AA284B Team A
Preliminary Design Review

February 24, 2020

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Goal

Startup, shutdown, and restart of LOx-GCH_4 engine

Stretch Goals:

- Stable combustion (P_c oscillation <5% mean)
- Measure C* efficiency
- Image engine startup and reignition

System-Level Design & Analysis

System Parameters

Oxidizer	Liquid Oxygen
Fuel	Gaseous Methane
Chamber Pressure	10 bar (~150 psia)
Thrust	640 N (~144 lbf)
Throat Diameter	25.4 mm (1 in)
O/F Ratio	2.5
Ox Mass Flow Rate	0.1986 kg/s
Fuel Mass Flow Rate	0.0795 kg/s
Ox Pressurization	Compressed Nitrogen
Nozzle Expansion Ratio	2.18 (Sea Level Optimal)
Injector	Coaxial Liquid-Centered Swirl (LOx center swirl, Methane annular axial)
Igniter	Gas-Gas Impinging with spark plug ignition
I_{sp}	230 sec

O/F Ratio Survey

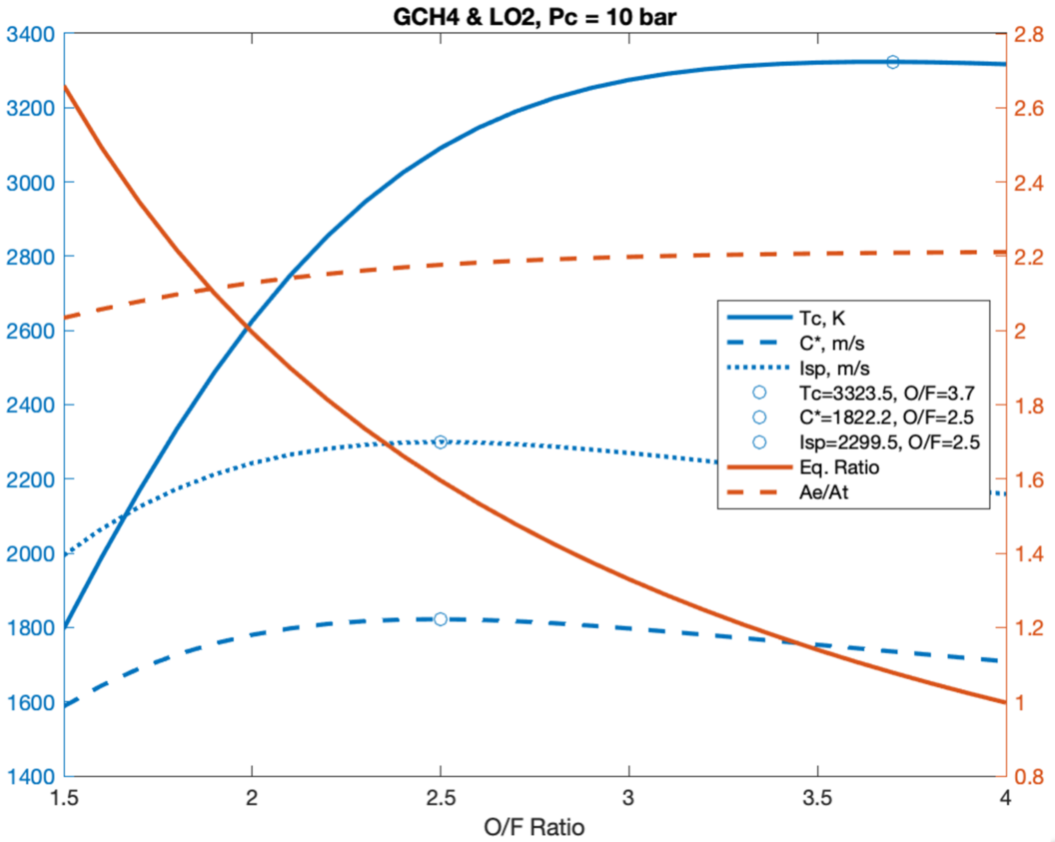
CEA Inputs:

- CH_4 298.15 K (25°C)
- O_2(L) 90.17 K (boiling)
- P_c 10 bar
- P_c/P_e 9.87 (P_e 1 atm)
- Frozen Flow

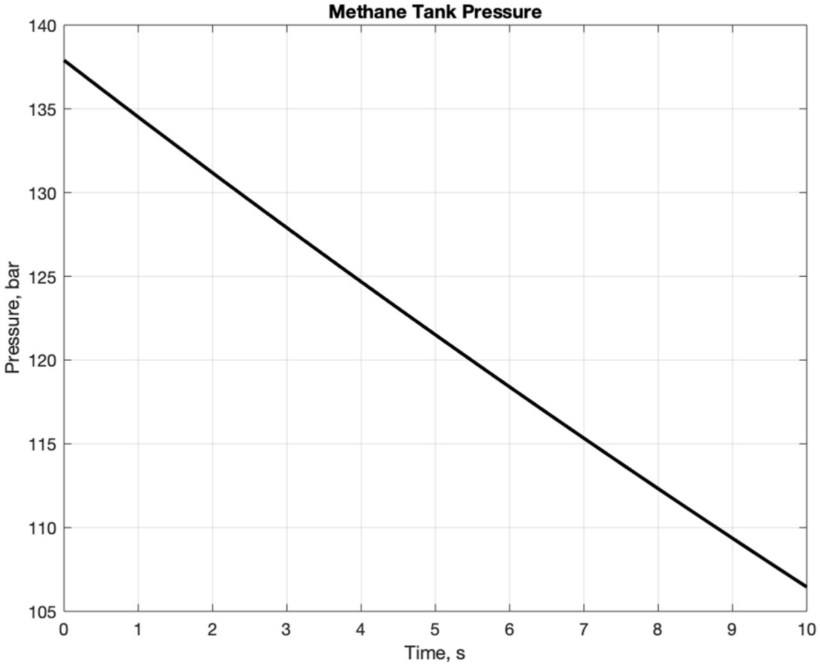
At O/F 2.5

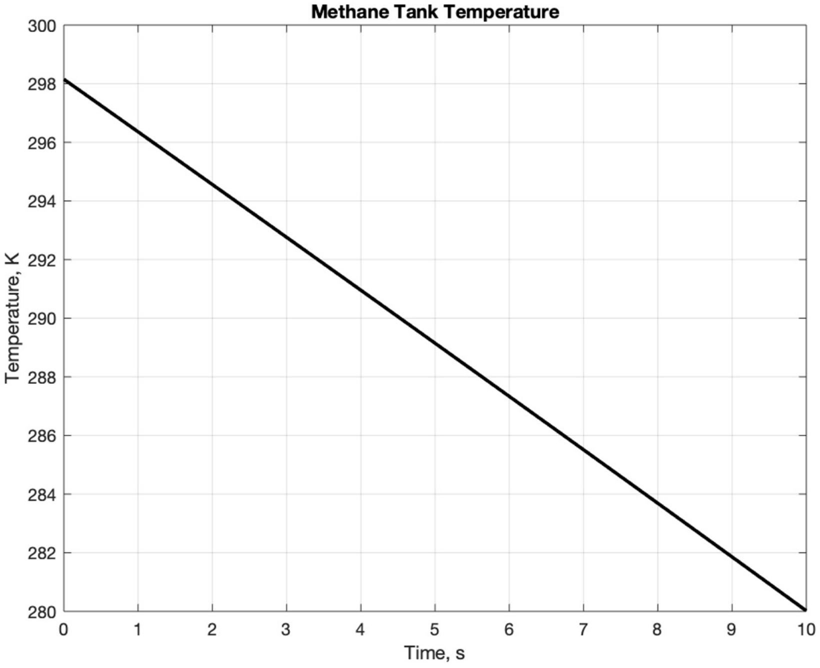
- T_c = 3100 K
- C^* = 1822 m/s
- I_{sp} = 2299 m/s (234 s)

