Helios (+ Test Stand)
Design Review

Objective

- Long term
    - Learn about liquid propulsion technologies through the design, build and testing of bipropellant liquid rocket engines
- Short term
    - Develop a test stand and feed system capable of supporting future engine iterations
    - Conduct hot fire testing of simple, uncooled engine

Safety

- Adherence to EHS guidelines when dealing with high pressure gasses and cryogenic fluids
- SOPs for the following will be approved before any testing is conducted:
    - Handling of LOX
    - High pressure testing
    - Hot fire testing
- Operational safety measures
    - PPE (safety glasses, hearing protection, etc.)
    - Long shirt/pants, closed toed shoes, etc.
- Material Safety Data Sheet (MSDS) will be referenced for any hazardous materials

Contents

- Test Stand Review
  - Feed architecture
  - Operating conditions
  - Parts breakdown: Regulators, relief valves, control valves, etc.
  - Tanks
  - Test stand structure
  - DAQ/Electronics
  - Oxygen cleaning
- Engine Review
  - Engine sizing
  - Injector
  - Chamber
  - Ports
  - Igniter
  - Engine mounting
- Project Timeline

Test Stand / Feed System

Overview

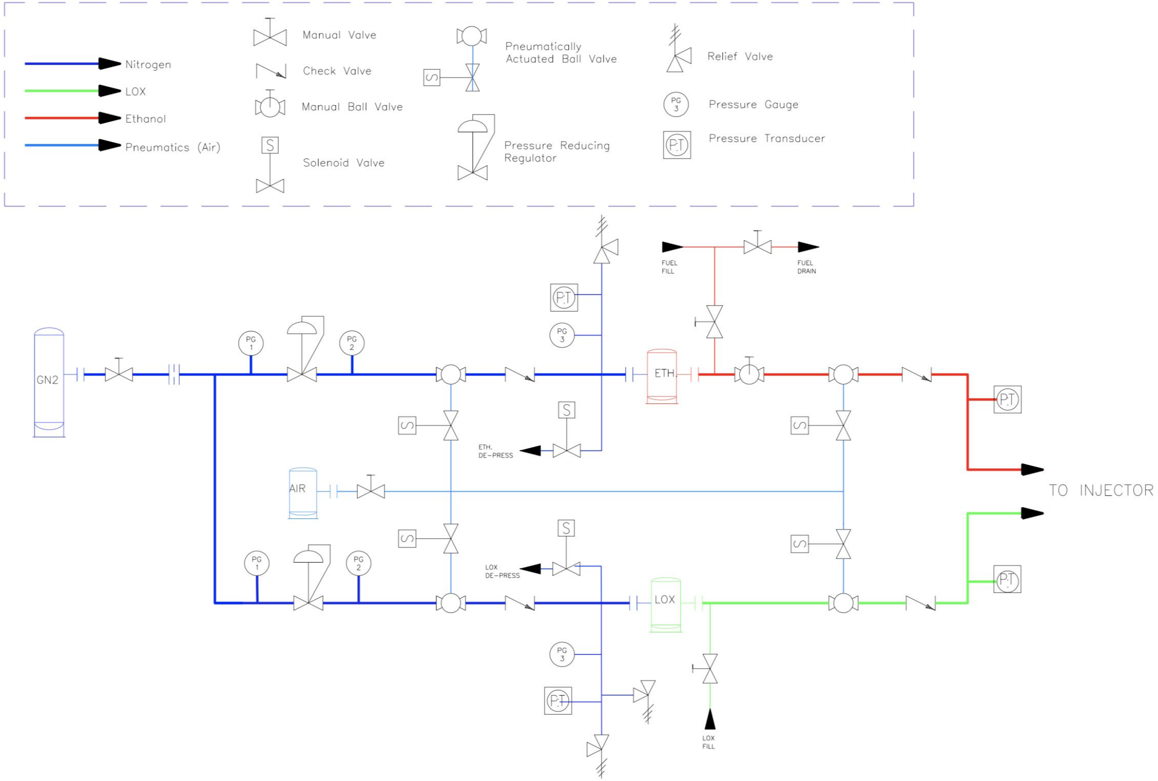
- Feed system capable of supporting a pressure-fed LOX-ethanol test engine
  - Tanks
    - 2x aluminum tanks, one insulated for LOX
  - Plumbing
    - ½” SS piping, pneumatically actuated control valves, see P&ID
  - DAQ
    - Load cell, thermocouples, pressure transducers, stored on MicroSD
  - Structure
    - 1.5” 80/20 structure, staked to the ground w/ ratchet straps

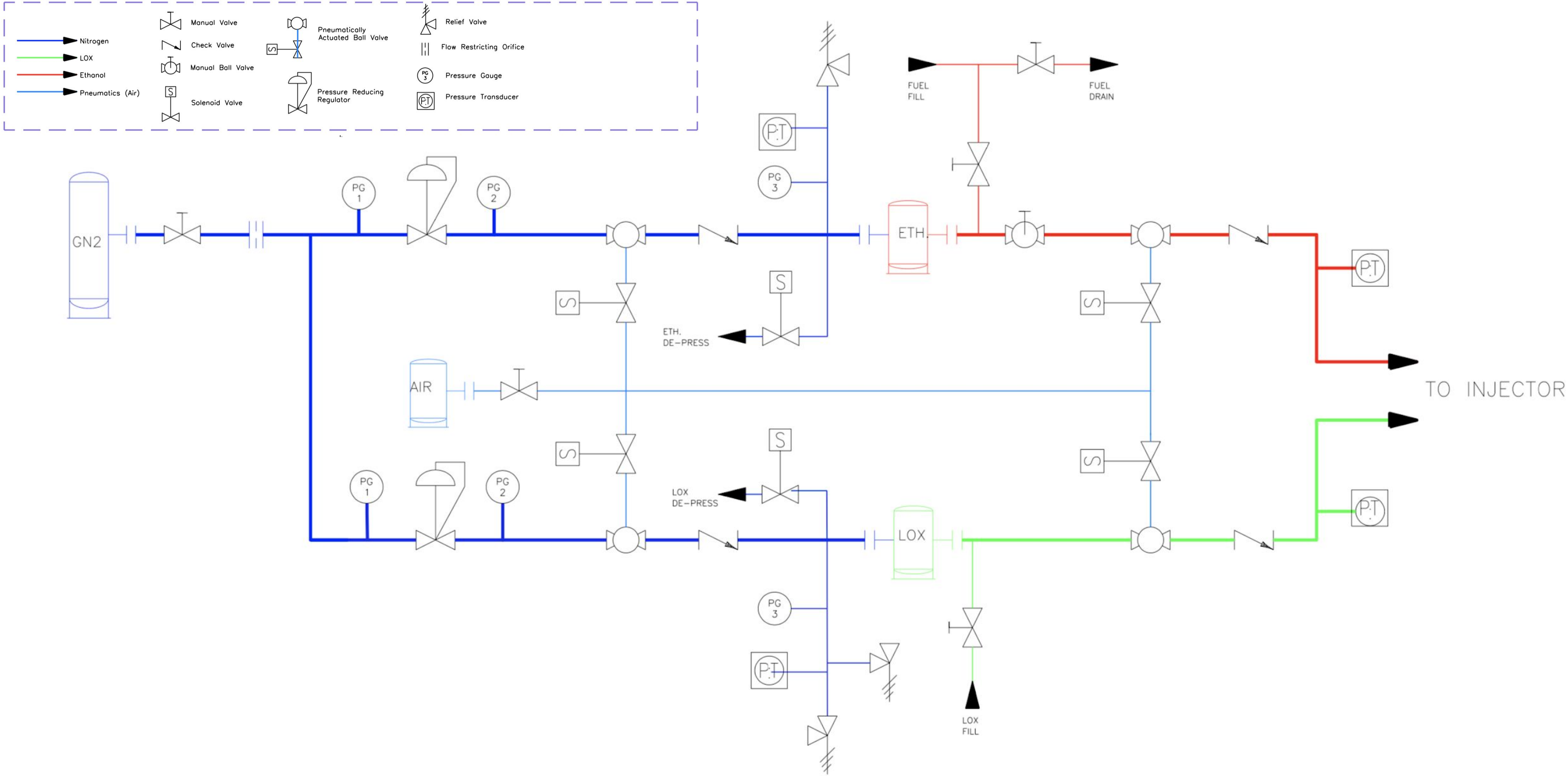
System Fluids and Gases

- Fuel:
    - **Ethanol** was chosen for good combustion properties and lower combustion temperature when diluted (using 70% ethanol solution)
    - Ease of procurement and low cost
- Oxidizer:
    - **LOX** chosen due to ease of procurement, prevalence in modern propulsion systems
    - Safer than GOX due to autoignition point
    - Allows for learning on handling cryogenics
- Pressurant:
    - **Nitrogen** used for Ethanol and LOX pressurant: inert, easy to procure and cheap
    - Pressurants will be stored in COTS tanks at 3000 psi (tank pressure), and pressure will be reduced with regulator

Feed System

- Nearly identical GN2-LOX & GN2-Ethanol lines, ½” piping
- 3000 psi GN2 reduced to ~600 psi for propellant tank pressurization
- Manual valves for safe on-site fueling

