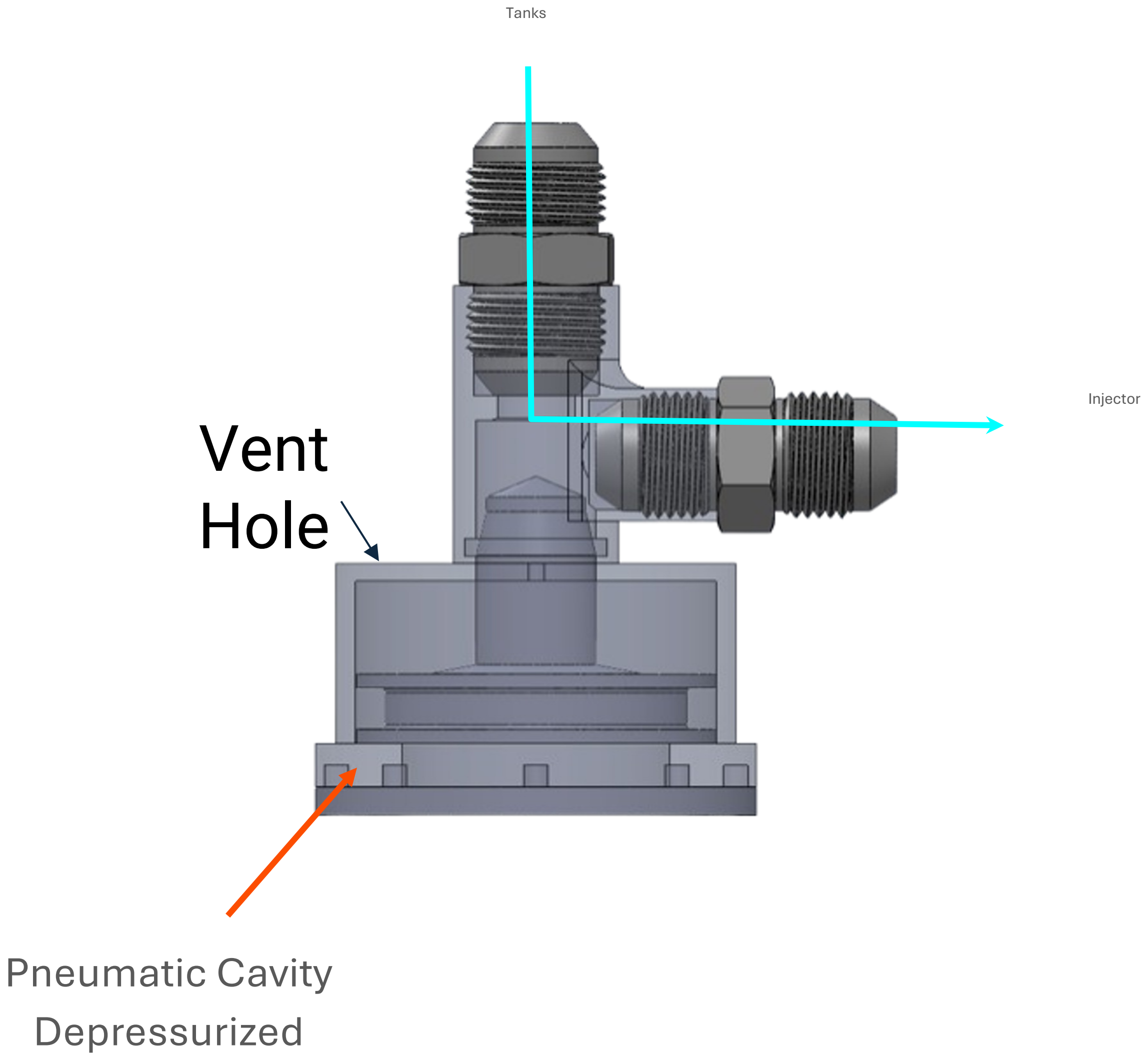


Dev MPV

Closed Position

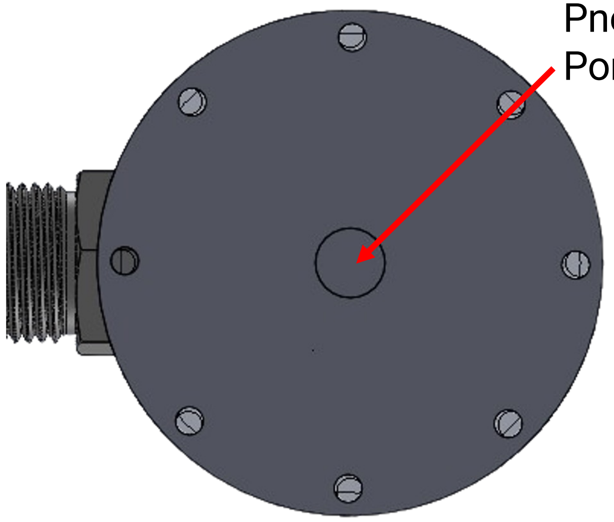


Open Position



Dev MPV Actuation

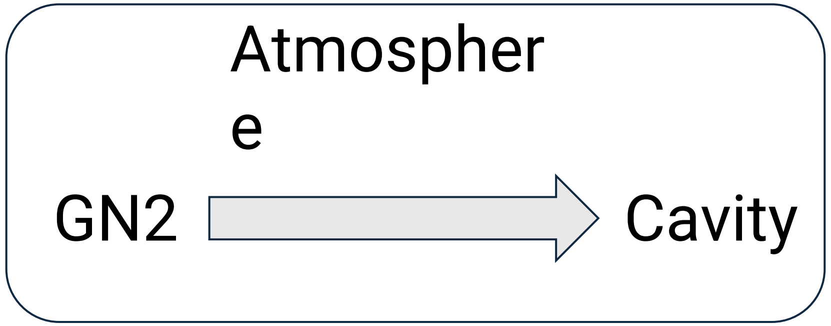
- The pneumatic cavity functions as an actuator
  - 1 port on the bottom of the cavity connected to a 3-way solenoid
  - Solenoid is off-rocket, much like the heritage pneumatics box
  - One vent hole on the top of the cavity to vent out pressure
    during actuations
  - Actuated with a GN2 bottle on the pad
