Prometheus Propulsion CDR

5/7/24

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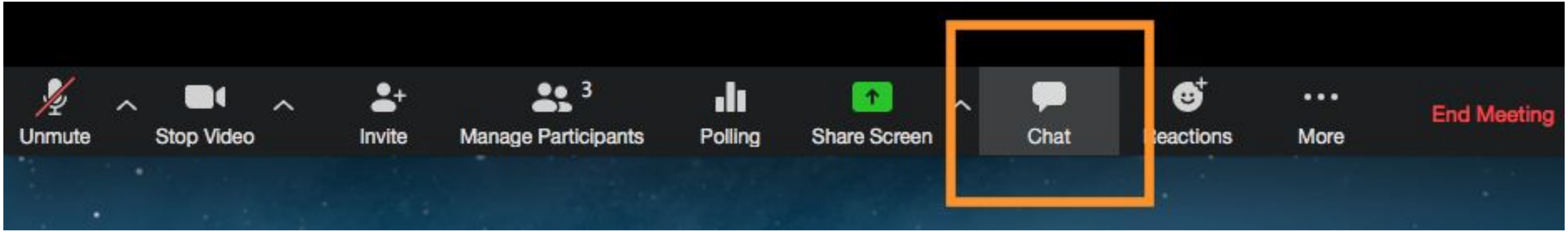
Review Goals

1. Provide an update to reviewers on the current status of the project
2. Receive validation of, and feedback on manufactured components and testing results before proceeding to flight system testing, vehicle integration and launch
3. Confirm feasibility of target launch window

Recommended Feedback Format

- Questions will be taken at the the end of each test + result reviews
  - Want to prevent review interruption as much as possible in the interest of time and giving equal attention to all sections
- Feel free to post questions in chat box or raise hand throughout review
  - Project leads will be monitoring chatbox, and will interrupt presenters to ask critical questions if deemed necessary



Hybrid Engine Goal

The propulsion team focuses on researching and developing a hybrid rocket engine that can reach an apogee of 10,000 feet.

Milestones this year:

- Successfully casted fuel grain in-house
- Created new test infrastructure (test-stand, fill-stand, and bottle inverter)
- Successfully casted custom igniters
- Integrated full-chamber phenolic liners

Preliminary System Design

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Engine Systems

Initial Design Overview

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Engine Design

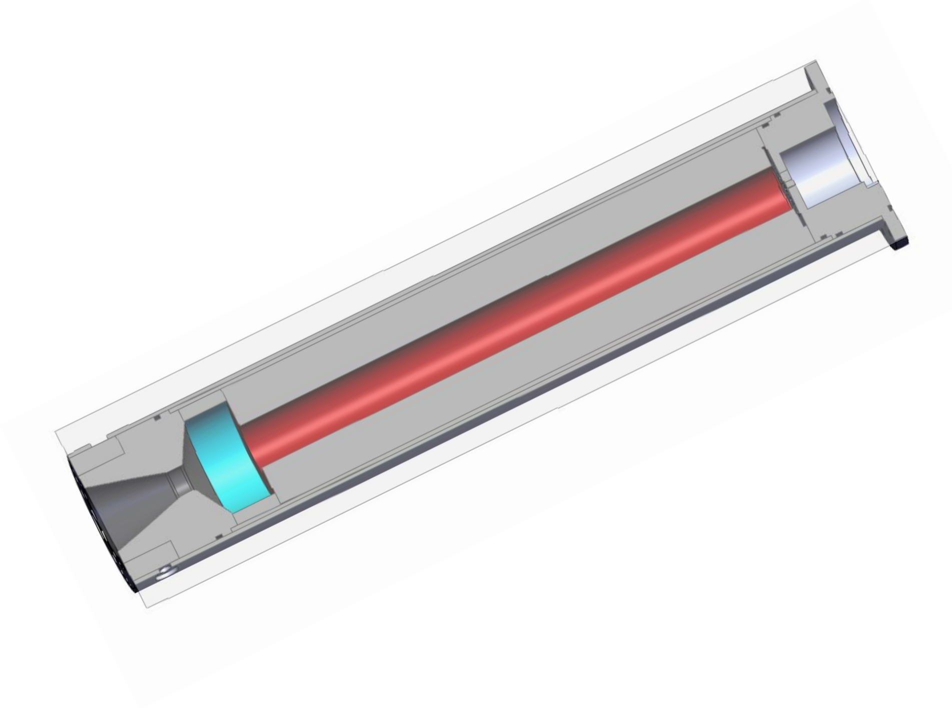
Design Parameters:

- 600 lbf peak thrust
- OF Ratio of 5.33
- Chamber Pressure of 500 PSI
- 11 seconds target burntime

Key Design Details

- 83 1/32” orifices for injector
- No Pre-CC to separate injector from fuel grain
- ¼” liner groove into nozzle
- Radially-bolted retaining ring
- Stepped nozzle with O-ring

Original ignition system from IDR used rocket candy, quickly changed to home-made igniter that would be easier to make.



Feed Systems

Initial Design Overview

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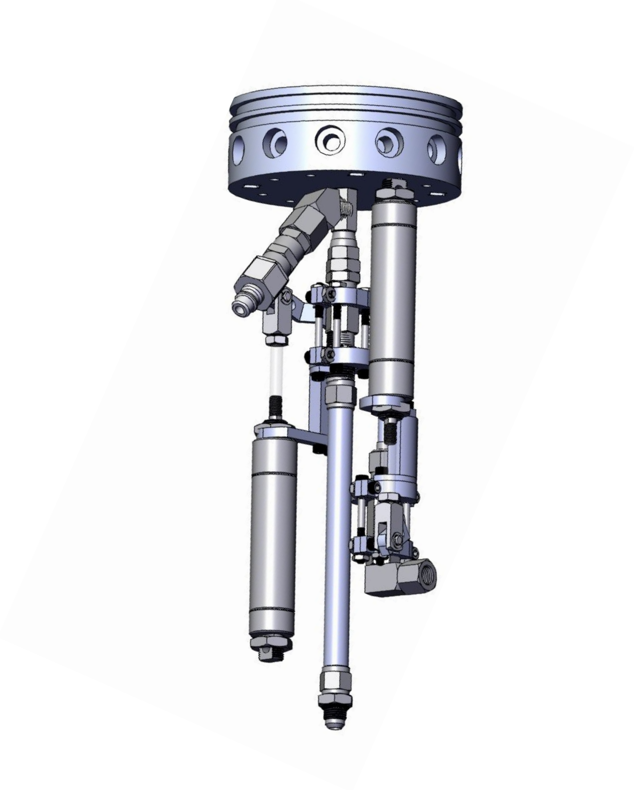
Feed System Design

- MPV
  - Originally -6
  - Around 14 inches in length
  - ⅜” compressed ball valve
  - Two small brackets that clamped to the valve to support the bimba
- Vent
  - .01” orifice w/ 90 degree elbow
  - ¼” compressed ball valve
  - Two small brackets that clamped to the valve to support the bimba
- QD
  - Jutted out from MPV cross at 45 degree angle
  - Utilized push-to-connect to attach to GSE



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Tank Systems

Initial Design Overview

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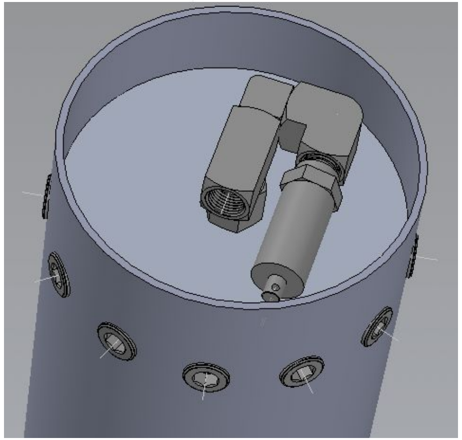
Tank Initial Design



Overview

- ❖ 650 psi
- ❖ ⅛" thick, 6" OD
- ❖ 12 ½" bolts (24 tot.)
- ❖ 2 2-356 O-ring (4 tot.)
- ❖ Diptube sized for 20% ullage

GSE

Initial Design Overview

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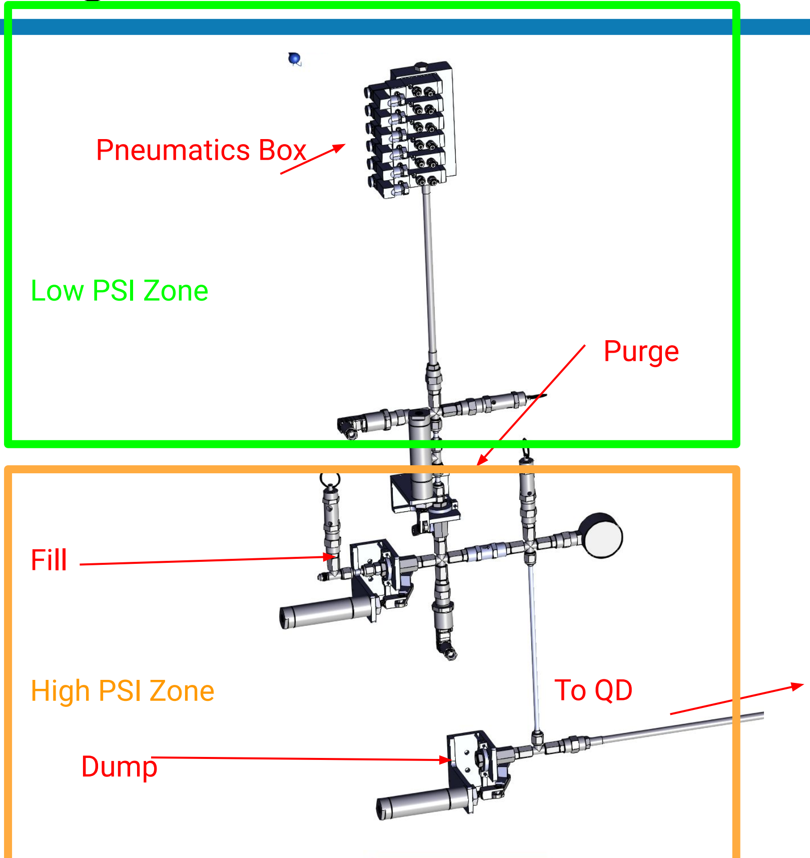
Old GSE Design

Fill Table:

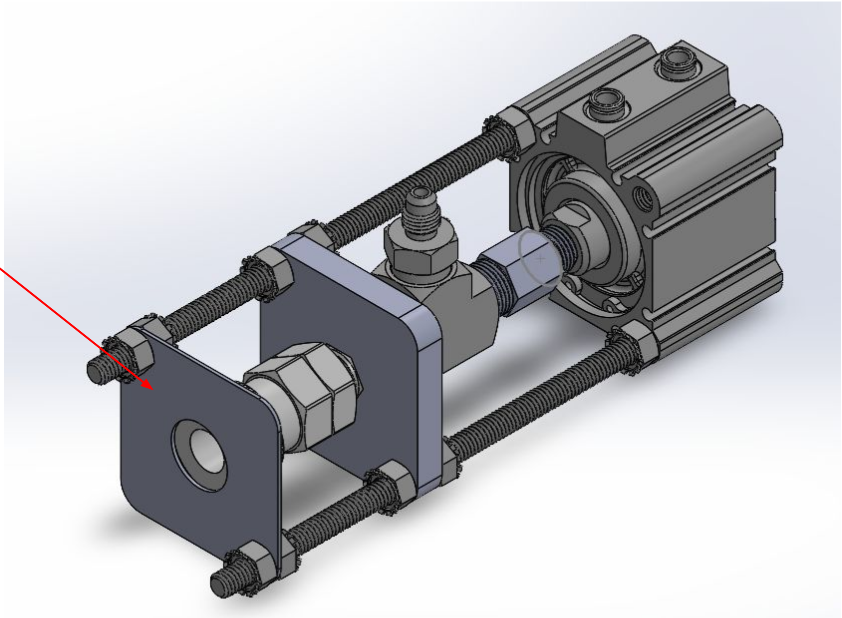
- Integrated Pneumatics/Purge
- Machined Braces
  - Not snug
- Extra AN fittings for modularity
- 120 PSI and 650 PSI sections
- Prone to leaks at junctions
- Lateral pressure on pipe



QD Design

Main change:

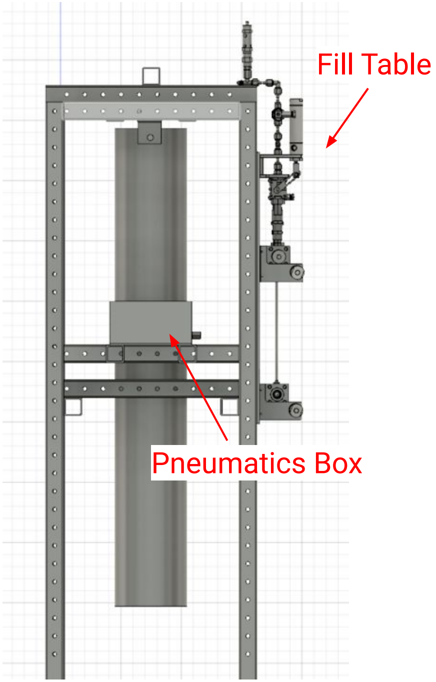
- Top QD plate is precisely caliper-measured to have a center hole with diameter 0.9 inches.
- Planned to utilize custom fittings to reduce length.

