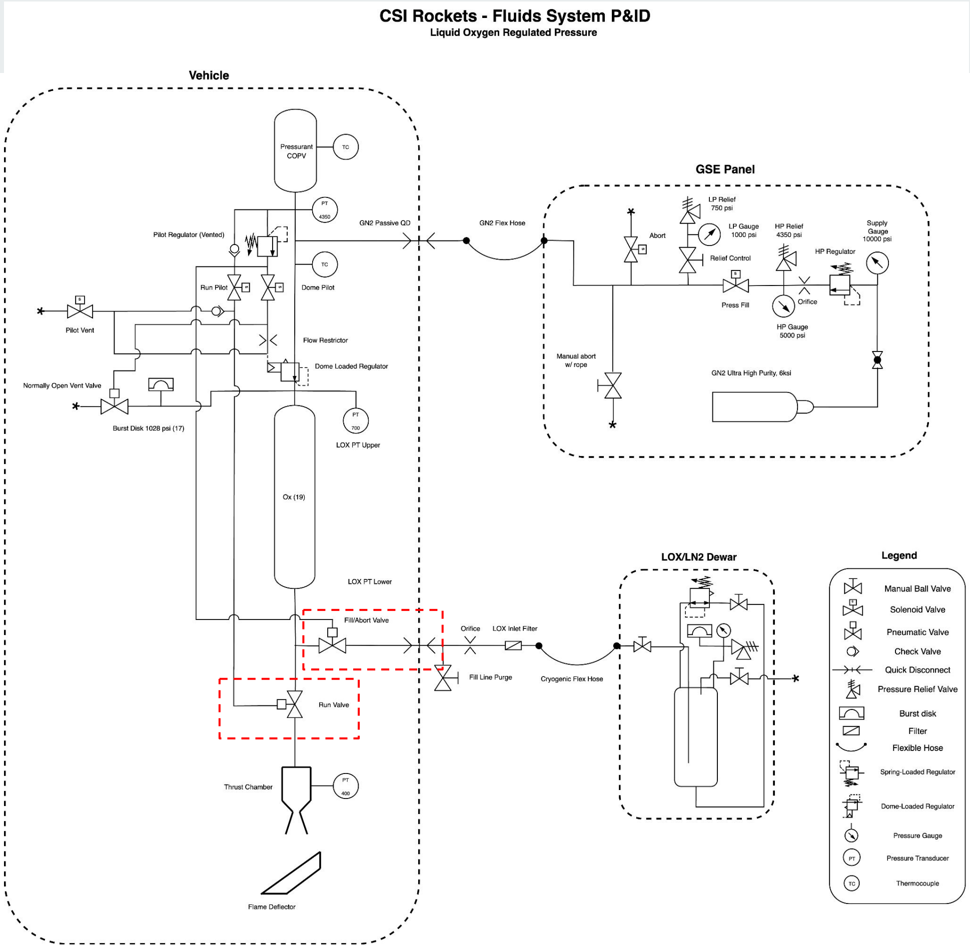
Cryogenic Liquid Oxygen Valves

System Overview

- Regulated pressure LOX feed system
- Requires 3 cryogenic oxygen valves
    - Run valve: normally closed, high flow main oxidizer valve
    - Fill/Drain valve: normally open, low flow fill and drain valve
    - GOX vent valve: normally open, high flow GOX vent
- Balances:
    - Oxygen safety
    - Cryogenic reliability
    - Manufacturability
    - Mass
    - Cost
    - Design for assembly

P&ID



CSI Rockets - Fluids System P&ID
Liquid Oxygen Regulated Pressure
Vehicle
Pressurant COPV
TC
PT 4350
Pilot Regulator (Vented)
GN2 Passive QD
GN2 Flex Hose
Run Pilot
Dome Pilot
Pilot Vent
Flow Restrictor
Dome Loaded Regulator
Normally Open Vent Valve
Burst Disk 1028 psi (17)
PT 700
LOX PT Upper
Ox (19)
LOX PT Lower
Fill/Abort Valve
Orifice
LOX Inlet Filter
Fill Line Purge
Cryogenic Flex Hose
Run Valve
Thrust Chamber
PT 400
Flame Deflector
GSE Panel
LP Relief 750 psi
Abort
LP Gauge 1000 psi
HP Relief 4350 psi
Supply Gauge 10000 psi
HP Regulator
Relief Control
Press Fill
Orifice
HP Gauge 5000 psi
Manual abort w/ rope
GN2 Ultra High Purity, 6ksi
LOX/LN2 Dewar
Legend
Manual Ball Valve
Solenoid Valve
Pneumatic Valve
Check Valve
Quick Disconnect
Pressure Relief Valve
Burst disk
Filter
Flexible Hose
Spring-Loaded Regulator
Dome-Loaded Regulator
Pressure Gauge
Pressure Transducer
Thermocouple

