Fall 2021
Test Readiness Review

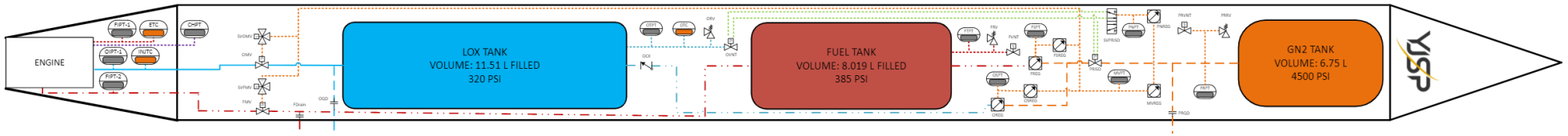
By: Ethan Heyns, Ben Woodman & Ben Breer

Flight Feed System

Overview

The Flight Feed System (FFS) is a pressure regulated feed system designed to use gaseous nitrogen (GN2) to deliver liquid propellants (LOX and Jet-A) to an engine at a desired mass flow rate and pressure. The system uses an array of pressure regulators to pressurize the propellant tanks at desired operating pressures. Once pressurized, actuating the Fuel (FMV) and Oxygen (OMV) main valves delivers these propellants to the engine.

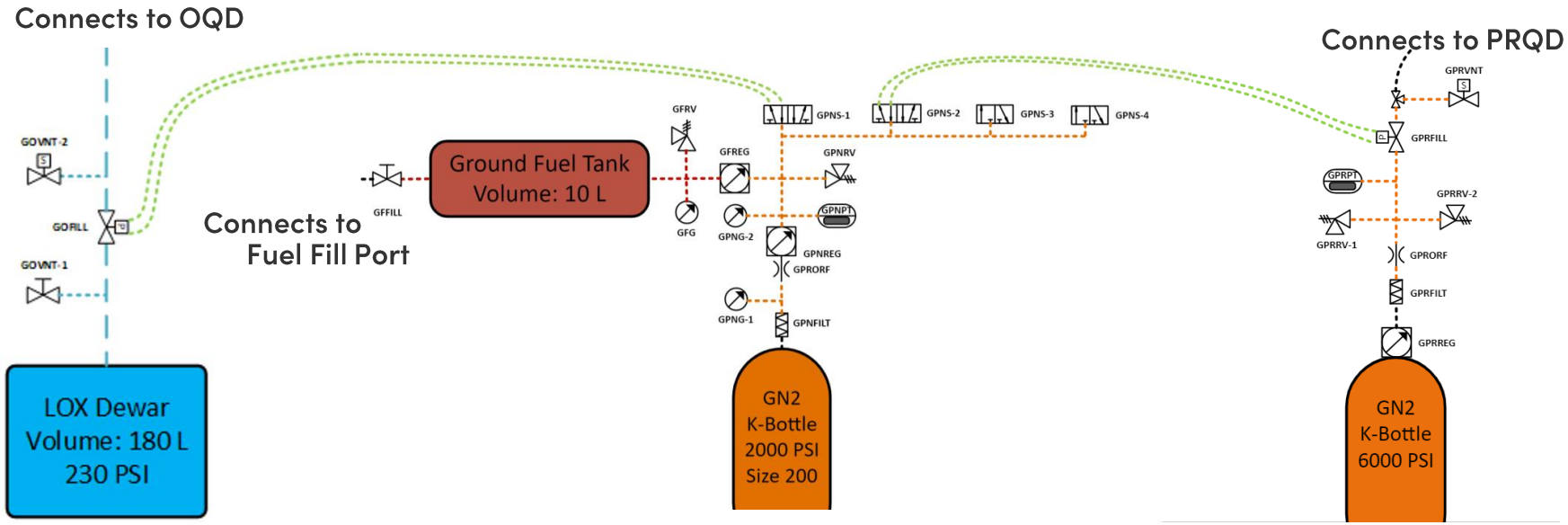
Plumbing & Instrumentation Diagram (P&ID)



Launch Fluids System (LFS)

Overview

The Launch Fluids System (LFS) is a pressure fed system designed to supply the FFS with propellant and pressurant during fill procedure. LFS is designed to regulate 6000 PSI K-Bottles to 4500 PSI, the operating pressure for FFS. LFS has remote control of fill and vent valves for both the pressurant and cryogenic fill systems. LFS can also fill fuel, or in our case water, using a low-pressure system downregulated from the pneumatics pressure.



Overview

Purpose

Characterize FFS and LFS. Prove functionality at high pressure and with cryogenics.

General Testing Goals:

- Data Acquisition
- Tune System
- Test the accuracy of our prior calculations

Top Level Objectives

Data Acquisition

- Determine Tank to Injector pressure drop
- Fill and vent time on COPV
- Characterize the effect of hysteresis on tank pressures
- Valve Timings
- Time to fill LN2
- Boil-Off time after full flow
- COPV Sizing Validation (Collapse Factor)

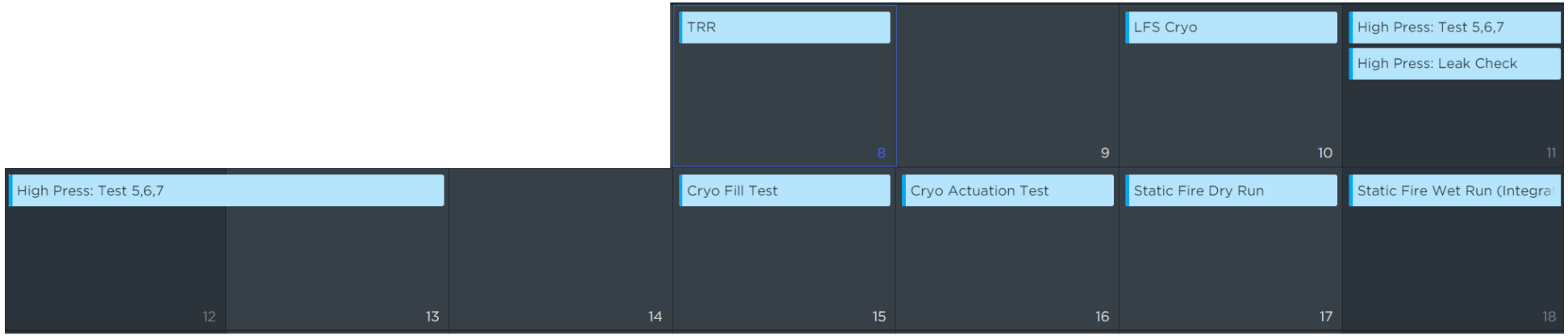
Tests

Overview

- **High Pressure**
  - COPV Fill
  - Full Flow at Flight Tank Pressures
  - Full Flow at DP Pressures
- **Cryo**
  - LFS Cryo
  - Cryo Fill
  - Actuation Under Cryo

Schedule

- **Extremely Fast Pace to reach static fire and potentially launch this semester**