- Valve currently sized for actuations with 150 PSI
  - Looking into whether we can safely provide and increase cavity pressure to reduce valve OD
    - OD currently 3”



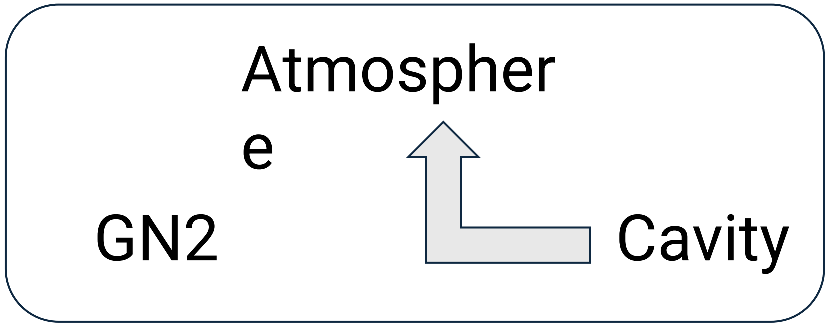
Dev MPV Actuation

- Safe Stating + Procedure:
  - Propellant will not be filled until the cavity is pressurized to close the valve
  - The 3 way 2 state solenoid is used such that if there is an electronic power failure, the cavity remains pressurized and closed.