Component Requirements

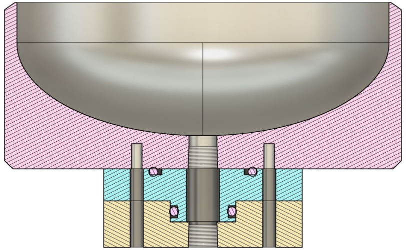
	Run Valve	Fill/Drain Valve	GOX Vent Valve
Working Fluids	LOX, LN_2, Water	LOX, LN_2, Water	GOX/LOX
MEOP	700 psi	700 psi	700 psi
Designed Pilot Pressure	250 psi	250 psi	700 psi
Implemented Pilot Pressure	700 psi	700 psi	700 psi
Sealing Duration	1 hour	30 minutes	30 seconds
Actuation Speed	< 20 ms	N/A	< 100 ms

Components Experience

- Team has previously developed a pyrovalve (21-22) and coaxial pneumatic valve (23-24) for nitrous oxide
- 1 YOE with pneumatics
- No club experience machining large stainless steel parts
- No club experience with cryogenics
- No club experience with oxygen, liquid or gas

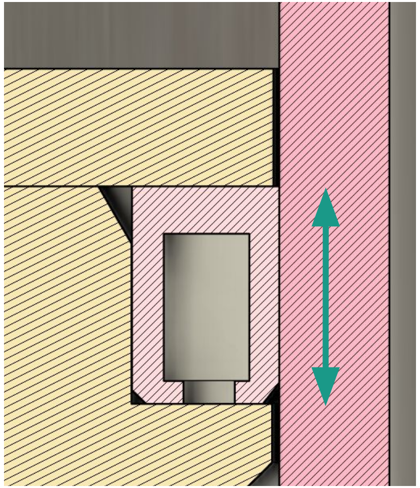
Static Seal Qualification

- Integrated with welded 6061-T6 pressure vessel qualification for cryogenic operation.
- Static PTFE o-ring face seals and Viton o-ring piston seals.
- Saved > $1500
- Hydrostatic testing up to 1,925 psi
- Liquid nitrogen testing to 250 psi
- Results:
    - Static PTFE o-ring face seals with 35-40% compression sealed adequately.
    - Static Viton o-ring piston seals did not seal, required injector design rework.
    - PTFE o-rings were single use, but still significantly more cost effective than spring loaded seals for static applications.



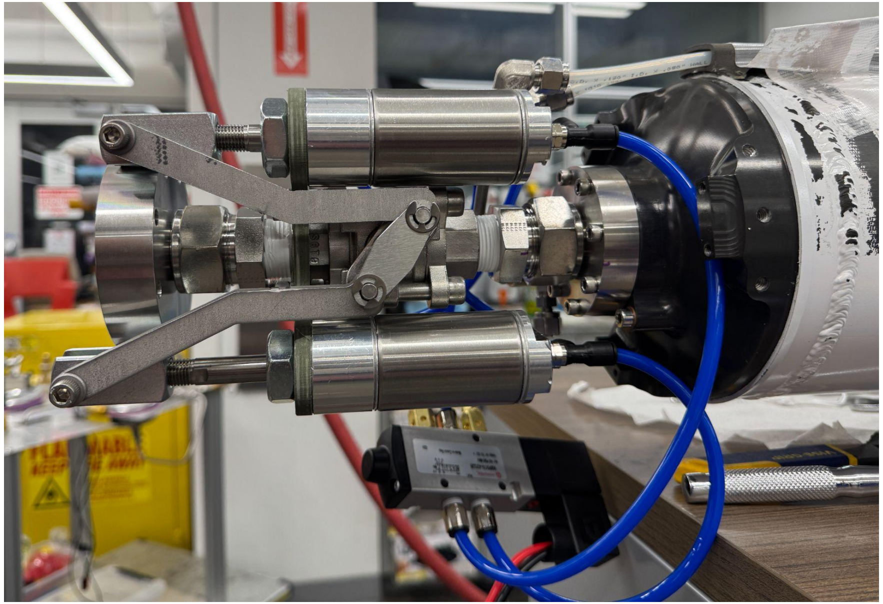
COTS Dynamic Reciprocating Seals

- Spring-energized seals consist of an outer layer of sealing material (PTFE) supported by metal springs
- Cryo temps → PTFE contraction → spring extension
- Pressure assisted and unidirectional
- Requires two piece design for installation, not elastic like o-rings are
- Expensive, fragile, and limited sizes available



Why Custom?