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LOX
Ethanol
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Check Valve
Manual Ball Valve
Solenoid Valve
Pneumatically Actuated Ball Valve
Pressure Reducing Regulator
Relief Valve
Flow Restricting Orifice
Pressure Gauge
Pressure Transducer
GN2
PG 1
PG 2
PG 3
P.T
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ETH.
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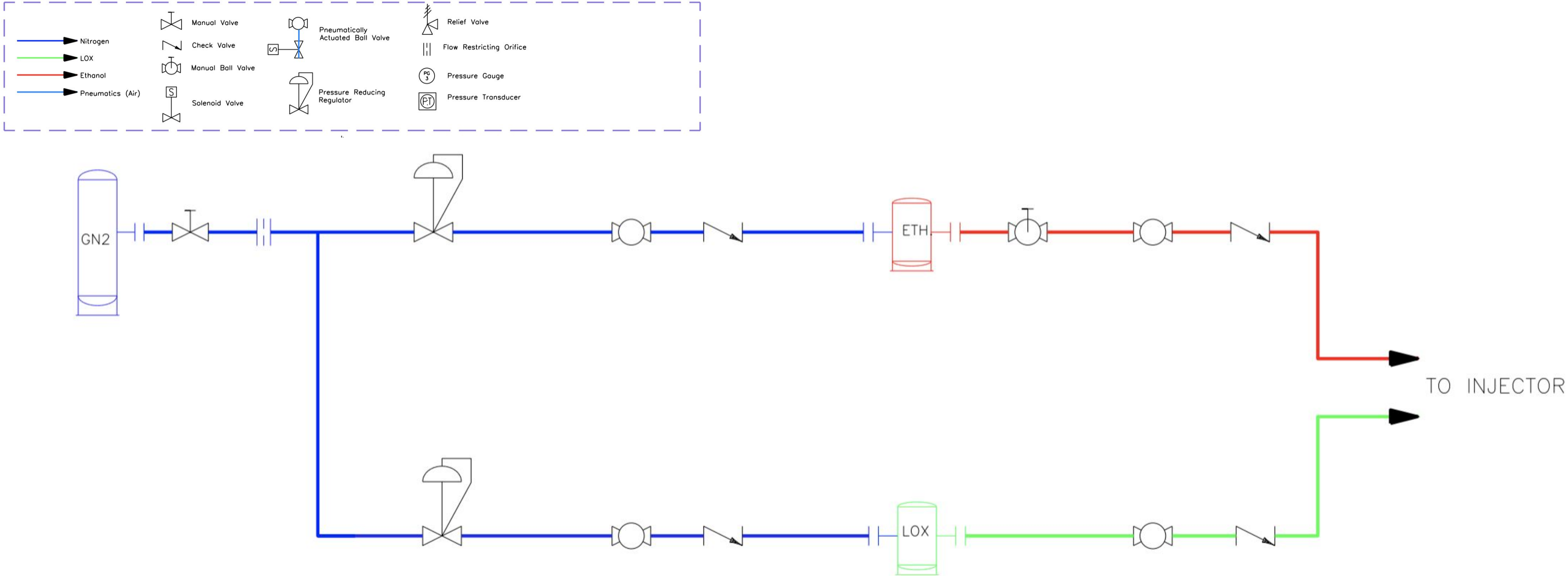
TO INJECTOR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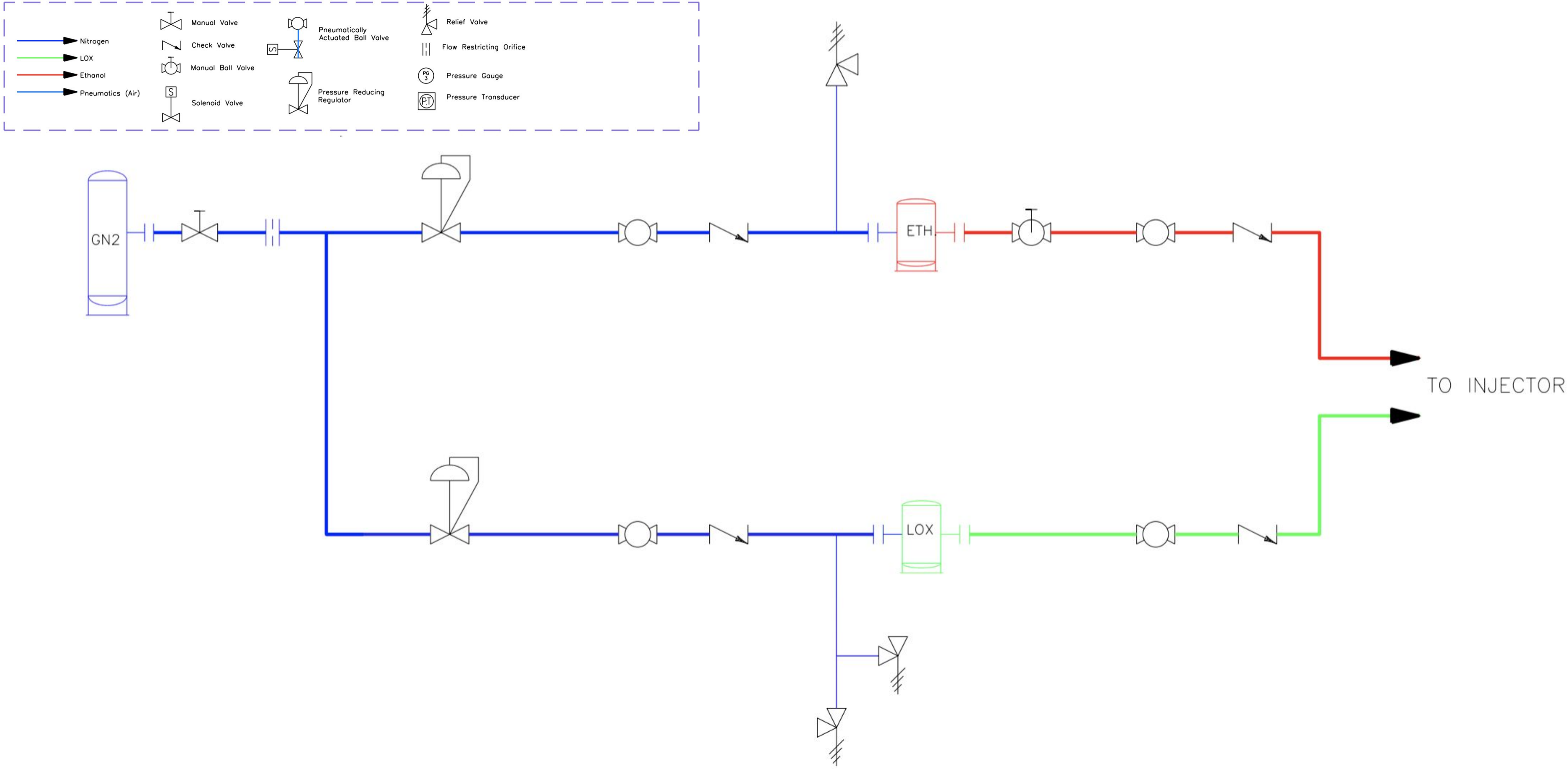