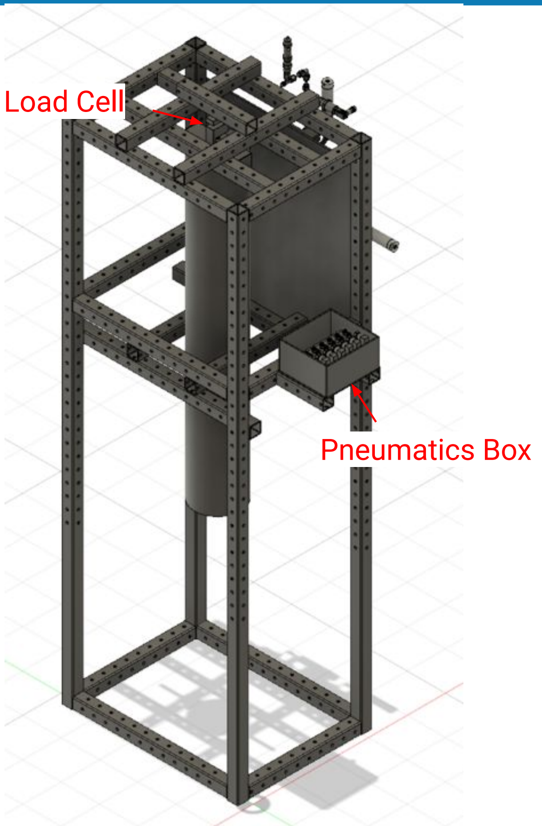


Fill Structure Design

Fill Structure: Overview

- Moved the pneumatics box to the side of the fill structure
- Changed to a single load cell mounting system (will go in depth on the next slide)





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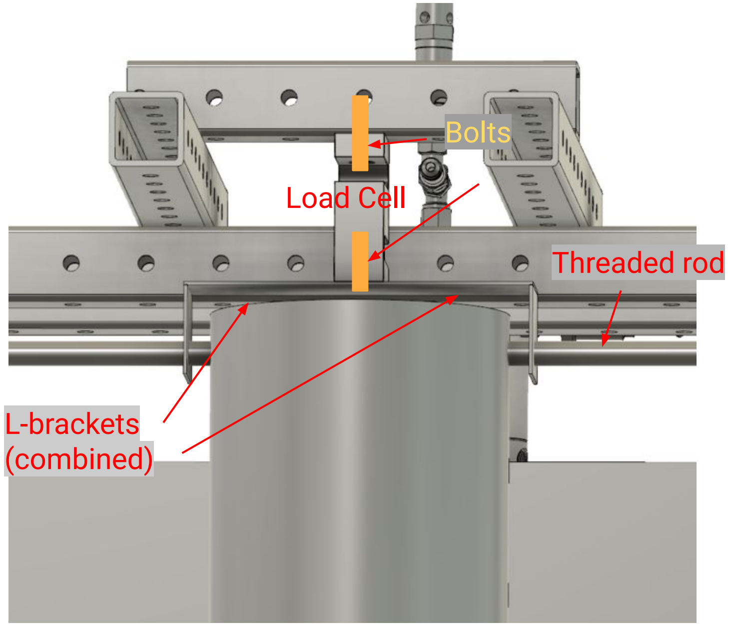
Fill Structure Design

Fill Structure: Load Cell Mounting

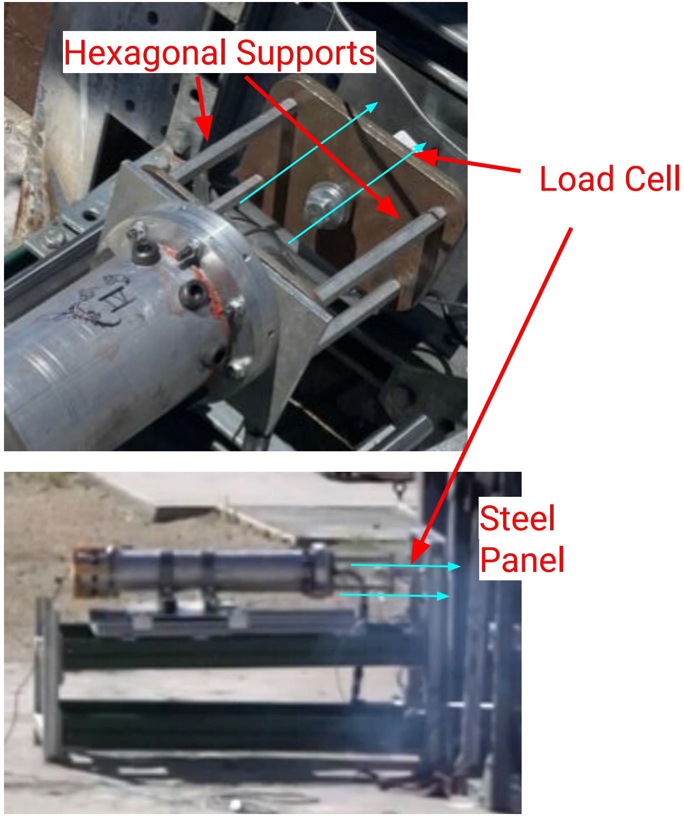
- Single load cell attachment
  - More accurate readings
- Load cell held in tension by 2 bolts
- Bottom bolt connects to 2 L brackets which are connected to each other
- Tank threaded through the L brackets and secured with washers and nuts



Test Stand Design

Test Stand: Rationale

- Single load cell attachment to a metal block which makes direct contact with the steel support
- Sliding rails to allow for engine to slide into the load cell
- Flex-hose connecting MPV and engine
- Hexagonal supports for maximized strength



Propulsion Test Campaign

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Coldflow 1

NOTES:

- Flow was way to long (20 seconds observed ~ 6 seconds expected)
- CO2 was at a pressure of ~550 PSI
- GSE+Fill systems took extremely long time to leak check
- QD successfully disconnected
- No injector connected

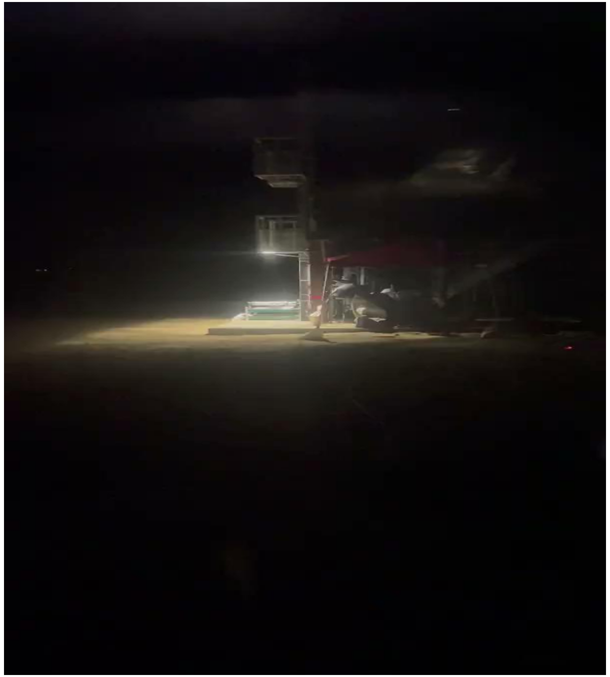
CHANGES:

- GSE secured their fill table to remove shakiness
- Feed system upsized for better flow
- Feed valves tested to ensure full activation

Hotfire 1

NOTES:

- Last-minute changes to fill table + feed system meant that leak checks took a very long time
- Confusion about ignition procedures led to multiple scrubbed fires from ignition failure
- Extreme cold + hail meant K bottles only reached ~500 PSI
- Poor engine integration blocked a significant amount of the injector orifices, making flow time 23 seconds



Coldflow 2

NOTES:

- Used test stand+bottle inverter to simulate hotfire setup and check system pressure losses
- Implemented changed procedures for better ignition / more effective safe stating
- CO_2 bottles only reached ~650 PSI
- Long flow time indicated that we needed to open up injector / reduce feed system pressure losses (still 20 seconds)

CHANGES:

- De-Integrated Engine, drilled more injector orifices
- Waterflowed, remanufactured Feed System for full valve actuation

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Hotfire #2 - Engine 1

- Moving K-Bottles to the shade too early made our K-bottles run at a lower pressure than anticipated (700 PSI)
- Poor nozzle manufacturing, large orifice area, and poor injector stiffness meant we had crazy combustion instability
- Poor nozzle/liner integration meant we burned through their interface at the bottom of the engine

Hotfire #2 - Engine 2

- We were able to very quickly switch out engines and re-do high press checks
- We were able to get bottles to an initially higher temp, but we over-filled ox and immediately dropped back to our lower pressure
- We still suffered from pretty bad combustion instability
- Same nozzle/liner burnthrough
- Integration of hard line helped us reduce feed system losses

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Coldflow 3

NOTES:

- Proved that mass flow issues were improving (9 seconds to dump all liquid)

Improvements to be made:

- We hadn't finished new bracket for feed which was implemented after this flow
- Minimal System changes as flow time was closest to correct yet

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Hotfire 3 - Engine 3

NOTES:

- Same Nozzle issue
- Post-fire inspection revealed that the throat and 1” of the diverging section stayed intact, validating that we had successfully prevented burn-through
- Total impulse and nominal thrust were slightly lower than expected
- Longer Burn time decided to be a non-issue, given resolution of burn-through

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Hotfire 3 - Engine 4

NOTES:

- Nozzle flew out roughly 3 seconds into burn
- Post-fire inspection revealed that the throat and .5” of the diverging section stayed intact, validating that we had successfully prevented burn-through
- Total impulse and nominal thrust were lower than expected

Unresolved Issues

- Tank pressure-drop despite higher press - has dropped from both 750 and 800 down to 650 PSI
- Burntime remains longer than what it should be based off of large number of holes in injector(too low dp from manifold to chamber is current theory on why)
- Each engine exhibits a steam whistle -> low growl progression in burn
  - Unsure if combustion instability, chugging, some other issue