LFS Safety Systems

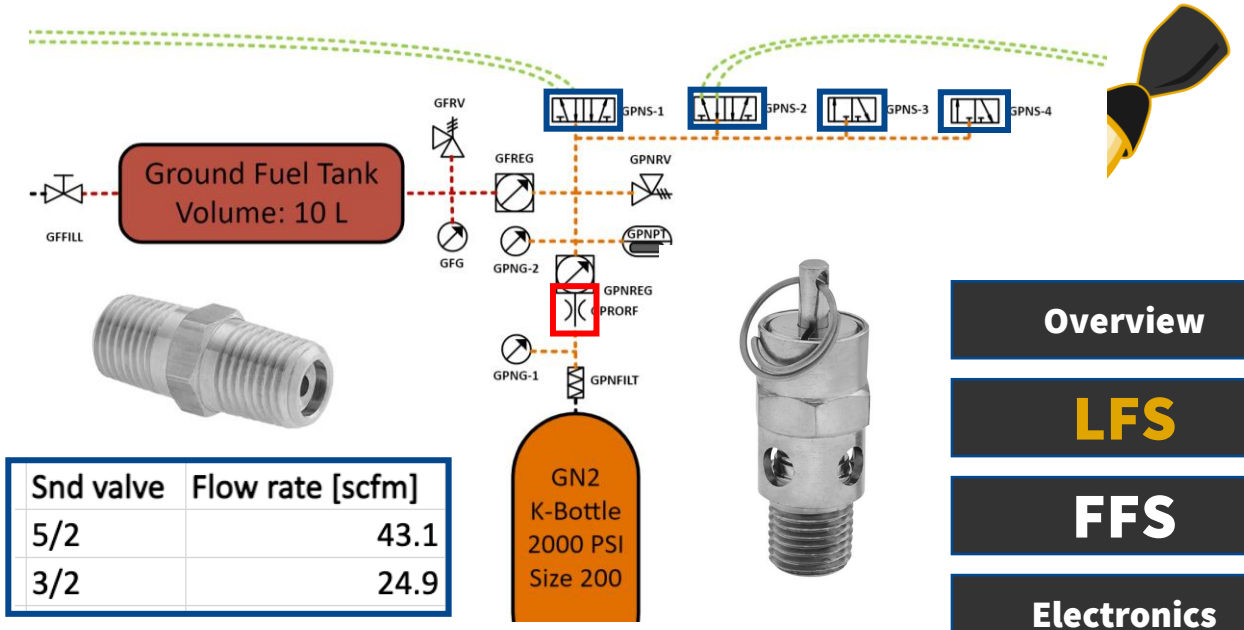
- Pneumatics
  - 2200 psi K bottles regulated to 100 psi
  - Choke orifice to limit flowrate
  - Relief valves sized accordingly
- Pressurant
  - 6000 psi K bottles immediately regulated to 4500 psi
  - Choke orifice to limit flowrate
  - Relief valves sized accordingly
- Fuel Fill
  - 100 psi pneumatics regulated to 15 psi
  - 50 psi crack pressure relief valve
    - Tank has been proofed to 60 psi
- LOX Fill
  - One manual and one remote vent valve

Actual Image Not Shown

Pneumatics

Failure Considerations

- 0.035" brass McMaster control orifice
- Chokes flow in case of pneumatics reg failure
- Isentropic flow approximation to find size given a desired flow rate
  - Selected 35 scfm @ 2200 psi
- Must be fast enough for solenoids, but slow enough to choke before relief valves
  - RV crack pressure: 150 psi
  - RV flow rate: 130 scfm @ 150 psi
    - FOS of 3.7 on relief



Snd valve	Flow rate [scfm]
5/2	43.1
3/2	24.9

Compressible Flow Approximation

Variable	Value	Units
R	8.31462	J/K*mol
R	8314.62	J/kmol*K
MW	28.014	g/mol
R_spec	296.8023131	J/kg*K
Gamma	1.4	
P	2200	psi
	15168472	Pa
T	294	K
M	1	Choked Flow
Flow rate	35	scfm
	0.237936462	acfm
	0.000112293	m^3/s
Density	187.2155689	kg/m^3
m_dot	0.021023058	kg/s
A	5.97917E-07	m^2
	0.000926772	in^2
Diameter	0.034351163	in

Notes

Mass Flow Choking — Glenn Research Center

A = Area, R = Gas Constant, V = Velocity, T_t = Total Temperature
r = Density, γ = Specific Heat Ratio, M = Mach, P_t = Total Pressure

Mass Flow Rate: $\dot{m} = r V A$

For an ideal compressible gas:

$$\dot{m} = \frac{A P_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Mass Flow Rate is a maximum when M = 1
At these conditions, flow is choked.

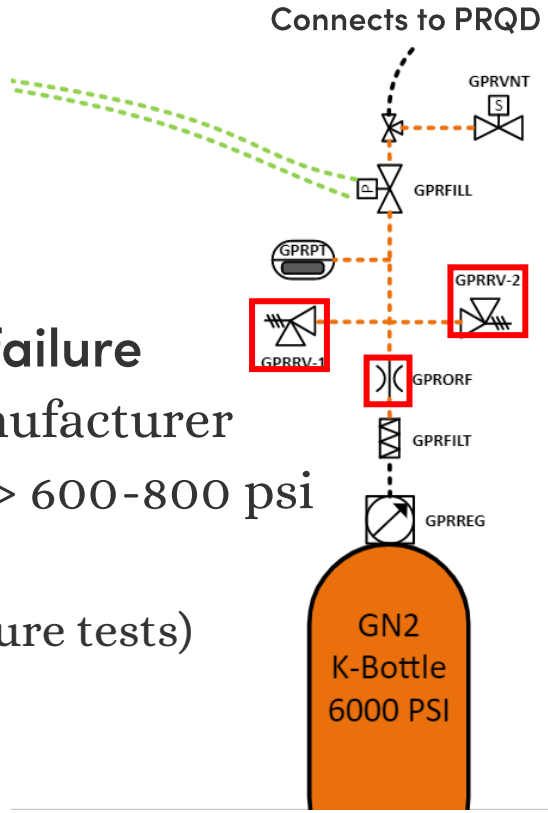
$$\dot{m} = \frac{A P_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Overview
LFS
FFS
Electronics
Configuration
Test Objectives
Risk Avoidance
Procedures
Contingency Plan