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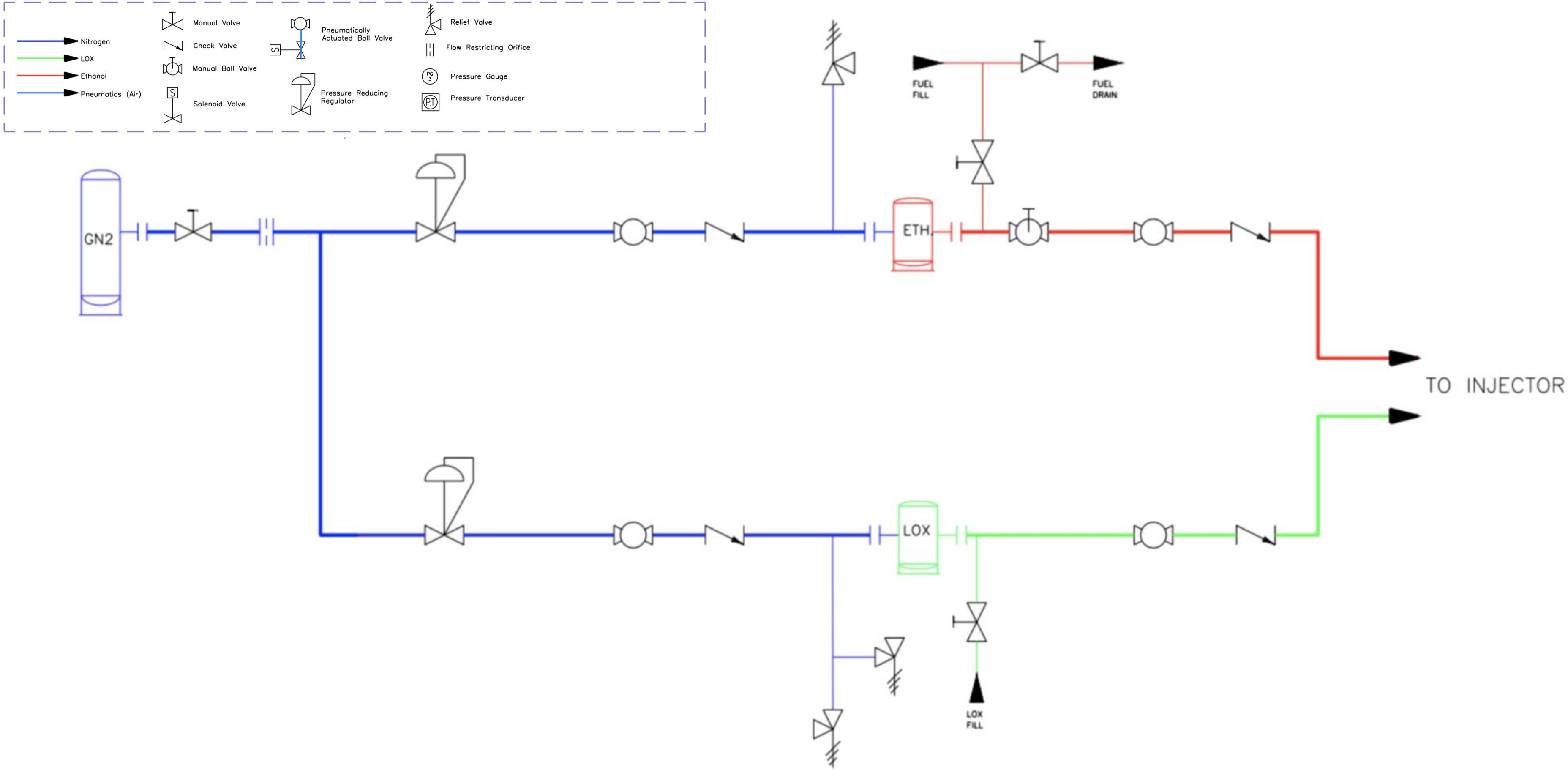
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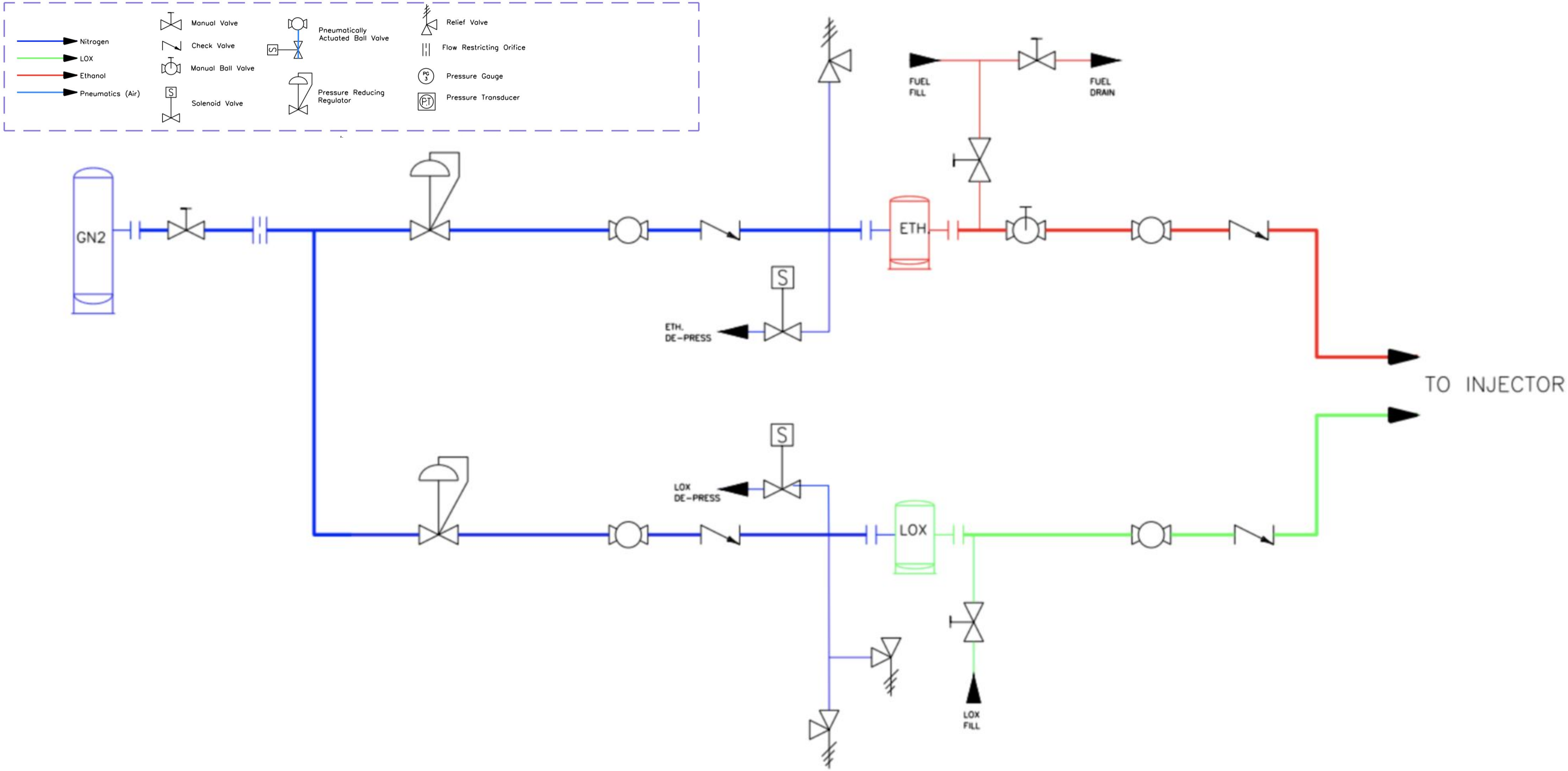
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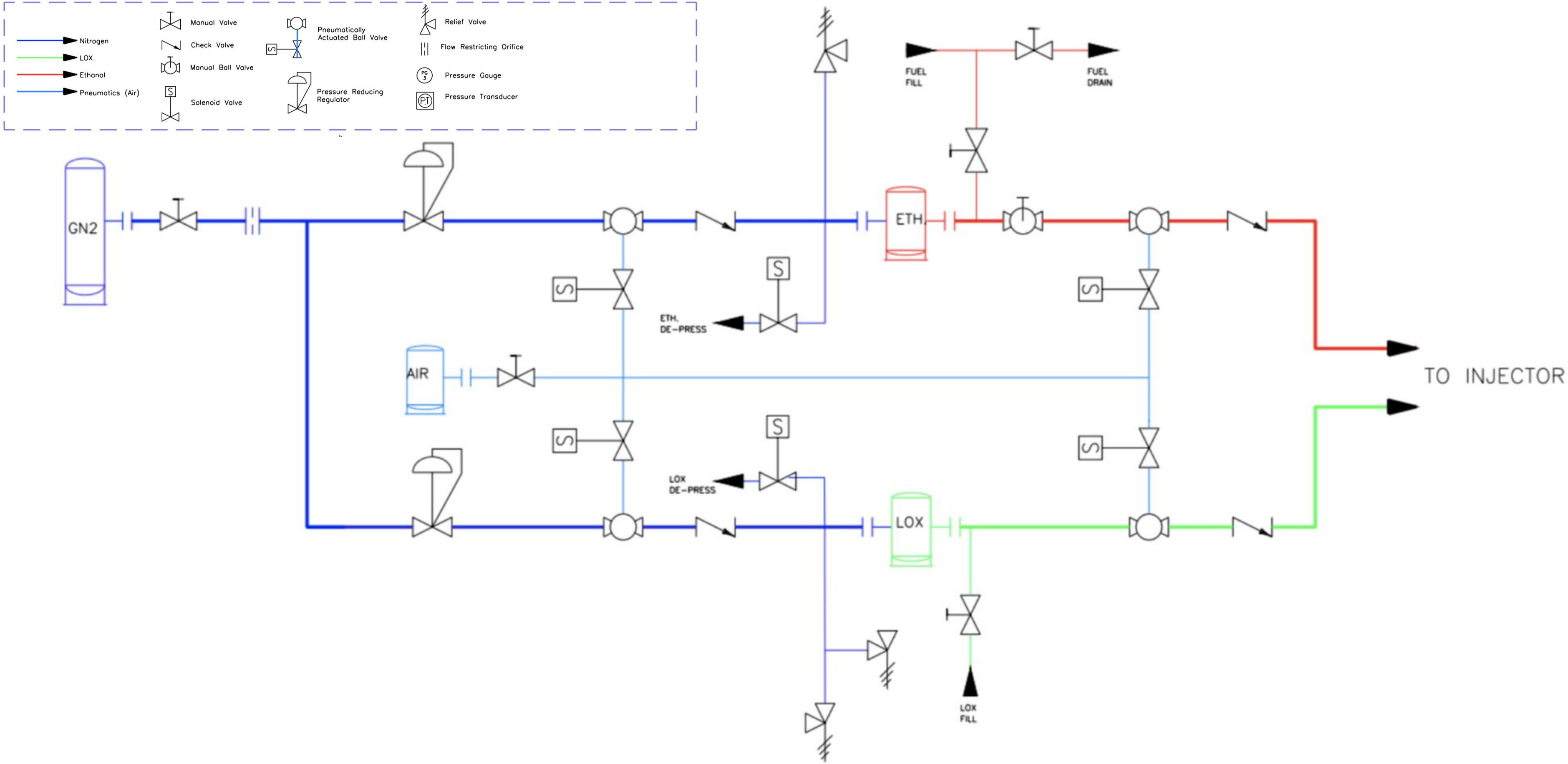
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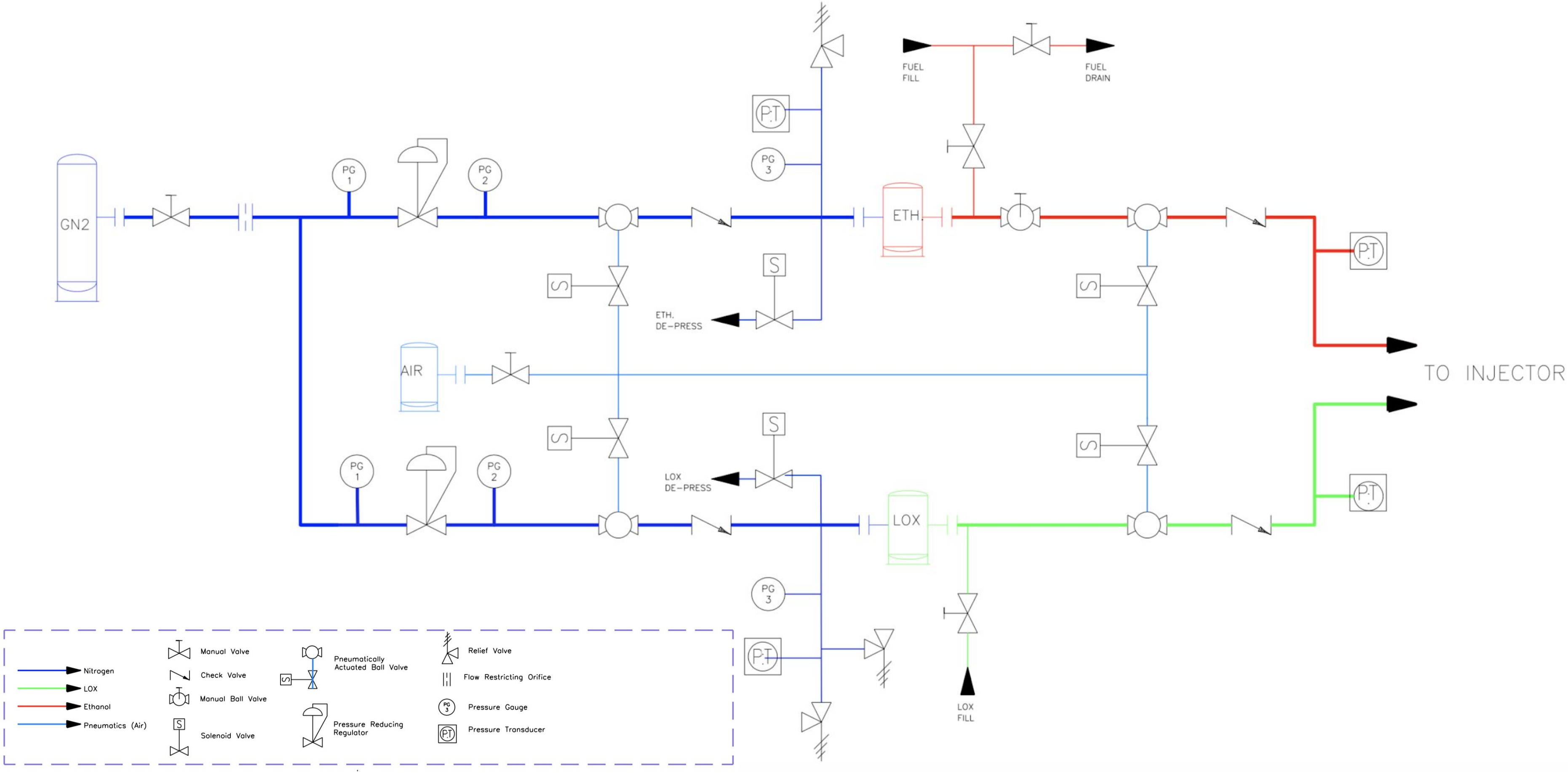
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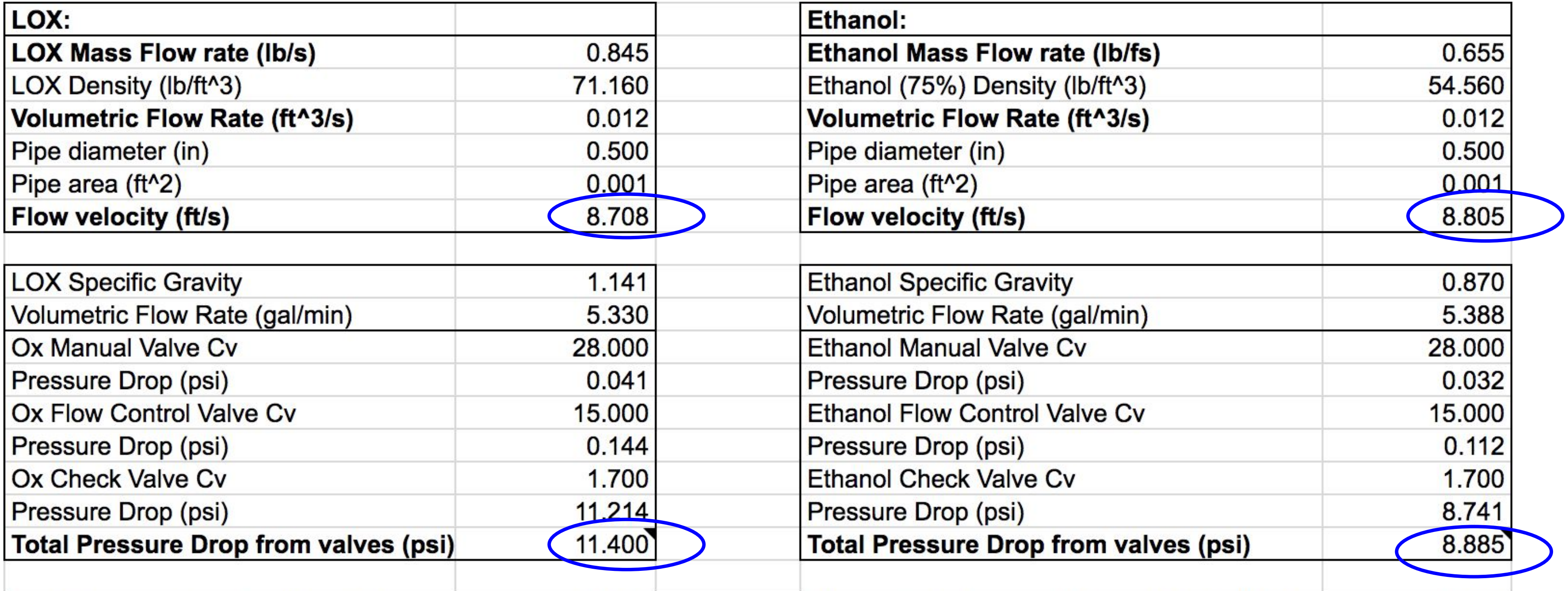
Flowrates (cont.)