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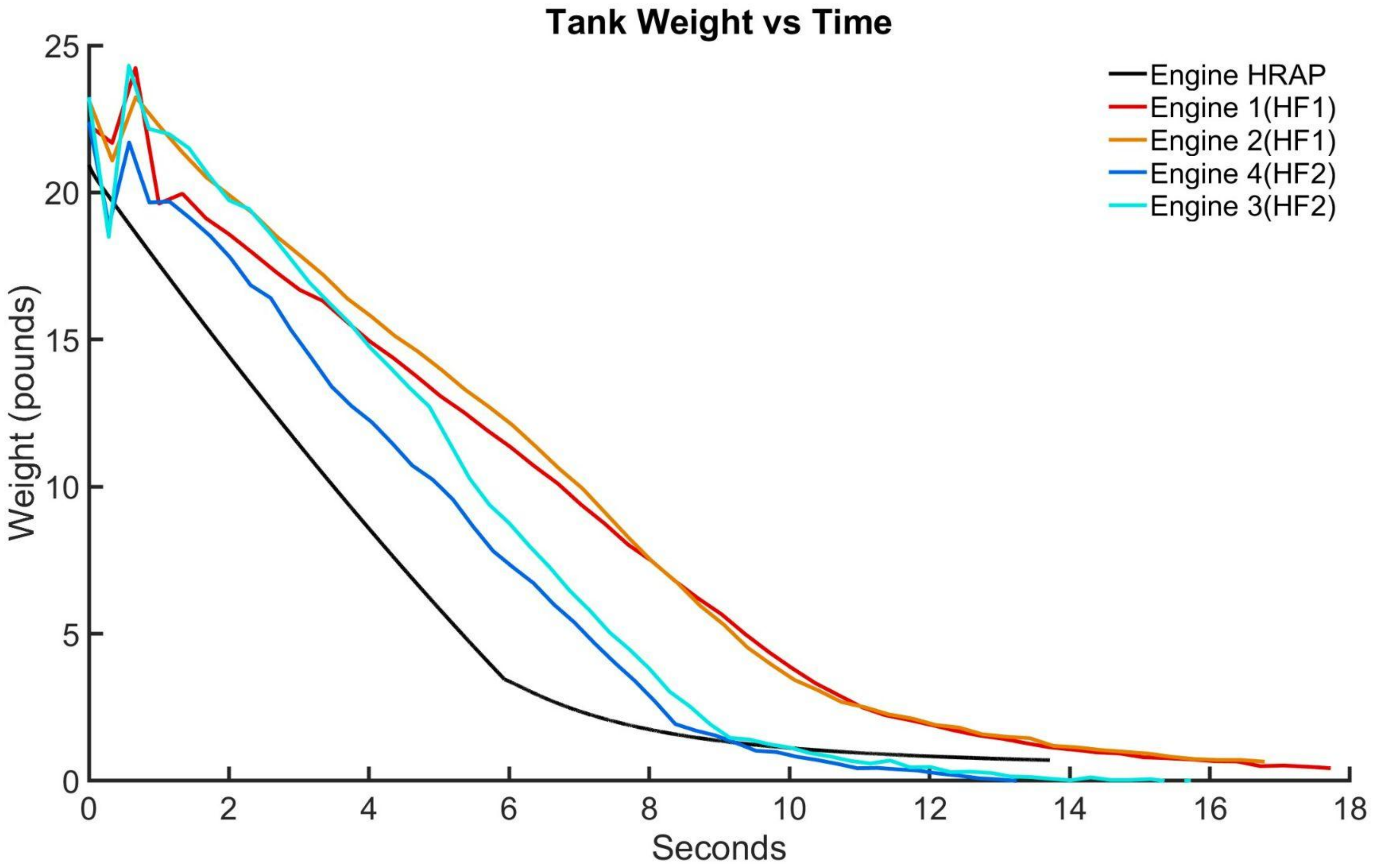
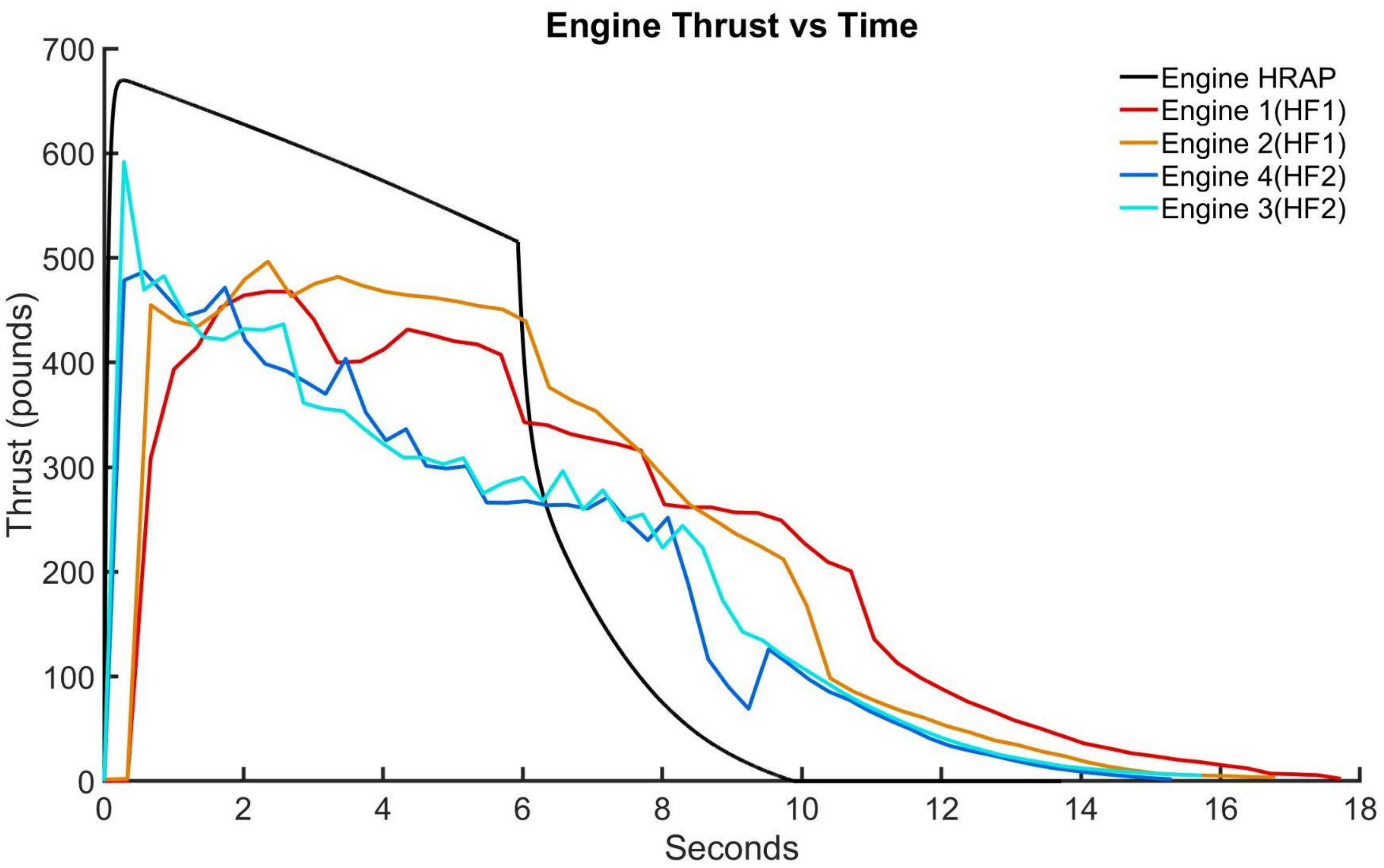
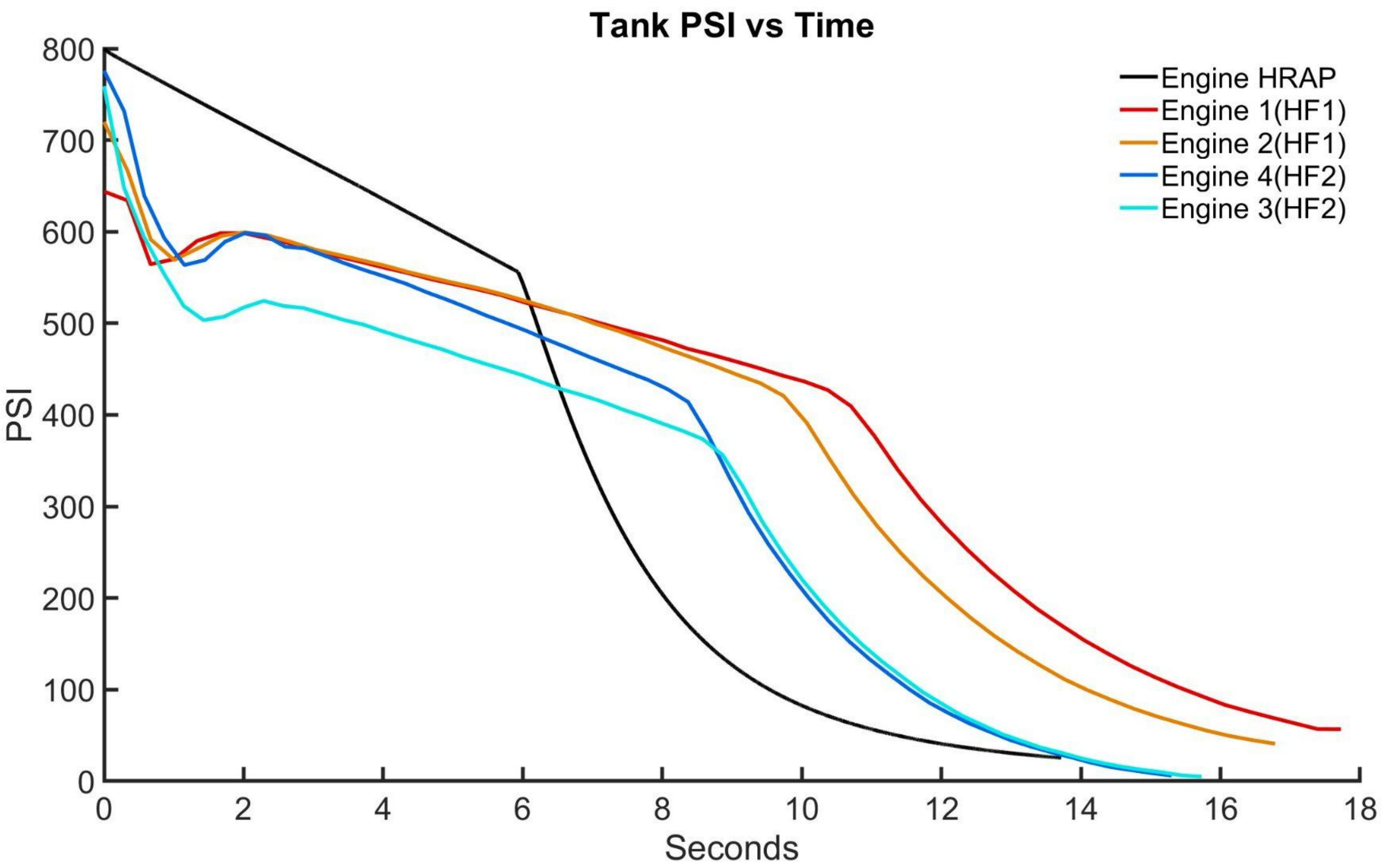
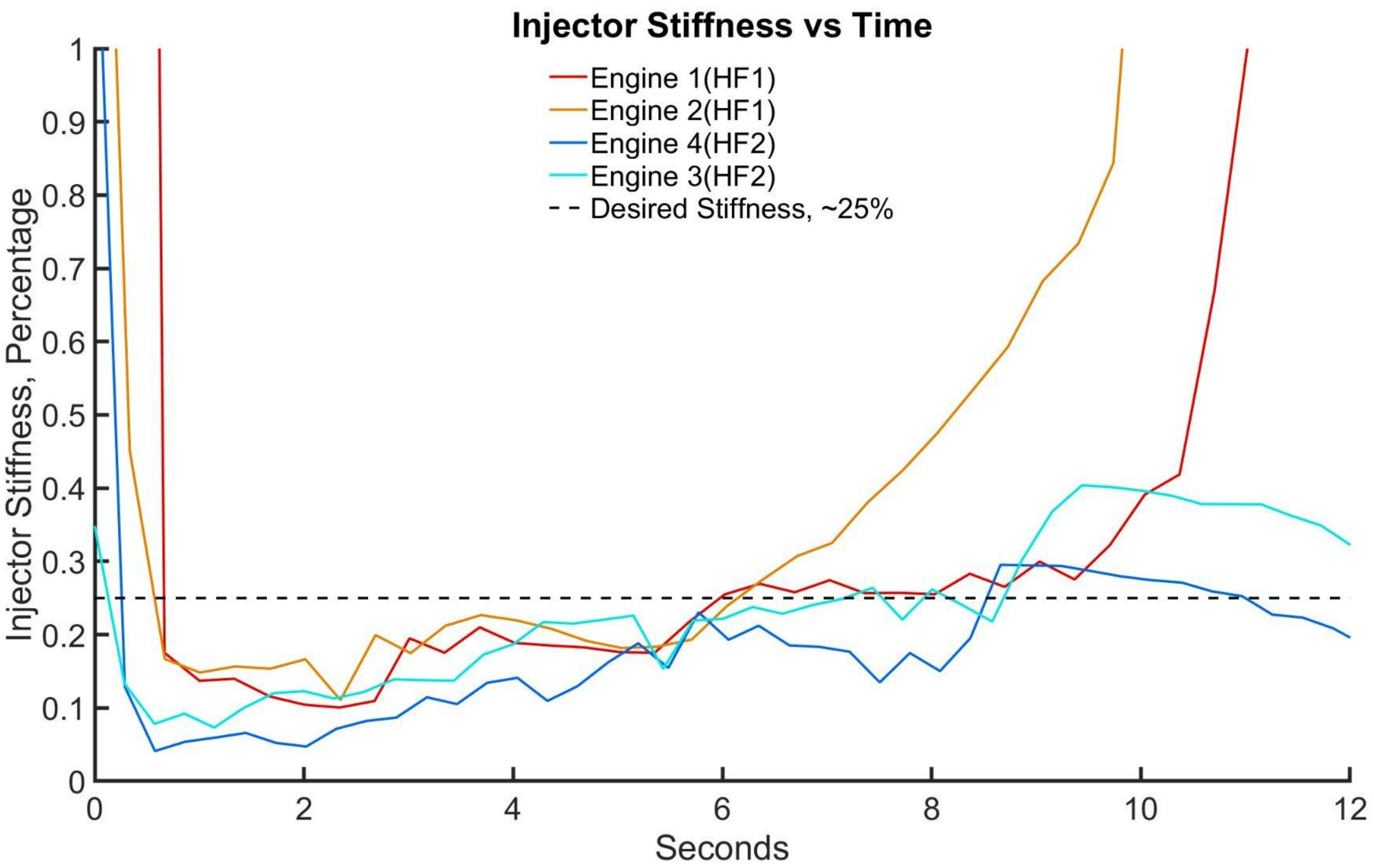
Questions?