Pressurant

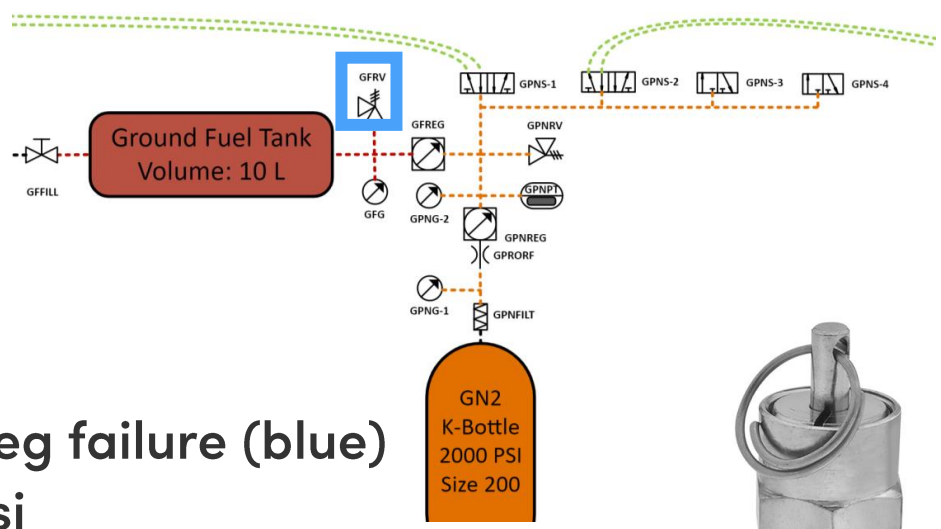
Orifice and Relief Valves

- Mutliple orifice options so we can test with different fill times
  - 35 thou - flowrate @ 6000 psi: 99 scfm
  - 78 thou - flowrate @ 6000 psi: 493 scfm
  - 93 thou - flowrate @ 6000 psi: 700 scfm
- Orifice limits COPV fill rate
- Reliefs keep pressure below 4700 psi in case of reg failure
  - Flowrate range of 300-400 psi @ 4500 psi per manufacturer
  - For this reason, 2 have been used on the system => 600-800 psi
  - Min FOS:
    - 35 thou: 6.06 (will be filling with this for high pressure tests)
    - 78 thou: 1.22
    - 93 thou: 0.86 (will not use on high pressure fill)



Fuel Fill

Failure Considerations

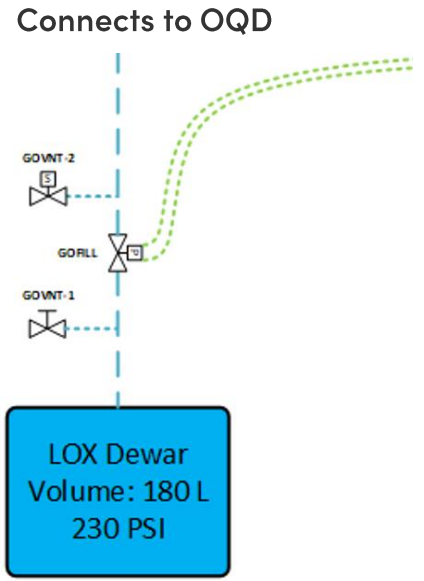


- McMaster fast-acting
- Will relieve pressure in case of fuel reg failure (blue)
  - Pressure jumps from 20 to 100 psi
- Set pressure: 50 psi
  - Nominally fuel lines should be regged to 20 psi
- MOP: 300 psi (100 psi in reg failure case)
- 70 scfm flow rate so flow will remain choked at orifice which chokes at 35 scfm

LOX Fill

Failure Considerations

- Will be running all cryo tests at NARA with LN2, not LOX
  - 230 psi, 230 L LN2 dewar
- Would a filter out of the dewar be wise here?
- Two vent valves, one solenoid, one manual
  - Handles both trapped volumes



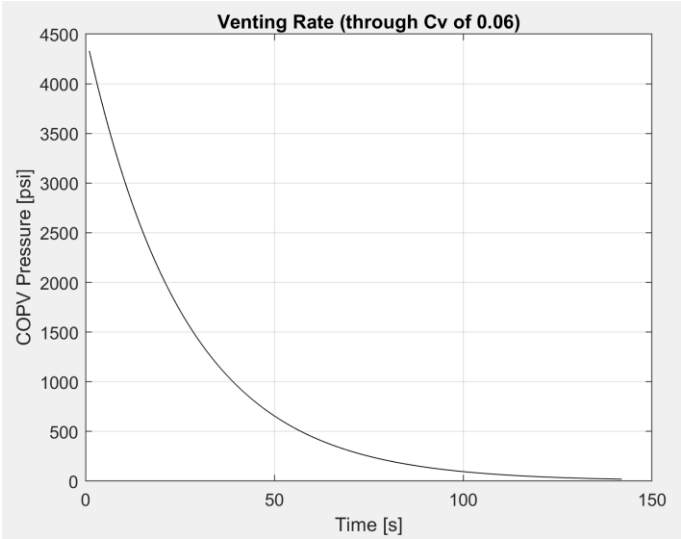
Vents

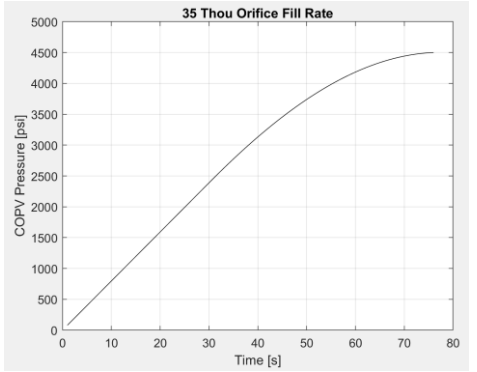
- **Currently upgrading pressurant vent (GPRVNT) to be normally open**
  - Safes system in case of power loss
- **Potential problem: GOVNT-2 is normally closed**
  - Looking for an alternative
  - Operator can then approach system to open GOVNT-1 and safe the cryo lines
  - If power is lost during integrated cryo flow, PRVNT will vent COPV pressure and ORV will prevent overpressing due to boil off
  - If QD is disconnected during power loss there is no safe way to vent the system
    - For this reason we will not test cryo fill with QD disconnect until cryo vent is made NO

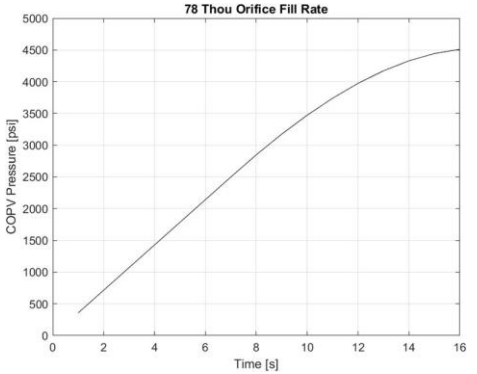
COPV Fill + Venting Rates

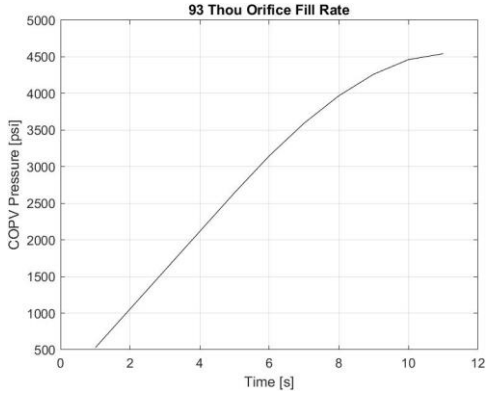
Filling and Venting

- Estimates assuming isentropic flow of ideal GN2
- Filling Rate
  - **35 Thou – 76 seconds**
  - 78 Thou – 16 seconds
  - 93 Thou – 11 seconds
- Venting Rate
  - 142 seconds
  - ~2.3 minutes