Survey repeated for varying chamber pressures

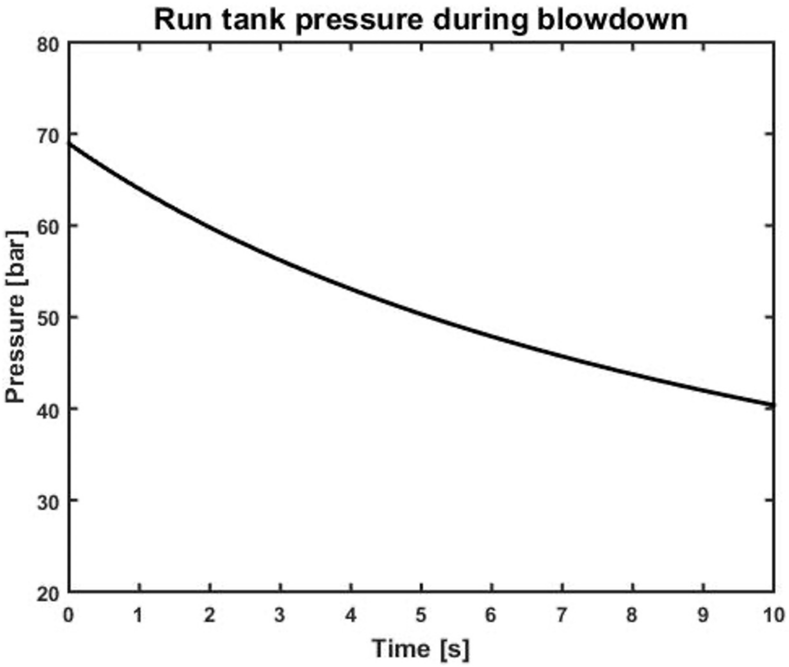


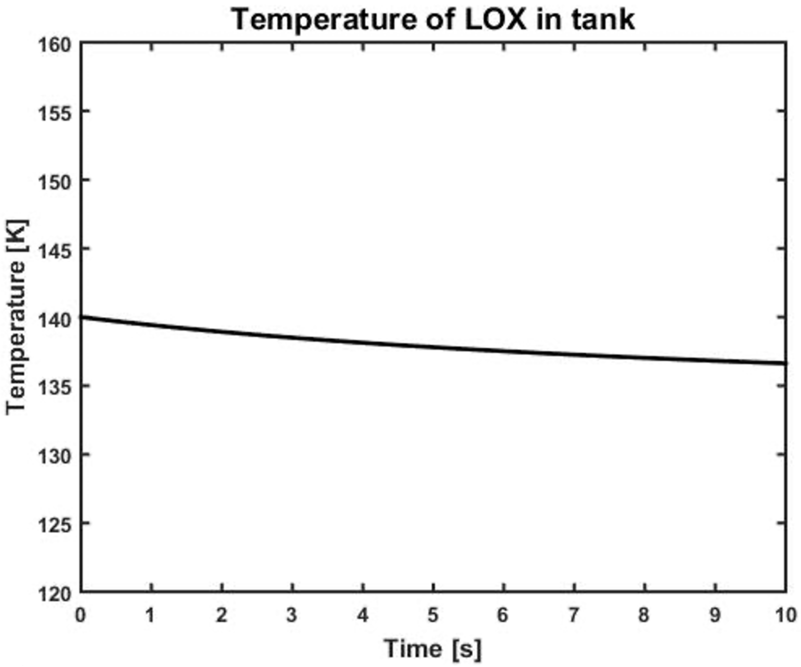
Tank Time Histories - Methane



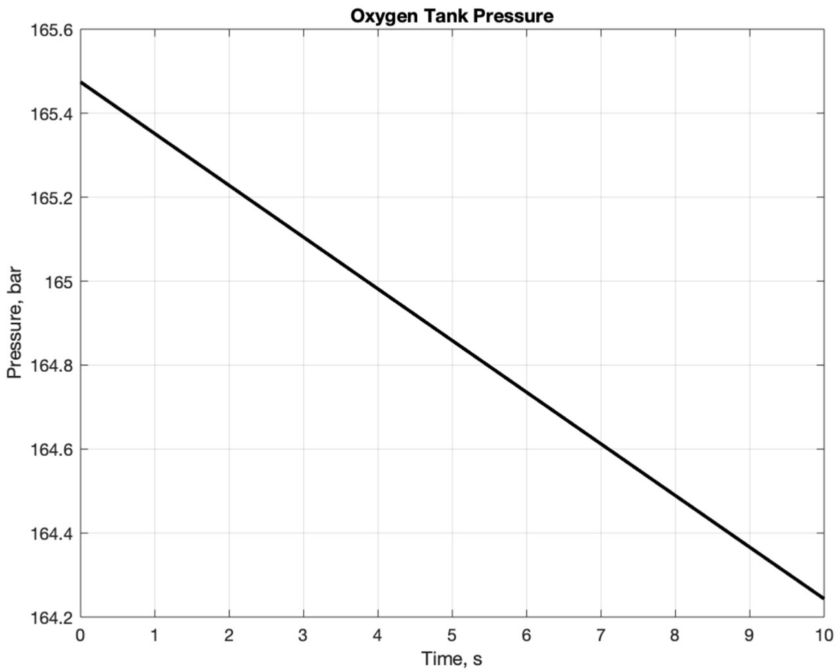


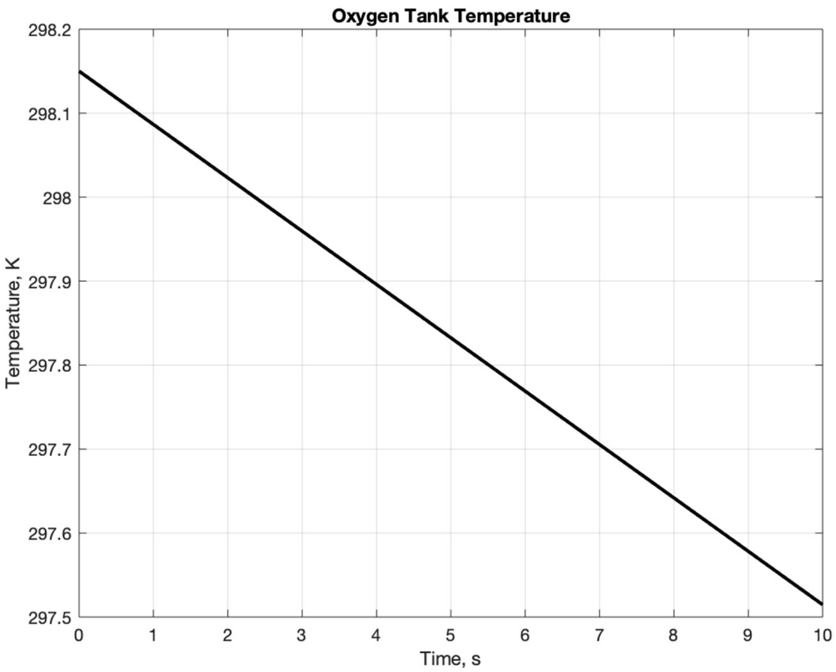
Tank Time Histories - Liquid Oxygen



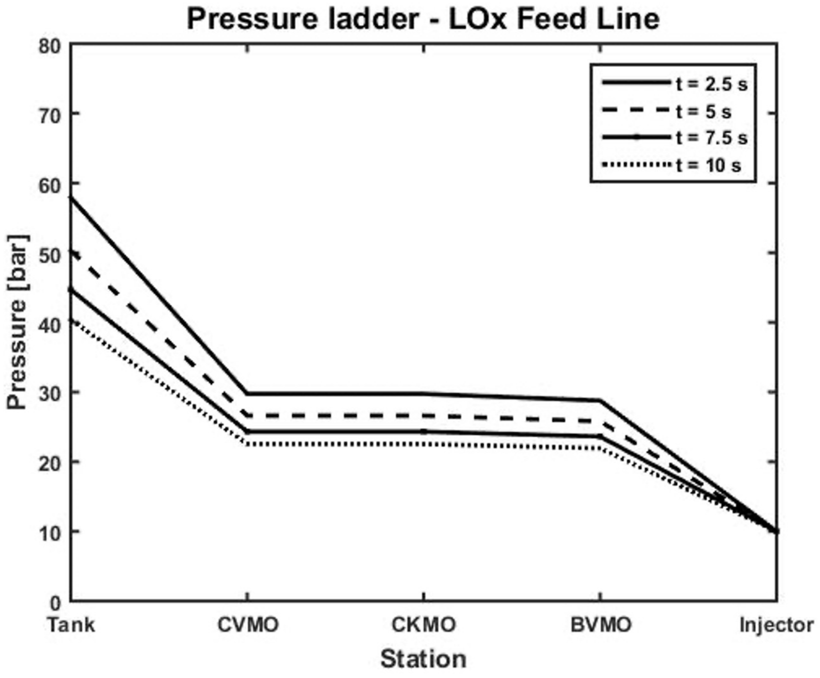


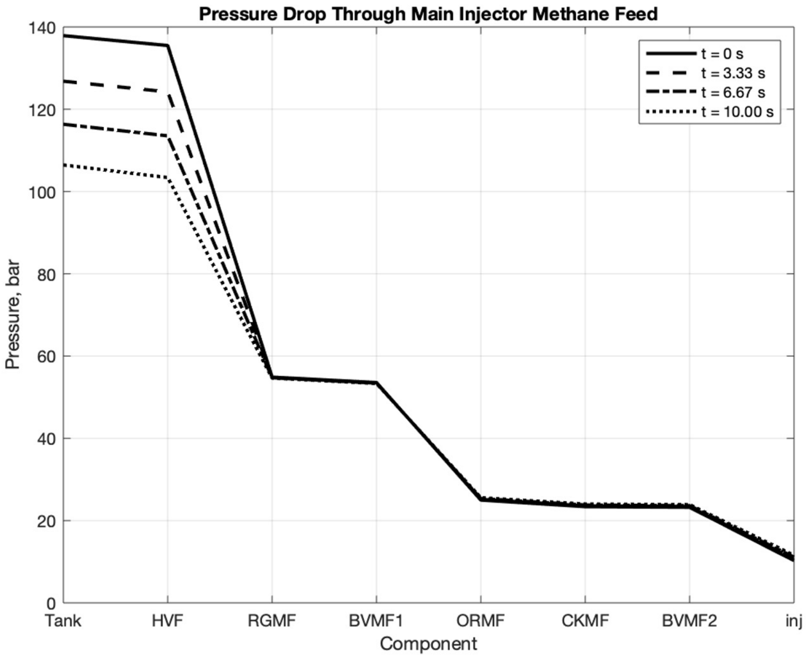
Tank Time Histories - Gaseous Oxygen



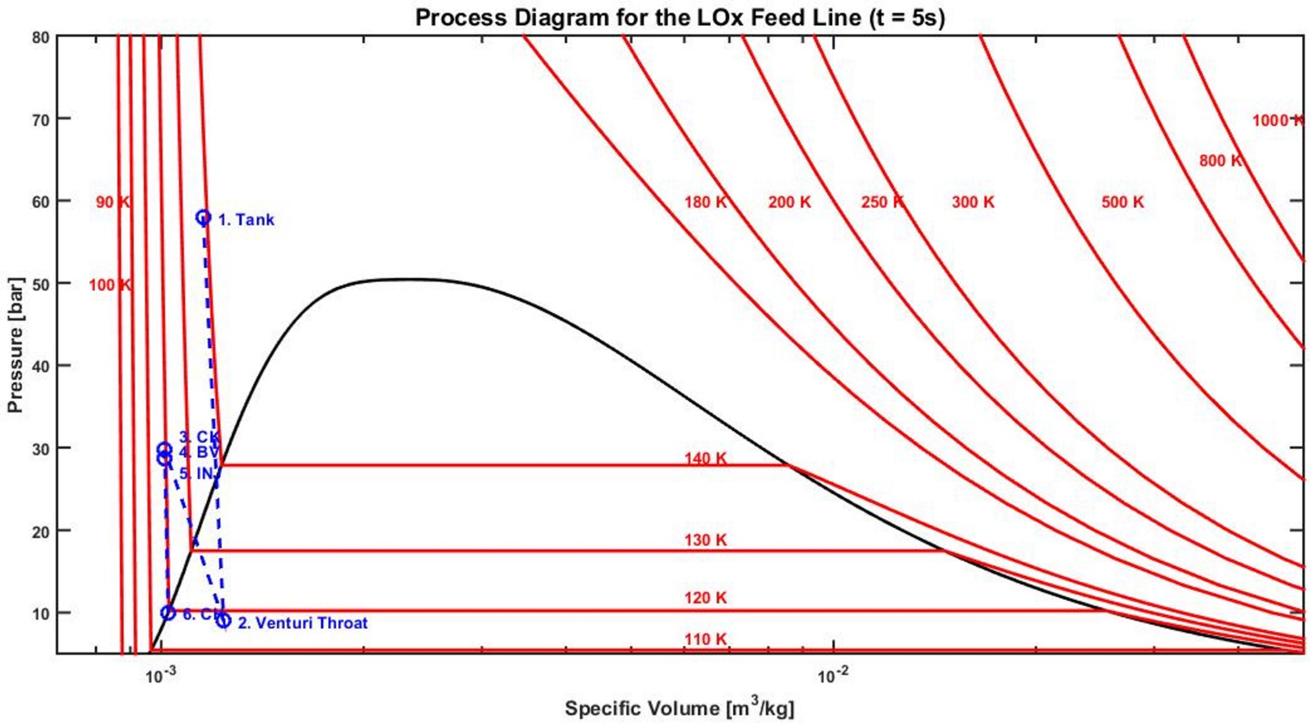


Feed System Pressure Ladder - Main Injector

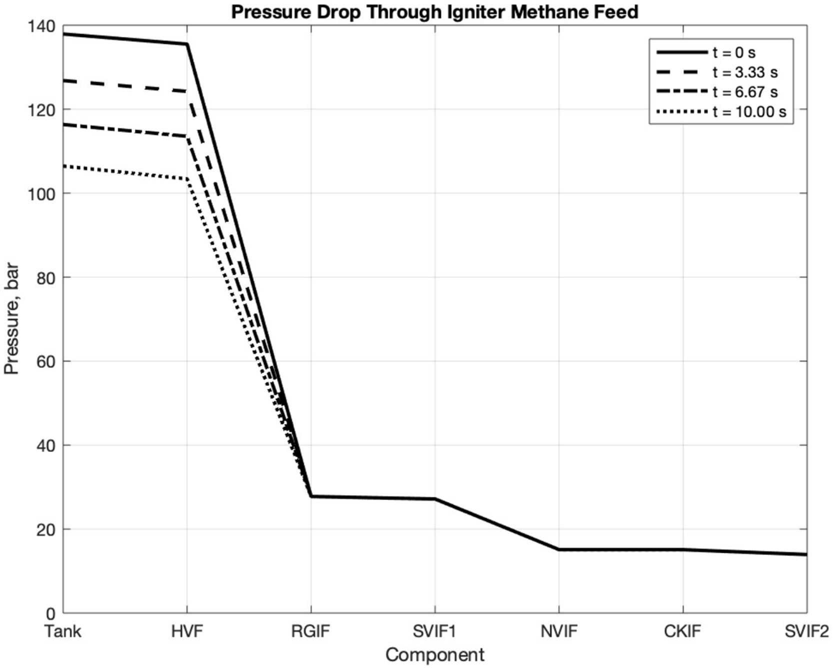


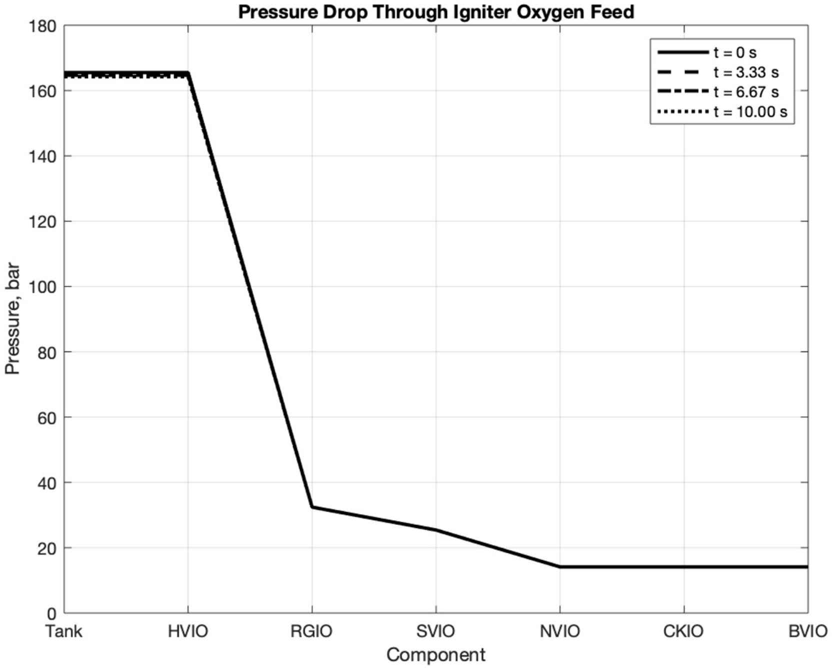


Process Plot - Main Oxidizer Feed

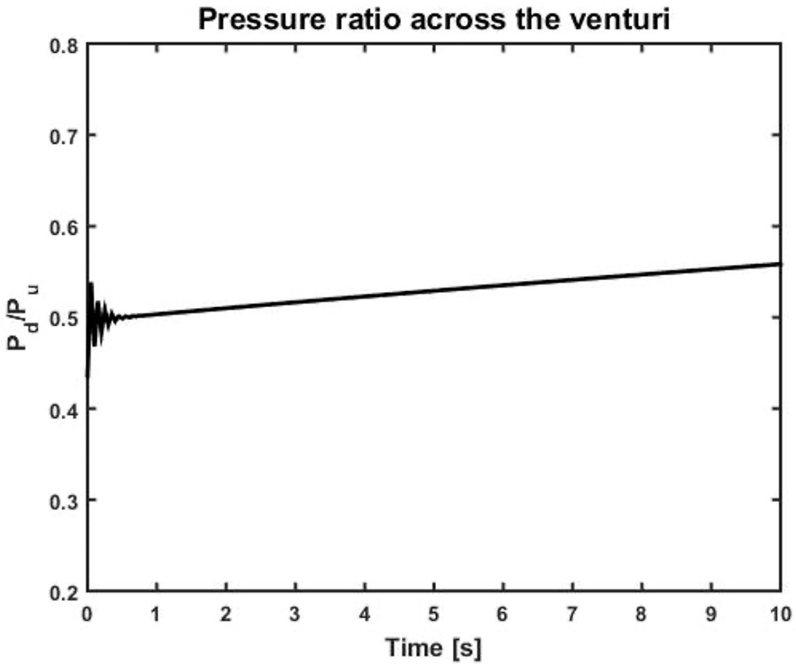


Feed System Pressure Ladder - Igniter





Cavitating Venturi: Pressure Ratio & Design

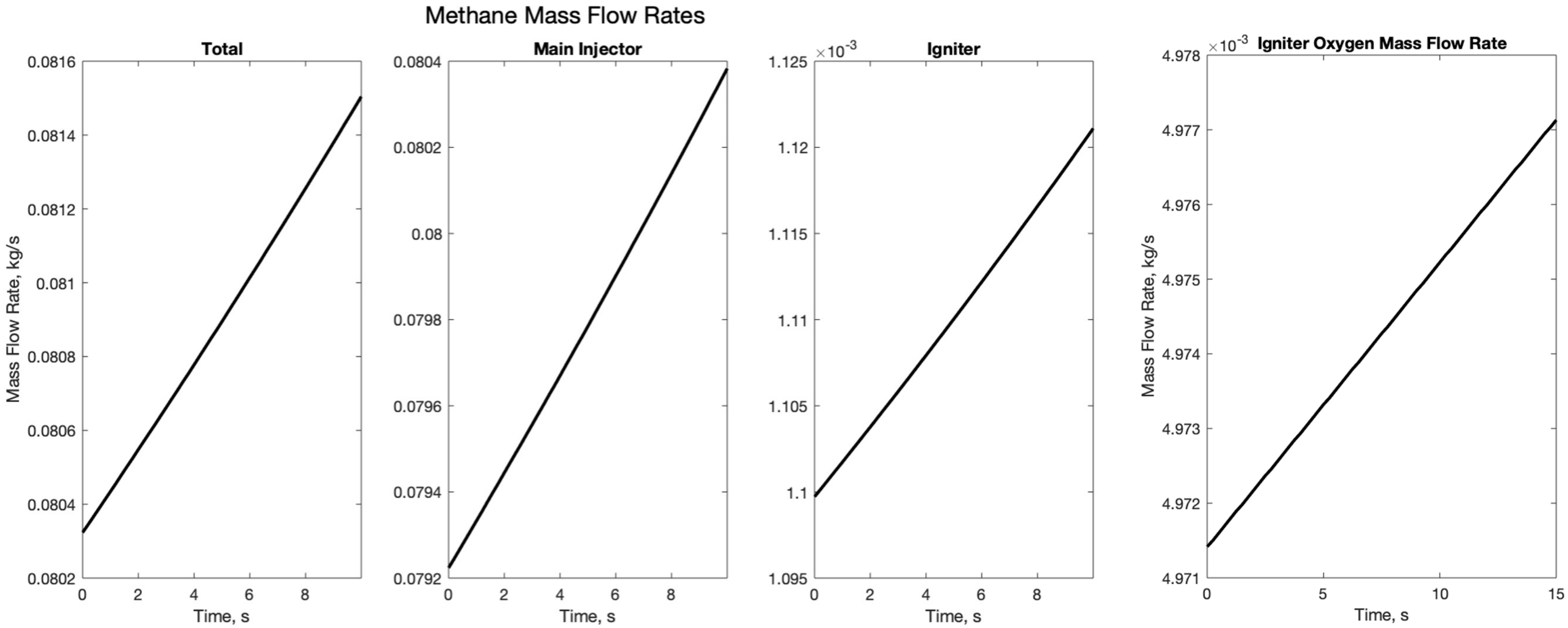


Designed Specifications
Ox Mass Flow Rate: 0.1986 kg/s
Inlet Pressure: 40 bar
Inlet Temperature: 135 K
Throat Temperature 117K
Cd : ~0.95

$$d_{th} = \left[\frac{4\dot{m}}{C_d \pi \sqrt{2\rho(P-P_{th})}}\right]^{1/2}$$

Throat Diameter: 2.18 mm

Propellant Mass Flow Rates



Gas Feed System Sim - Method

- Specify simulation parameters
  - Tank Volume, Temperature & Pressure
  - Fluid Medium
  - Time Step
- Input system components to parameter table in order of flow
  - Valve: Cv
  - Regulator: Cv, Set pressure, droop
  - Orifice: Cd, Area
- Propagate P & T through system with trial mass flow rate