Valve Closed (Safe State)

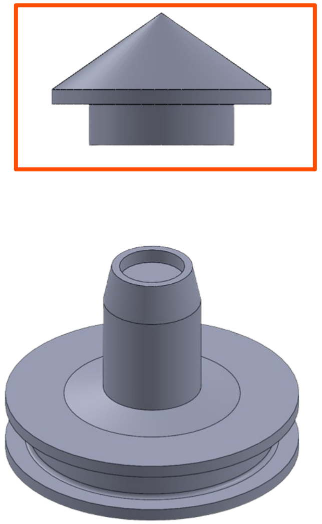


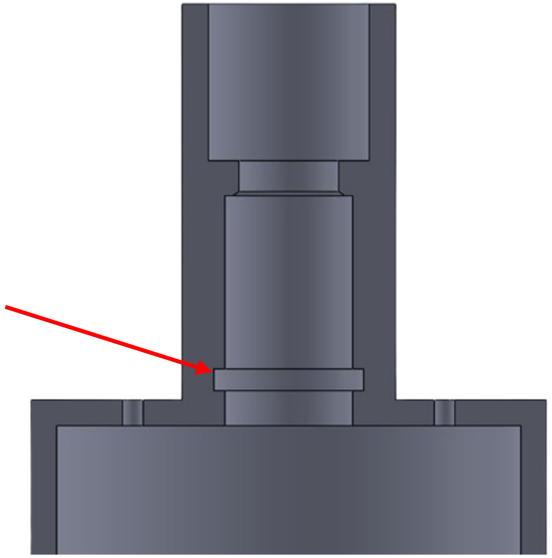
Valve Open

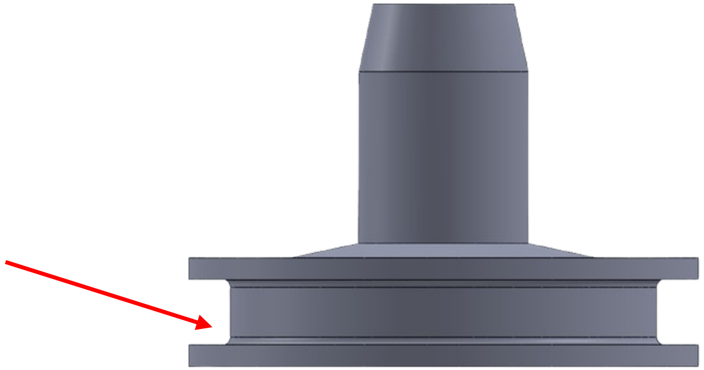


Dev MPV Sealing

- 3 main seals:







PTFE Taper

- Seals against the inlet to close the valve
- Has .2 Inches of solid PTFE to prevent wear and tear during sealing action
- Taper sits on a chamfer for a full seal
- Sealed inside internal Cavity in piston with Cryogenic Epoxy

Internal Groove - Radial Seal

- Body of the valve has a radial seal installed into an internal groove
- Seal: Astra-Seal Spring Energized PFA
  - Rated for -420 degrees F and 1500 PSI
  - Astra-Seal is designed for piston movement and other such rod seals

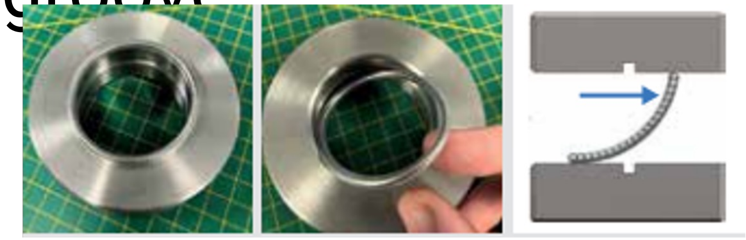
Pneumatic Cavity Seal

- PTFE O-ring for LOx and Nitrile O-ring for fuel side

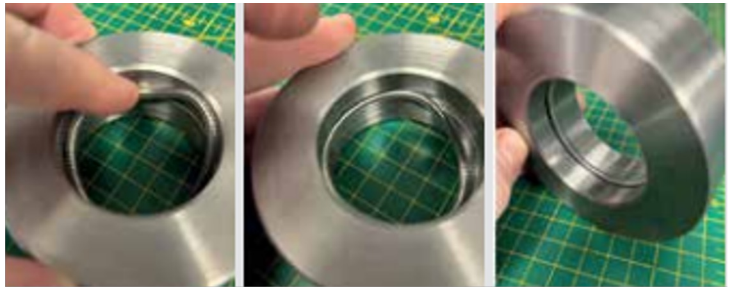
Astra-Seal Installation

- Plan is to follow the manufacturer’s specified guidelines to install the seal into the internal groove

