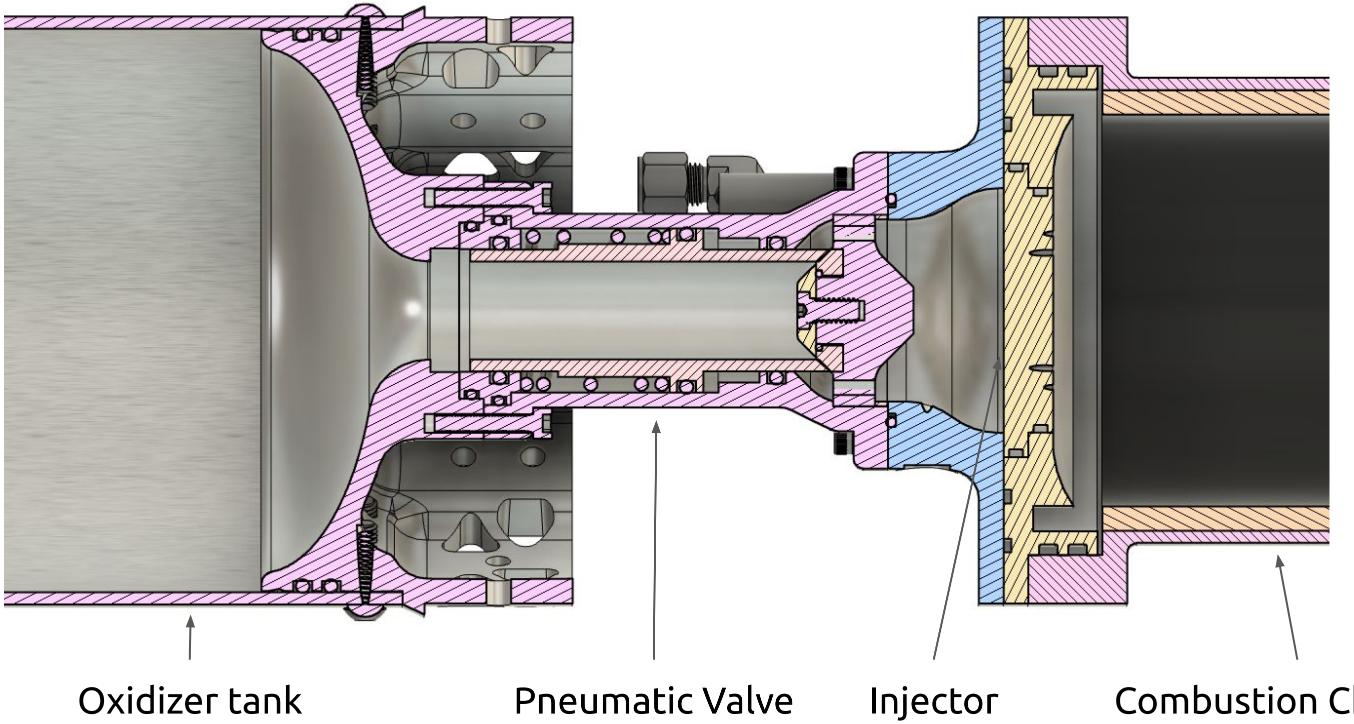
Coaxial Pneumatic Valve

Presented by Aadam Awad and Skylar Bogdanowitsch

Agenda

Performance → Mechanics → Materials → Manufacturing → Iteration



Performance

Why?

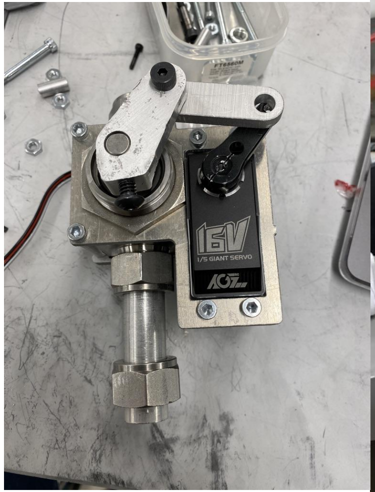
- Amateur rockets without active guidance require very high thrust-to-weight ratios (TWR)
- Engines must be designed to have high thrust & low burn time
- For hybrid rocket engines, this means large mass flow rates through the main oxidizer valve

Role of the Run Valve

- Oxidizer run valve opens once at engine startup
- Enables full thrust – before this state, the igniter is building a flame front in the engine

Legacy Valve (22-23)

- Low mass flow rate (upstream flow constriction)
- Slow actuation time (~ 1s)
- 316 Stainless Steel instrumentation valve, 125 kg-cm servo → heavy
- Required fittings and adapters for integration, increased overall length



High-Level Requirements

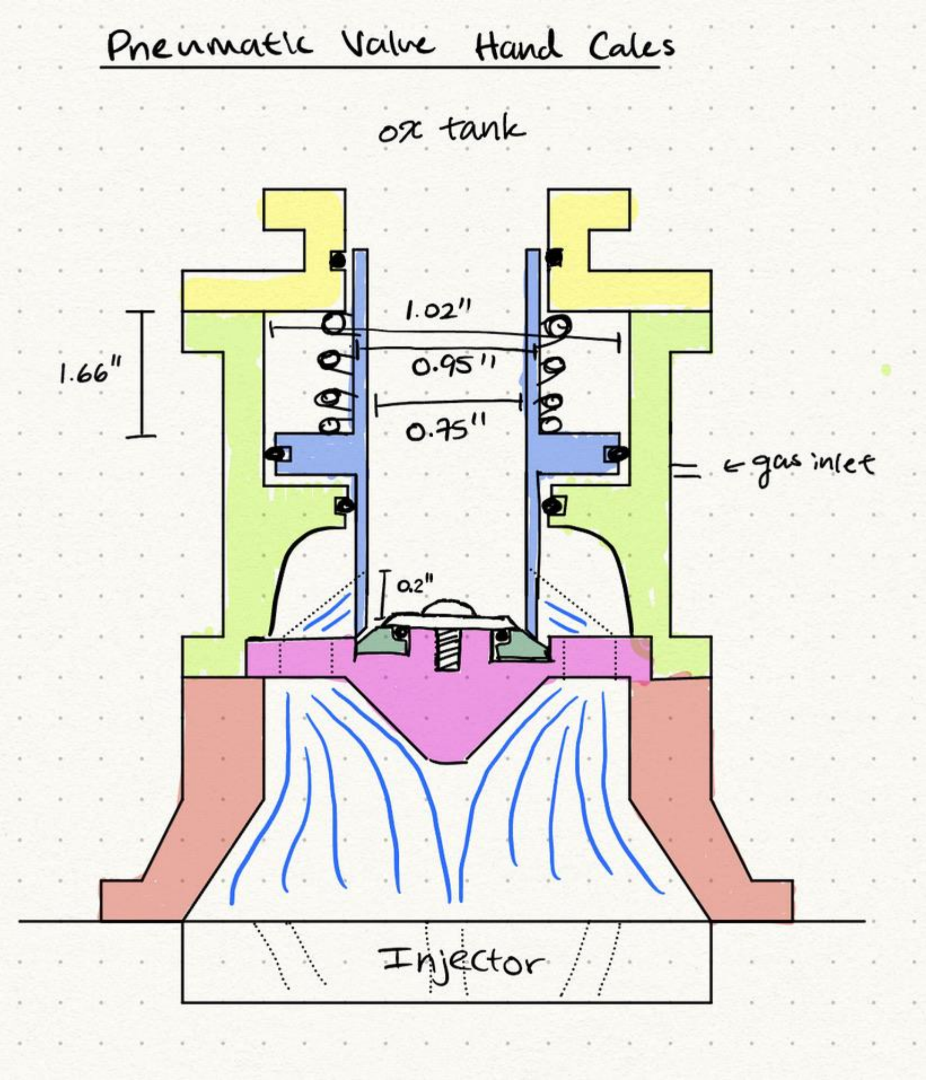
- Support 2.29 kg/s (3.5 L/s) nitrous oxide mass flow rate (+ margin)
  - Based on Valkyrie Mk II performance parameters
- Achieve subsecond actuation - maximizes acceleration off-the-rail
- Lightweight - servos and steel are heavy
- Compact (axially and radially) to minimize vehicle length
- Either available commercially (for cheap) or machineable in-house