  - Calculate P from upstream conditions & component parameters (Peng-Robinson EoS for local relations)
  - Calculate T from P using isothermal, adiabatic, or isentropic correlation (All plots in slides use adiabatic)
- Start from low trial mass flow and “sneak up” on choked condition
  - Asymptotically approaching choked condition allows full definition of P & T downstream of choke
  - Simultaneous iteration for coupled methane systems
- Update tank density using mass flow and time step size
  - Update tank P & T using isentropic relations & Peng-Robinson Equation of State

Gas Feed System Sim - Temperature Relations

Isentropic: T2 = T1*(P2/P1)^(k/(k-1))

- Tank is modeled as isentropic

Adiabatic: enthalpy polynomial fit, h(P2, T2)==h(P1, T1)

Example mass flow differences:

	Temperature Correlation					
System	**Isentropic**		**Adiabatic**		**Isothermal**	
Main Injector CH4	0.079495 kg/s		0.072554 kg/s	91.3%	0.068943 kg/s	86.7%
Igniter CH4	0.001102 kg/s	100% (def)	0.000978 kg/s	88.7%	0.000925 kg/s	83.9%
Igniter GO2	0.004962 kg/s		0.004318 kg/s	87.0%	0.004129 kg/s	83.2%

Gas Feed System Sim - Output

Methane System Table (After Simulation) - Tank Valve, Main Injector, Igniter tables

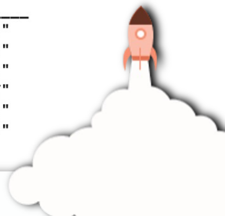
PartName	Type	Cv	RegP2	RegDroop	Cd	A	P1	P2	T1	T2	Choked
"HVF"	"valve"	0.69	0	0	0	0	10645240.5850848	10339627.1526633	280.019261046158	279.097030117597	"N"