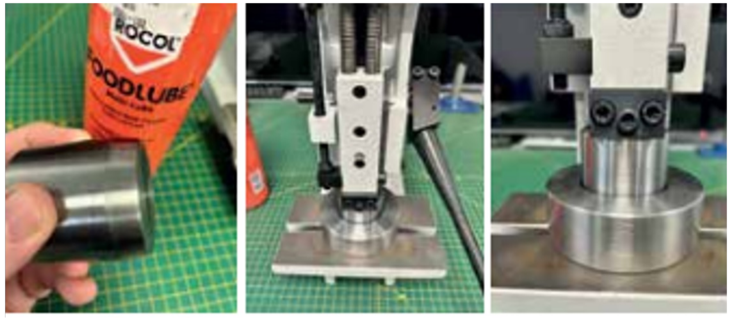
Step 1



Step 2

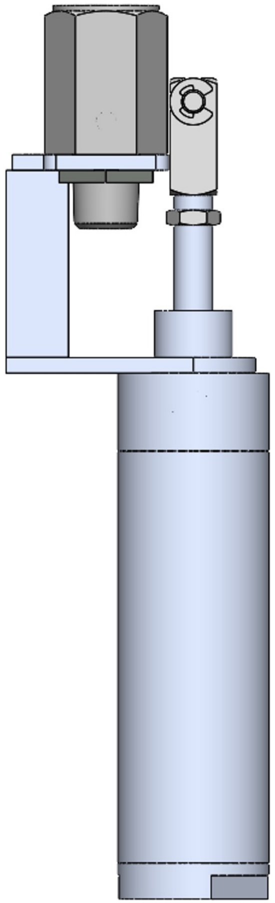


Step 3



Main Propellant Valves - Backup Heritage

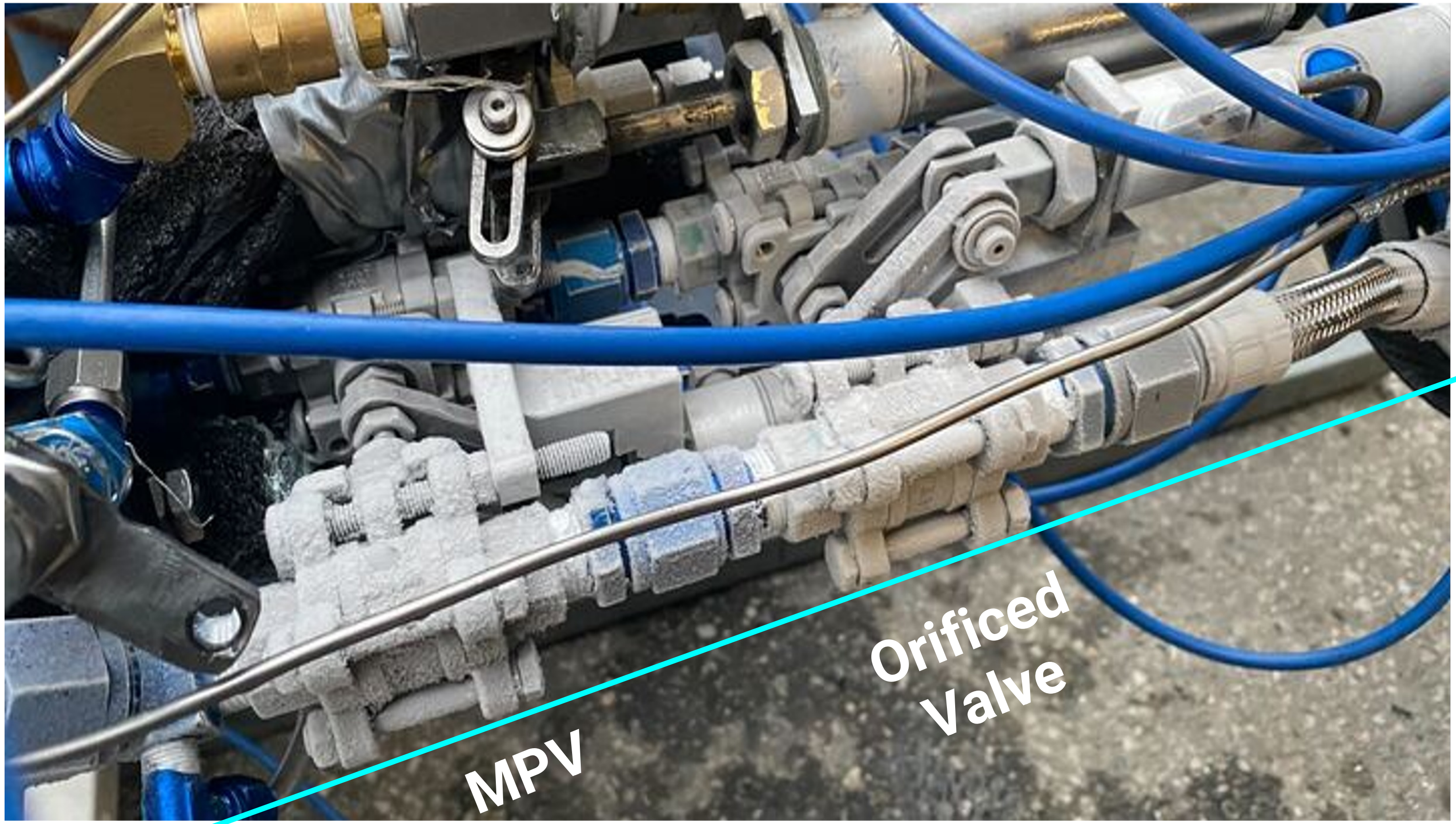
- *Main Idea: Two ball valves mechanically controlled via pneumatic actuators*
- Primary Changes:
    - If we fly with a regen engine, the MPVs will be decoupled with a predetermined time offset to allow fuel to flow through all of the channels first