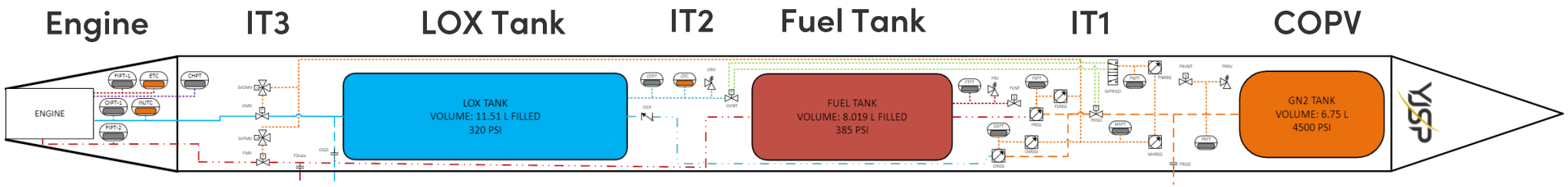




Flight Feed System

Overview

- **Fluid Storage**
  - COPV, Fuel and LOX Tanks
- **Intertanks**
  - IT1 – High Pressure, Pneumatics, Fuel Tank Components
  - IT2 – LOX Tank Components
  - IT3 – Main Valves, Fill Ports, Engine Feed



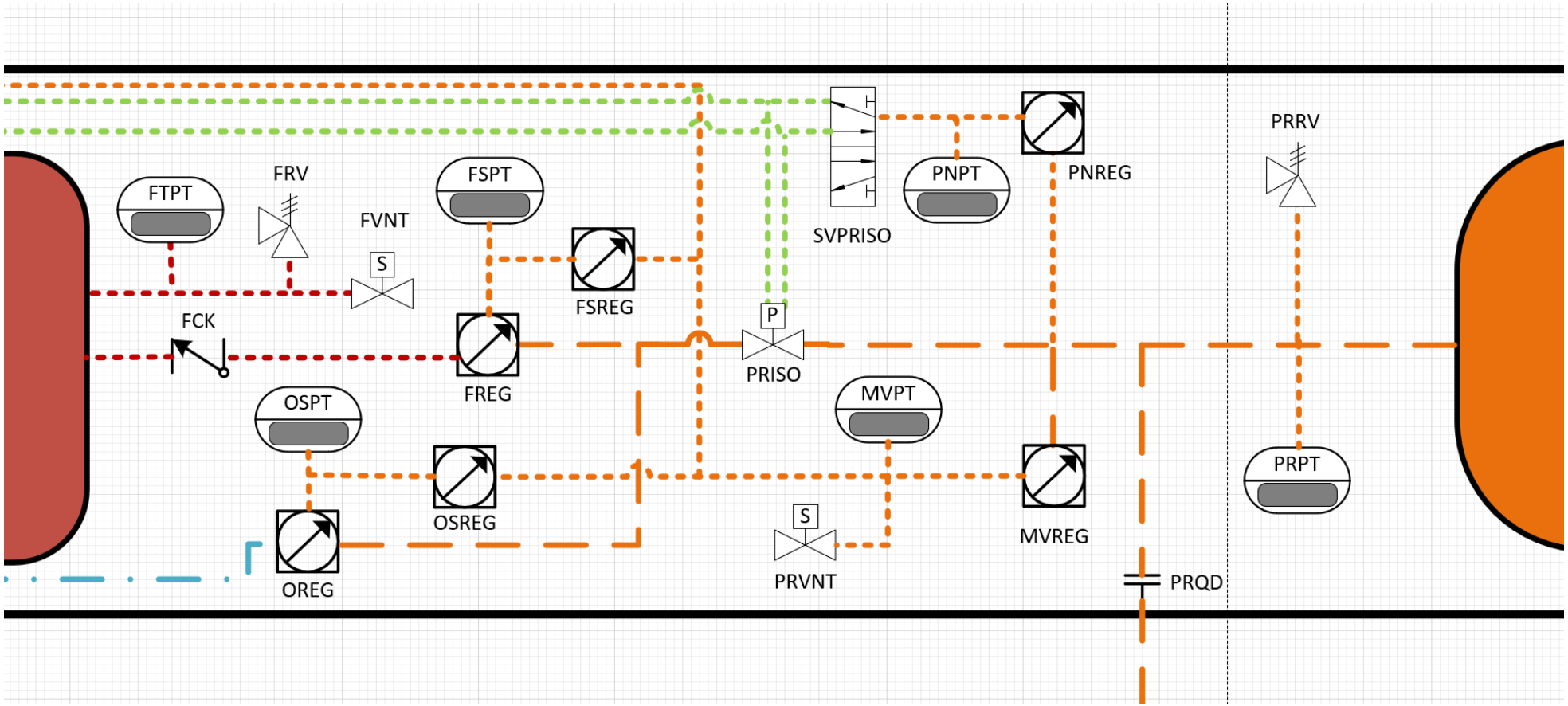
COPV – Composite Overwrapped Pressure Vessel

GN2, 4500 PSI

- Type 3 Pressure Vessel: Aluminum Liner, Carbon Fiber and Fiber Glass Composite
- 6.75 L, 15 year service life, DOT Specification
- Operating Pressure: 4500 PSI
- Proof Pressure: 7500 PSI, 1.67 FOS
- Burst Pressure: 15300 PSI, 3.4 FOS
- Hydrostatic Tested to 5000 PSI
- Proof Tested to 7500 PSI within the last 5 years (9/14/17)