PartName	Type	Cv	RegP2	RegDroop	Cd	A	P1	P2	T1	T2	Choked
"RGMF"	"regulator"	0.3	7100000	20349856	0	0	10339627.1526633	5464217.61458008	279.097030117597	263.464822550212	"N"
"BVMF1"	"valve"	1.4	0	0	0	1.77190538365604e-05	5464217.61458008	5332691.16445952	263.464822550212	263.017419364726	"N"
"ORMF"	"orifice"	0	0	0	0.6	8.29576810088555e-06	5332691.16445952	2556330.83705003	263.017419364726	253.223148293279	"Y"
"CKMF"	"valve"	1.9	0	0	0	0	2556330.83705003	2402146.38105093	253.223148293279	252.658731193423	"N"
"BVMF2"	"valve"	6	0	0	0	4.00101292570175e-05	2402146.38105093	2386894.12629458	252.658731193423	252.602775383832	"N"
"inj"	"orifice"	0	0	0	0.6	1.91e-05	2386894.12629458	1157276.64243174	252.602775383832	248.017542384846	"N"

PartName	Type	Cv	RegP2	RegDroop	Cd	A	P1	P2	T1	T2	Choked
"RGIF"	"regulator"	0.1147	2900000	111924205	0	0	10339627.1526633	2774521.79016965	279.097030117597	254.018044019087	"N"
"SVIF1"	"valve"	0.04	0	0	0	1.11337092575134e-06	2774521.79016965	2715230.46745058	254.018044019087	253.802480341181	"N"
"NVIF"	"valve"	0.0125	0	0	0	0	2715230.46745058	1508465.97271769	253.802480341181	249.342279033876	"Y"
"CKIF"	"valve"	1.9	0	0	0	0	1508465.97271769	1508421.65267246	249.342279033876	249.342112627524	"N"
"SVIF2"	"valve"	0.04	0	0	0	1.11337092575134e-06	1508421.65267246	1392906.02469712	249.342112627524	248.907729129338	"N"

Igniter Oxygen System Table (After Simulation)