Acceptance Criteria

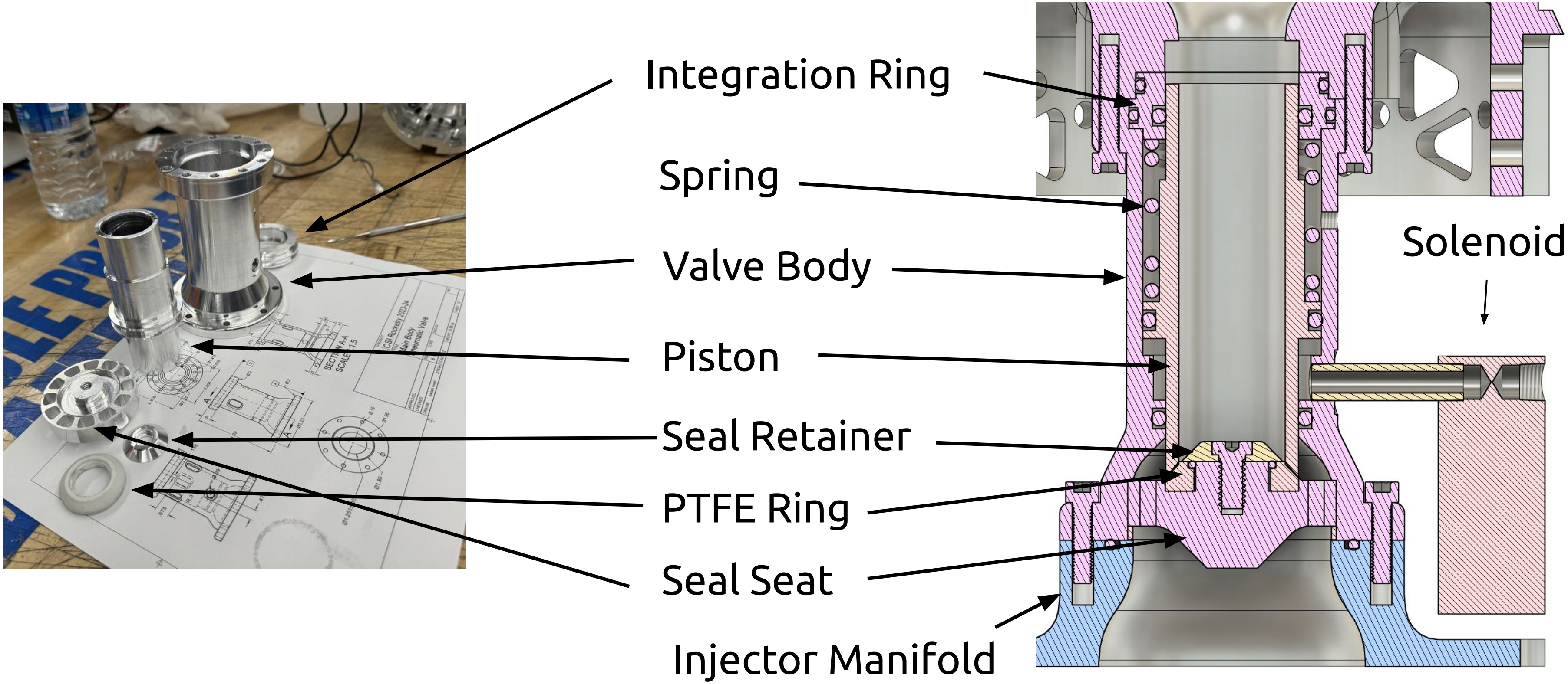
- Low-leakage seal
- Enables target mass flow rate
- < 10 psi pressure drop
- Lighter than commercially available solutions
- Compact, enables small interstage