Intertank 1

Pressurant, Pneumatics, Fuel



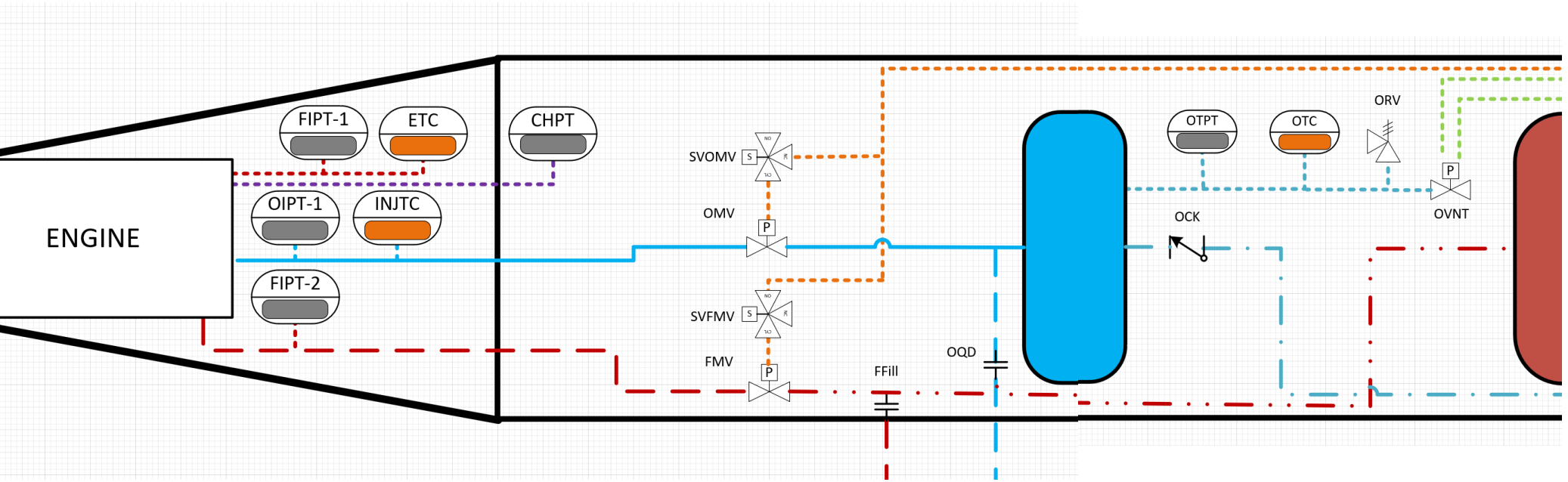
Propellant Tanks

Jet-A and LOX / Water and LN2

- **Fuel Tank**
  - Aluminum
  - Welded, Rods
  - 425 PSI MEOP, 3.3 FOS based on stress analysis
  - Proof tested to 700 PSI, 1.65 FOS
- **LOX Tank**
  - Stainless Steel
  - Welded
  - 355 PSI MEOP, 3.75 FOS based on stress analysis
  - Hydrostatic Proof Tested to 600 PSI, 1.7 FOS

Intertank 2 & 3

LOX, Main Valves, Engine



FFS Critical Components

- All vents are Normally Open
- Relief Valve Sizing
  - Relief valves have higher flow than regulators
  - ORV and FRV crack at 600 PSI
  - PRRV cracks at 4750 PSI, 0.14 in orifice

Component	Cv	Flow Rate (Ideal L/s)
FRV	1.041714676	3.626963885
FREG	0.8	2.785379888
ORV	1.041714676	3.626963885
OREG	0.8	2.785379888
PRRV	-	2.912321538

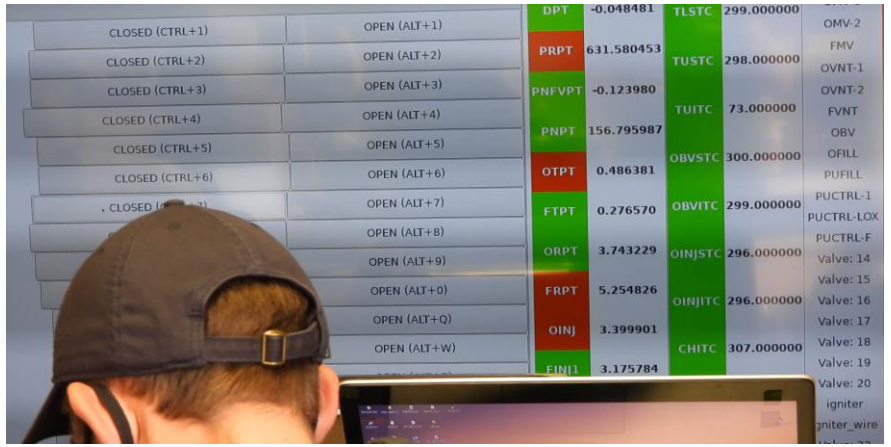
Avionics & MCFS

Remote Operation and Data Acquisition

Avionics systems designed to control the flight valves along with collecting sensor data. The Flight Stack is composed of a Data Acquisition device (DAQ) and Engine Controller (EC), and the stack uses the Master Computer Flight Software (MCFS) to receive commands from the Flight Operator. The operator can send electronic signals through the EC and read/collect data from the DAQ using the MCFS on their laptop to operate FFS completely remotely.

Flight Stack

MCFS



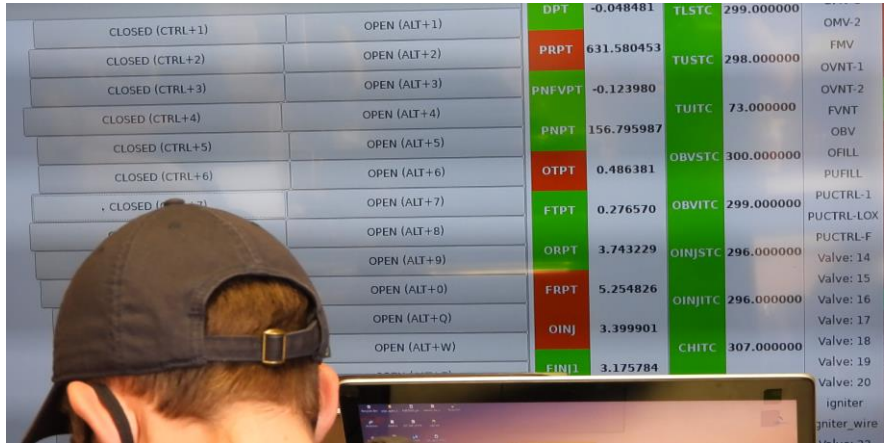
Ground Electronics & MCFS

Remote Operation and Data Acquisition

electronics are composed of a ground Data Acquisition device (DAQ) and ground Engine Controller (EC) which communicate to the Master Computer Flight Software (MCFS). The DAQ is used to collect and store sensor data within the combined ground and flight feed systems. The EC works to actuate electronic components, chiefly solenoids and motors. An operator can send electronic signals through the EC and read/collect data from the DAQ using the MCFS on their laptop to operate LFS remotely.