PartName	Type	Cv	RegP2	RegDroop	Cd	A	P1	P2	T1	T2	Choked
"HVIO"	"valve"	0.69	0	0	0	0	16362967.1967559	16362587.2885101	297.196649784664	297.195940685687	"N"
"RGIO"	"regulator"	0.1147	3800000	111924205	0	0	16362587.2885101	3242938.66735922	297.195940685687	267.229425356167	"N"
"SVIO"	"valve"	0.04	0	0	0	0	3242938.66735922	2540696.85754199	267.229425356167	265.242723424738	"N"
"NVIO"	"valve"	0.043	0	0	0	0	2540696.85754199	1411501.63502629	265.242723424738	261.943812153076	"Y"
"CKIO"	"valve"	1.9	0	0	0	0	1411501.63502629	1410987.30681188	261.943812153076	261.942279188667	"N"
"BVIO"	"valve"	6	0	0	0	4.00101292570175e-05	1410987.30681188	1410934.37927582	261.942279188667	261.942121435616	"N"



Gas Feed System Sim - Notes

- Increase in mass flow over time is due to tank cooling
  - Temperature upstream of flow control orifice & metering valves decreases, so density increases
  - Current flow control parameters set design mass flow rate near 5 sec run time
- All plots and current parameter studies have been done with adiabatic temperature relation
  - We believe most realistic for our short run times
- Valve & regulator pressure drop use formulas from Swagelok TB MS-06-84-E Rev. 4 (2007)
- Regulator droop & choking are hard to characterize
  - Choking currently defined as $Q > Q_c$, where Q_c is defined by choked valve flow rate from Swagelok TB
  - Droop is found from linear fit of regulator flow chart, with factor of 2 added for conservatism
- Orifice pressure drop uses formula from AA284B slides / Fox & McDonald Fluid Mechanics
  - Orifice Cd assumed to be 0.61 (sharp edged plate) until CFD study is done
- Polynomial fits for Adiabatic/Isenthalpic temperature relation found using MATLAB CFTool and enthalpy tables for P & T
- Some details are missing from the simulation
  - Viscous losses & heat transfer
  - Area changes & frictional losses are not included in current code

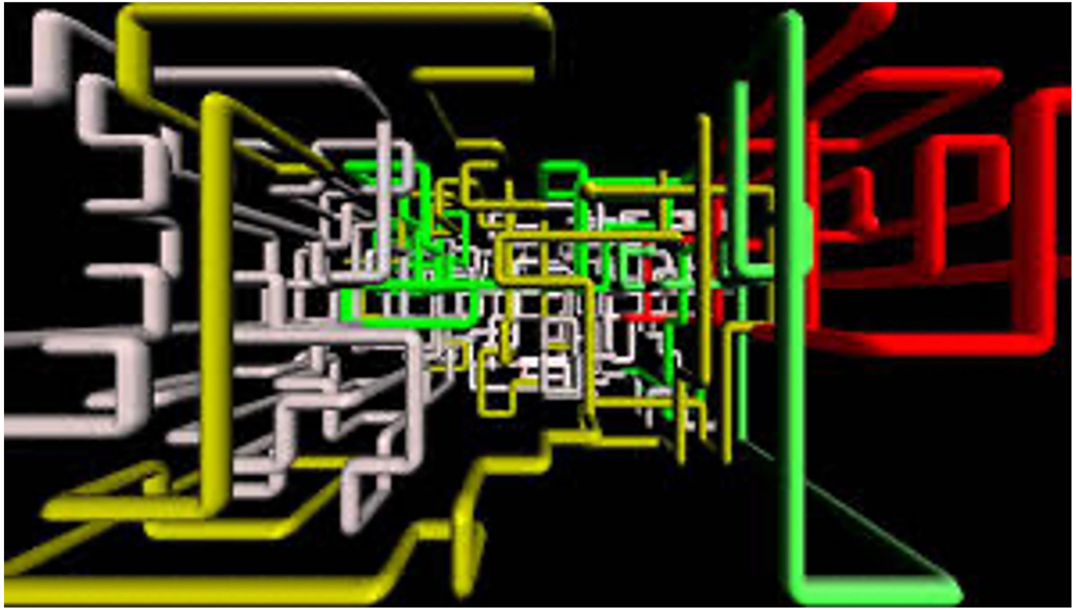
Cryo Liquid Feed System Sim

- Span (Nitrogen) and Schmidt & Wagner (Oxygen) multi-parameter EOS used for determining thermodynamic fluid properties
- Isentropic expansion of Nitrogen to occupy the volume generated by liquid oxygen leaving the run tank
  - No heat transfer from the surroundings
  - Heat exchange at the N2/LOx interface ignored
  - Constraint imposed: Total Volume remains fixed at all time steps
- Isenthalpic pressure drop across the valves
  - For a fixed backpressure, calculate the upstream pressure (till the venturi exit) using known discharge coefficients and mass flow rate from the previous time step
- Isentropic expansion from the tank exit to the venturi throat
  - Cavitation occurs if the state of oxygen at the throat is saturated (inside the vapor dome)
  - Mass flow at the subsequent time step determined solely by the tank pressure if choked

P&ID and Component List

P&ID

Flow Controls	
BV	Ball Valve
CK	Check Valve
HV	Hand Valve (Tank Valve)
NV	Needle Valve
OR	Orifice/Venturi
PR	Pressure Relief Valve
RG	Pressure Regulator
SV	Solenoid Valve
Instruments	
TT	Temperature Transducer
PT	Pressure Transducer
SC	Scale
Fluid Media	
MO	Main Injector (Liquid) Oxygen
MF	Main Injector Fuel (CH4)
IO	Igniter Oxygen (Gaseous)
IF	Igniter Fuel (CH4)
N, P	Nitrogen (N-Purge, P-Pressurant)
[Type][Working Medium][Adjacent Medium]	



P&ID

Flow Controls	
BV	Ball Valve
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MO	Main Injector (Liquid) Oxygen
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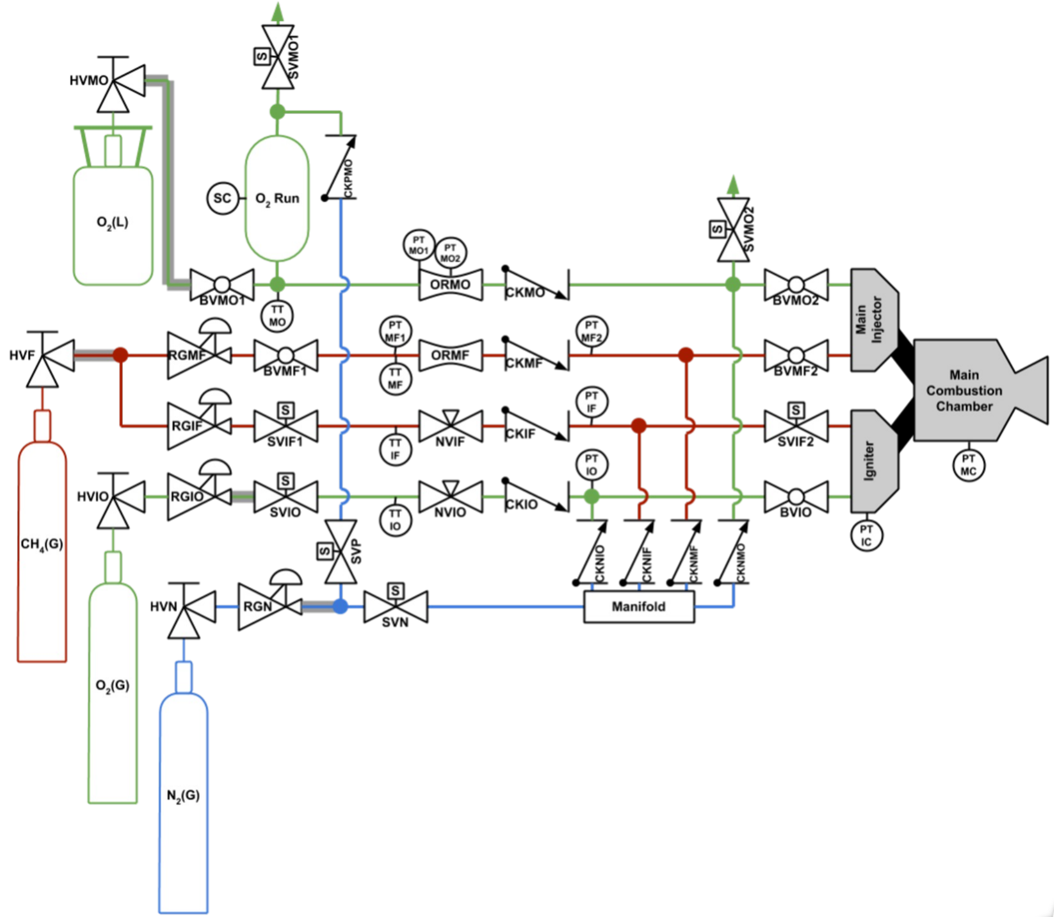