LOX:	
LOX Mass Flow rate (lb/s)	0.845
LOX Density (lb/ft^3)	71.160
Volumetric Flow Rate (ft^3/s)	0.012
Pipe diameter (in)	0.500
Pipe area (ft^2)	0.001
Flow velocity (ft/s)	8.708

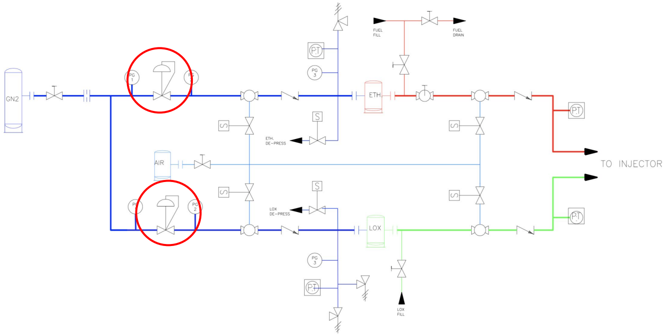
LOX Specific Gravity	1.141
Volumetric Flow Rate (gal/min)	5.330
Ox Manual Valve Cv	28.000
Pressure Drop (psi)	0.041
Ox Flow Control Valve Cv	15.000
Pressure Drop (psi)	0.144
Ox Check Valve Cv	1.700
Pressure Drop (psi)	11.214
Total Pressure Drop from valves (psi)	11.400

Ethanol:	
Ethanol Mass Flow rate (lb/fs)	0.655
Ethanol (75%) Density (lb/ft^3)	54.560
Volumetric Flow Rate (ft^3/s)	0.012
Pipe diameter (in)	0.500
Pipe area (ft^2)	0.001
Flow velocity (ft/s)	8.805

Ethanol Specific Gravity	0.870
Volumetric Flow Rate (gal/min)	5.388
Ethanol Manual Valve Cv	28.000
Pressure Drop (psi)	0.032
Ethanol Flow Control Valve Cv	15.000
Pressure Drop (psi)	0.112
Ethanol Check Valve Cv	1.700
Pressure Drop (psi)	8.741
Total Pressure Drop from valves (psi)	8.885

Regulators

- Requirements
    - Reduce bottle pressure from 3000 psi to the system operating pressure of ~620 psi
    - High flow rate capability
- The Victor FSH4 inert gas regulators fit our requirements for inlet and outlet pressure, flow rates
    - Cv = 0.114, minimal outlet pressure drop
- Tanks will be oversized to absorb pressure spikes during startup transients



Flow Control Valves

Requirements:

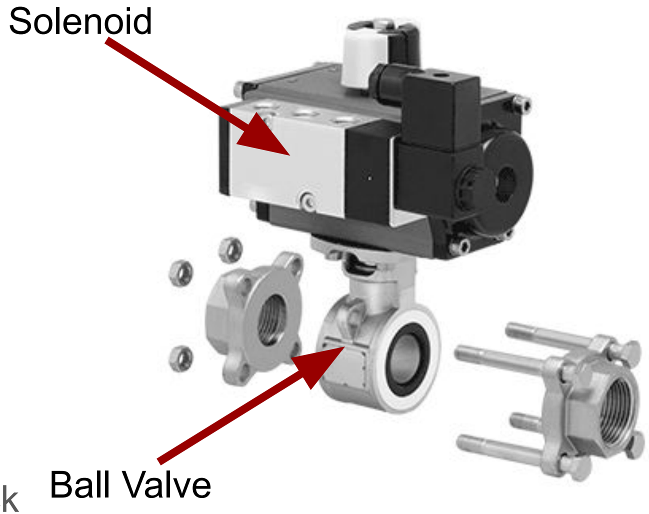
- Provide flow control (on/off) flow for the propellants and pressurants of the system.

Desired characteristics

- Rated for system operating pressure (600 psi)
- Large orifice
- Cryo-compatible w/ PTFE seal
- Remotely actuated

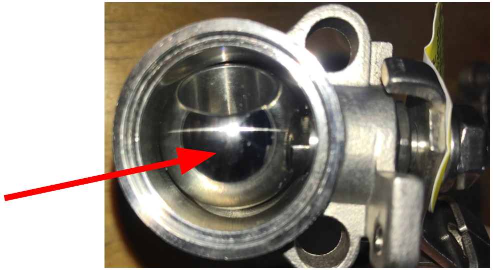
Ball Valves vs. Solenoid Valves

- Ball valve chosen over solenoids
- Solenoids typically have smaller orifices, lower flow rates, lack PTFE seals, and are more mechanically complicated.



Flow Control Valve Pt. 2

- A pneumatically actuated ball valve is the best option for our system
    - Chosen valve is cryo-compatible, has a max pressure of 1500 psi, and is operated via pneumatics controlled by a solenoid
- To prevent enclosed LOX within a closed ball valve, a small hole is drilled on the upstream side of the ball to allow LOX boil-off to vent



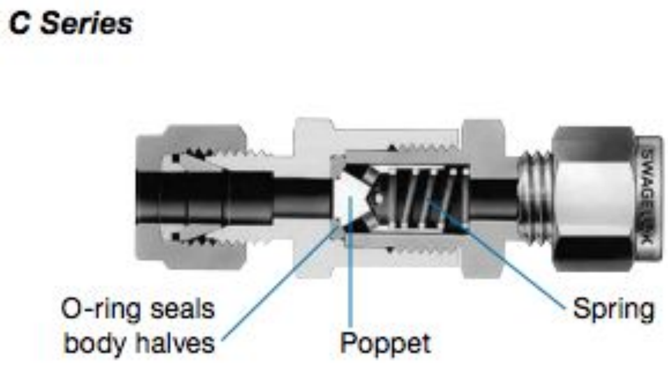
Check Valves

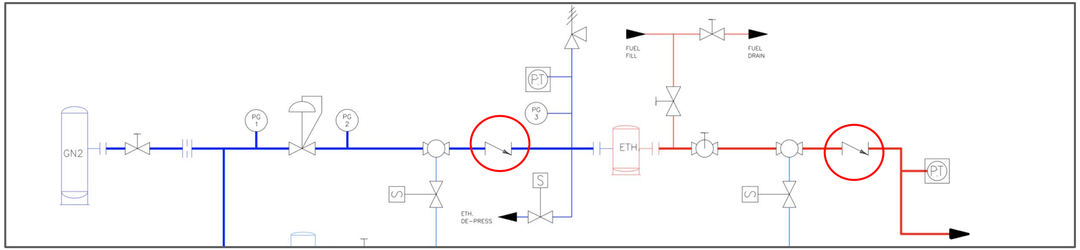
Requirements:

- Prevent combustion instabilities from propagating upstream
- Prevent flow of propellants into gas feed system

Valve characteristics:

- Cryo-compatible with a PTFE seal
- 3000 psi max pressure
- 1.68 Cv
- ½” NPT fitting
- 5 psi cracking pressure



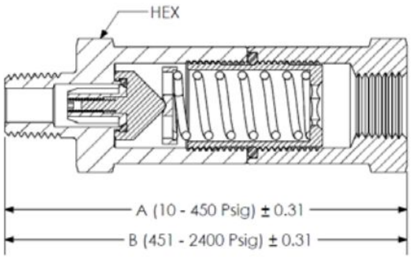


Relief Valves

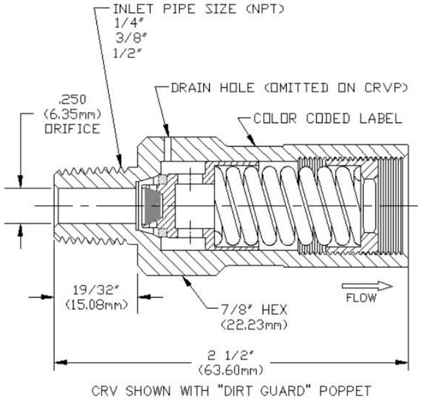
- Requirements
  - Provide adequate pressure relief (venting to atmosphere) in the ever of an overpressure scenario
  - Vent LOX boil-off to atmosphere
- Relief valves require set pressure above operating pressure and sufficient flow rate in the situation of a malfunctioning regulator
- Burst disks will be used as a second layer of overpressure protection

$$m = K_d * A * P_i \sqrt{\frac{k * g}{T * R} * (\frac{2}{k+1})^{\frac{k+1}{k-1}}}$$ = 639 SCFM of relief capability

(Choked)



HPRV
Inline

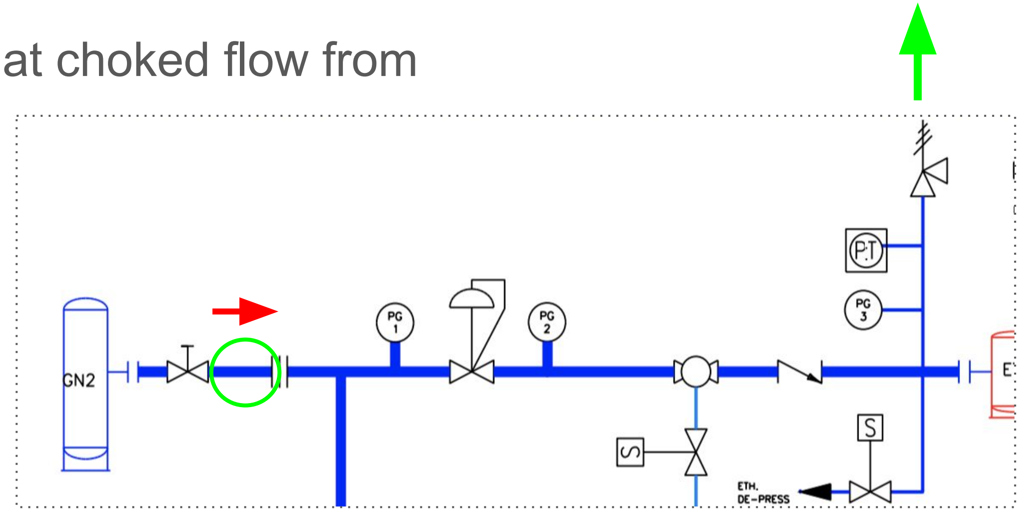


Relief Valves (cont.)