EC DAQ

MCFS



Test Config

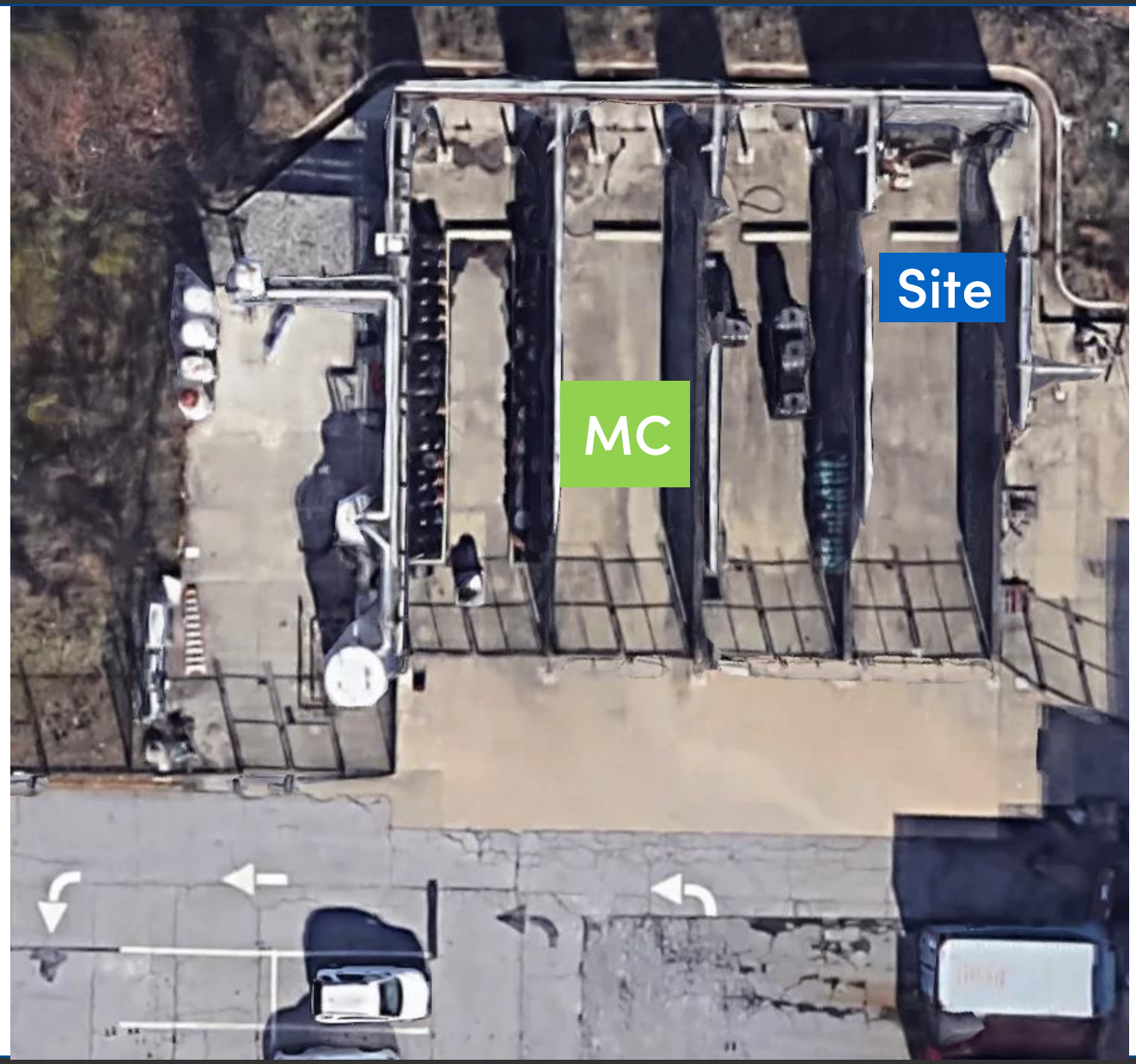
Test Site

FFS + LFS

Electronics

Mission Control

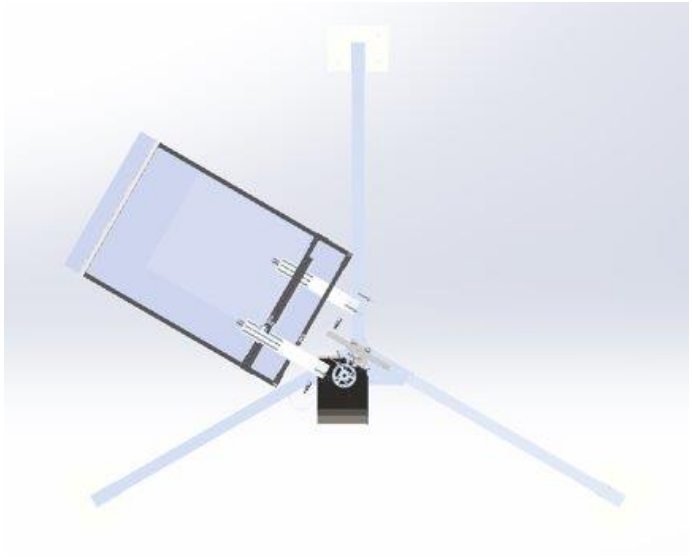
MCFS

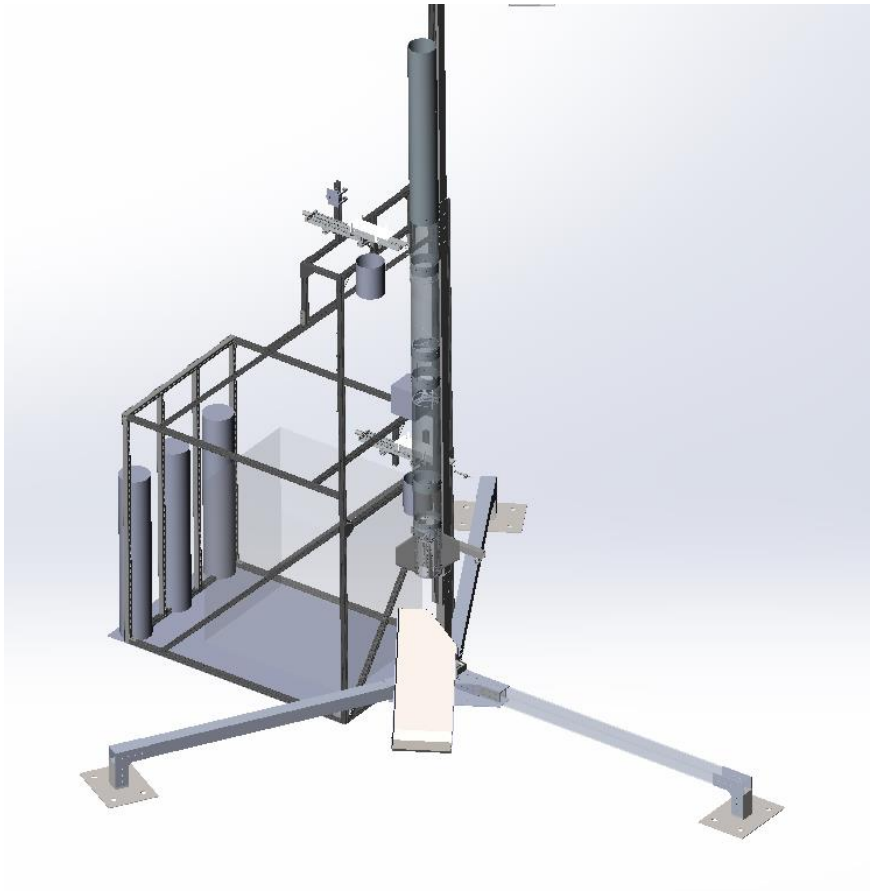


Test Configuration

Launch Config

- Launch Conditions
- Test integration between systems
  - Go Vertical with LCH
    Rail, Holddowns, Gantry, QDs,
    Blast Shield





Test Site Options

- Rightmost Test Cell

Issues & Solutions

LCH Configuration

- COPV Above Wall
  - Keep COPV below the top of the walls (secure to LR) and hose up to IT1, securing hose with hose clamps
- Fitting Launch Rail in Test Cell
  - Shorten one LR leg

Test Objectives

- COPV Fill Test
  - Fill and Vent Rate, Temperature Change, Leak Rate
- High Pressure Water Flows
  - Hysteresis, Validate COPV Sizing
- LFS Cryo
  - GOFILL Actuation, GOVNT Actuation, Chill-In Times
- Cryo Fill
  - Fill Time, Boil-Off, Insulation Validation
- Cryo Actuation
  - OQD Disconnect, OMV Timing, Collapse Factor

COPV Fill Test

Test Parameters: 4500 PSI, GN2, Horizontal Configuration

Objectives

- Confirm the COPV and IT1 can hold 4500 PSI of GN2.
- Measure the fill time with various sized orifices (GPRORF) on LFS, options include a 35 and 73 thou orifice.
- Measure the temperature change during and after fill to calculate the change in pressure as a result of temperature rise (as opposed to leaking).
- Measure the effects of hysteresis on the flight regulators by comparing their changes in outlet pressures as a result of an increasing or decreasing inlet pressure.
- Find the time to vent COPV from 4500 PSI to 0 PSI through PRVNT.