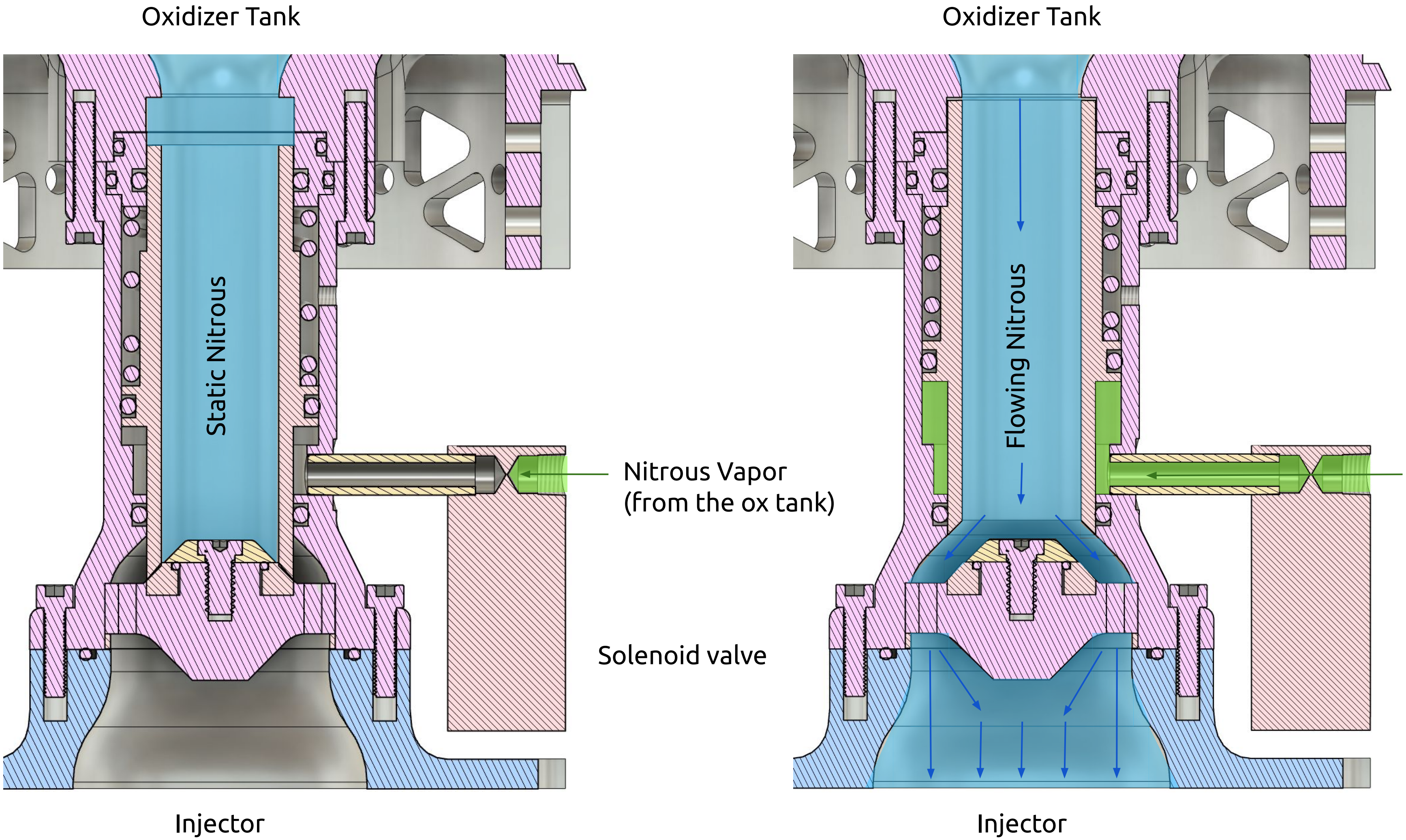
Mechanics

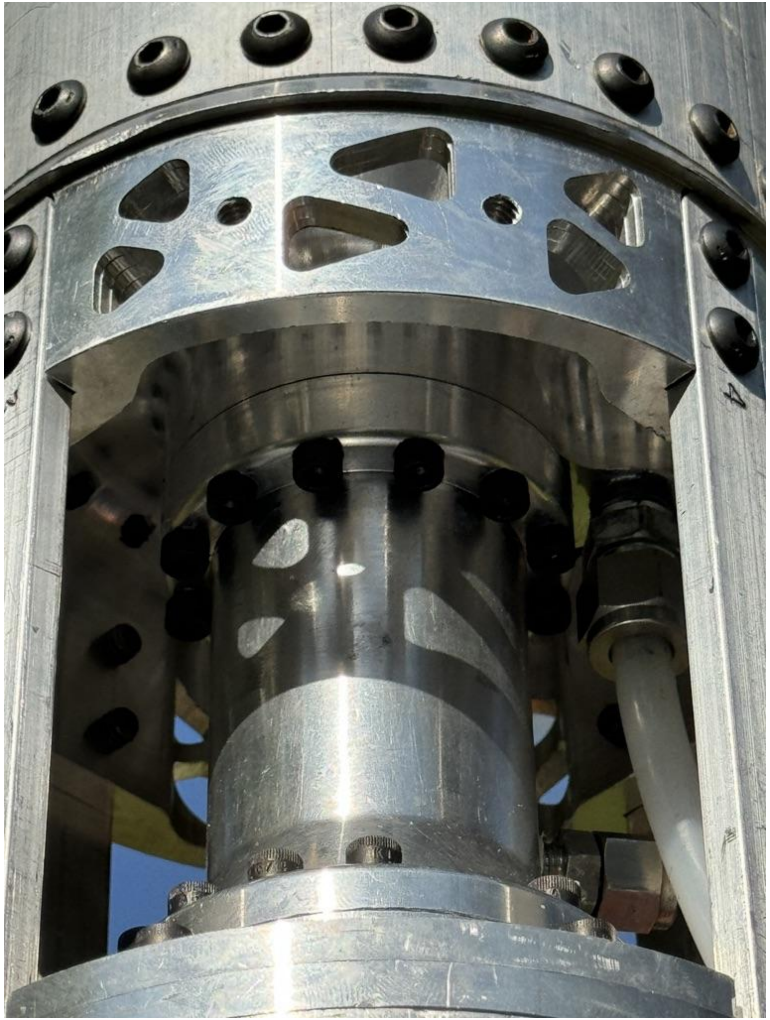
Early Ideation



Components


Integration Ring
Spring
Valve Body
Piston
Seal Retainer
PTFE Ring
Seal Seat
Injector Manifold
Solenoid


Oxidizer Tank
Static Nitrous
Injector
Oxidizer Tank
Flowing Nitrous
Nitrous Vapor
(from the ox tank)
Solenoid valve
Injector



Force Balance

- Overcome nitrous static pressure + spring force + o-ring friction
- Cannot have large outer diameter
  - Interferes with other components in the interstage
- Double-acting capability
  - Designed for the spring to close the valve
  - In testing, the spring was not strong enough; a 10-32 pneumatic port w/ ~ 100 psi easily closed the valve
- Simple formulas used
  - $F_C = [(\text{Cavity radius})^2 - (\text{Piston radius})^2] \cdot \pi \cdot P_{vapor}$
  - $F_P = [(\text{Piston radius})^2 - (\text{Orifice radius})^2] \cdot \pi \cdot P_{liquid}$
  - $\Sigma F = F_C - F_P$