P&ID Rationale

Downstream on/off valves (BVMO2, BVMF2, BVIO, SVIF2)

- Propellant feed control for run prep and start
- As close as possible to injector & igniter to minimize slosh volume

Propellant stream check valves (CKMO, CKMF, CKIO, CKIF)

- Prevent backflow into propellant tanks
- Provide closed purge volume for test abort or post-test safing

Purge check valves (CKPMO, CKPMF, CKPIO, CKPIF)

- Prevent propellant flow into purge system before & during test
- Prevent backflow in case of anomaly during purge

Flow Rate Controls (ORMO, ORMF, NVIO, NVIF)

- Mass flow rate metering via flow choking (cavitation on LOx line)
- Vernier handle needle valves for igniter mixture & flow rate tuning

P&ID Rationale

Upstream on/off valves (BVMF1, SVIF1, SVIO)

- Propellant shutoff for igniter (after startup) and main injector (test termination)
- Close before downstream on/off valves to allow purge
- SVMO1 substitutes on LOx line by venting feed pressure

Pressure regulators (RGMF, RGIF, RGIO, RGN)

- Maintain steady feed pressure for gas systems to maintain steady mass flow rates through orifices

Hand valves (HVMO, HVF, HVIO, HVN) - Installed on tanks before delivery, included for completeness

LOx System Specifics

- BVMO1: Fill control for LOx, to allow full remote control of run tank during chill-in
- SC: Load cell for LOx load monitoring
- SVMO1: LOx run tank relief & vent - could not find cryo relief valves with set pressure >1000 psi
- SVMO2: Line vent for chill-in & safing, to prevent trapped cryo volume

P&ID Rationale

Nitrogen System Specifics

- SVP: Remote control for pressurization of LOx run tank
- SVN: Remote control of propellant purge
- CKPMO: Prevent O2 backflow into inert gas system if vapor pressure rises above Nitrogen feed
- Manifold: Split purge feed to different lines

Instrumentation

- Propellant lines have P & T measurements to validate operating conditions & settings prior to test
- Cavitating venturi ORMO has PTs at inlet & throat to ensure cavitation
- Pressure downstream of metering orifices in igniter streams
  - Ensure choking (compare to regulator set pressure)
  - Monitor igniter feed conditions closely
- Igniter & main chamber pressures
  - Thrust calculation
  - Ignition check

P&ID Key Components

Cryo Ball Valve
Triad 60C - 005
MAWP: 2000 psi
Wetted Material: SS 316, PTFE
Actuation Torque: 180 in/lbs

Cryo Check Valve
Check All U3 Series
MAWP: 3000 psi*
Wetted Material: SS 316, PTFE
Cracking Pressure: 1.5 psi

Solenoid Relief Valve
Gems D-Cryo Series
MAWP: 1000 psi
Wetted Material: Rulon, PTFE, SS 316

Pressure Transducer
GP 50-311 C
MAWP: 15000 psig
Wetted Material: 17-4 SS
6' stand off from LOX line

P&ID Key Components

Cv: 0.16

Cv: 0.04

Cv: 0.3

Vernier Needle Valve
Swagelock SS 4M & SS 4L
MAWP: 2000 psi
Wetted Material: SS 316, Fluorocarbon

Tank Regulators*
Victor SRJ-4 - Tank Specs
MAWP: 3000 psi
Wetted Material: Brass, Delrin

Fuel feed Regulator
Tescom Pressure Regulator
MAWP: 6000 psi
Wetted Material: Brass, Viton

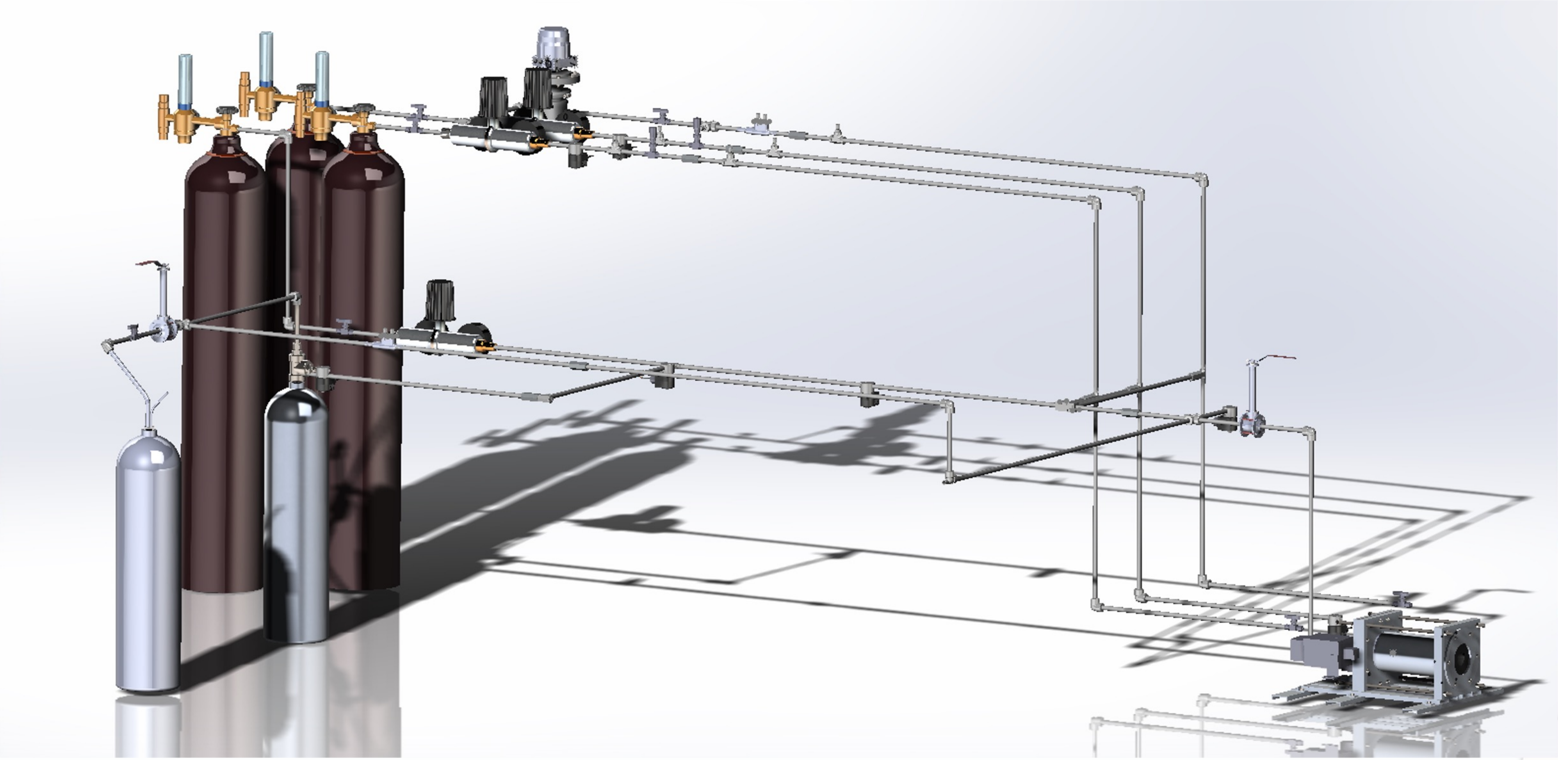
RTD
Namac A8A-45-6
Min Temp: -270 C

P&ID Fitting Accounting Spreadsheet

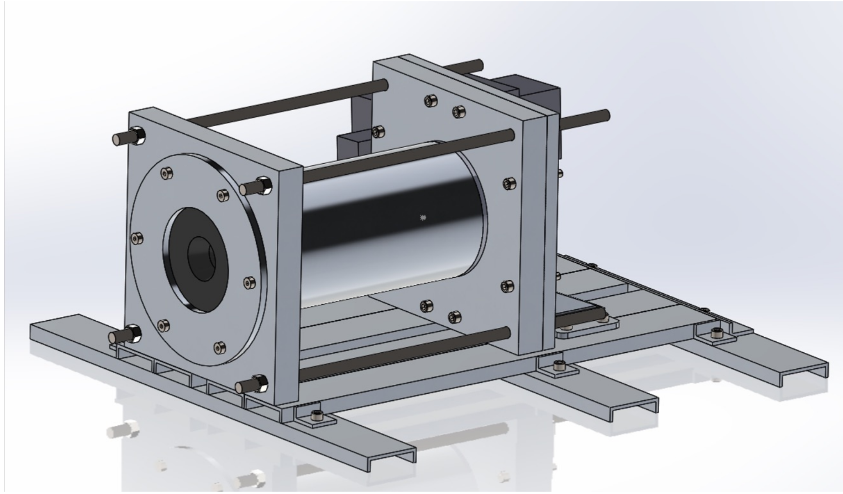
https://docs.google.com/spreadsheets/d/1Akb-G0P3gi-R2JIjckR0jrPFSVN0DPMDoXRMupv_SYY/edit?usp=sharing