Procedure Outline

1. Set Up
    1. MCFS and Electronics
    2. FFS and LFS
2. Click Checks (COPVTC and ORFTC)
4. COPV Fill
    1. Fill 4500 PSI with LFS
    2. Hold Pressure for 5 minutes
    3. Vent with PRVNT to 4000 PSI
    4. Refill COPV to 4500 PSI
    5. Hold for 1 minute
    6. Vent to ambient, wait 3 minutes
    7. Switch Orifice and Repeat

High Pressure Water Flows

Test Parameters: 4500 PSI, GN2 and Water, Vertical Configuration, LCH Rail or Vertical Stand

Objectives

- Reconfirm test results from low pressure water flows.
- Find the remaining pressure in the COPV, starting with 4500 PSI, after a complete 11 second.
- Compare the remaining pressure in the COPV when there is no top off from LFS after opening PRISO and when there is a top off filling back to 4500 PSI.
- Find the fuel purging rate, the rate that GN2 escapes through the fuel annulus from a known pressure in the COPV to the minimum closing pressure of FMV.

Procedure Outline

1. Set Up
    1. MCFS and Electronics
    2. FFS and LFS
2. Click Checks
3. Go Vertical
4. Fill Tanks
5. COPV Fill
    1. Hold 4500 PSI for 1 min to quantify leak rate
6. Water Flow
    1. 11 second flow Fuel and LOX sections, run 3-5 times
    2. Flow / purge till FMV closes, run 3 times
7. Reset
    1. Vent to ambient
        1. Adjust regulators if needed due to hysteresis or pressure drop
    2. Refill
        1. Adjust Fill Volume if 11 seconds was not met
    3. Repeat Water Flow

LFS Cryo

Test Parameters: GN2 and LN2, LFS Only

Objectives

- Validate LFS Cryo Capabilities
- Measure chill-in time
- Confirm functionality of GOVNT-2 and GOFILL

Procedure Outline

1. Click Check
2. Reg up pneumatics and ensure GOFILL actuates
3. Open Dewar and GOVNT-1. GOFILL is closed. Chill in Dewar-GOFILL line
4. Open GOFILL and chill in lines up to OQD
5. Test venting of GOVNT-2
6. Measure chill rate with TCs
7. Close dewar and open vents to safe the system

Cryo Fill

Test Parameters: 2000 PSI, GN2 and LN2, Vertical Configuration, LCH Rail

Objectives

- LCH Integration
  - QD Alignment
- LFS + FFS Cryo Integration
- Validate FFS Cryo Capability
- Fill Time
- Insulation Testing
  - Validate Insulation Calcs
  - Fuel Line Freezing
- Boil-Off Time after Flow
  - OVNT Cryo Actuation

Procedure Outline

1. Go Vertical
2. Connect QDs
3. Open Pneumatics K-Bottle
   1. Confirm GPRFILL and GOFILL Actuation
4. Open Dewar, Chill-In LFS
5. Open Pressurant K-Bottle, Leave Test Site
6. Fill LOX Tank
   1. Open GOFILL, Confirm OVNT is open, OTC and Load Cells measure fill amount
7. Fill COPV to 1500 PSI
   1. Open GPRFILL, Confirm PRISO is closed
8. Pressurize Tanks
9. Open OMV for 9 seconds
10. Vent boil-off through OVNT
11. Refill and Repeat

Cryo Actuation

Test Parameters: 4500 PSI, GN2 and LN2, Vertical Configuration, LCH Rail

Objectives

- LCH Integration
- QD Disconnect
- OMV Actuation under Cryo and Valve Timing
- Collapse Factor
- Pressurant Remaining with and without refilling COPV after pressurizing tanks
- Boil-Off Time after Flow
    - OVNT Cryo Actuation

Procedure Outline

1. Go Vertical
2. Connect QDs
3. Open Pneumatics K-Bottle
    1. Confirm GPRFILL and GOFILL Actuation
4. Open Dewar, Chill-In LFS
5. Open Pressurant K-Bottle, Leave Test Site
6. Fill LOX Tank
    1. Open GOFILL, Confirm OVNT is open, OTC and Load Cells measure fill amount
7. Disconnect OQD
8. Fill COPV to 4500 PSI
    1. Open GPRFILL, Confirm PRISO is closed
9. Pressurize Tanks
10. Refill COPV
11. Disconnect PRQD
12. Open OMV for 9 seconds
13. Vent boil-off through OVNT
14. Refill and Repeat

Risk Avoidance

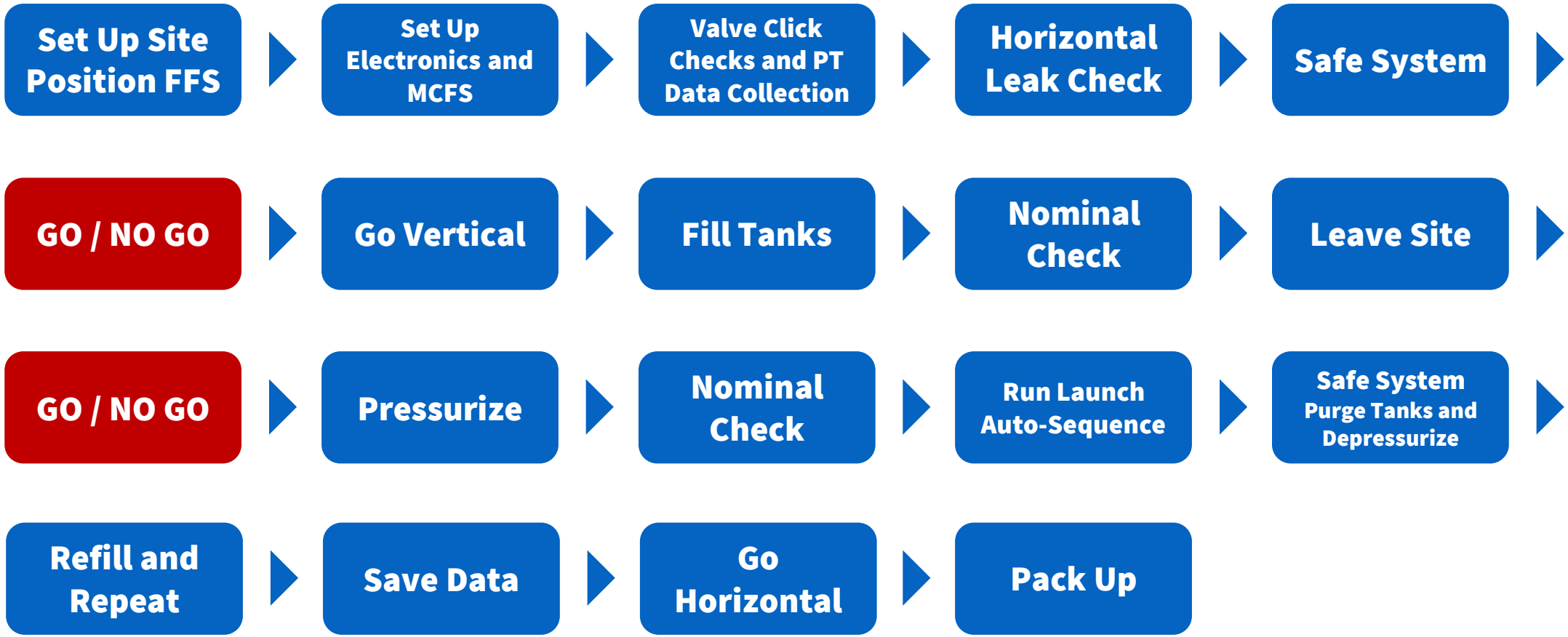
- PPE
  - Eye Protection
  - Ear Protection
  - Hardhats
  - Cryo Gear
- Safety Checks Prior to working with high pressure
  - Click Checks
  - Man Safe Leak Checks under 500 PSI
- Remotely Controlled System while under high pressure
  - Operated from a safe distance
  - Live camera streaming of test site
  - Approaching system only when upstream of GPRFILL has pressure to open/close K-Bottle