- Cryogenic LOX solenoid valves are expensive and hard to procure
- Pneumatically actuated ball valves are bulky and heavy, not ideal for vehicles
- Ex: Large diameter pneumatically actuated ball valve
    - 4.79” increase in length
    - 2.75 lb increase in mass
    - Additional complexity for COTS pneumatics with lower MEOP

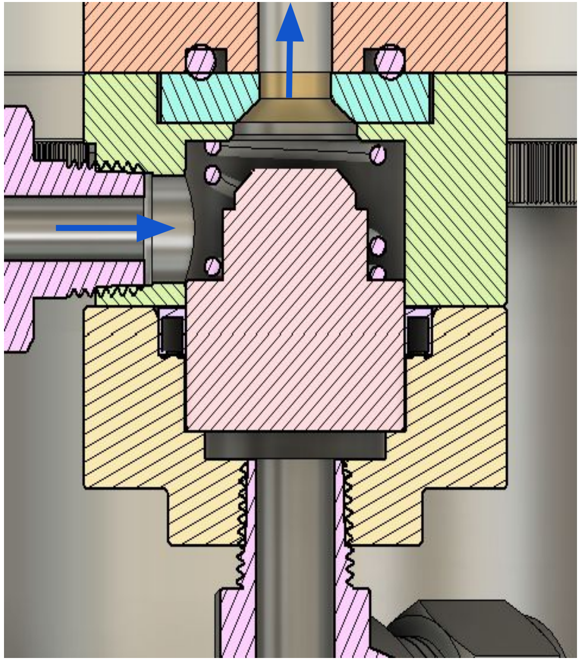


Poppet Valve Summary

Fill/Abort Valve, Normally Open

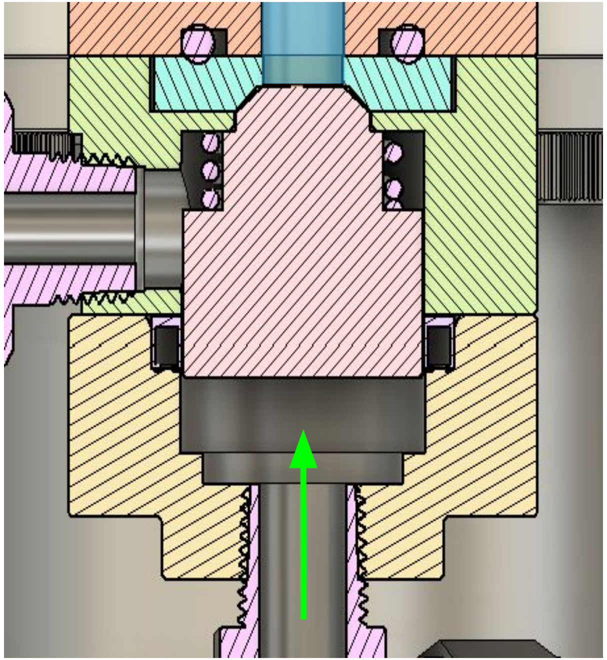
LOX Tank

LOX Umbilical



Pilot Line

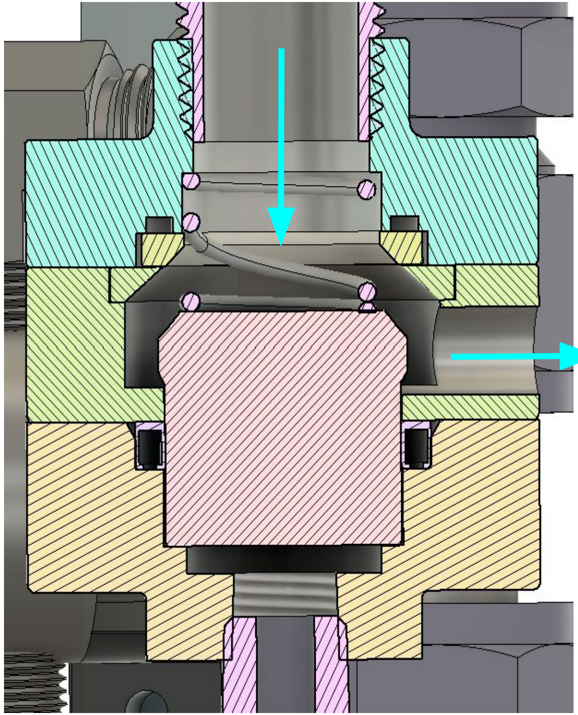
LOX Tank



Pilot Line

Vent Valve, Normally Open

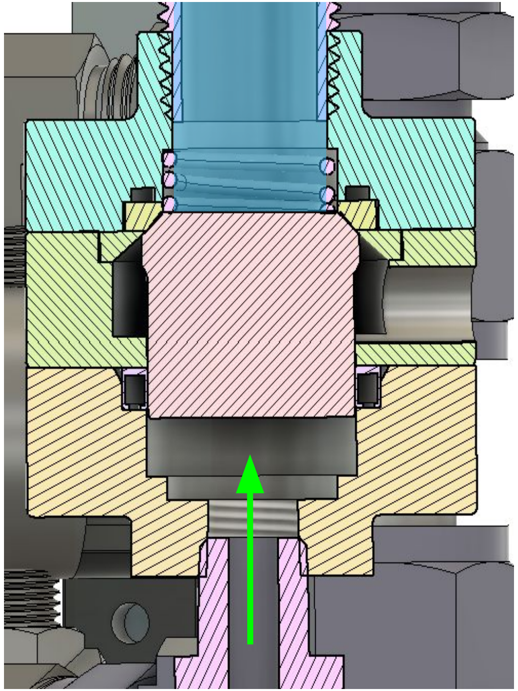
LOX Tank Ullage



Ambient

Dome Pilot

LOX Tank Ullage



Dome Pilot

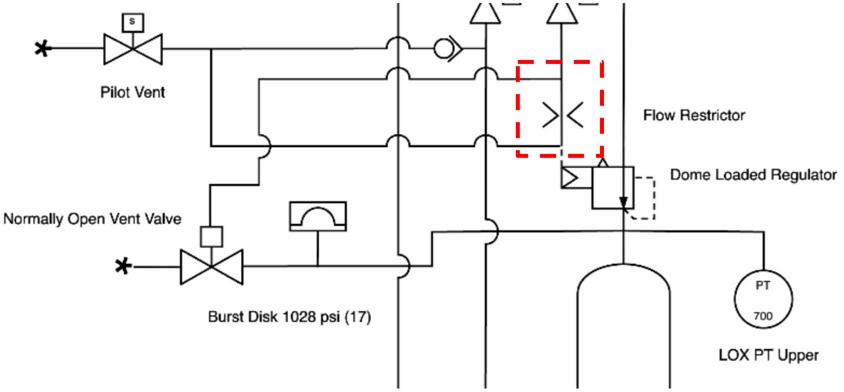
Force Balance

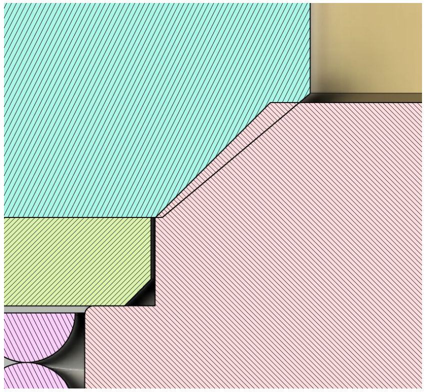
	Fill/Drain Valve	GOX Vent Valve
Eq. Orifice Size	0.250"	0.354"
Spring Force, Closed	12.5 lbf	10.5 lbf
Sealing Force, 250 psi	101 lbf	30.5 lbf
Sealing Force, 700 psi	283 lbf	85.3 lbf

Challenge: Due to high flow rate requirements, the GOX vent valve experiences significant hysteresis with small inlet and pilot pressure differences.

Additional Poppet Valve Design Challenges

- Inclusion of a 0.010" flow restrictor to flow to the regulator, giving the vent valve time to seal
- When the poppet seals, the exposed outer sealing surface ices over
- Operationally constrains the vehicle to a single fill/drain cycle per cryo cycle, valves do not adequately reseal after 10+ minutes exposed to ambient air.
- Tolerance stackup on small diameter poppets required a sharper knife edge to account for concentricity offsets