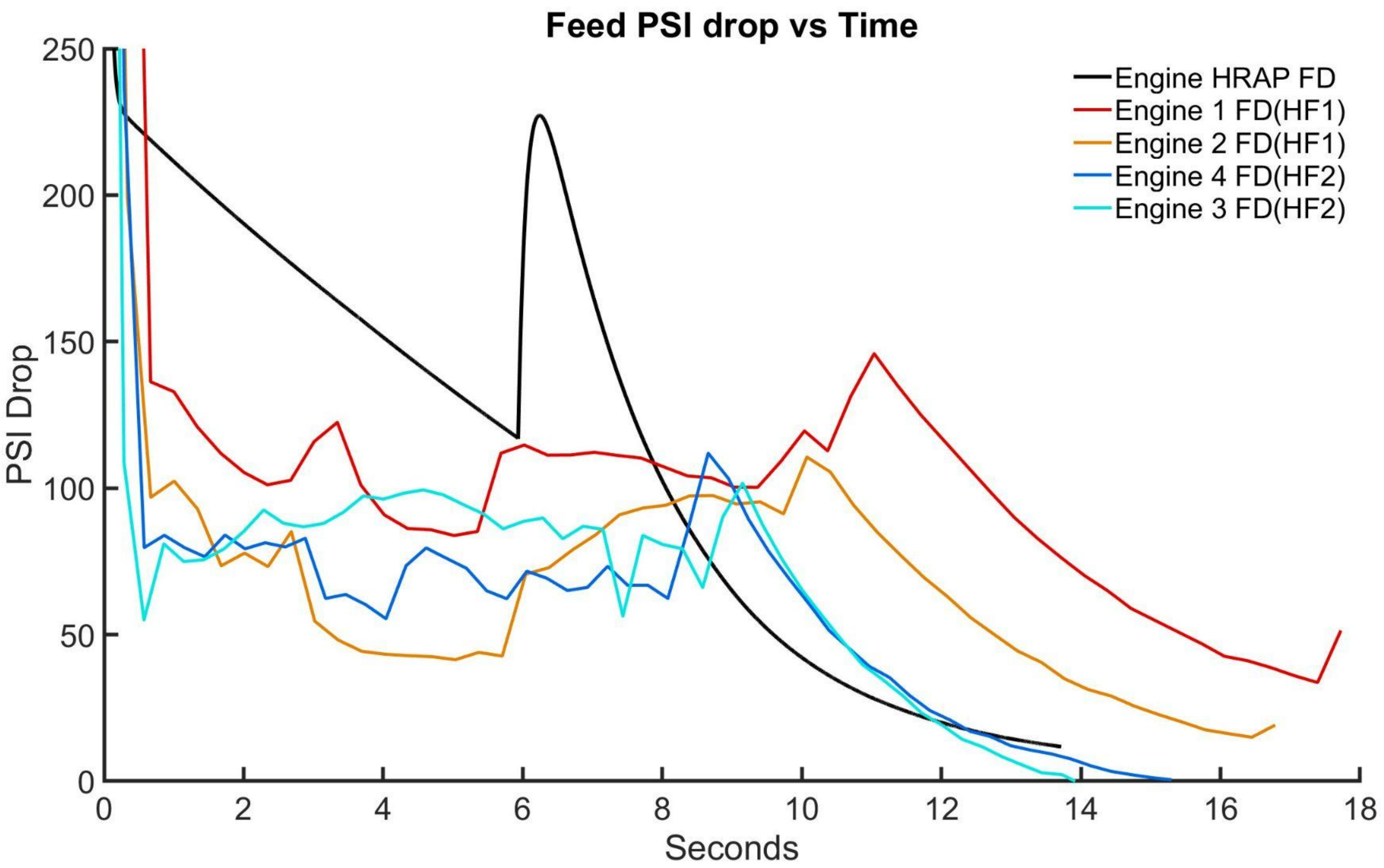
Data Review

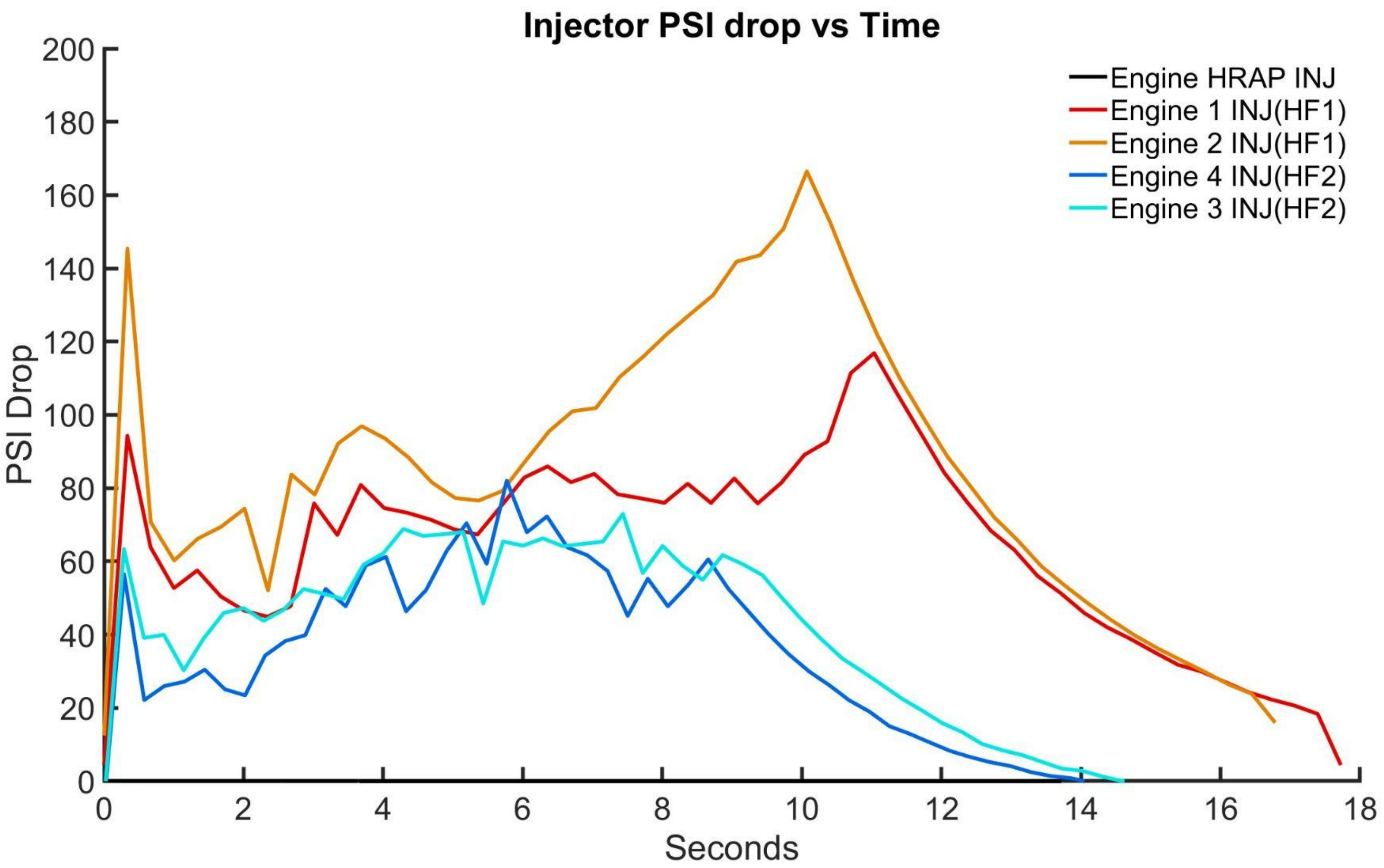

Tank Weight vs Time
Engine HRAP
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)
Weight (pounds)
Seconds
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
18

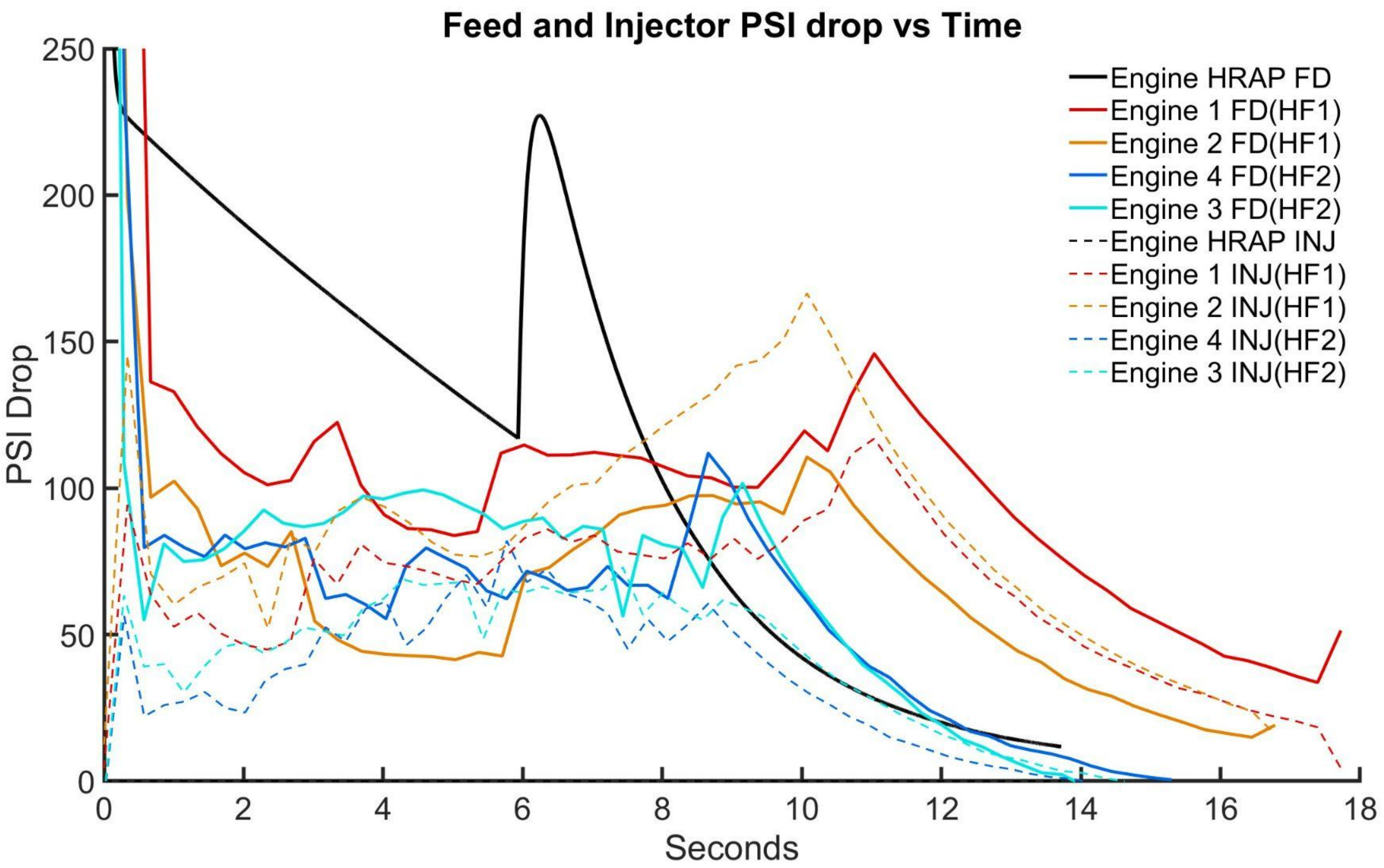

Engine Thrust vs Time
Engine HRAP
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)
Thrust (pounds)
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Seconds


Tank PSI vs Time
PSI
Seconds
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Engine HRAP
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)