Test Procedures

Personnel

- **Test Responsible Engineer (TRE):** Follows procedures and makes final decisions. Directs personnel and sends commands to MCFS Operator.
- **Down Range Personnel (DRP):** Set up test and inspects system to ensure test readiness.
- **MCFS Flight & Ground Operators (OP):** Sets up and controls MCFS. Communicates directly with TRE relaying data and system states.
- **Note Takers:** Writes down every issue, solution, delay, and change to procedure. They also note important values from our data, time stamps for major events, and any other notable occurrences. There are two designated note takers, one down range and one in MC taking note of MCFS.
- **Go Vertical Crew:** Minimum of 5 required to go vertical with water flow stand, 8 required for LCH Rail.
- **Water Filler:** Fills ground tank for "Fuel Fill" using water.
- **Cryo Warrior:** Wears cryo gear and opens and closes LN2 dewar

General Flow Procedure



COPV Fill Test Procedures

1. Set up live camera feed of FFS and LFS. Confirm visibility in MC.
2. Everyone except for the K-Bottle Opener/Closer Leaves the Test Site. They should have a walkie and all PPE, including over ears.
3. Confirm that everyone is wearing ear and eye protection, including those in MC.
4. Confirm PRISO is closed.
5. Set Up LFS
    1. Confirm GPNREG is backed out
    2. Open pneumatics K-Bottle
    3. Set GPNREG to 80 PSI
    4. Open and Close GPRFILL it to confirm it actuates.
    5. Confirm GPRFILL is closed.
    6. Confirm GPRREG is backed out
    7. Open pressurant K-Bottle
    8. Set GPRREG to 4500 PSI
    9. TRE goes to MC, Confirm the test site is empty of people
6. Nominal Check
    1. Confirm Correct Valve States for FFS
        1. All valves closed except for OVNT. Ensure PRISO is closed.
    2. Confirm PTs and TCs read ambient
        1. Ensure COPVTC and ORFTC are working
7. Pressurize COPV to 4500 PSI
    1. Open Plot of PRPT, COPVTC, and GTC
    2. Create MCFS Marker
    3. Open GPRFILL
    4. Wait until COPV is Filled to 4500 PSI
    5. Close GPRFILL
    6. Create MCFS Marker
8. Hold Pressure for 5 minutes
    1. Calculate leak rate for each minute
    2. Take Picture of All PT Readings
    3. Analyze Plots of PRPT, COPVTC, and GTC
9. Vent with PRVNT to 4000 PSI
10. Refill COPV to 4500 PSI
11. Hold for 1 minute
12. Vent to ambient, wait 1-5 minutes, observe COPVTC
13. Repeat COPV Fill once with current orifice
14. Switch Orifice and Repeat COPV Fill

Cryo Procedures

1. Confirm Valve and Sensor States, and data collection is enabled on MCFS.
2. Set up live camera feed of FFS and LFS. Confirm visibility in MC.
2. Everyone except for the TRE leaves test site.
3. Confirm that everyone is wearing ear and eye protection, including those in MC, and Cryo Warrior has cryo PPE.
5. Set Up LFS
    1. Confirm GPNREG is backed out
    2. Open pneumatics K-Bottle
    3. Set GPNREG to 80 PSI
    4. Confirm GPRFILL actuates and remains closed
    5. Confirm GOFILL actuates and remains closed
    6. Connect cryo hose to dewar
    7. Confirm GOVNTs are closed
    8. Confirm GPRREG is backed out
    9. Open pressurant K-Bottle
    10. Set GPRREG to desired pressure
    11. Open LN2 Dewar
    12. Leave Test Site
1. Fill
    1. Confirm OVNT is open and PRISO is closed
    2. Open GOFILL, close once LOX Tank is full based on Load Cells and OTC
    3. Disconnect OQD
    4. Open GPRFILL, watch PRPT
    5. Pressurize Tanks
    6. Refill COPV, close GPRFILL, disconnect PRQD
2. Flow
    1. Open OMV for desired flow time
    2. Measure boil-off time of remaining LN2 through OVNT
3. Safe System
    1. Close PRISO
    2. Open PRVNT and FVNT
    3. Wait until PTs read ambient
    4. Close K-Bottles
    5. Close LN2 Dewar
    6. Vent Cryo Hose with OVNT-1

Contingency Planning

- Pressure Leak
  - System will depressurize automatically, and eventually become safe to approach. We will then redo the horizontal leak check using snoop to find and tighten each fitting to torque spec.
- Pneumatics Loss
  - If pneumatic valves can no longer be actuated while OVNT is closed, the LOX tank can be vented manually by cracking a fitting. Everything else can be vented remotely beforehand.
- MCFS Power Loss
  - The system will remain in the same state, and we can reconnect without altering the state of the system. If disconnected for 5 min all valves return to their normal states.

Contingency Planning

- EC Power Loss
  - The system will immediately go to its default, unpowered state. This will open all vents. We will then attempt to reconnect to the system, which will briefly power all valves, but we will do this remotely.
- DAQ Power Loss
  - Operators will safe the system using safing procedures and we will attempt to reconnect the DAQ.
- Flipped Logic
  - The valve will be noted and everyone will be informed, and if the valve is in the auto sequence, we will halt the test, safe the system, and fix the logic.

Contingency Planning

- LCH Rail Falling
  - LCH Rail will be secured with guy wires and all personnel within 20 ft will be wearing hardhats.
- PRVNT Failure
  - GPRVNT can be vented as back up as long as PRQD is not disconnected. Pressure can also be vented through FVNT although it would be extremely slow or opening one of the main valves could also be used to vent.
- OVNT Failure
  - If OVNT cannot be actuated, we will vent out of OMV if it is safe to do so with no personnel near the vehicle.
- FVNT Failure
  - If FVNT is unable to actuate, we will vent out FMV to ~100 PSI, then go crack a fitting to vent the rest.