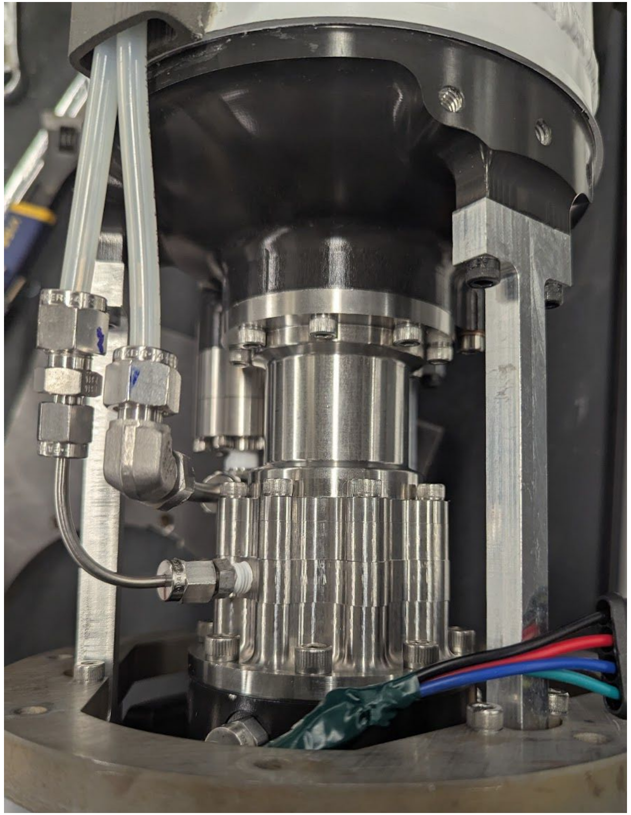


Component Validation

Run Valve Design

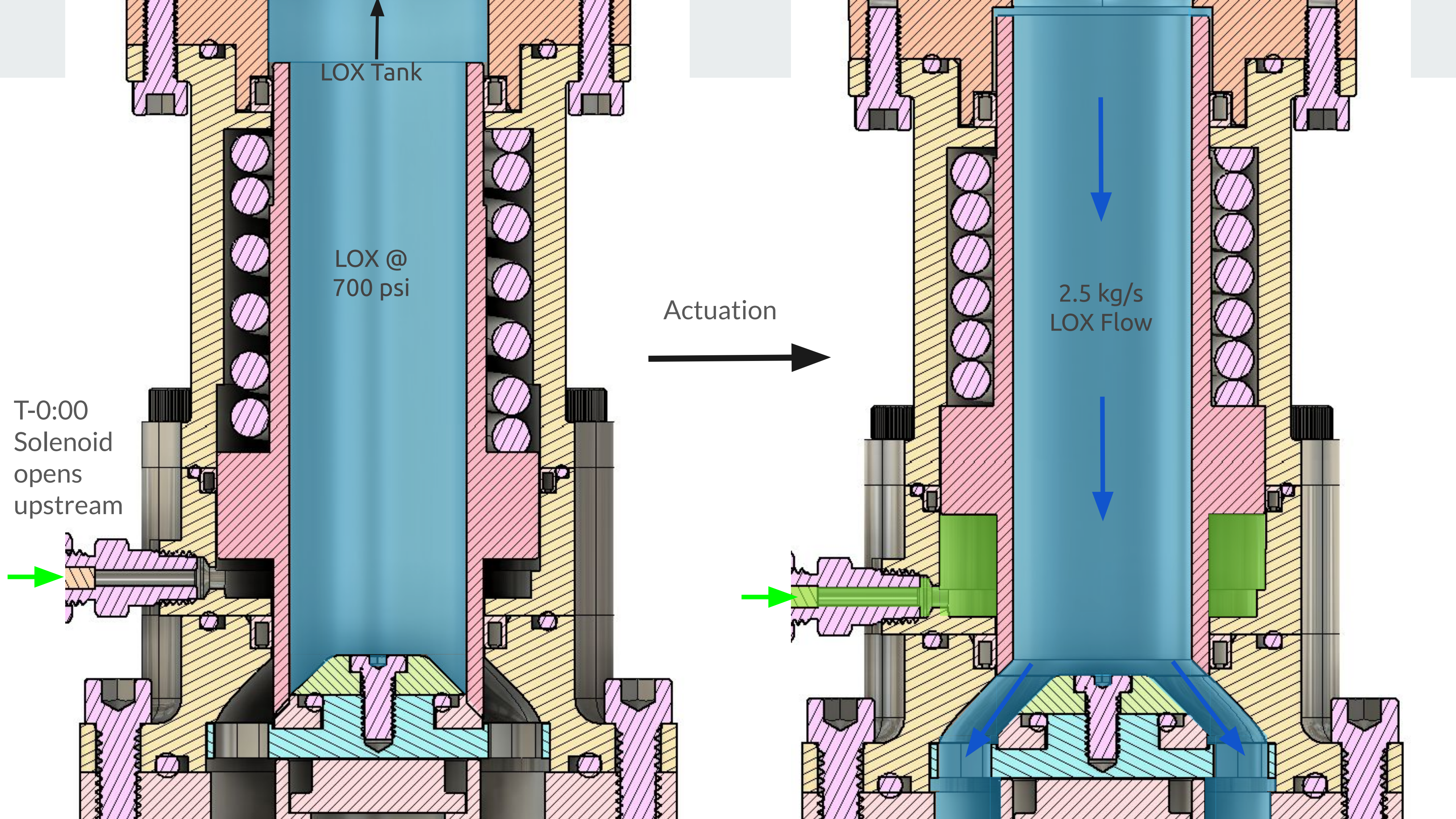
Run Valve Overview

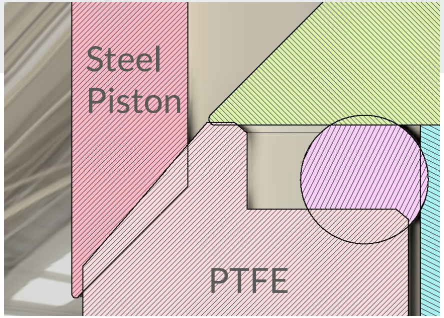
- Controls cryogenic high pressure liquid oxygen (MEOP 700 psi)
- Design burst FOS of 3, proof tested to 1.5
- Pneumatically actuated open at T-0
- 1” Orifice delivers 2.5 kg/s of LOX to the combustion chamber
- Minimal pressure drop (~1 psi)
- Height: 4.1in
- Weight: 3.5 lbs