- GN2-Ethanol Line
    - 1x Large orifice pressure relief valve to protect against overpressure events (failed regulator, etc.)
    - Flow restricting orifice on GN2 source limits flow rate from high-pressure bottle
- GN2-LOX Line
    - 1x Cryogenic Relief Valve (CRV) for boil-off venting
    - 1x Large orifice pressure relief valve to protect against overpressure events (failed regulator, etc.)
    - Flow restricting orifice on GN2 source limits flow rate from high-pressure bottle
- Pneumatics
    - 1x Low pressure relief valve

Flow Restricting Orifice

- Flow restriction orifice necessary in the event of a regulator failure
- Limits maximum flow rate such that choked flow from N2 bottle < relief valve flow rate



$$m = K_d * A * P_i \sqrt{\frac{k * g}{T * R} * (\frac{2}{k+1})^{\frac{k+1}{k-1}}}$$ (Choked)

$$m = K_d * A * \rho * (\frac{P_o}{P_i})^{\frac{1}{k}} * \left(\frac{1}{144}\right) * \sqrt{2 * g * R * T * \frac{k}{k-1} * (1 - \left(\frac{P_o}{P_i}\right)^{\frac{k-1}{k}})}$$ (Unchoked)

Manual Control Valves

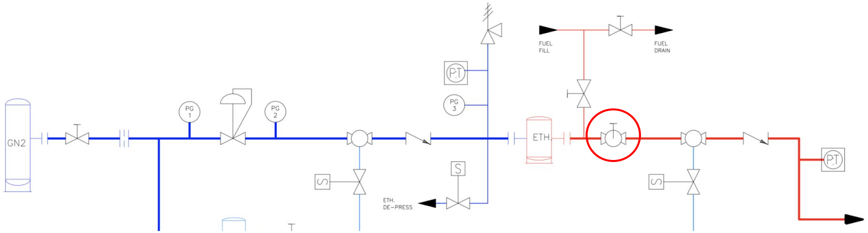
*Located before the flow control valves

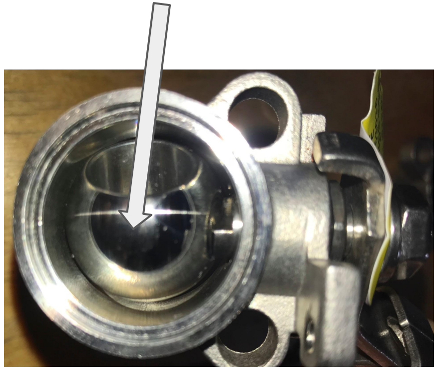
Requirements:

- Act as an extra safety precaution when the system is not in operation
- Provide manual control for filling the ethanol line

Specifications:

- Identical to the ball valve component of the flow control valves.
  - Same Cv, orifice size, etc.
- Easy maintenance
- Parts breakdown of a manually actuated ball valve>>




Vent hole machined here

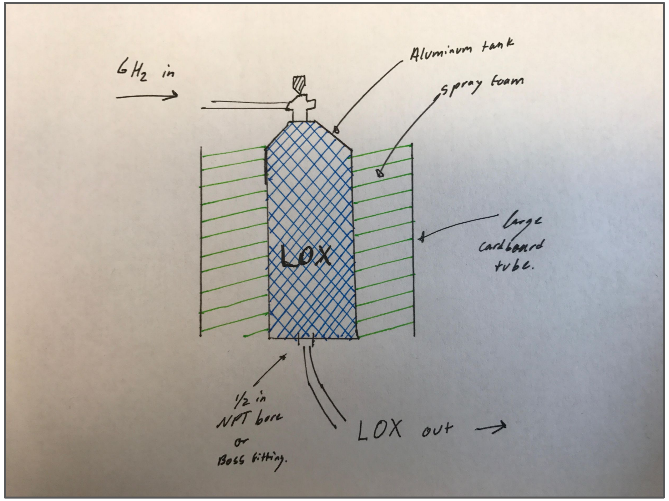
Tanks

Requirements:

- Hold pressurized LOX/Ethanol after pressurization and before ignition
- Must be rated much higher than system pressure & cryo compatible
- minimum ~2L capacity for 5 second burn time of both ethanol and LOX

Tank Specifications:

- Two Aluminum 10lb CO2 Beverage Tanks
- Machined in-house to hold Liquid Oxygen and Ethanol propellant compatible with ½” NPT plumbing.
- LOX tank insulated with spray foam.
- Tanks rated to 1800 psi, will be pressurized to ~600 psi



Liquid Oxygen Safety

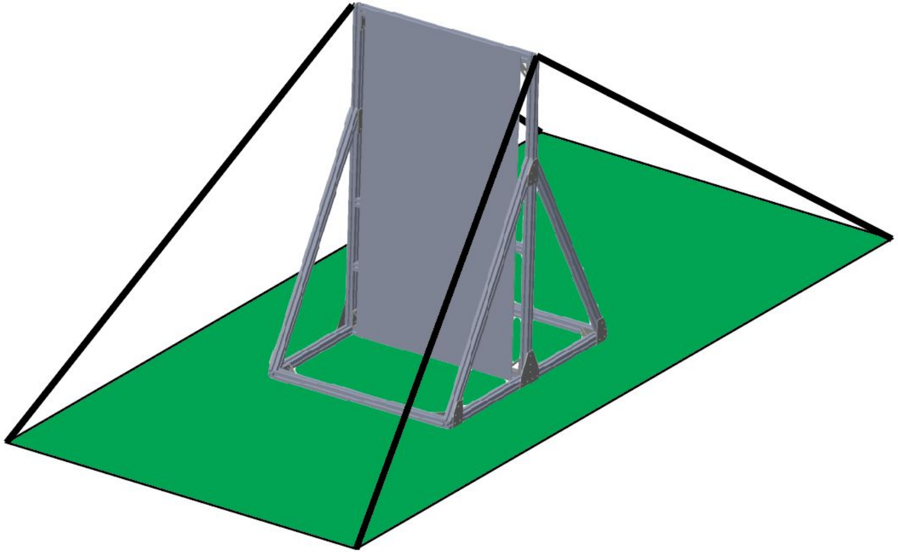
- **Hazards**
    - **Exposure to cold temperatures**
        - Proper PPE (face shield, insulated gloves, pants + long sleeve shirts, close-toed shoes)
    - **Boil-off overpressurization**
        - Pressure relief valves
        - Burst disks
        - Modification of ball valves
    - **Oxygen enrichment of surrounding atmosphere**
        - Testing done outdoors
        - Proper ventilation during transport
    - **Combustion**
        - Selection of oxygen compatible materials (stainless steel, brass, etc.)
        - Proper oxygen cleaning of materials

Oxygen Cleaning

- LOX is reactive w/ contaminants (dust, dirt, greases, oils).
- To prevent autoignition, we will clean components that feed/contact LOX as follows:
  - Mechanical cleaning (scrubbing parts)
  - Rinse with distilled water
  - Remove oils with diluted household cleaner
  - Use an ultrasonic jewelry cleaner to finish off small parts
- As an extra layer of cleaning, diluted citric acid will be run through the LOX line
- Seals & O-rings are difficult to clean, and instead will be replaced as necessary.

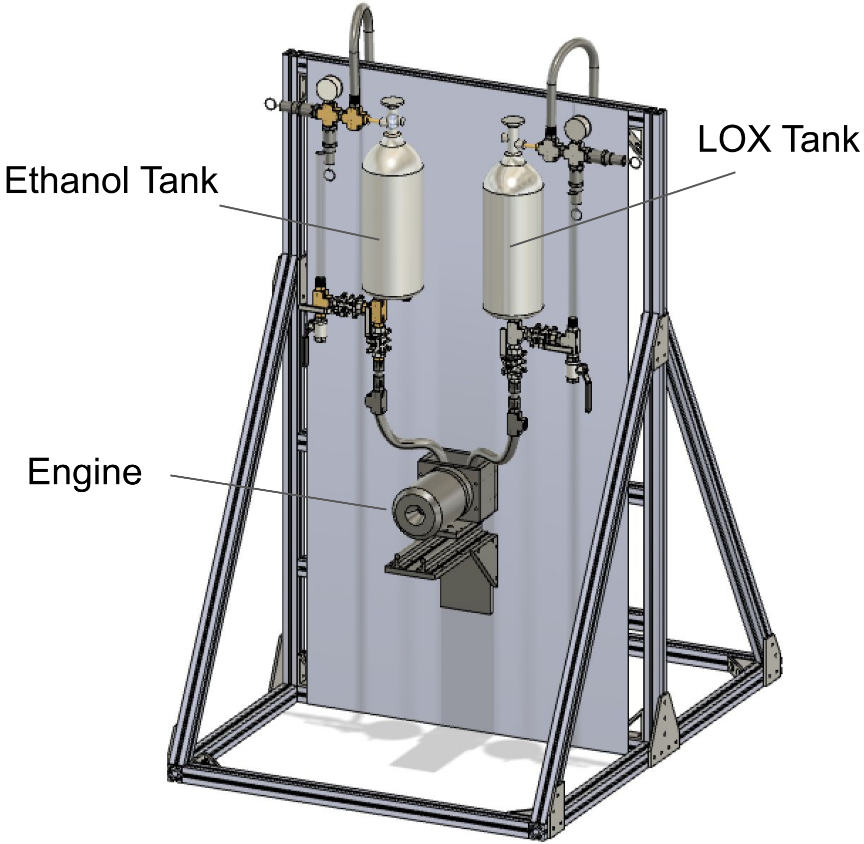
Test Stand Design Requirements

- Secure engine and feed system components
- Safely take up thrust from the engine