O-Ring Friction Modeling

- Used empirical coefficients from Parker ORD handbook
  - Compression friction based on required o-ring squeeze to form a seal
  - Hydraulic friction based on o-ring extrusion under pressure
- First order model
  - Lacked expertise to control surface roughness, lubrication level, etc. during machining and test
- Combined Hooke's law, o-ring model, and piston force balance
  - Found actuation time and velocity using Euler integration
  - Used for dynamic FEA of piston hard stop
  - 17.5 ms predicted actuation time, 56 fps hardstop

```python
import numpy as np
import sys
sys.setrecursionlimit(100000)
# All values in units of lbs, lbf, or in

ff = 54.16
fp = 474.42
xi = 0.27
xf = 0.77
k = 46.66
mp = 0.125

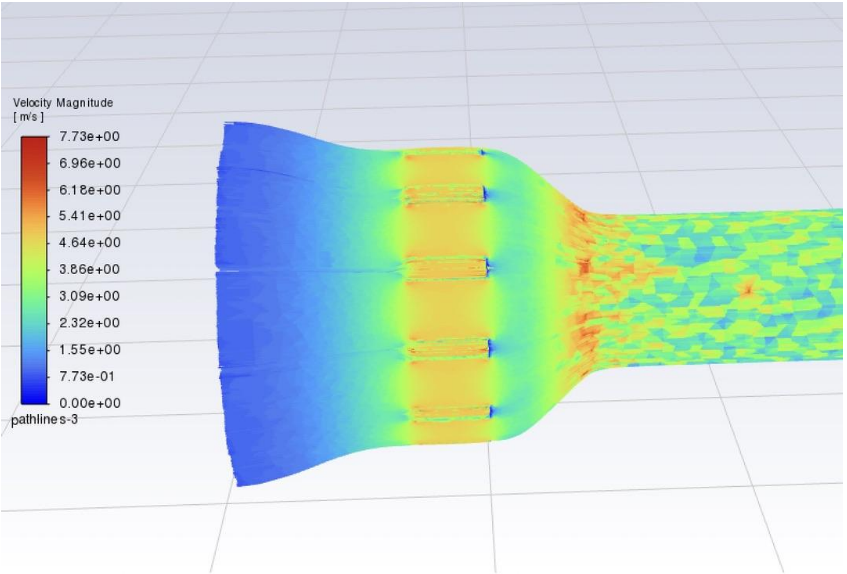
dt = 0.00001

def main (x, v, t):
    F = fp - ff - k*x
    # print(F)
    a = F/mp
    vn = v + a*dt
    xn = vn*dt + x
    tn = t + dt
    if (xn < xf):
        return main (xn, vn, tn)
    return xn, tn, vn

print (main(xi, 0 ,0))
```

Simulations

- Performed Ansys Fluent CFD simulations of compressible and incompressible flow
- Found simulated pressure drop
- Particle count limited due to student license



Materials

Overview

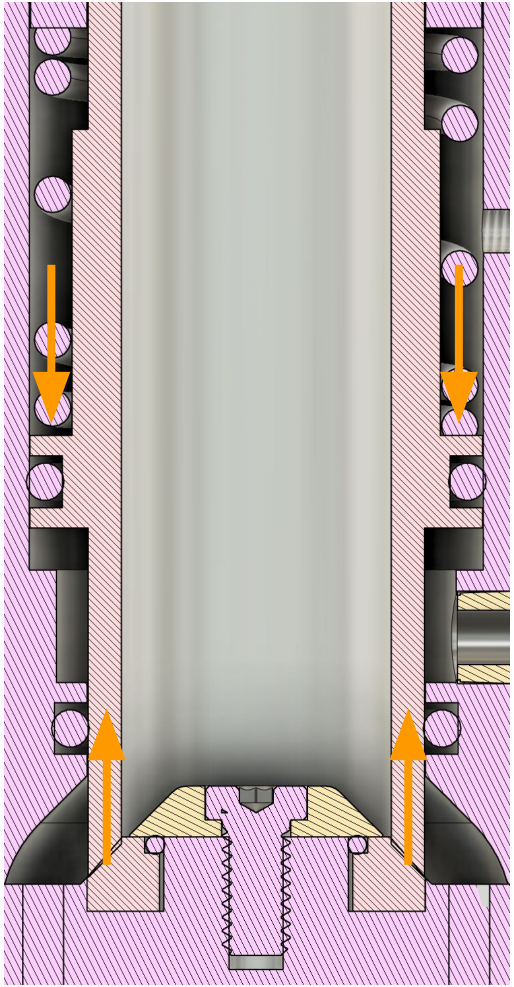
- 6061-T6 aluminum selected due to weight, cost, and machinability
  - Not as safe with LOX or GOX, but we use nitrous oxide and this isn’t a cryogenic valve
- PTFE selected as the seal material
  - Exceptional machinability
  - Extensive public documentation
  - Univ. of Waterloo had previous success with a similar valve design

Design for Manufacturability

- At Columbia we are fortunate to have access to a 4-axis Haas ST-20Y lathe and 3-axis Haas Mini-Mill
- Knowledge is passed down through successive generations of students (shoutout Ryan Wu)
- We machined all coaxial pneumatic valve components
    - Great learning opportunity
    - Saved us a LOT of money
- Minimal new tooling and no custom tooling ($$$)

Spring Sizing & PTFE

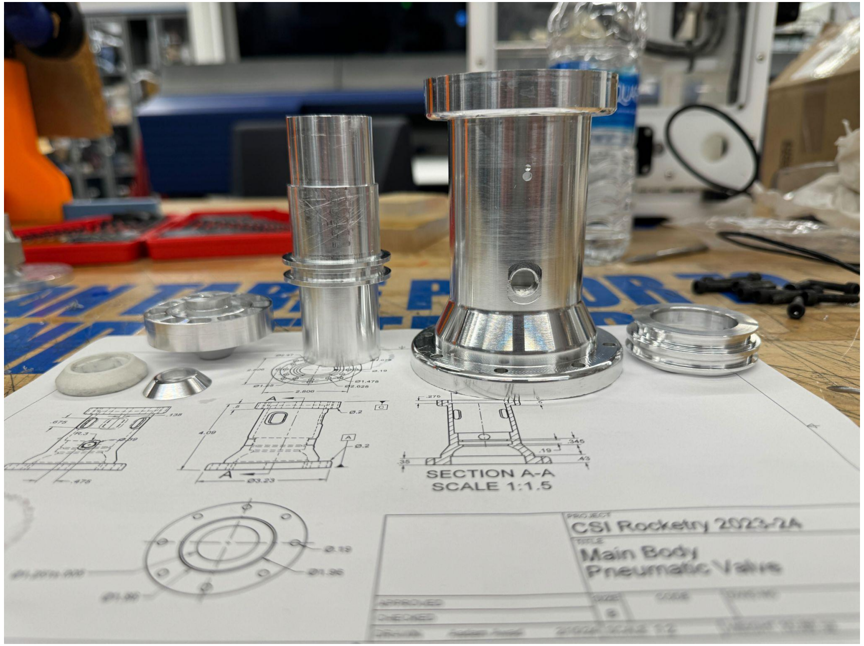
- Spring is required to maintain seal during fill
- Apollo-era NASA documentation cited 4 lbf per linear inch of circumference for PTFE
  - NASA leak testing performed using 400 psi of Helium
  - Empirical value from Marquardt Corporation c. 1965
  - Study initially done for hypergolic service valves on Apollo
- This gave a minimum spring force of 12.6 lbf
- Additional margin was provided for up to 30 lbf
- Selected spring based on these parameters
  - k = 46.67 lbf/in
  - Free length = 2”
  - Compressed length = 1.325”