- Total # of seals: 9



Material Selection

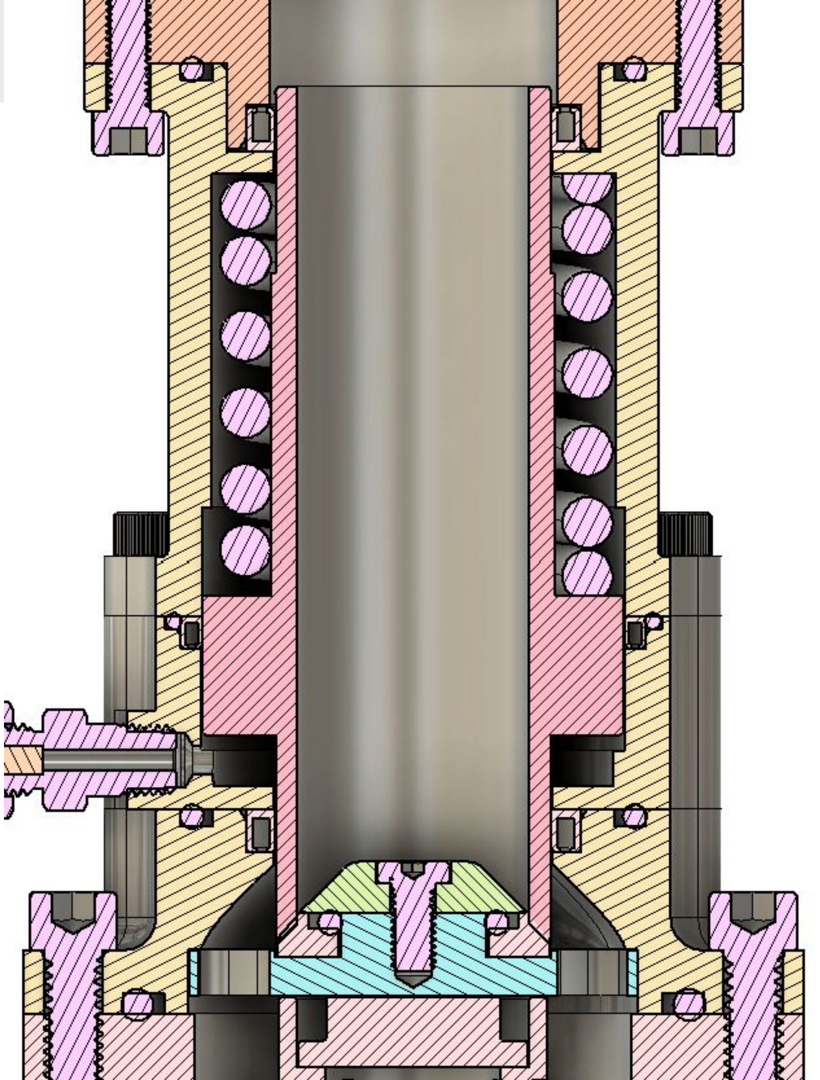
- Passivated 303 Stainless Steel construction
  - 303 is more machinable than 304 and 316
  - Similar oxygen resistance to 304
- COTS passivated 302SS ground springs
- PTFE static and dynamic seals
  - O-rings and custom face seals for static sealing
  - V-spring energized seals for dynamic reciprocating sealing


LOX Tank
LOX @
700 psi
T-0:00
Solenoid
opens
upstream
Actuation
2.5 kg/s
LOX Flow