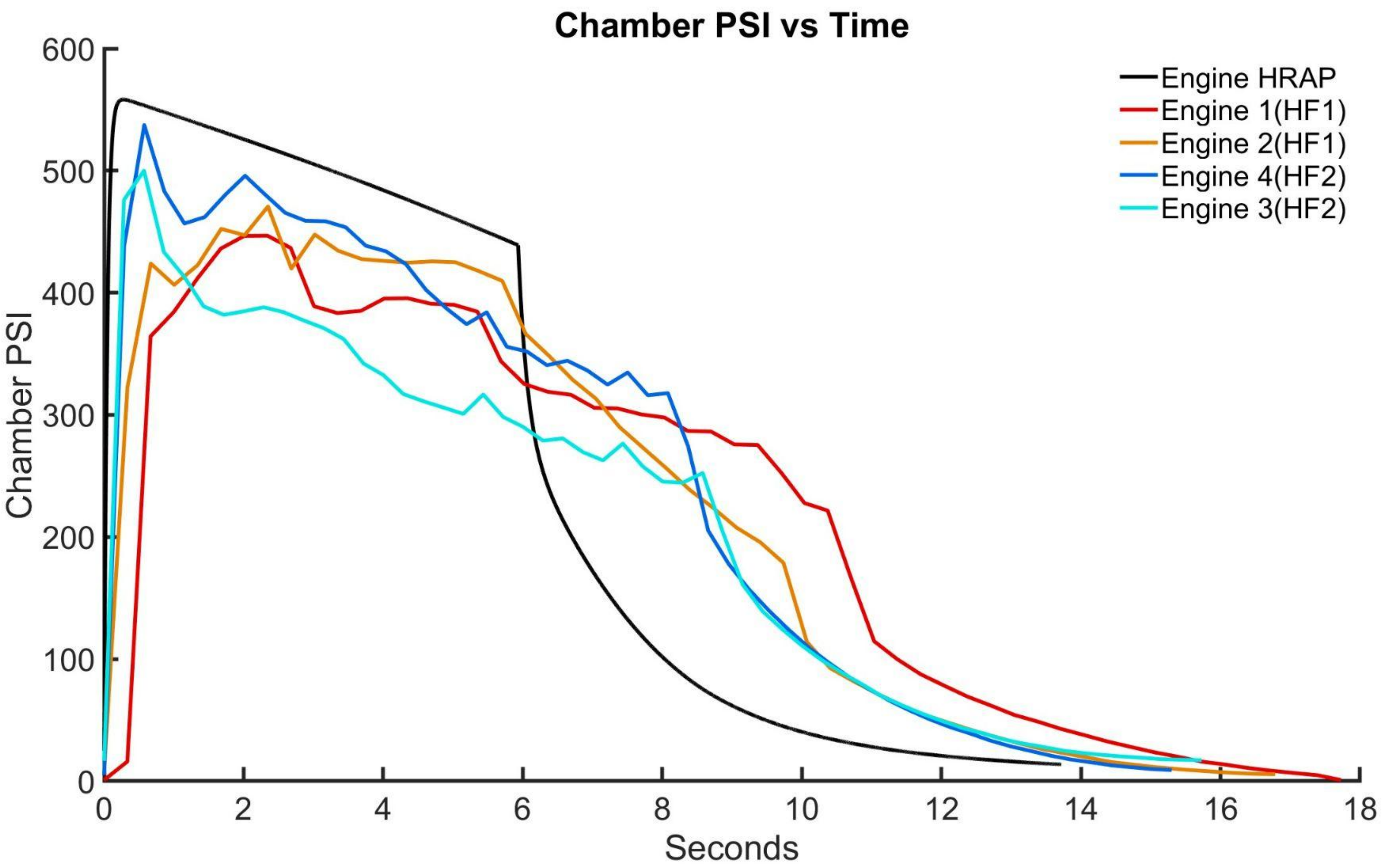

Injector Stiffness vs Time
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)
Desired Stiffness, ~25%
Injector Stiffness, Percentage
Seconds
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12

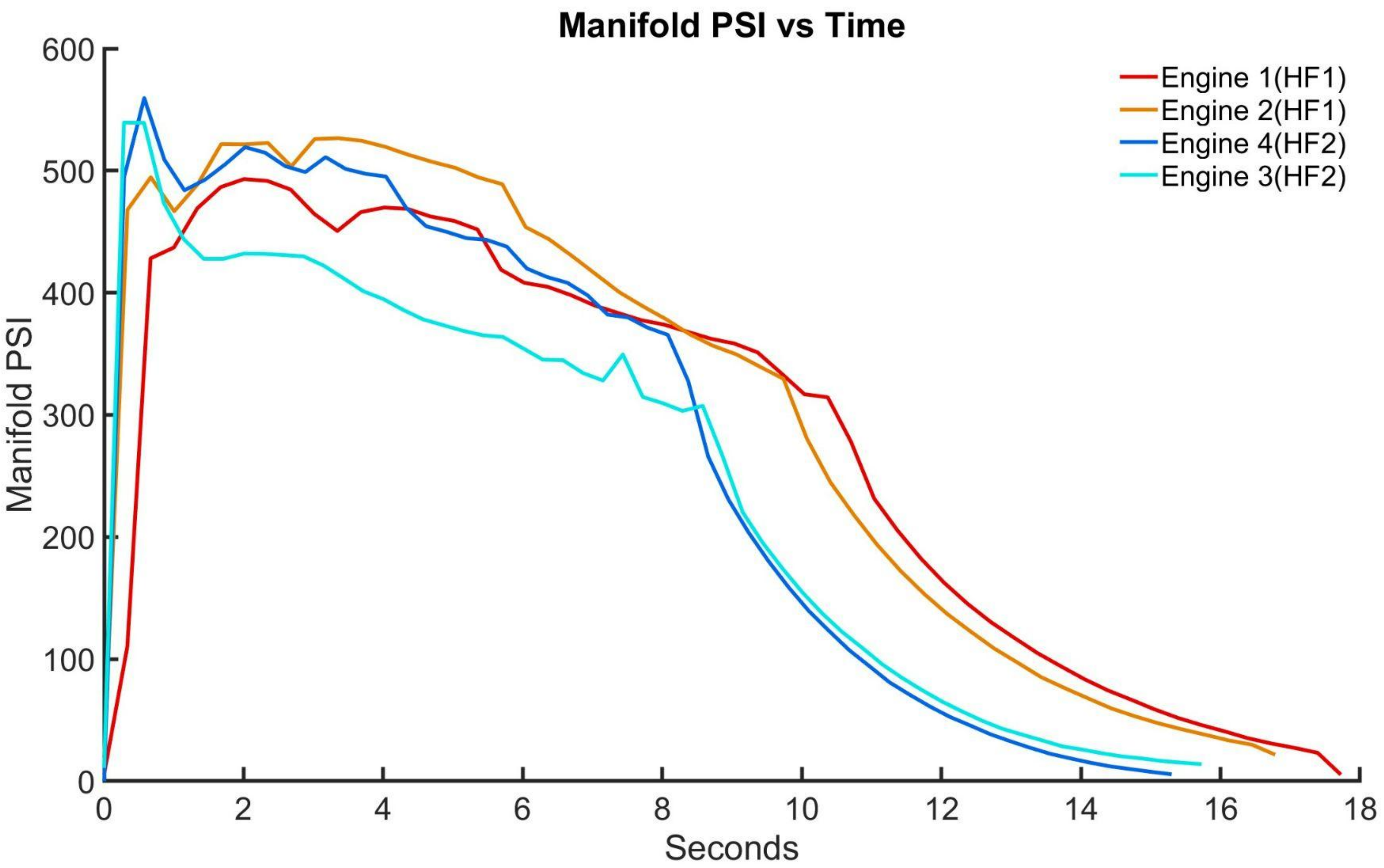

Feed PSI drop vs Time
Engine HRAP FD
Engine 1 FD(HF1)
Engine 2 FD(HF1)
Engine 4 FD(HF2)
Engine 3 FD(HF2)
PSI Drop
Seconds
0
50
100
150
200
250
0
2
4
6
8
10
12
14
16
18


Injector PSI drop vs Time
Engine HRAP INJ
Engine 1 INJ(HF1)
Engine 2 INJ(HF1)
Engine 4 INJ(HF2)
Engine 3 INJ(HF2)
PSI Drop
Seconds
0
20
40
60
80
100
120
140
160
180
200
0
2
4
6
8
10
12
14
16
18



Feed and Injector PSI drop vs Time
PSI Drop
Seconds
0
50
100
150
200
250
0
2
4
6
8
10
12
14
16
18
Engine HRAP FD
Engine 1 FD(HF1)
Engine 2 FD(HF1)
Engine 4 FD(HF2)
Engine 3 FD(HF2)
Engine HRAP INJ
Engine 1 INJ(HF1)
Engine 2 INJ(HF1)
Engine 4 INJ(HF2)
Engine 3 INJ(HF2)


Chamber PSI vs Time
Chamber PSI
Seconds
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18
Engine HRAP
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)



Manifold PSI vs Time
Manifold PSI
Seconds
Engine 1(HF1)
Engine 2(HF1)
Engine 4(HF2)
Engine 3(HF2)
0
100
200
300
400
500
600
0
2
4
6
8
10
12
14
16
18

Questions?

Engine Systems

Final Design Overview

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Initial Design Changes (Pre HF1)

Issue	Design Change	Justification
Fuel Grain sank during curing	**Added Pre CC** to fill in void and integrate with injector	Several sources attribute Pre CC to better propellant mixing Outer ring of orifices on injector would be blocked by fuel grain without Pre CC
Nozzle O-ring would always tear during integration	**Removal of Nozzle - CC O-ring** and replaced with surplus of RTV	O-ring had no actual functionality, gas would burnthrough at chamber before contact with O-ring

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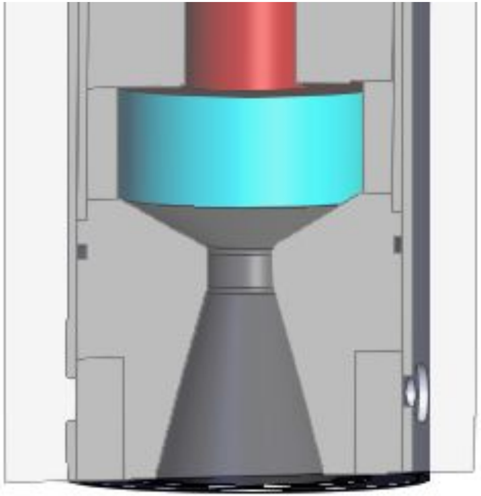
Initial Design Changes (Pre HF1)

Fuel grain sank during curing



Initial Nozzle - CC O-ring

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Hotfire 1 Engine Recap

- Ignition failure
- Extended flowtime (~20s)

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Design Changes - E1&E2 (Post HF1)

Issue	Design Change	Justification
Low $\dot{m}_{ox}$ (lower Cd than expected)	**Added 6 x ⅛" holes to injectors** increasing orifice area and raising our $\dot{m}_{ox}$	Coldflow and waterflow tests exposed a lower Cd than expected, lowering our mdot and resulting in a long flow time; thus mdot was raised to decrease this flow time
Low $\dot{m}_{ox}$ (blocked orifices from RTV)	**Reduced RTV application** on injector-pre CC seal	Prevent outer ring of orifices from getting clogged with RTV
Failed Ignitor (faulty ignition sequence)	**Cast new in-house ignitor** with redundancies (2 e-matches, flammable solid motor shavings) and update ignition sequence Composition: Al, CuO, $KClO_4$, Silicone Mix)	MPV opened before ignitor could heat up, several ignition tests to determine new countdown: T-3: ignite, confirm ignite, T-0: MPV

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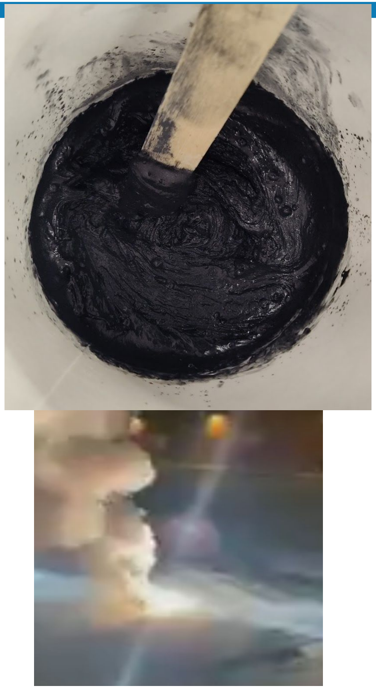
Design Changes - E1&E2 (Post HF1)

Issue	Design Change	Justification
Torn Injector-Chamber O-ring	**Implementation of PLA radial hole fillers** to provide smooth surface for o-ring integration	Injector-Chamber O-ring would catch on the radial holes and tear. Hole fillers held radially by hose clamp minimized tears

Design Changes - E1&E2 (Post HF1)

Adding 6 x ⅛” holes to injectors

Decreasing RTV



Ignition Casting and Testing

Radial Hole Fillers

Hotfire 2 Engine Recap

- Successful ignition
- Burnthrough of both engines
- Extended burntime (~16s)
- Nozzle Shear