Throttling

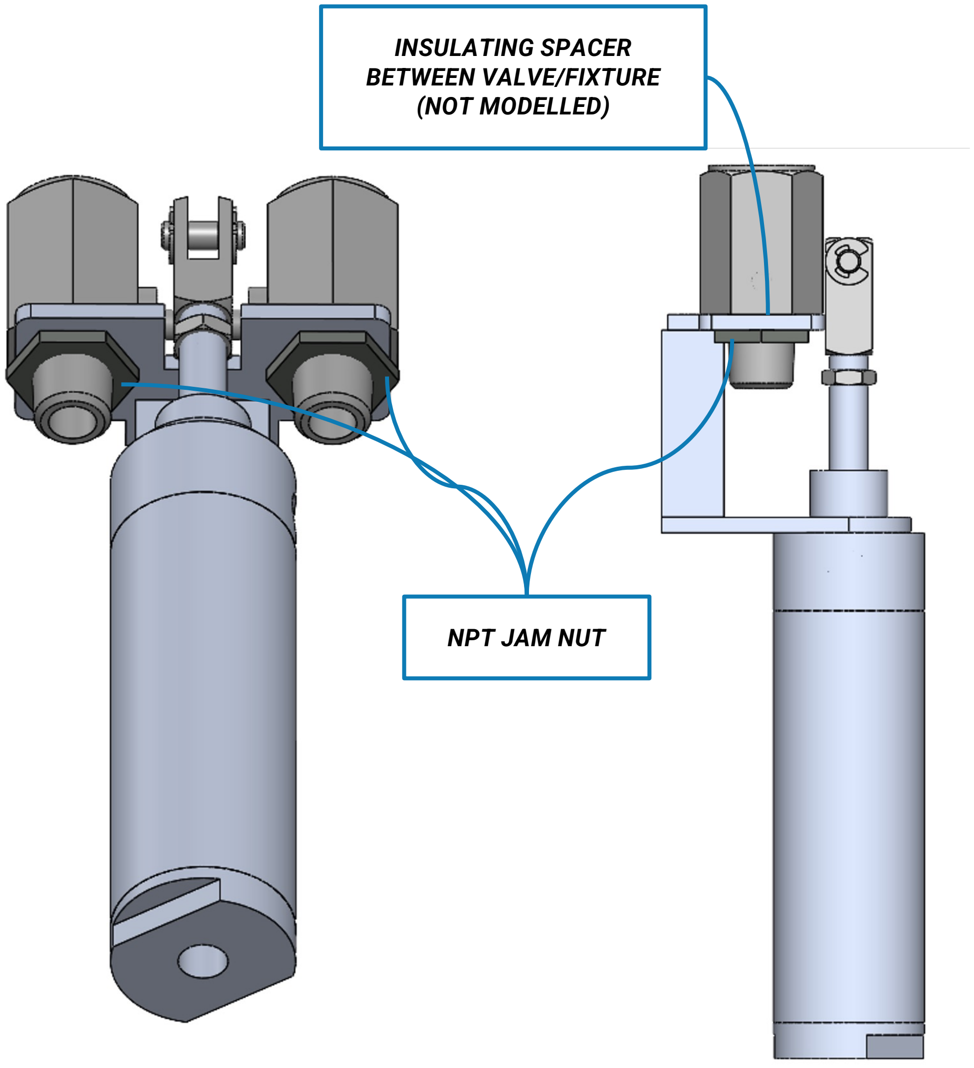
- Current objective is to design for an engine that can throttle from 100% throttle to 75% throttle to meet Vehicle Engineering requirements
  - 2000 lbf → 1500 lbf
- Primary method of throttling will be through the CMFV pending sufficient static fire validation
- Backup method involves an optimized version of heritage throttling system
  - Heritage system:
    - 2 full-port ball valves in series per propellant
    - First ball valve functions as a standard MPV
    - Second ball valve has an orifice drilled through it with a target CdA. At the beginning of flight, the ball valve is in the fully open, non-constricted position. To throttle, a pneumatic actuator tapping off the pressurant with a solenoid closes this valve, putting it in the position with the orifice in the flow path

Throttling - Backup Heritage



Vent Valves

- *Main Idea: Two ball valves mechanically connected and actuated/de-actuated via pneumatics*
- Primary Changes:
  - Coupled vents to single pneumatic actuator to reduce mass/volume (no critical operational state to need independent valve control)
  - Potential to make our own custom actuators - similar to MPV dev valves
  - Moving vent valves to the press bay to prevent potential freezing in the feed bay with the MPVs



Quick Disconnects

- Goal is to allow for remote filling of LOX and Helium
  - Ethanol will be filled ahead of time by hand
- Ox Disconnect will remain the same as heritage Swagelok QTM2 PTFE Sealed Quick Connect
- Helium Swage Pressurant Disconnect will remain the same as heritage Swagelok QC8-D-810
- QDs remotely controlled via a pneumatic actuator engaging with custom sleeves mating with the relevant bodies on the QDs
- Both QDs extensively tested and refined over the course of last year to maximize ease of actuation and reliability, and maintain a small profile

Quick Disconnects

LOx QD

Press QD

Remote Actuation Infrastructure

- LOx and Pressurant QDs will use heritage arms made of steel c-strut and truss clamps that mount directly to the launch rail with a bungee to pull the QD away from the rocket
  - Proved to provide sufficient structural stability with the flexibility to have the QD port on the rocket in most orientations such that guide rails can be mounted in the most optimal position