Design

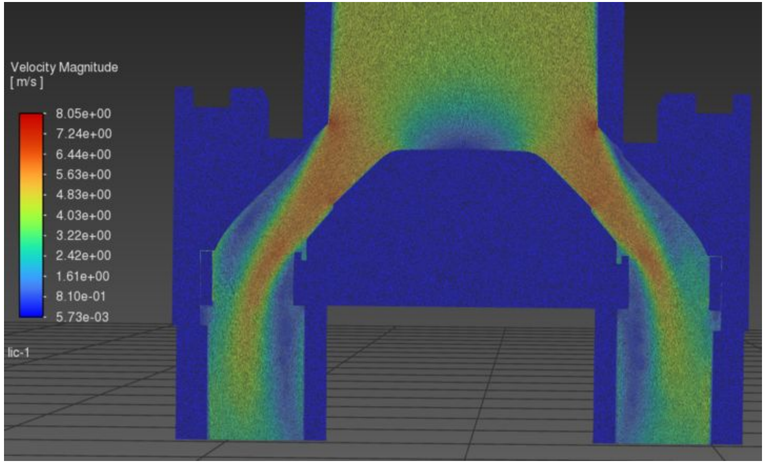
- Spring pushes piston into PTFE valve seat, sealing at the knife edge
  - Validated sealing method from 23-24 valve
- Spring-assisted seals are not flexible, flanges are needed at each seal for installation
- To prevent ice formation, PTFE o ring face seals are placed on each flange

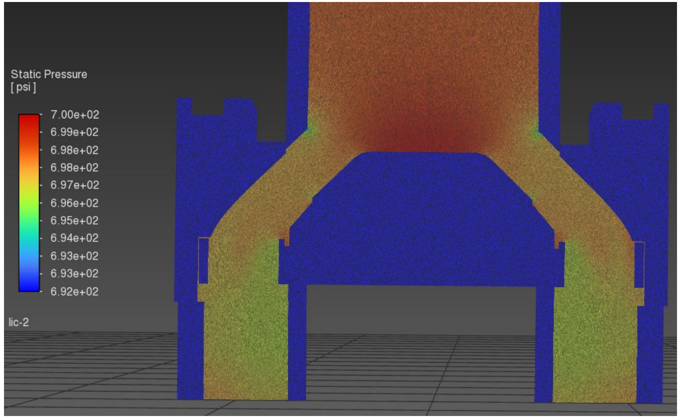


Simulation

CFD

- Simulated 2.5 kg/s of LOX flowing through valve
- Pressure drop ~1-2 psi across valve
- Maximum velocity ~6 m/s





Manufacturing

Machining

- All 18 valve components were machined by the team
- Machined using Haas ST-20Y and Haas Mini-Mill
- Spring-assisted seals required tight tolerances (0.006” diametric tolerance)
- Careful attention to concentricity and parallelism while machining valve bodies was necessary to ensure piston fit snugly without rubbing
- Several small components could be done in one operation using 4-axis functionality, improving geometric tolerances and saving time

Testing & Validation

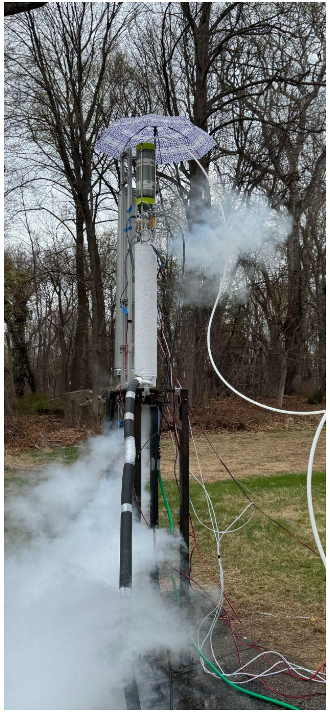
Hydrostatic Pressure Testing

Cold Flows & Cryogenic Testing

Static Fire!

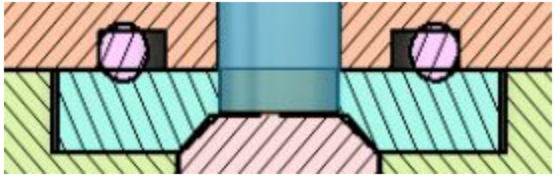
Results

- Hydrostatic testing revealed no significant leakage and structurally proofed all three valves to 1.5x MEOP
- Initial cold flow attempts had significant leakage in the run valve during low pressure cryo fill