Manufacturing

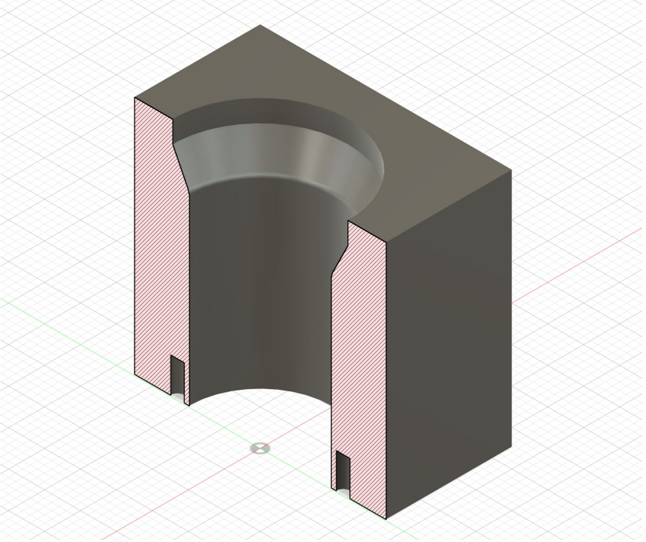
Tolerancing

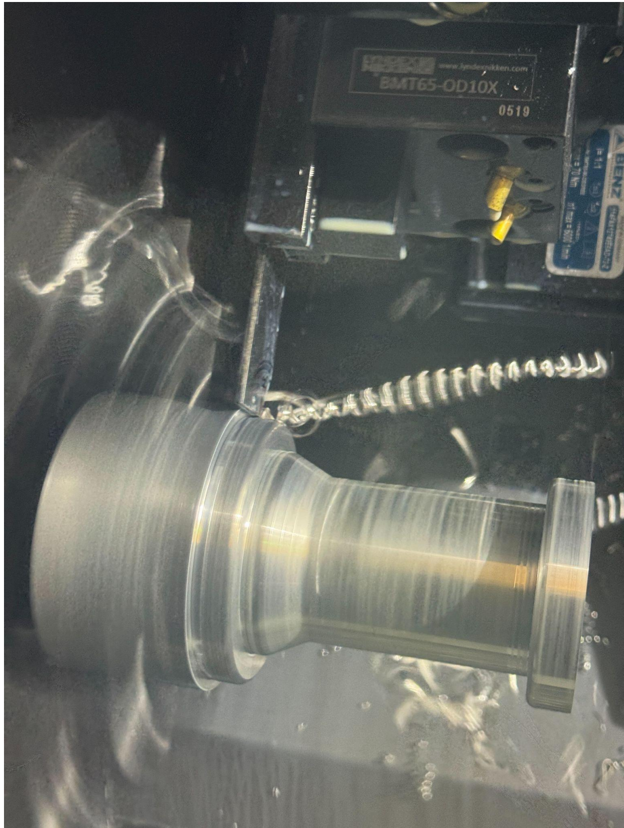
- Sealing surfaces had .005” profile tolerance
    - Based on Parker ORD table
- MMC and LMC applied where possible (e.g. piston ID, valve body non-sealing surfaces)
- Tolerance stackup caused leakage in early iterations



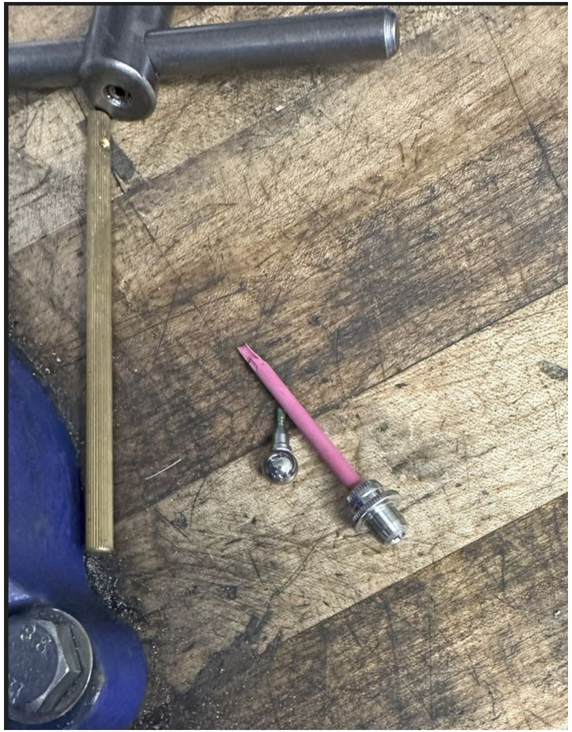
Machining

- Material - Aluminum 6061
- Every component of the valve was made in house
- Machined using Haas ST-20Y and Haas Mini-Mill