Design Changes - E3&E4 (Post HF2)

Issue	Design Change	Justification
Burnthrough from long burntime (low $\dot{m}_{ox}$)	**Added 3 x ⅛" holes** to injectors	Increasing area to increase $\dot{m}_{ox}$ to decrease burntime
Burnthrough at Nozzle-Liner Seal	**Added nozzle step into post-CC**	Increased labyrinth sealing to further prevent burnthrough by cooling hot gas
Nozzle Sheared (E1)	**Chamfered RR** on the nozzle-interface side, smoothing out RR ID - nozzle interface (E3)	Nozzles cracked and separated at the throat. Suspected cause: sharp ID of RR chipped into the nozzle inset filet causing a stress crack.
Suspected Flow Issues	**Changed nozzle converging angle** (60° -> 45°)	Steep change in converging angle led to inefficient conversion from high pressure gas to high velocity gas, decrease angle

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Design Changes - E3&E4 (Post HF2)

Issue	Design Change	Justification
Unsupported post-CC/pre-CC lengths were initially chosen	**Set post-CC, pre-CC length** (1.3”, 1.95” respectively)	Researched length/ID ratios (0.4 pre, 0.6 post) to optimize propellant mixing and reaction
Concerns with nozzle gas sealing and thermal conductivity	**Extended liner step** into nozzle, all the way to the throat depth	More labyrinth sealing, as well as additional thermal insulation layer between graphite nozzle and aluminum chamber
Fuel leaked/sank from molds during curing process	**Radially clamped molds,** weighed down, O-ring on bottom mold	Seal with O-ring to prevent leaking, hose clamp radially to increase friction, preventing mold from expanding

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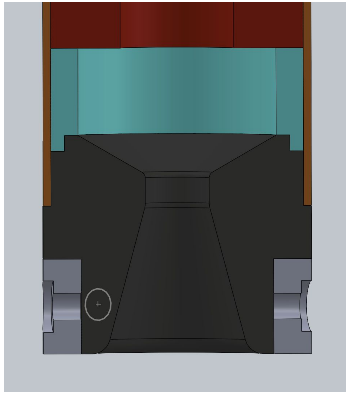
Design Changes - E3&E4 (Post HF2)

Burnthrough on both engines at post CC - nozzle interface



Post CC step into nozzle
Extended liner into nozzle

Nozzle Shear at RR plane

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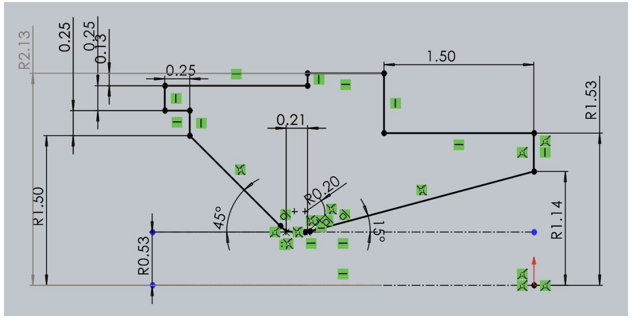
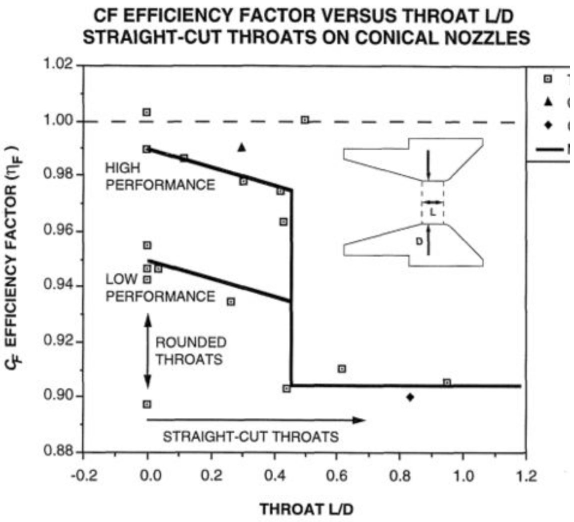
Design Changes - E3&E4 (Post HF2)



Change converging angle of nozzle



Justification behind Pre CC/Post CC lengths

Clamping and securing of fuel grain mold

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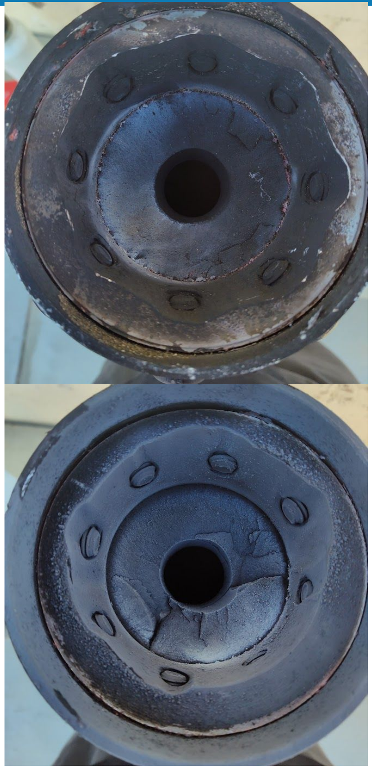
Hotfire 3 Engine Recap

- Successful ignition
- Burnthrough prevented
- Nozzle Shear
- Extended Burntime (~15s)

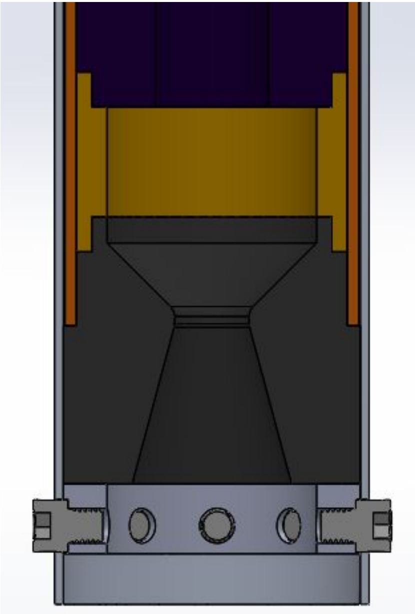
Design Changes - E5&E6 (Post HF3)

Issue	Design Change	Justification
Shearing of both nozzles at retaining ring plane	**Retaining ring moved below nozzle** instead of inset around nozzle, de-constraining nozzle radially	Suspected cause of shearing: RR and CC radially constrained the nozzle at different surfaces. When the graphite thermally expands from the combustion, the difference in distance causes reaction force in direction opposing thermal expansion, causing shearing at RR plane. Moving RR below nozzle eliminates problem, acting as a bigger snap ring (which was not feasible to manufacture due to chamber thickness)
Near burnthrough at grain - post CC seal (CC wall internally exposed)	**Adding grain - post CC step** with post CC sticking into fuel grain, increasing compression during integration (0.25” -> 0.4”)	Increase labyrinth sealing, gas will hit post CC before liner if the seal is not formed properly. The near burnthrough only occurred in E3, suggesting the sealing issue stemmed from integration error. Increasing compression will decrease chance for error and improve sealing (target 2 tons of compression)..

Design Changes - E5&E6 (Post HF3)



Shearing of both nozzles at RR plane



Retaining ring below nozzle
Post CC step into grain

Severe ablation at grain - Post CC seal

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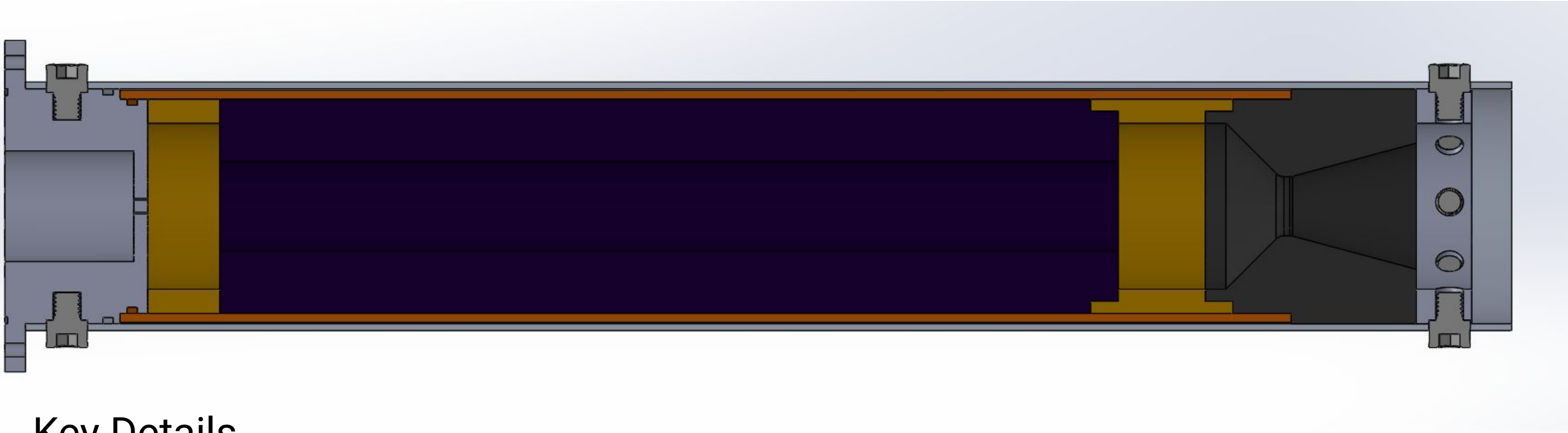
Final Design (E5&E6 - Launch Engine)



Key Details

- Retaining Ring designed to prevent shear
- Liner step up to throat to prevent burnthrough
- Post CC - Grain step to prevent burnthrough
- Post CC - Nozzle step to prevent burnthrough
- 9 ⅛” holes + 81 1/32” holes for injector

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Questions?

Feed Systems

Final Design Overview

Major Issues with Feed

Issue	Cause	Fix
Burn Time Too Long	• Using a flex hose connection to the injector added a large dp across feed creating a low dp between the injector and chamber • Lower than desired tank pressure • Overfill of oxidiser	• Use of hardline + short flex hose • Keep K- Bottles in the Sun longer • Trim dip tube for proper weight
Inability to resolve leaks	• Clocking of Feed system created leaks, and tight proximity of fittings + tank skirt blocked fittings • We suffered a 15 PSI/Min leak in the feed system before hotfire 2	• Installation of feed system before leaving for hotfire • Using consistent fittings in AN tubes (ie aluminum sleeves w/ aluminum pipes)
Consistent BIMBA Actuation	• Losses in the feed system may be caused by valves not opening fully • Fixing the vent actuation at hotfire required removal of entire system, which was time intensive	• Steel lever arms for consistent actuation • Checks of valve alignment / system clocking before hotfire • One piece bracket to ensure no movement in the system

Major Wins with Feed

Issue	Details	Further Optimization
Minimal Leaks across Fill Table	- Our fill table had almost no leaks during both our low pressure checks and high pressure	- If we can get even more efficient at our leak checks we'll be able to fire even more engines and work faster than ever
Tank ability to hold High Pressure	- We filled our tank 50 PSI past our originally planned PSI. Thankfully because our MEOP was 800, this served no problem which validated our tank design and structural integrity	- Need to adjust relief valves on fill / tank to reflect the higher operating pressure
Fixed Feed Actuation	- Vent and MPV originally had very significant rigidity and travel problems, which were much less pronounced at this hotfire	- While the brackets have been fixed we want to further optimize them to ensure a FULL actuation and stability

Feed Systems Changes

- Feed QD rebuilt at 90 degree angle to shorten MPV
    - Previously quick disconnect was jutting out and touching the rim of the ox tank
- Poor clocking of MPV caused the vent line to bend
    - Attempt to bend dip tube caused dip tube to be remade, and vent to directly connect to dip tube without intermediate pipe
- Dip Tube was oversized, leading to the making of a new dip tube with new flaring to connect to the rebuilt vent system
- MPV upgraded to -8 (Integrated larger ball valve)
    - The MPV at -6 was too small for the oxidizer flow
- Switched to one piece brackets
    - Previous brackets were too difficult to work with, and weren't size properly for the upgraded MPV