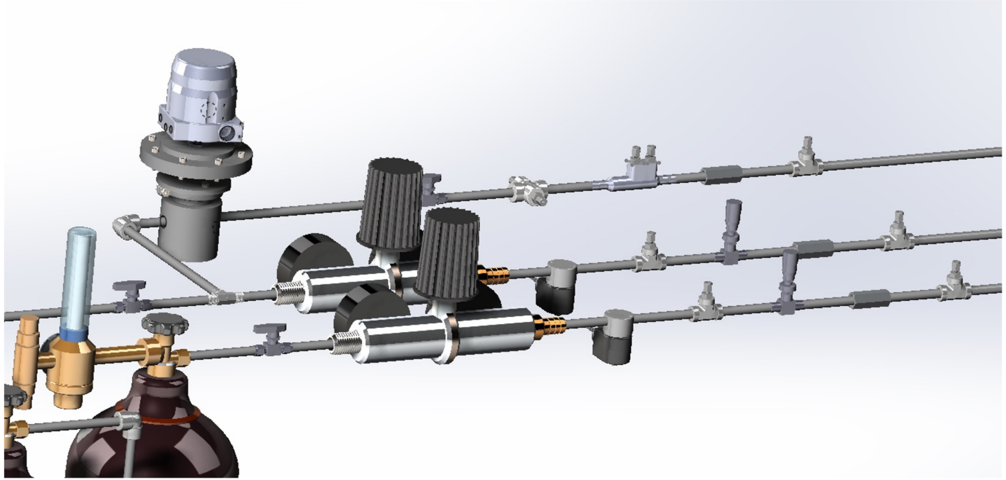
Component Design

Overall System Layout

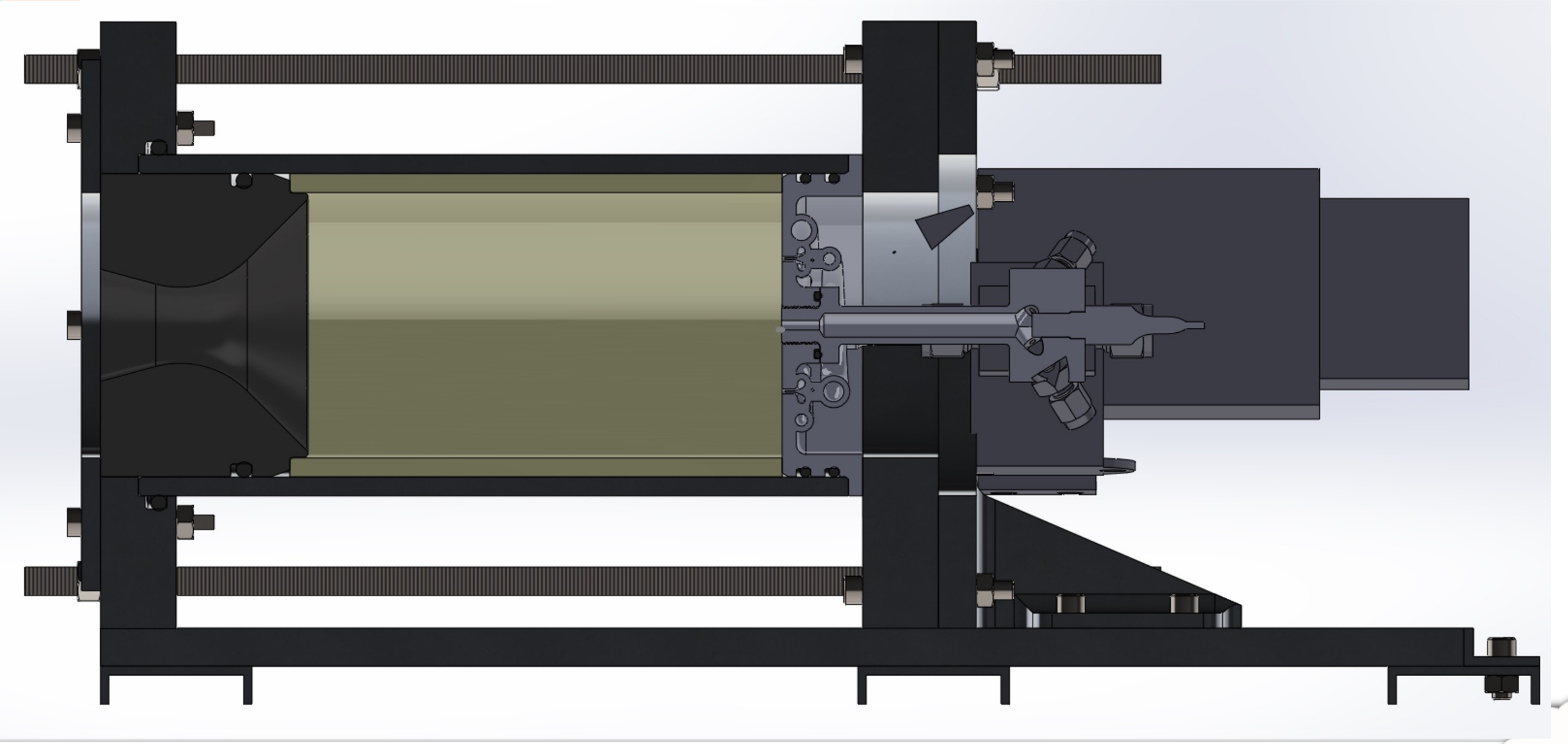


Overall System Layout





Rocket/Test Stand Integration



Tube Sizing

SS 316 Welded Tubing

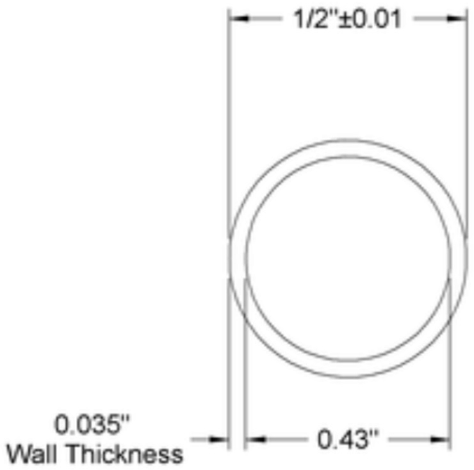
- 0.5” OD x 0.035” Wall thicknesses
- ASTM 213
  - 2.5 Safety Factor on 1000 Psi Working Pressure

Flow Velocity LOX

- 2.5 m/s
- 0.3 psi / ft pressure drop in tubing

Flow Velocity GCH4

- 128 m/s
- 1.9 psi / ft pressure drop in tubing



Nozzle

Material selection:

- Nozzle: High density graphite
- Chamber wall, flange and support plate: AL6061-T6
- Canvas phenolic