Fun Workarounds



Iteration

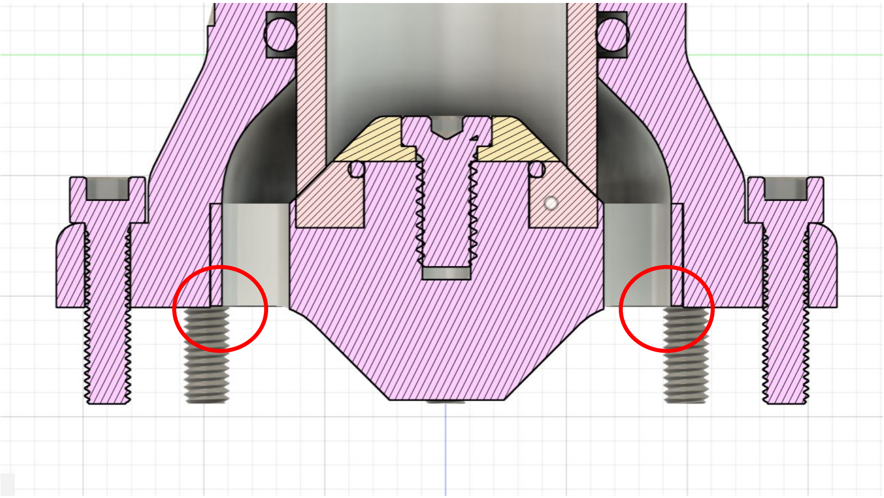
Testing

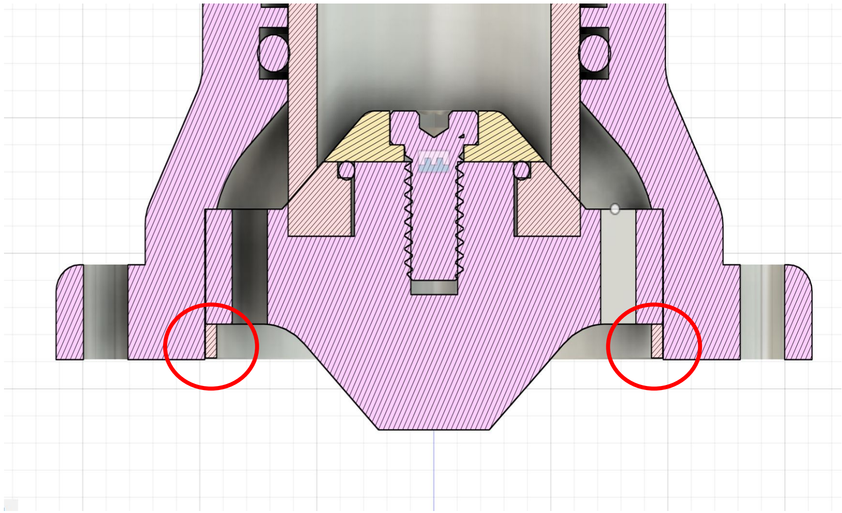
- Seal testing
  - The point contact area was too large not putting enough force at one point to create a seal
  - The outer piston was hitting the aluminum of the seal seat, not sealing with the PTFE

Seal Seat Iteration

- Included a spacer to increase the static force of the spring

V1 vs V2

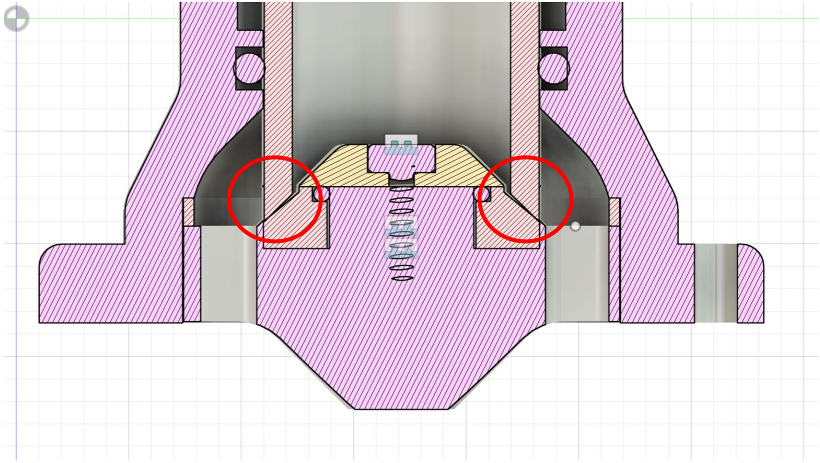


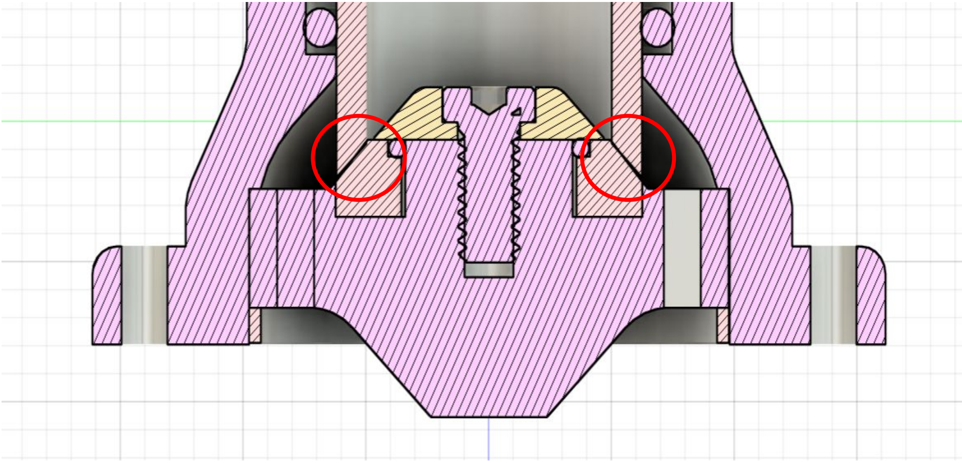


Seal Seat Iteration

- Changed the angle of the PTFE seat so there is only 1 point of contact.