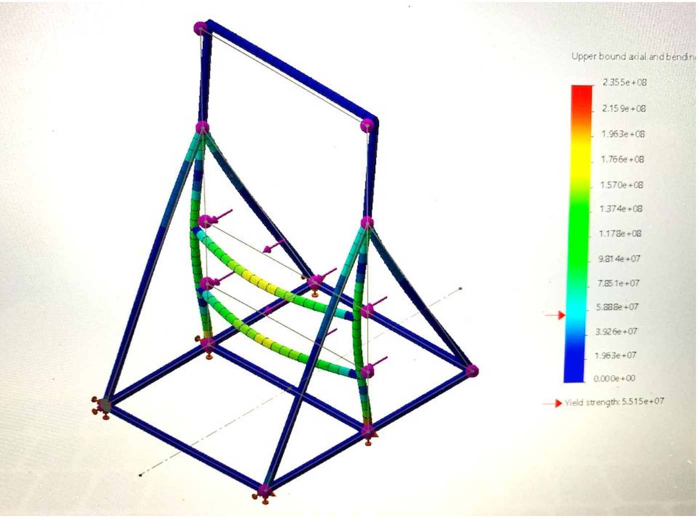
Test Stand De

- Propellant tanks mounted on the front of the test stand
- Pressurant bottle and N2 feed system mounted on the back



Test Stand Design

- Constructed from 80/20 series 15 (1.5”)
- Anchored to the ground with screw stakes and ratchet straps
- Structure will be tested at full load before hot fire
- Structure can withstand 4000 lbf (>10x margin)
- 16” screw stakes can hold 475 lbs each



Electronics

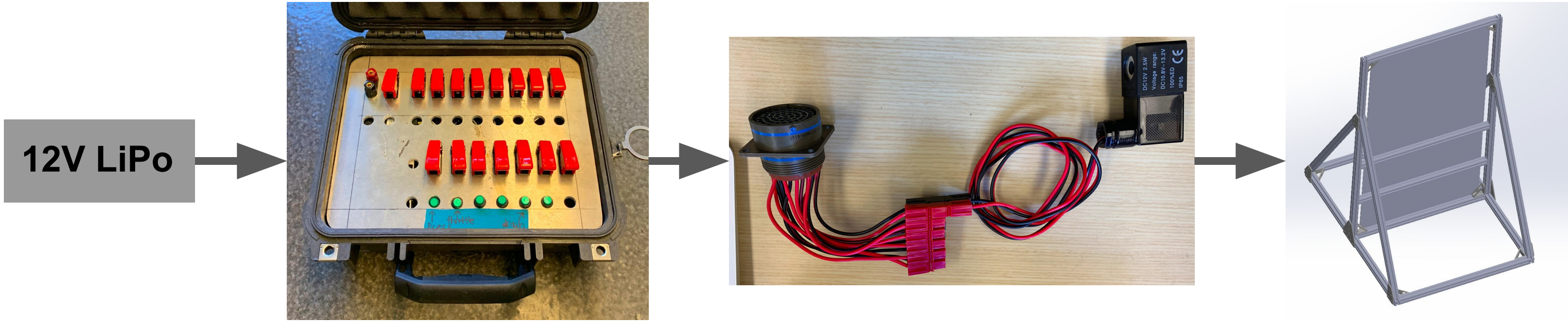
Requirements:

- Provide a reliable power supply, instantaneous actuation system for the fluid components.

Components:

- Switch box for valve actuation control
- Cable connection interface on the test stand
- Long-distance data cable for DAQ

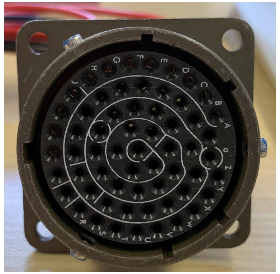
Electronics: Switch Box



12V LiPo

Specifications

- Power supply: 12V LiPo battery
- Switches & indicator lights for the press valves and throttle valves
- All wiring feeds into a circular connector & 500ft cable



DAQ - Data Products

After an engine test we want to be able to create the following data products:

- Engine thrust (N)
- Chamber pressure (psi)
- Tank pressures (psi)
- Propellant pressures upstream of injector (psi)
- Engine Temperature (K)
  - Estimated from chamber wall temperature readings

DAQ Architecture

Acquisition

- Sensors
    - 6 Thermocouples
    - 5 Pressure Transducers
    - 1 Load cell
- ADC and amps needed for some sensors

Collection

- Arduino collects data from each sensor
- Raw data stored on SD Card
- Separate onboard battery

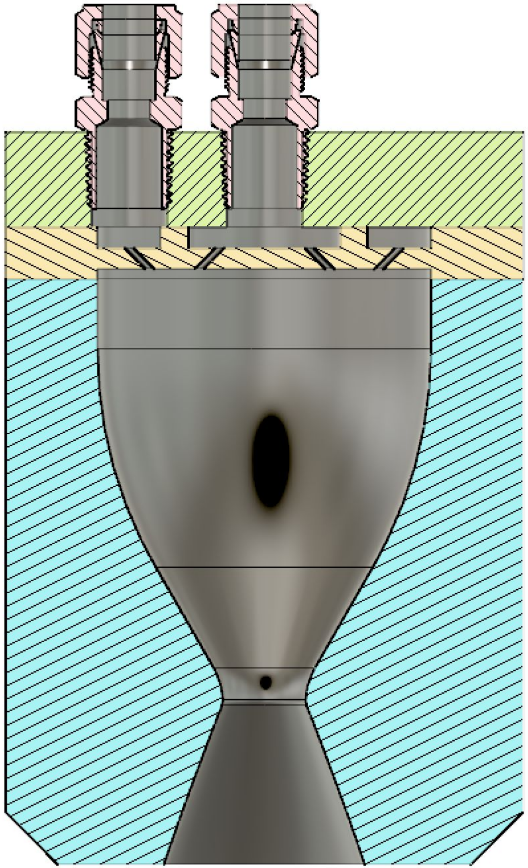
Analysis

- Parser to generate data products from raw data generated
    - Extract performance values
    - Create final graphs
- Final data products created using python

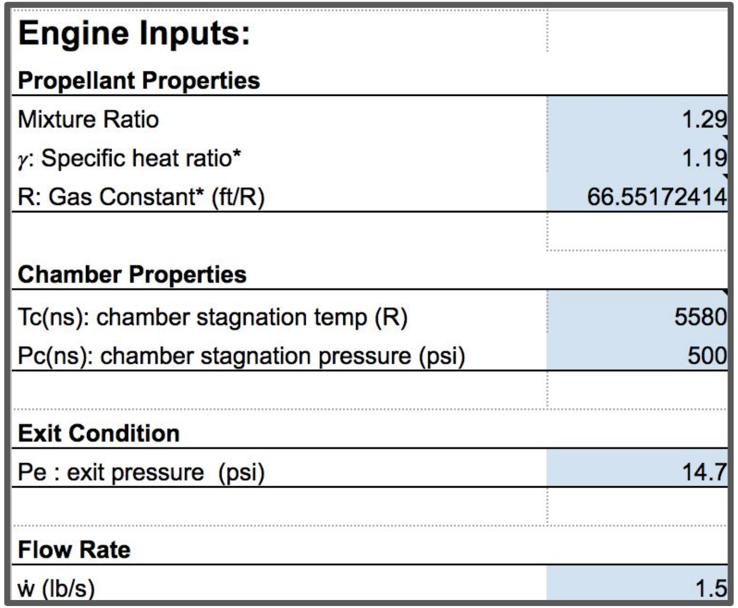
Engine

Overview

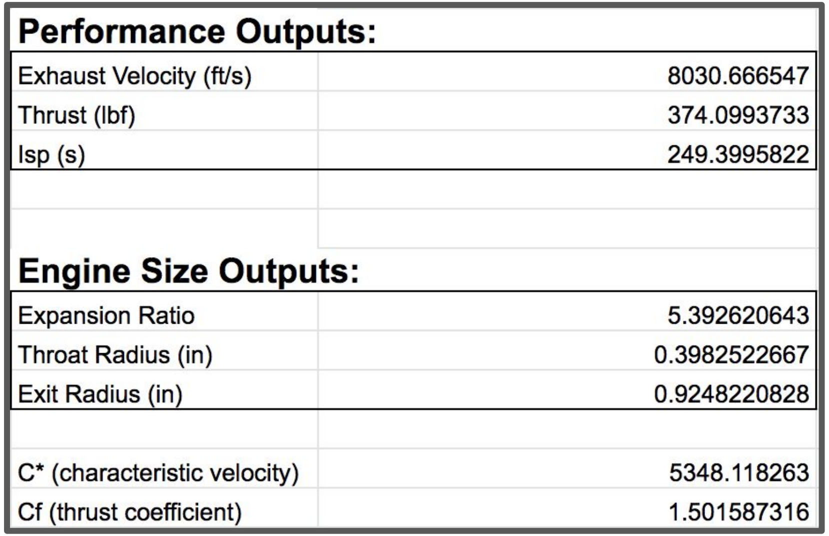
- Pressure-fed, uncooled (heat-sink)
- Chamber pressure (Pc): 500 psi
- Thrust: 370 lbf
- 5 second burn time
- Propellant flow rate: 1.5 lbs/s
- Injector: 8 unlike impinging pairs
- Grafoil seals



Engine Properties



Engine Inputs:	
Propellant Properties	
Mixture Ratio	1.29
γ: Specific heat ratio*	1.19
R: Gas Constant* (ft/R)	66.55172414
Chamber Properties	
Tc(ns): chamber stagnation temp (R)	5580
Pc(ns): chamber stagnation pressure (psi)	500
Exit Condition	
Pe : exit pressure (psi)	14.7
Flow Rate	
ẇ (lb/s)	1.5



Performance Outputs:	
Exhaust Velocity (ft/s)	8030.666547
Thrust (lbf)	374.0993733
Isp (s)	249.3995822
Engine Size Outputs:	
Expansion Ratio	5.392620643
Throat Radius (in)	0.3982522667
Exit Radius (in)	0.9248220828
C* (characteristic velocity)	5348.118263
Cf (thrust coefficient)	1.501587316

$$F = \frac{\dot{W}}{g} v_e + A_e(p_e - p_a)$$

$$\dot{W} = A_t (p_c)_{ns} \sqrt{\frac{g\gamma[2/(\gamma+1)]^{\frac{\gamma+1}{\gamma-1}}}{R(T_c)_{ns}}} \quad (1\text{-}19)$$

$$v_e = \sqrt{\frac{2g\gamma}{\gamma-1} R(T_c)_{ns} \left[1 - \left(\frac{p_e}{(p_c)_{ns}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \quad (1\text{-}18)$$

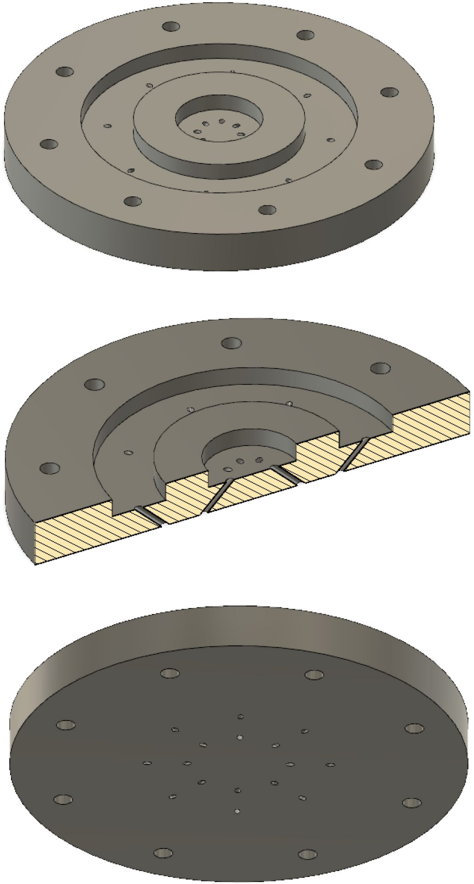
$$\epsilon = \frac{A_e}{A_t} = \frac{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \left[\frac{(p_c)_{ns}}{p_e}\right]^{\frac{1}{\gamma}}}{\sqrt{\frac{\gamma+1}{\gamma-1}\left[1 - \left(\frac{p_e}{(p_c)_{ns}}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \quad (1\text{-}20)$$