Feed System Final Design

MPV

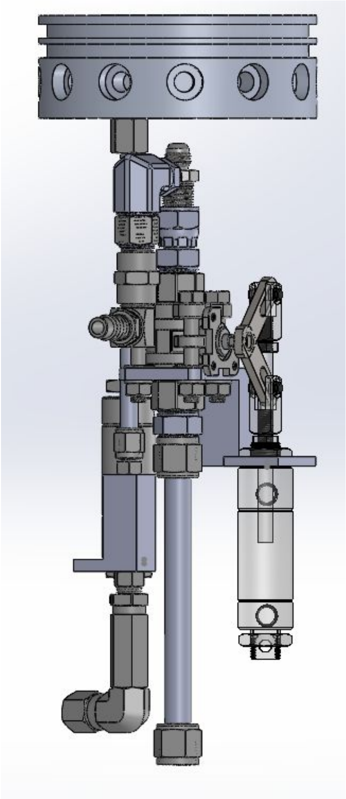
- -½” ball valve w/ -8 fittings/flex hose
- One piece bracket to hold bimba
- 14” in length
- Custom Steel Valve handle

Vent

- ¼” ball valve
- One piece bracket with fitting chain to hold bimba
- Currently 1/8” orifice at elbow

QD

- Jutting out from MPV cross at 90 degrees downwards, then points 90 degrees away from MPV



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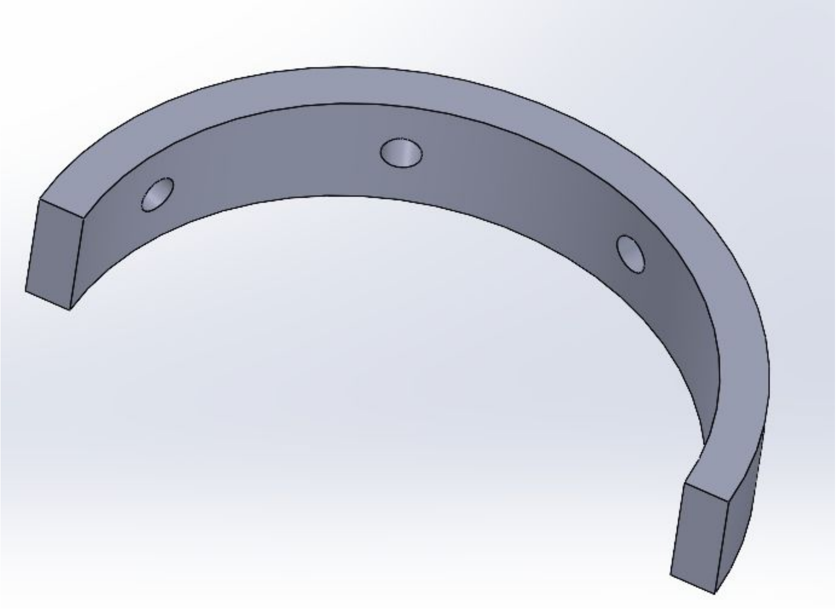
Feed Bay VE Integration Updates

Design of Ring for Body Tube Nuts

- Instead of epoxy and nut-holders that would seal the end cap we're using this two-part ring with tapped bolt holes
- Sized to .1 inch less than available space between endcap and cross fitting for QD
- Split in half so we can fully leak check feed and attach to tank, then integrate ring

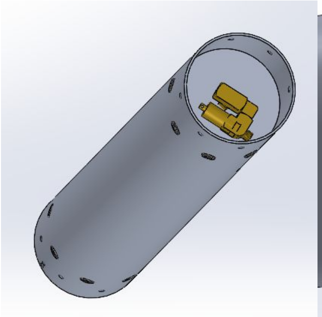


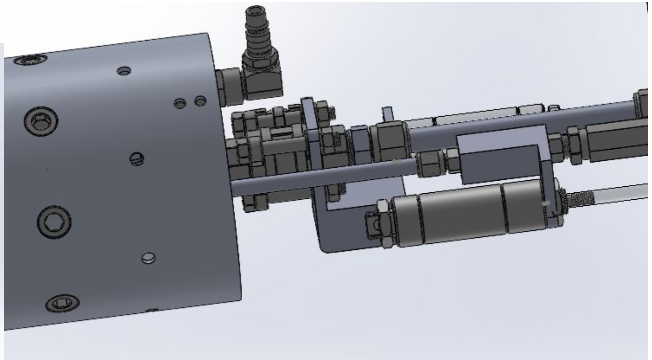
Questions?

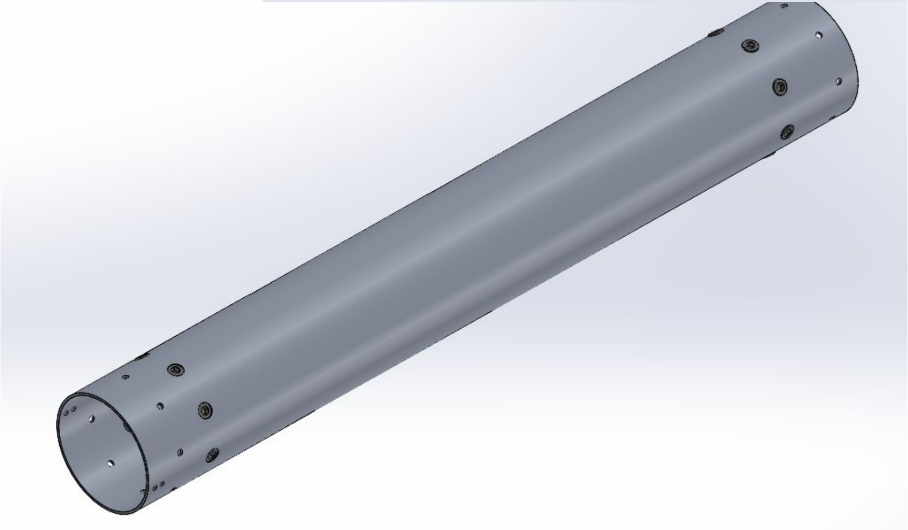
Tank Systems

Final Design Overview

Tank Design Changes







- 8 bolts (16 tot.)
- Fill to 800psi, expect a firing pressure of 650 psi
- Dip Tube changed to swage, brought back to initial design (internal AN on bottom end cap)
- Ullage 25%
  - Dip Tube length two inches above desired-> field decision not design decision, likely neg. due to lower expected density in proceeding fires

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Questions?

GSE

Final Design Overview

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Major Issues with GSE

Issue	Cause	Fix
QD plate integration and leaks along the T junction on the QD	Allowance space for integration of the QD plate is too small. Old plate was drilled perfectly to size, overtime the edges of the hole became worn and the QD was able to slip through too easily. T junction leaks even after retefloning, most likely due to integration with the flex-hose loosening the joint.	Make a new QD plate with a chamfer design. Be vigilant about the leaks on the T junction and always be sure to leak check extensively even having tefloned the joint.
Tank wobbling during fill	Load cell mounting mechanism only nullifies rotational moments in 1 axis and not the other causing it to oscillates back and forth like a bell.	2 sets of support beams too secure the tank in place. Support beams placed after the tank is integrated with the fill structure.
Orthogonality of the fill structure	Lack of foresight. We shouldn't have used the angle grinder when cutting the c-strut.	Extensive amounts of supports. Made sure that the tank was always leveled by leveling off the attachment of the load cell with washers.

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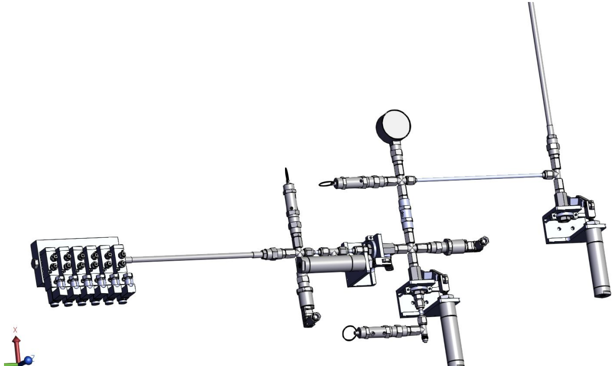
Major Wins with GSE

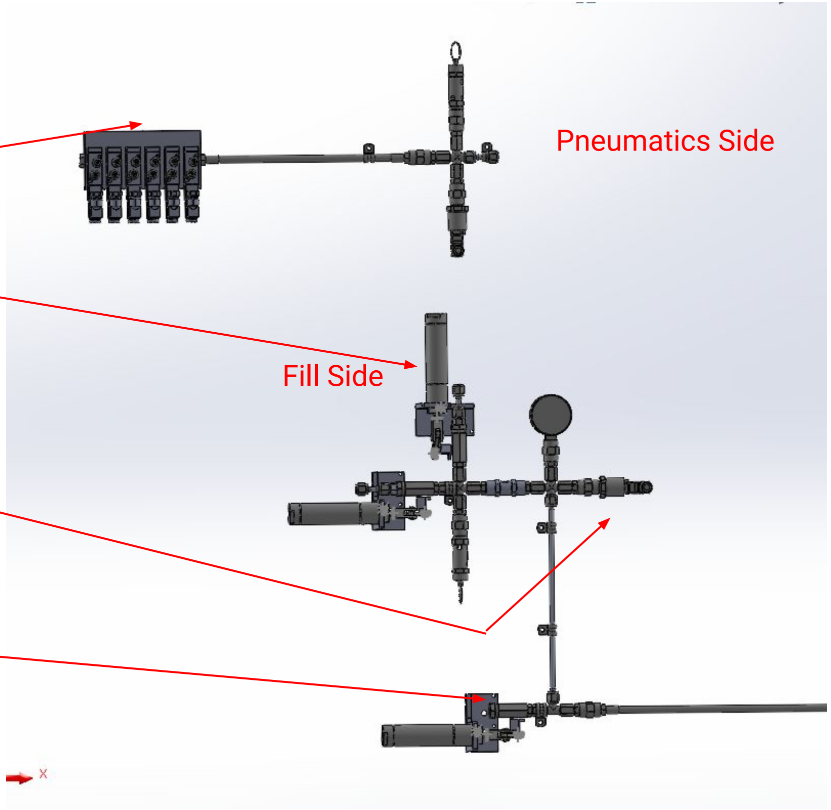
Issue	Details	Further Optimization
Leaks (or should I say the lack of them :D)	Relatively little leaks throughout the whole fill structure. Haven't had much need to take apart the AN fittings, only major leaks are usually in the relief valves or the PTs.	Make sure tefloning is clean with NPT fittings. Be especially careful with the PTs since they are taken on and off all the time.
Ball valves not opening/closing all the way	Ball valve not allowing for full range of motion and point of integration with the ball valve and handle is being worn down causing a significant amount of slipping.	Swapped out the ball valve handles for new ones
Bottle Inverting	Created a more efficient bottle inverter where the k-bottle is sitting at a 10 degree tilt as opposed to tilting the bottle over 180.	Check for rigidity and tightness of joints after so many uses. Replace broken parts/ loose screws.

GSE Design

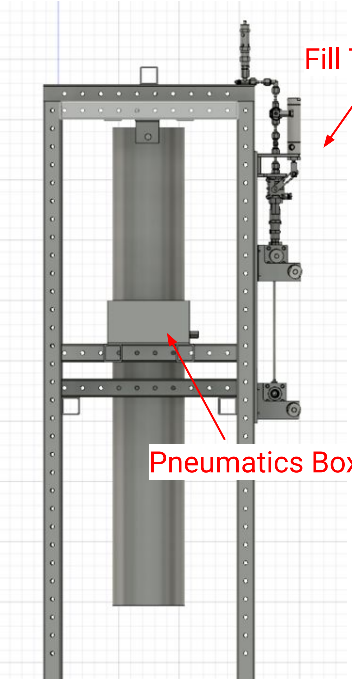
Fill Table Changes:

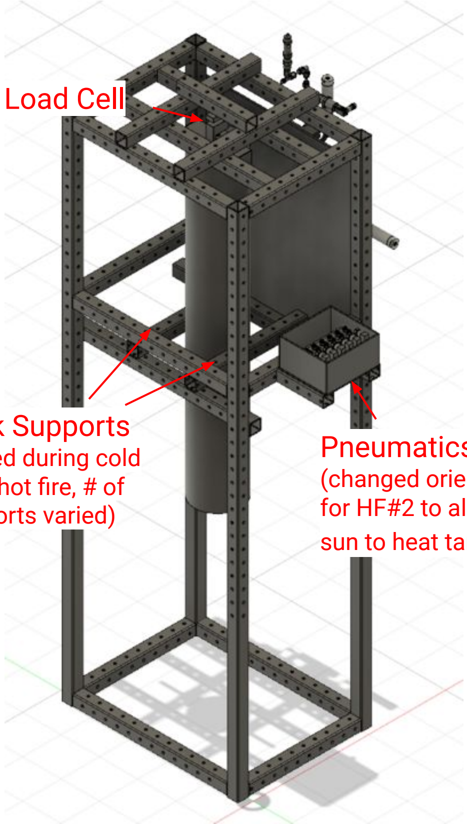
- Separated Pneumatics
  - Manual Purge
- Replaced brackets with clamps
  - Added more to compensate
- Moved PT to more accessible cross
- Added elbow to redirect dump