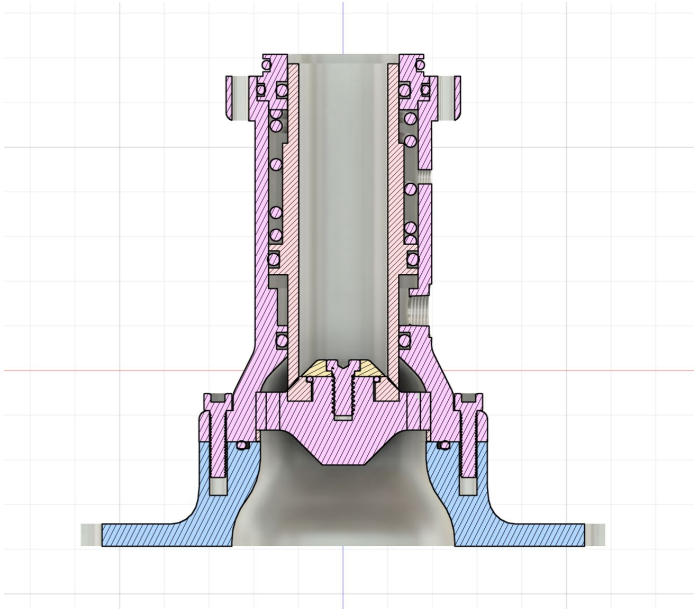
V3 vs V4

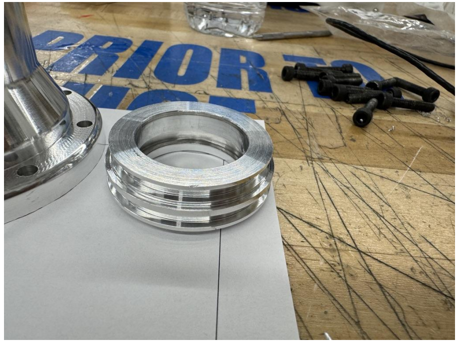




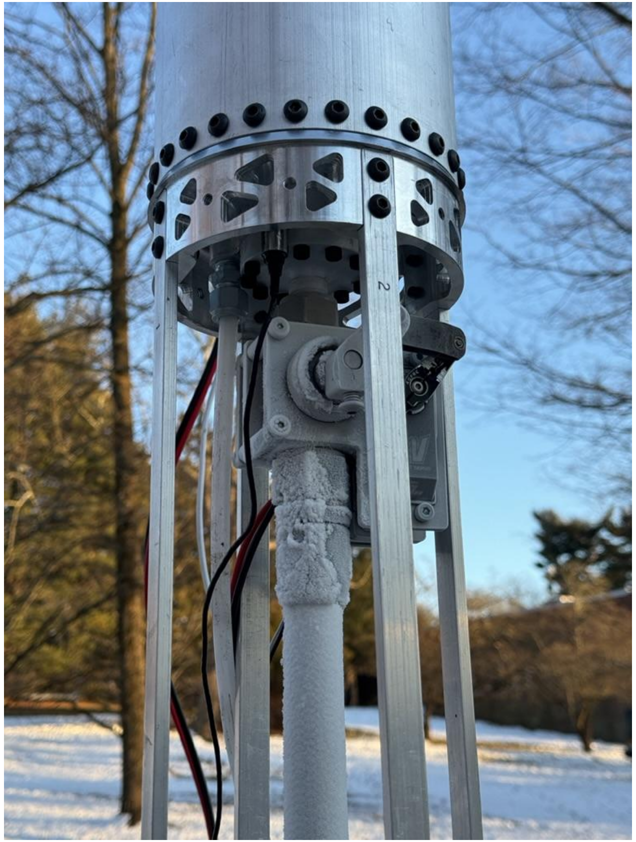
Actuation Testing

- Failure in meeting tolerances while machining built up and caused a failure in actuation