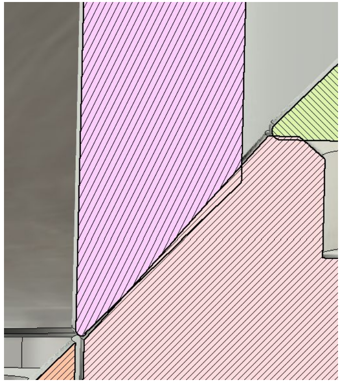
Troubleshooting and Iteration

Fill/Abort Valve Seal Seat

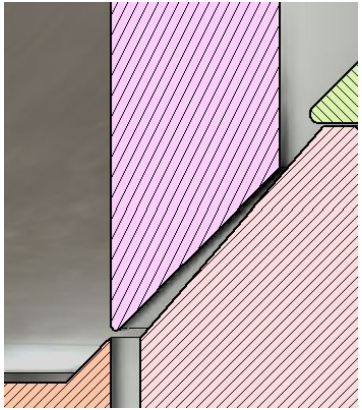


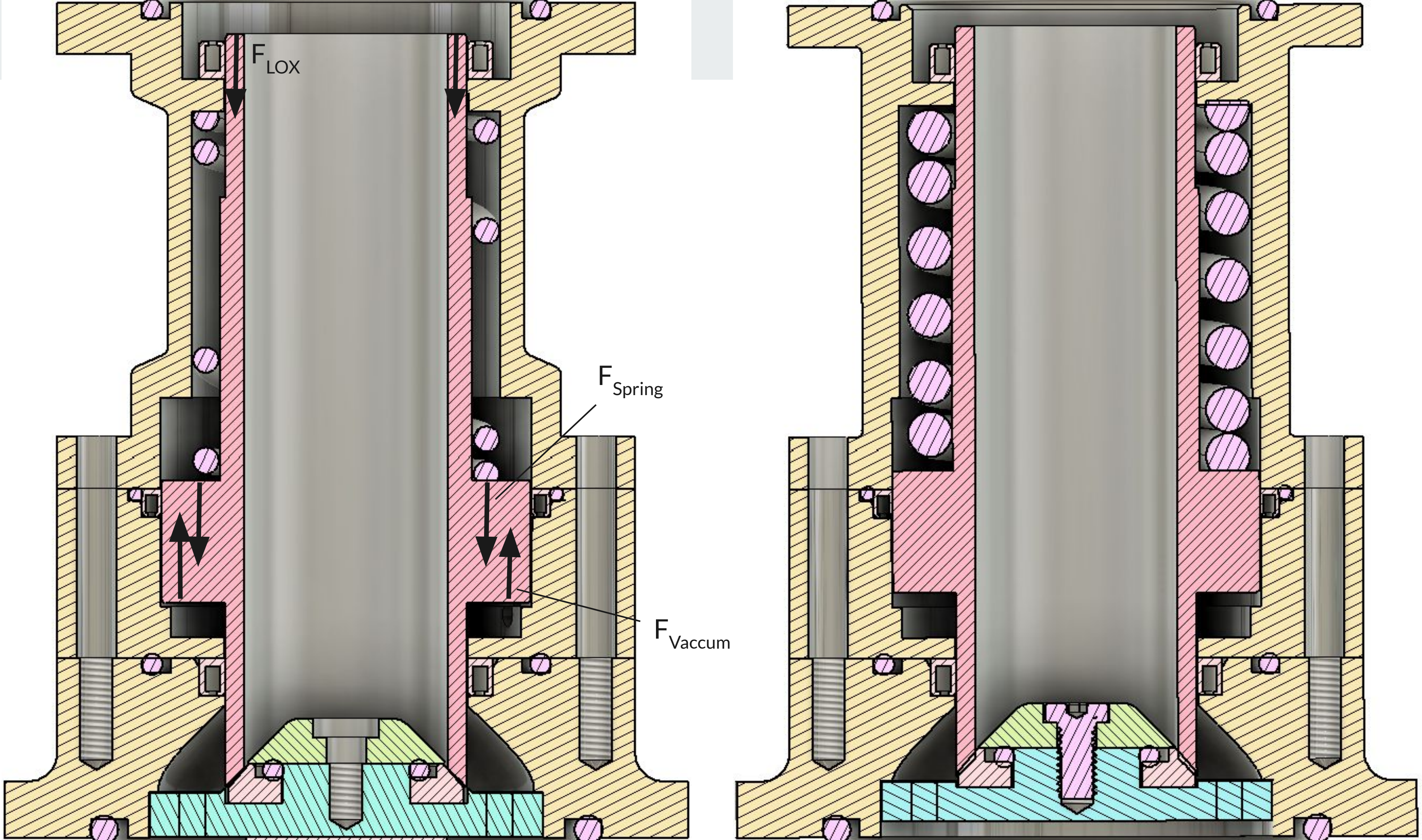
Failure Investigation

- The geometry of the run valve seat seal allowed the PTFE to thermally contract away from the piston
- The other valve seats face *inward*, leading to greater interference and better sealing after contraction
- The force balance on the run valve piston at cryo was not sufficient to push the piston further into the PTFE as it contracts



After shrinkage





F_{LOX}
F_{Spring}
F_{Vaccum}

Future Development

- No sensor data to quantify valve pressure drop
- Greater environmental resilience to icing
- Less reverse leakage through spring-loaded seals