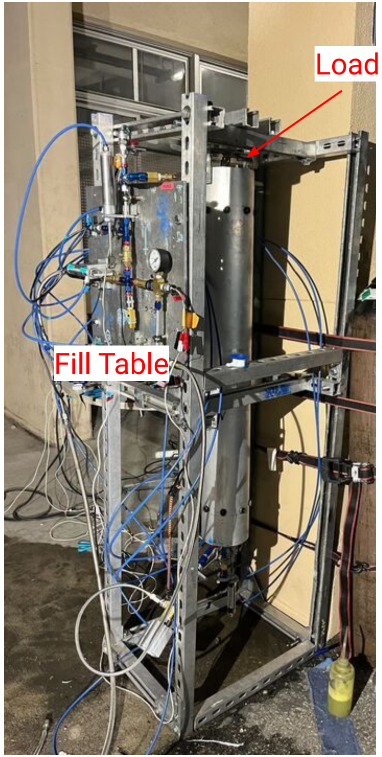




GSE Design Final: Fill Structure







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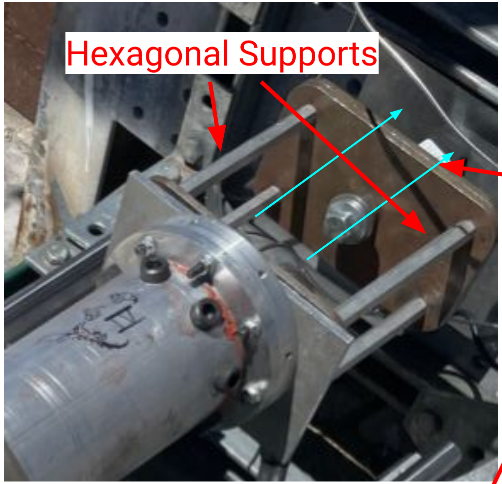
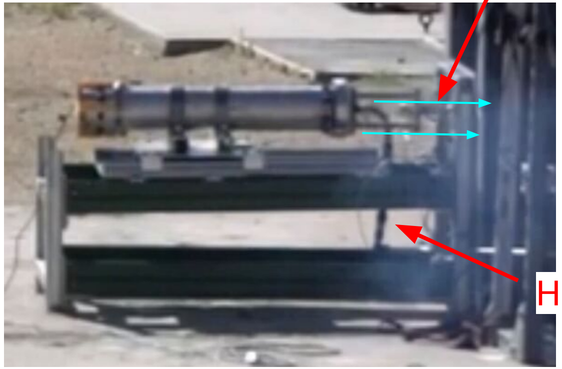
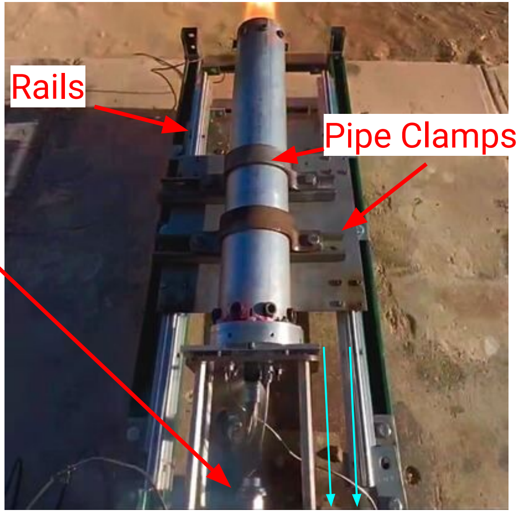
GSE Design Final: Test Stand







Load cell connects directly into metal support structure at RRS. Blue arrows show direction of thrust.

- Pipe clamps used to secure engine in place
- Engine secured to sliding rails to allow for linear movement

Major Change:

- Hard line used to connect MPV and engine to ensure minimal pressure loss

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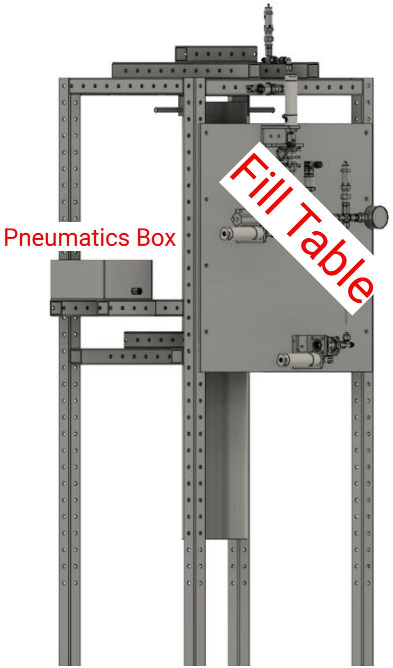
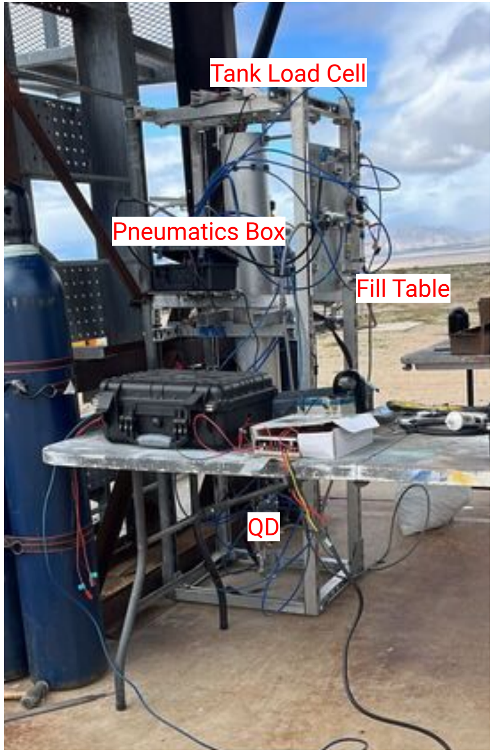
Bottle Inverter

- Created a bottle inverter than angles the bottle at ~10 degrees
- Stable w/ the addition of sandbags
- The legs flip out for more support

GSE Design Changes

- Single load cell mounting for tank
- Reconfigured fill table
    - Manual purging
- Moved pneumatics box to better integrate with electronics
- Added supports for the tank
- Revamped the QD
- Added a hard line to engine
- Changed engine mounting system and test stand configuration
    - Optimized load cell placement for engine thrust





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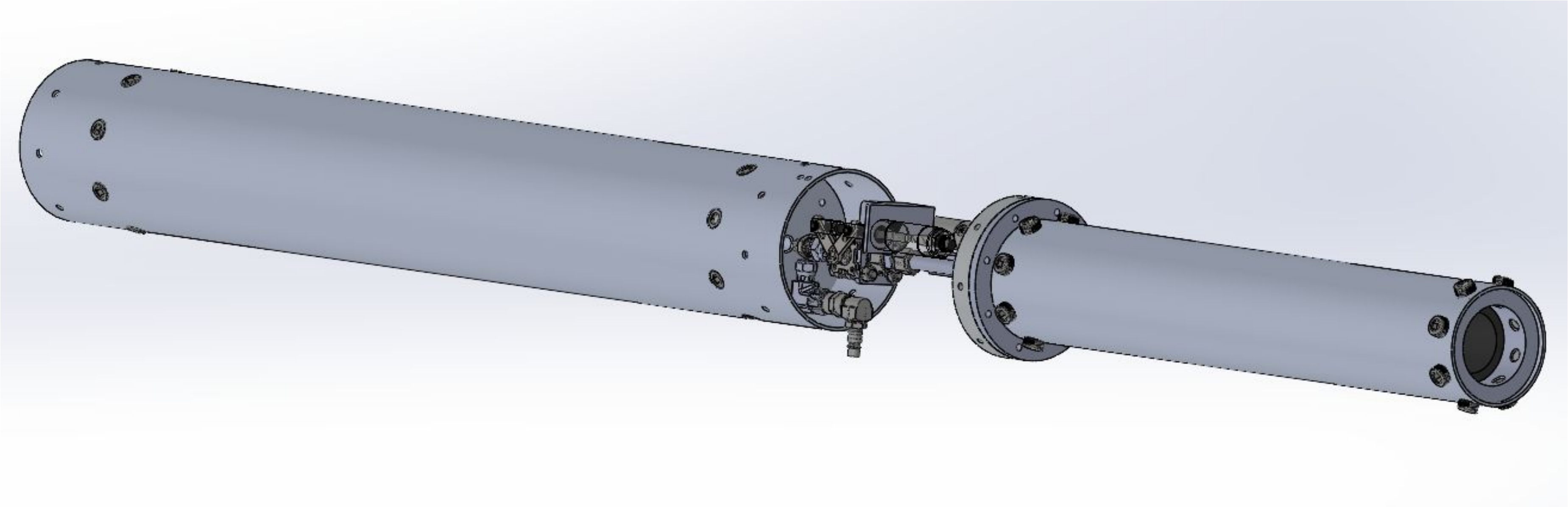
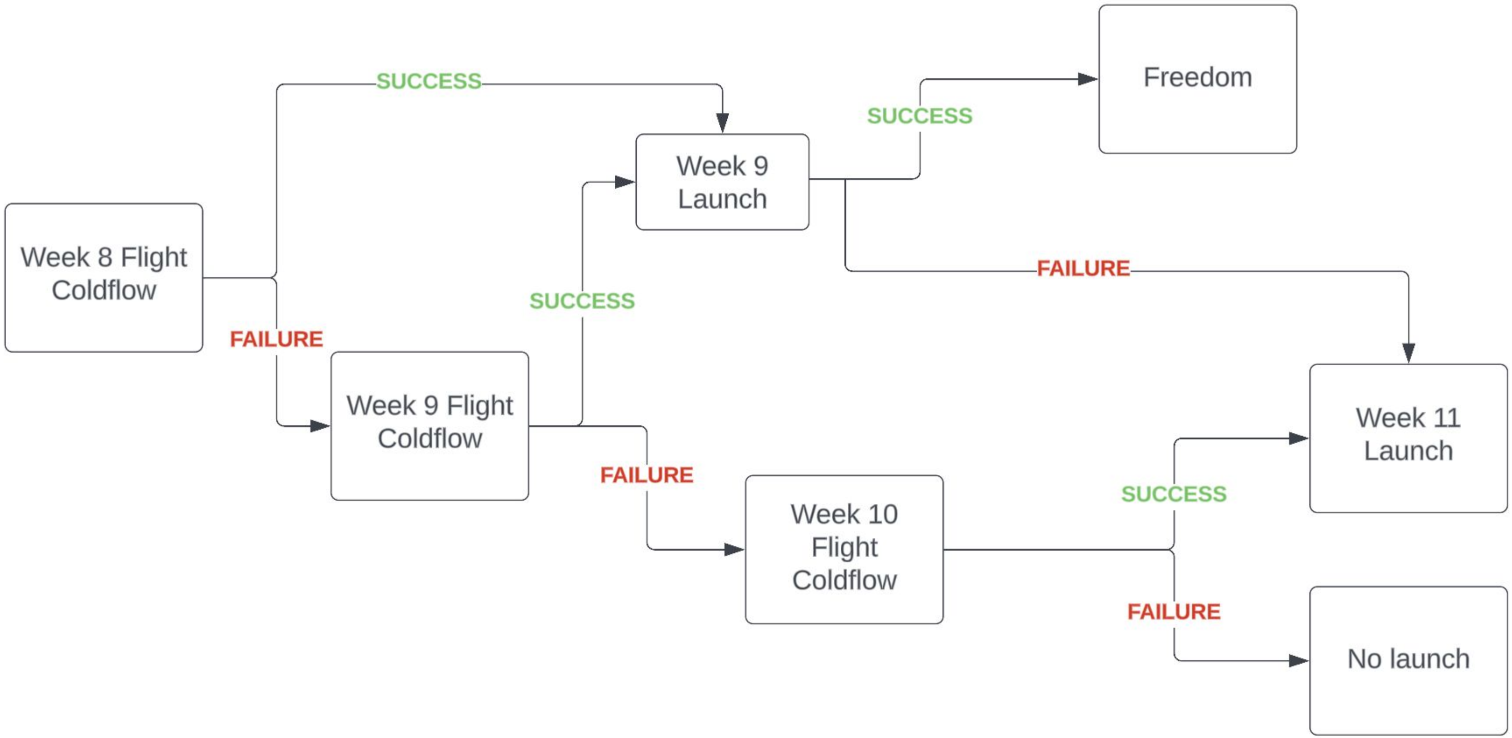
Questions?

Prop Assembly for Launch



Future Planning

Future Decisions



Questions?