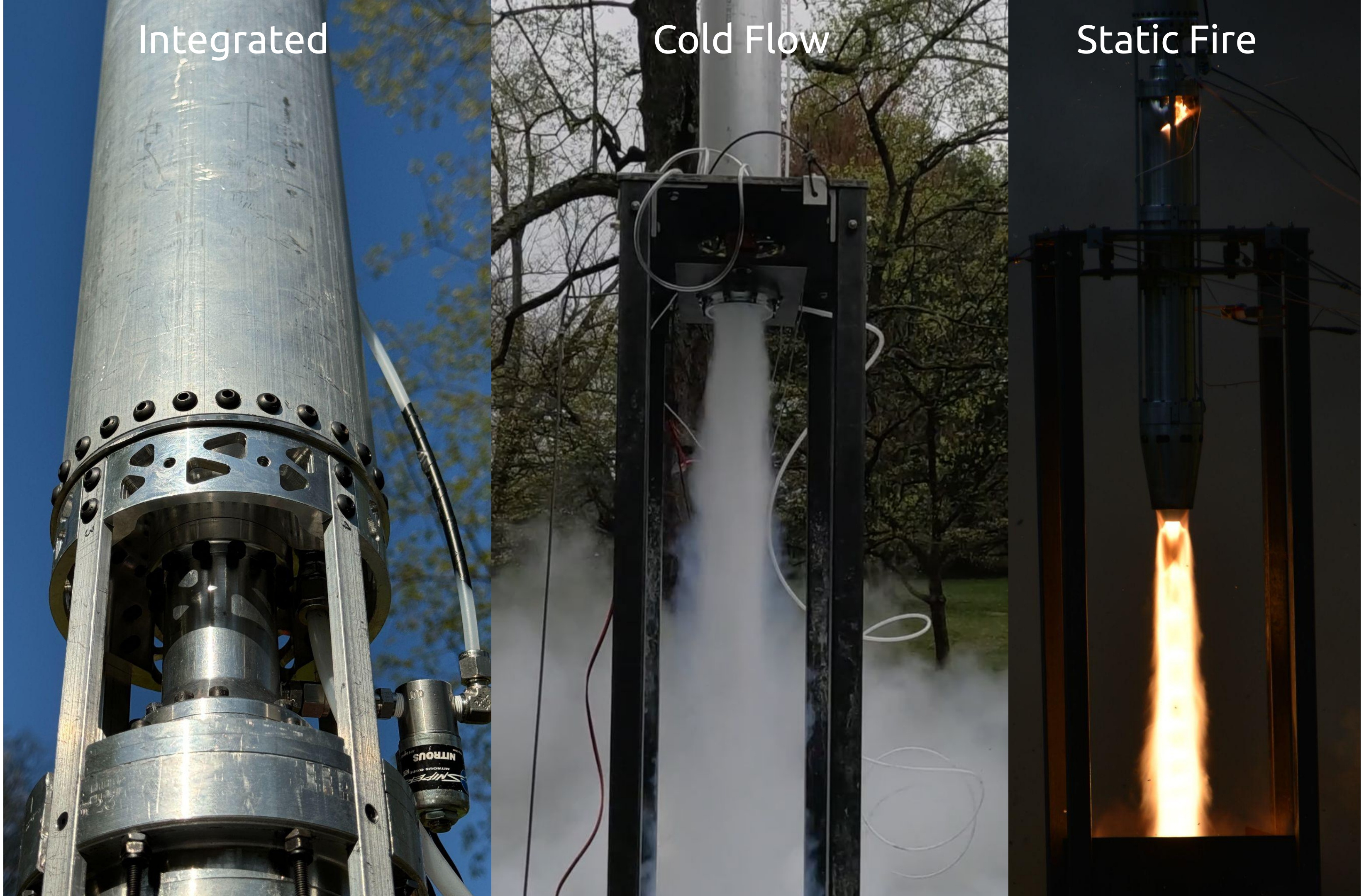




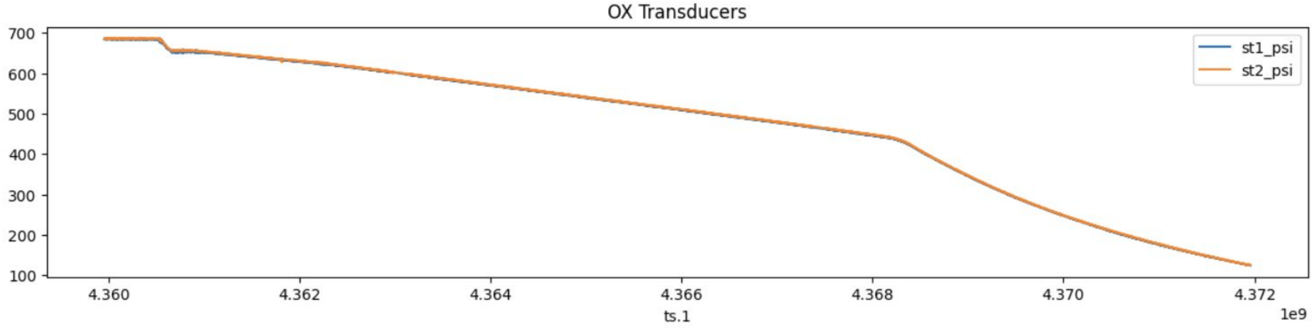
Results

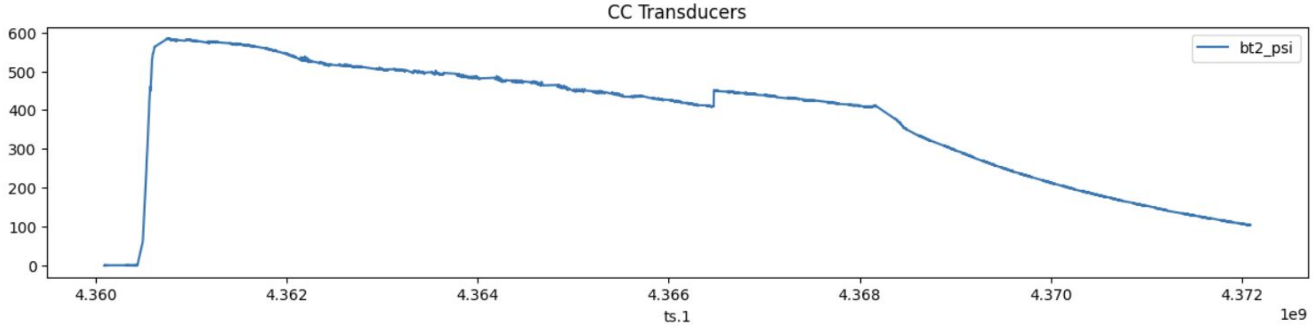


from too cold
to too warm


Integrated
Cold Flow
Static Fire

Total impulse (pound*sec): 5475.930986888257
Total liquid mass flow (kg/sec): 140996392.91924715





```
Min ts (sec):  1713550304.0
Max ts (sec):  1713550314.0
Total impulse (pound*sec):  303.71572773920417
Total liquid mass flow (kg/sec):  7487664.974825937
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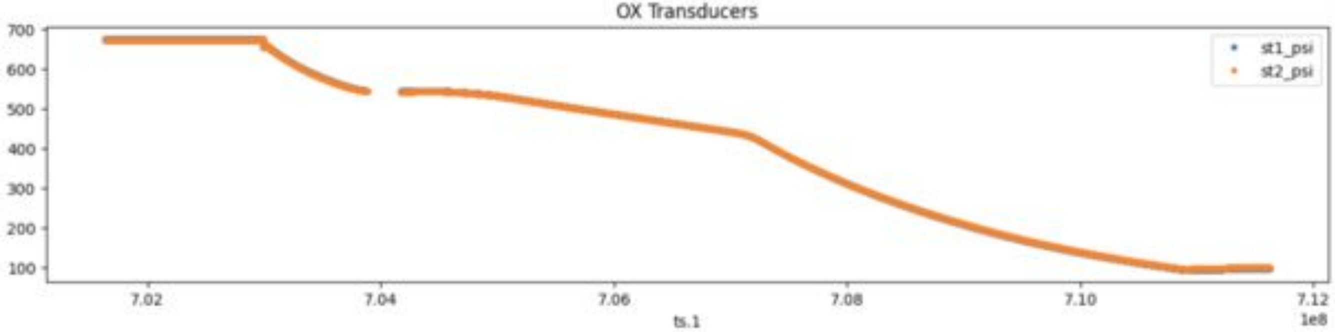

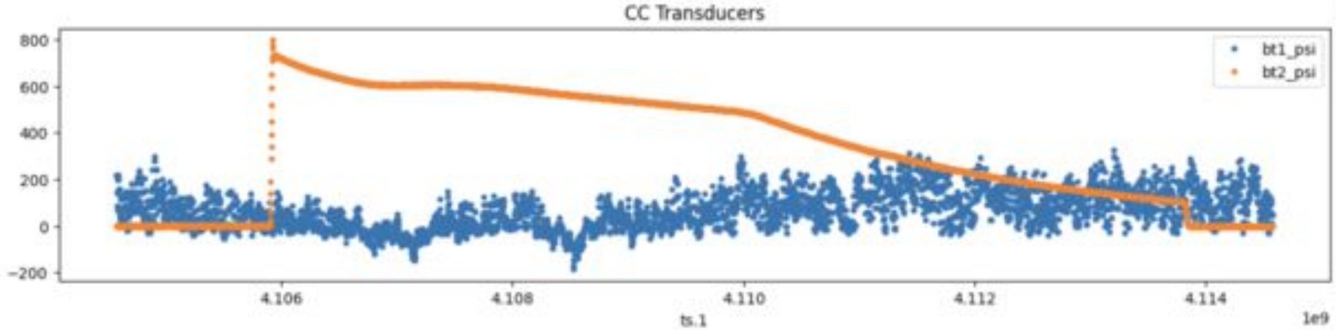

Future Work

- Pressure drop
  - Data from static fires shows -100 psi pressure drop
  - Unphysical result, requires further testing to fully quantify performance
- Flight testing
  - Coming tomorrow!
- Throttling?
  - Enhancing double-acting capability to have variable states