Injector

- 8 unlike impinging doublets
  - LOX on outer ring
  - Ethanol on inner ring
- Manifolds are ~4x the flow area of the orifices they feed (not tapered)
- Orifices sized to give ~120 psi of pressure drop across injector
- Material: 1018C Steel

$$A_{inj} = \dot{w}\sqrt{\frac{2.238K}{\rho \Delta P}}$$

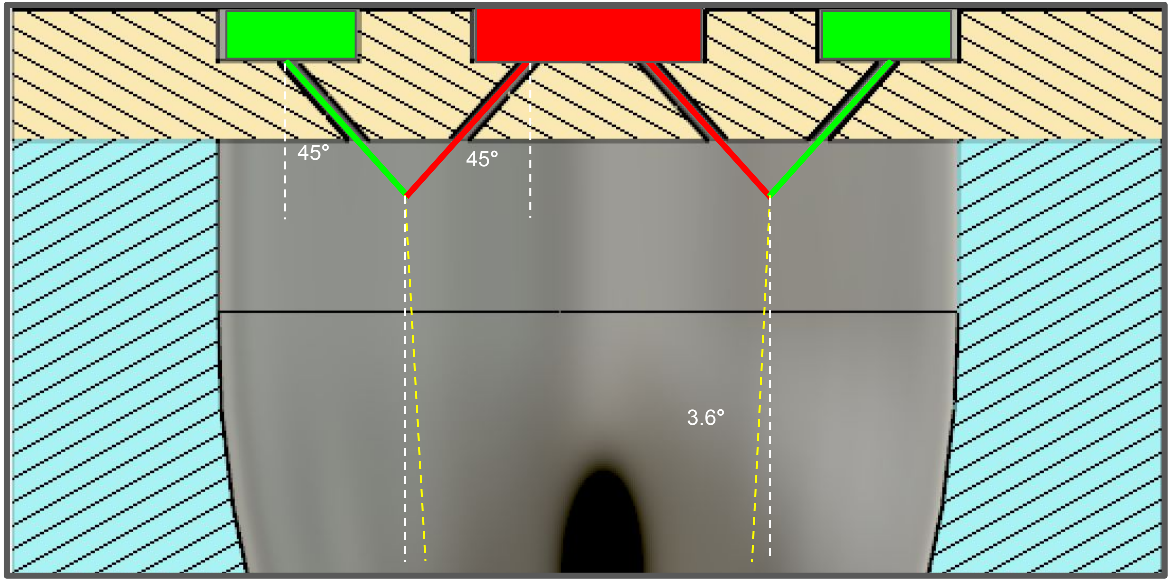
$$d_{orifice} = \left(\frac{3.627K\dot{w}^2}{\rho \Delta P N^2}\right)^{0.25}$$



Injector

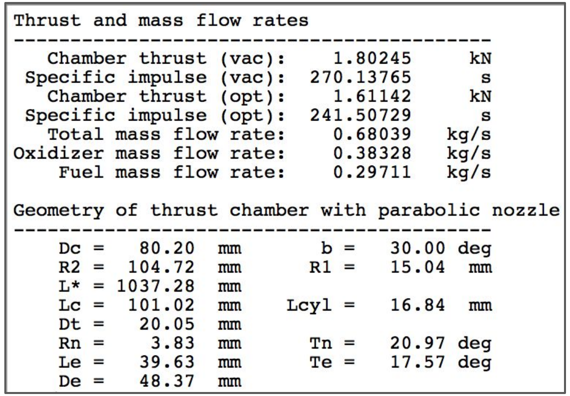
- Impingement angles
  - LOX: 45°
  - Ethanol: 45°
- Resultant angle: 3.6°
  - Towards centerline
  - Avoids hot spots on chamber wall

$$\tan \beta = \frac{\dot{w}_1 V_1 \sin a_1 - \dot{w}_2 V_2 \sin a_2}{\dot{w}_1 V_1 \cos a_1 + \dot{w}_2 V_2 \cos a_2}$$

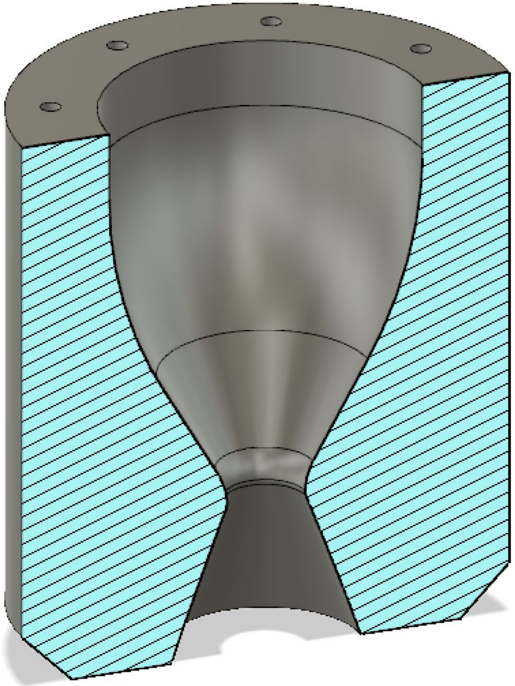


Chamber/Nozzle

- Chamber diameter: 3.157 in
- Throat diameter: 0.789
- Expansion ratio: 5.82
- L* : 40.83 in
- Material: 1018C Steel



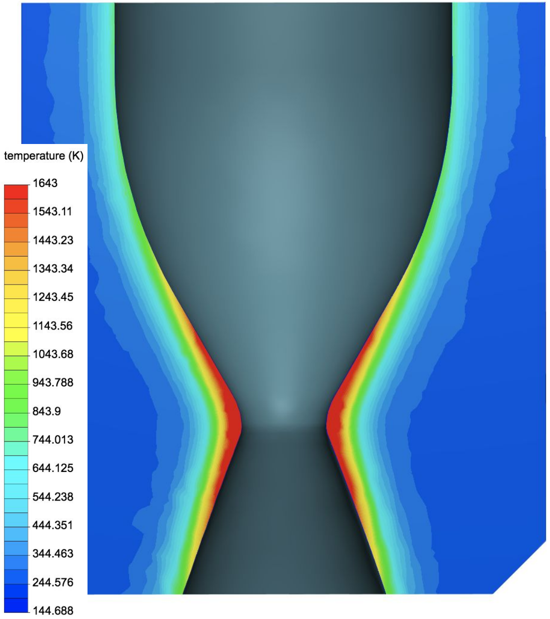
```
Thrust and mass flow rates
-------------------------------------------
   Chamber thrust (vac):     1.80245      kN
 Specific impulse (vac):   270.13765       s
   Chamber thrust (opt):     1.61142      kN
 Specific impulse (opt):   241.50729       s
     Total mass flow rate:     0.68039    kg/s
Oxidizer mass flow rate:     0.38328    kg/s
    Fuel mass flow rate:     0.29711    kg/s

Geometry of thrust chamber with parabolic nozzle
-------------------------------------------
    Dc =    80.20   mm         b =    30.00  deg
    R2 =   104.72   mm        R1 =    15.04   mm
    L* =  1037.28   mm
    Lc =   101.02   mm      Lcyl =    16.84   mm
    Dt =    20.05   mm
    Rn =     3.83   mm        Tn =    20.97  deg
    Le =    39.63   mm        Te =    17.57  deg
    De =    48.37   mm
```



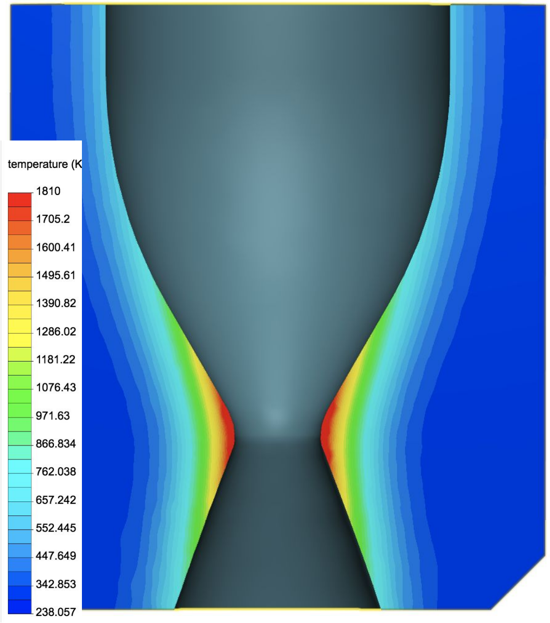
Hoop Stress: 7.48 MPa
Axial Stress: 2.93 MPa
Tensile Yield Strength: 370 MPa

Chamber/Nozzle (cont.)

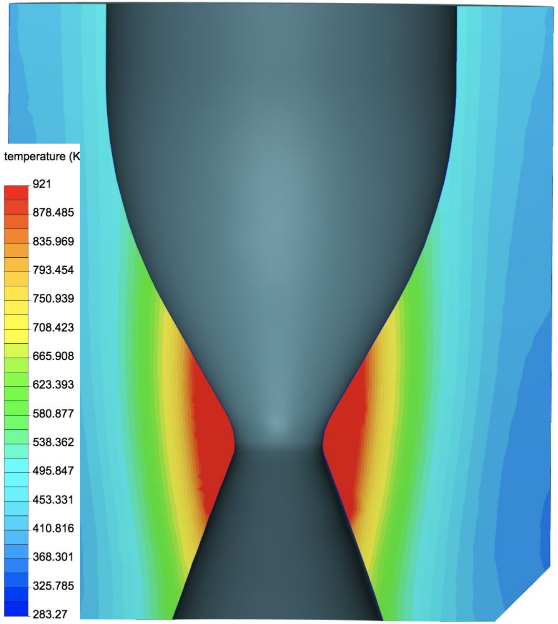
316 Stainless



1018 Steel



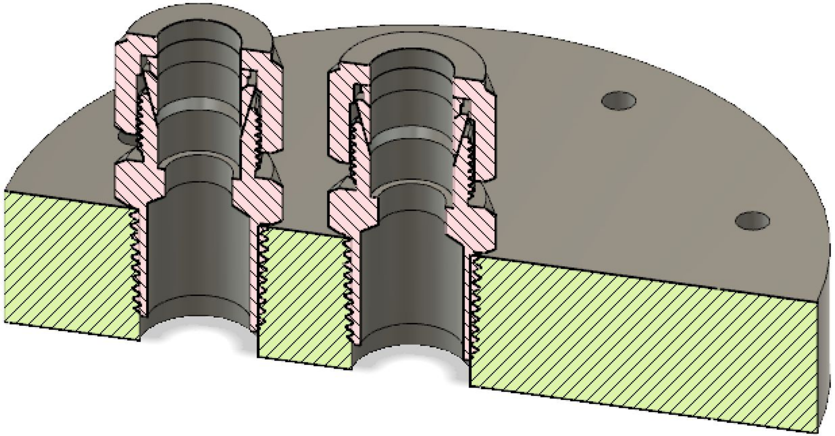
6061 Aluminum



*Each plot is normalized to the materials respective melting temperatures

Engine Cap

- ½” NPT Female Ports
- Material: 6061 Aluminum

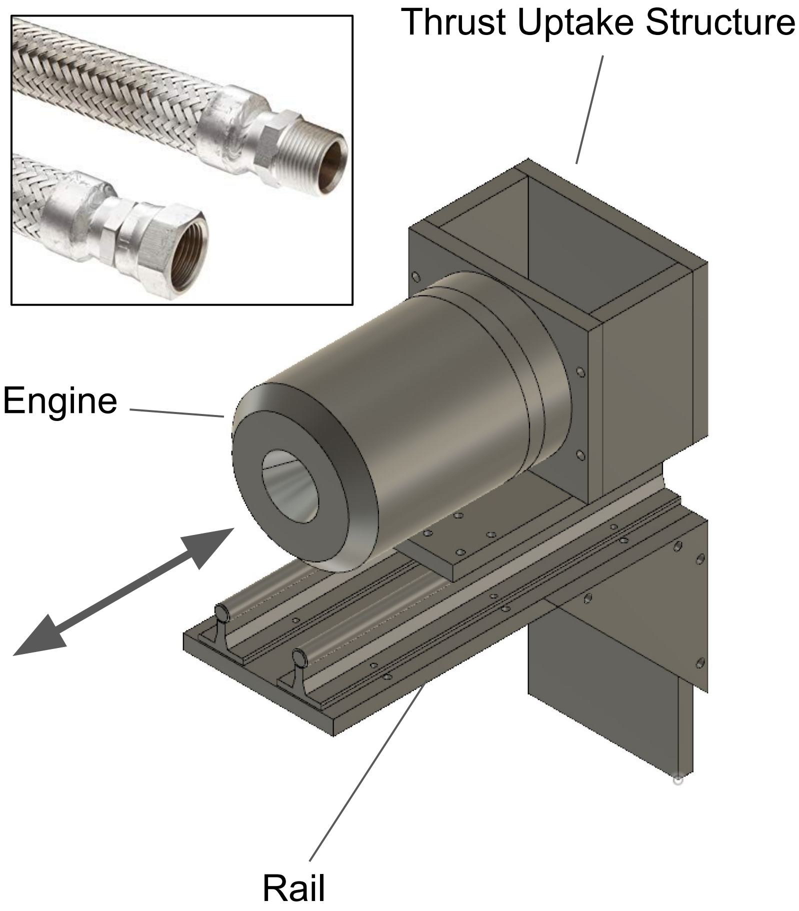


Ignition system

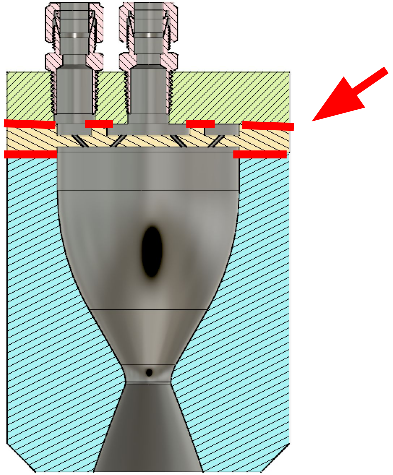
- Single C-class solid rocket motor
  - Clay nozzle removal results in less pressure and longer burn time
  - Fires into throat for 4 sec at ~5 N
- Remotely controlled from the switchbox
  - Heated wire wrapped with black powder ignites the motor
  - Standard for hobbyist solid rockets
- Hinged support structure allows safe release upon ignition

Engine Mount

- Engine will be mounted on carriage+rail to measure thrust against load cell
- Flexible, high-pressure hosing will feed propellants to engine ports
- Thrust uptake structure will contact load cell



Engine Component Sealing



- Requirements
  - Seal interfaces between engine components
- Grafoil flexible graphite sheet
  - Three crush seals
  - Minimum crush load = Y + Pc * m
    - m=2, Y=900.
    - 2300 PSI of required sealing stress
  - Bolts will be tightened to 126 in*lbs for 3357 lbs of force per bolt to satisfy sealing stress.
  - Surface finish: Concentric microgrooves 150 microinch depth, 14 grooves per radial inch.
  - Extremely high temperature tolerance.
- High Strength FNL Grade 9 Bolts
  - Required to withstand necessary torques.

Questions/Comments?

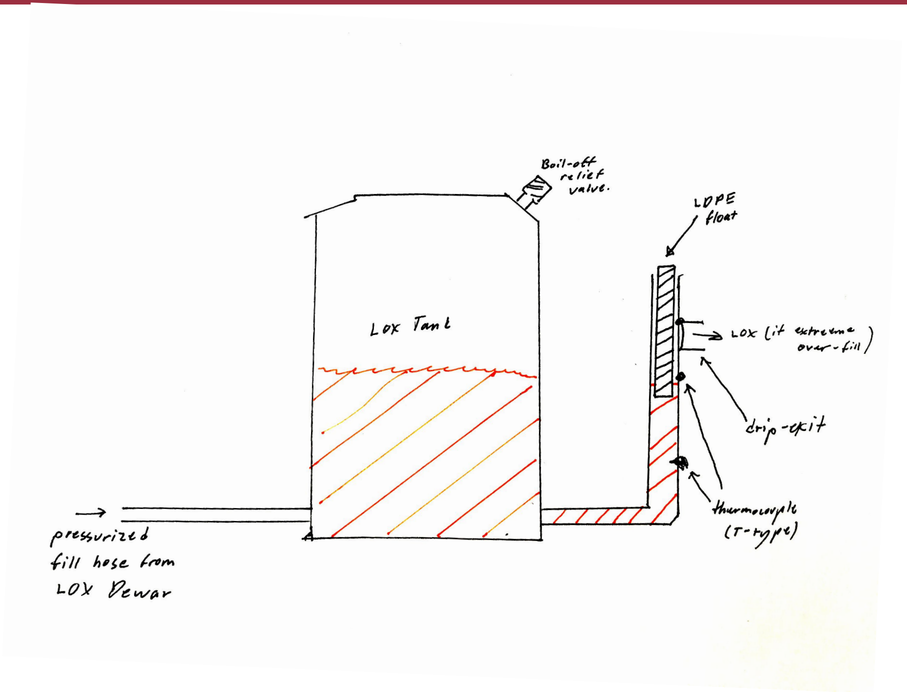
Appendix

Execution

- Make high-level design choices: fuel selection, etc.
- Fluids system research and design
- Valve selection, acquisition, and modification
- Test manual ball valve actuation
- Acquire and modify tanks (bore, apply insulation)
- Design test stand and acquire structural components
- Build test stand
- Assemble first half of fluids system on the test stand
- Research oxygen cleaning options
- Create switchbox / electronics system
- Begin designing DAQ system
- Complete an initial design review with Rocket Team
- Complete low-pressure cold flow test; debrief
- Brief high-pressure cold flow test procedure
- Complete high-pressure cold flow test
- Debrief tests; make system alterations as appropriate
- Design engine chamber and injector
- Design engine mount and rail structure
- Research/test ignition system options
- Machine practice aluminum chamber/injector
- Select, acquire, and test DAQ sensors
- Begin machining engine mount
- Build ignition system
- Design LOX fill device
- Test ignition system
- Finish LOX fill device
- Assemble fluids componentry
- Finish DAQ system
- Connect electronics to switchbox
- Machine steel chamber/injector
- Write/review operating procedure
- Ox cleaning/re-assemble LOX line
- Engine test fire at Crow Island

LOX Fill System

- Buoyant indicator
- Temperature sensor
- Overflow drip port (with large margin for buoyant indicator)



Fittings Standards

- ½ National Pipe Thread (NPT) standard for all major interfaces.
- Teflon tape on all seals.
- Pneumatic fittings are ¼ NPT.

Pneumatic Systems

- External air compressor
- ¼” push-to connect interfaces

Fill/Drain Procedure (TBR)

1. Test remote valve actuation
2. Close all valves
3. Ethanol Fill
    a. Close regulator
    b. Open tank valve
    c. Open remove vent valve
    d. Open fill/drain valve
    e. Fill Ethanol to desired height from fill funnel
    f. Close fill/drain valve
    g. Open drain valve
    h. Close drain valve

Fill/Drain Procedure (cont.)

1. LOX
    a. Close regulator
    b. Open tank valve
    c. Open remote vent valve
    d. Connect dewar to fill port
    e. Open fill/drain valve
    f. Use control valve on dewar to fill LOX, allowing it to periodically flash off as lines are chilled
    g. Close dewar control valve when LOX float has reached desired height
    h. Close fill/drain valve
    i. Disconnect dewar from fill port

Pre-test Procedure (TBR)

1. Open manual iso valves (4x).
2. Open nitrogen bottle valve
3. Open regulator to appropriate operating pressure of both lines.
4. **Leave test stand**
5. Close remote vent valve on both lines

Ignition / Hot Fire Procedure (TBR)

1. Open remote pressurization valves
2. Inspect test stand for leaks from distance
3. Ensure that tanks are pressurized to operating pressures*
4. Countdown
5. T-3: Engage igniter
6. Ensure that igniter is active.
7. T-0: Open remote throttle valves
8. Observe for rapid changes in plume shape or test stand condition
9. T+5: Close remote throttle valves.
10. Close remote pressurization valves
11. Open remote vent valves

Post-test Procedure (TBR)

1. Close FCV for LOX and and Ethanol lines
2. Close GN2 pressurant control valve
3. Open GN2 vent valve
4. Shut off GN2 bottles
5. Open GN2 pressurant control valve (to vent line upstream of the valve)
6. Open LOX and Ethanol drain valves to drain excess propellants (if any)
7. Open pneumatics relief valve

Abort Procedure (TBR)

1. Close remote throttle valve.
2. Close remote pressurization valves.
3. Open remote vent valves.

High-pressure test

- Tested ethanol line to expected operating pressures
    - Filled propellant tank with water
    - Pressurant: GN2
- Expelled water from tanks using pressurant
- All systems performed nominally

Test Stand Construction

- 80/20 frame built
- Steel mounting plate cut
- Working on:
    - Assembling feed system components
    - Mounting hardware to plate
    - Testing ratchet straps and ground anchors

Chamber/Nozzle (cont.)