A_e/A_0 = 2.18

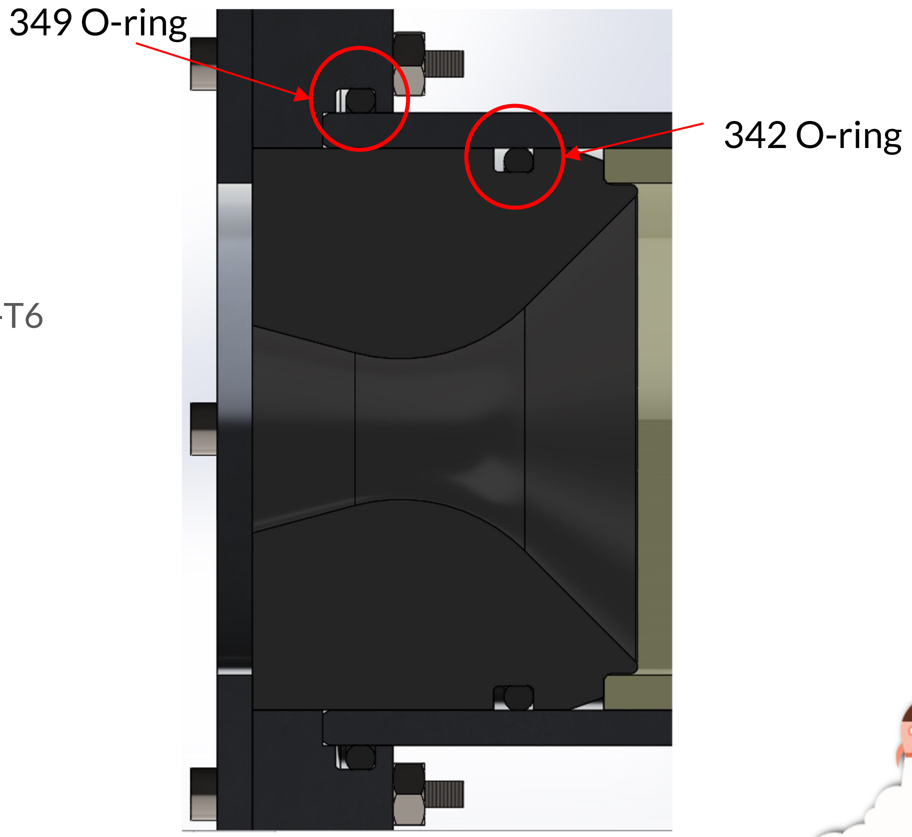
Standard 15 deg cone

σ_{hoop} = 2502 psi

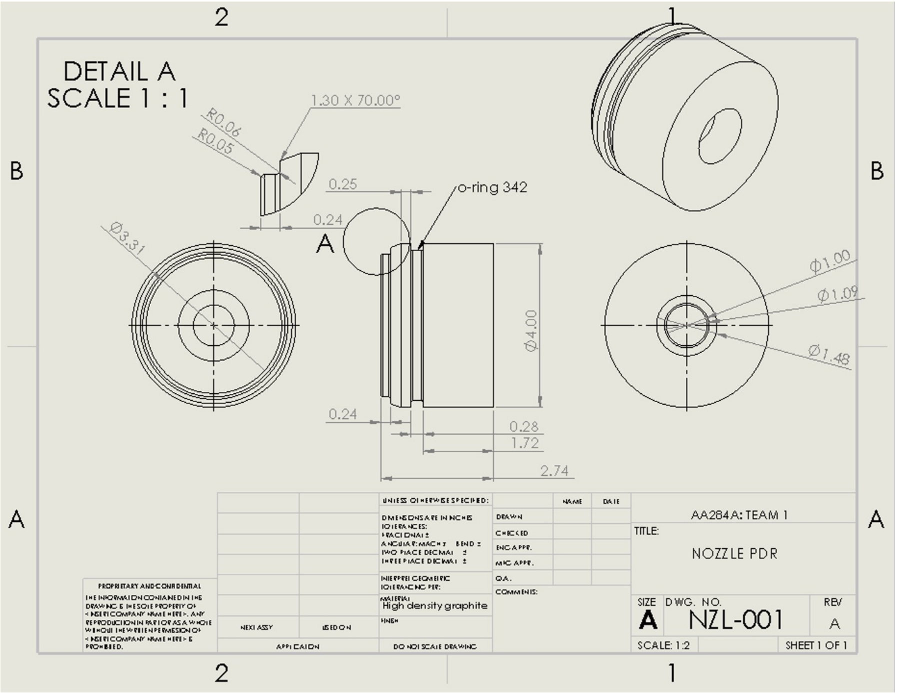
FS = 16 (designed for 150 psi)

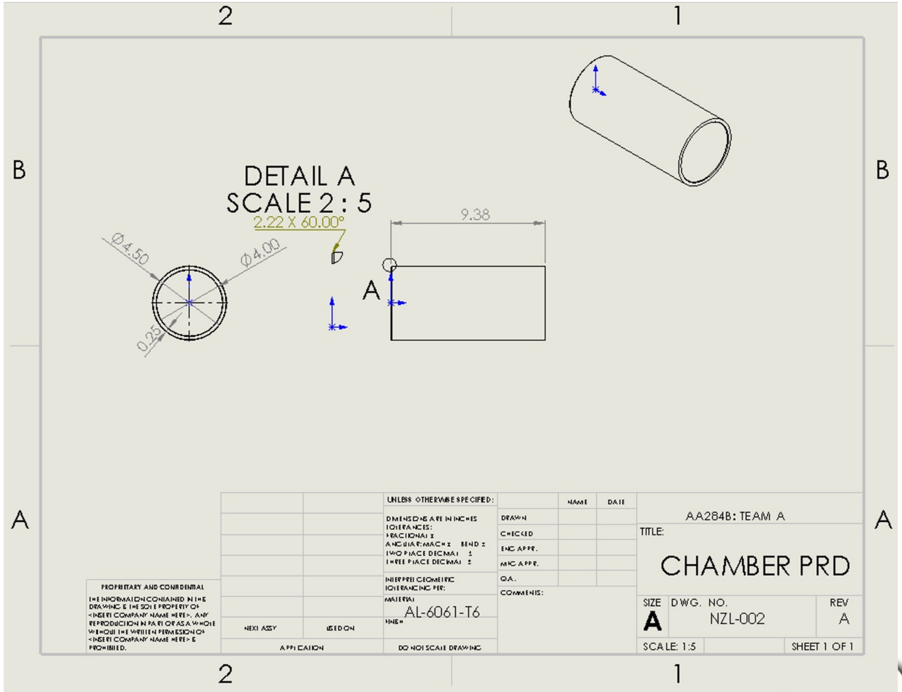
Sealing interfaces:

- 2 O-rings:
  - 342 size O-ring
  - 349 size O-ring



Nozzle


DETAIL A
SCALE 1 : 1
1.30 X 70.00°
R0.06
R0.05
0.25
0.24
o-ring 342
A
Ø3.31
Ø4.00
Ø1.00
Ø1.09
Ø1.48
0.24
0.28
1.72
2.74
AA284A: TEAM 1
TITLE:
NOZZLE PDR
High density graphite
SIZE A
DWG. NO.
NZL-001
REV A
SCALE: 1:2
SHEET 1 OF 1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SCALE 2 : 5
2.22 X 60.00°
9.38
Ø4.50
Ø4.00
0.25
A
AA284B: TEAM A
TITLE:
CHAMBER PRD
AL-6061-T6
SIZE A
DWG. NO.
NZL-002
REV A
SCALE: 1:5
SHEET 1 OF 1

Combustion Chamber Overpressure Relief

Notched design

Designed to fail at 800 psi

Axial force in bolts: 9000 N

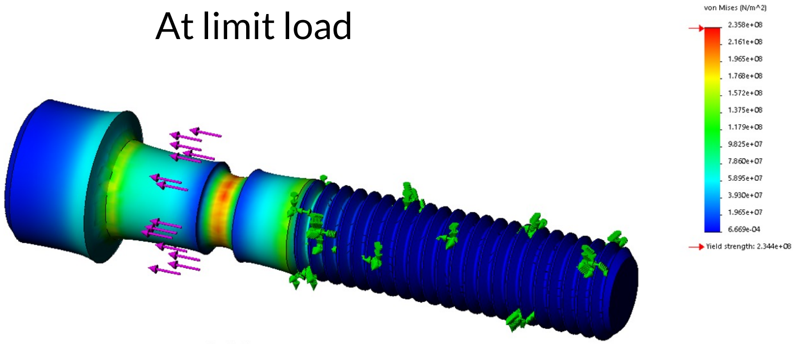
Max $\sigma_{von\text{-}mises}$ = 230 MPa

Stainless steel

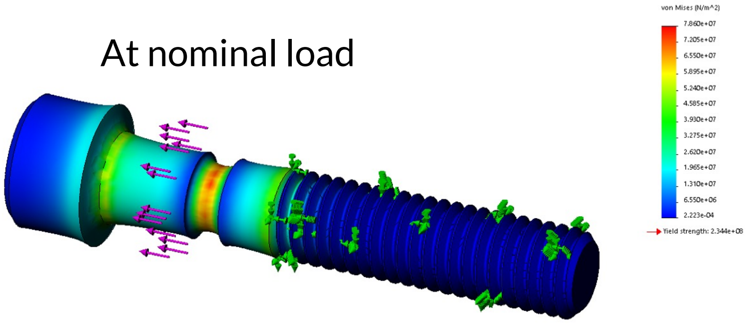
Cut is 0.06 inch deep

Tool diameter: 0.1 inch

At limit load



At nominal load

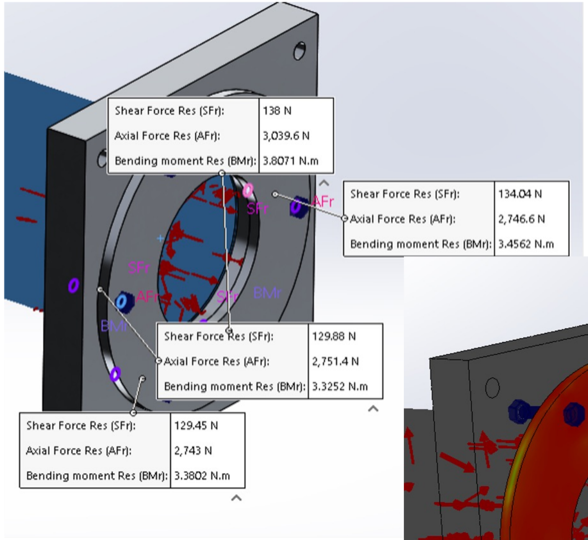


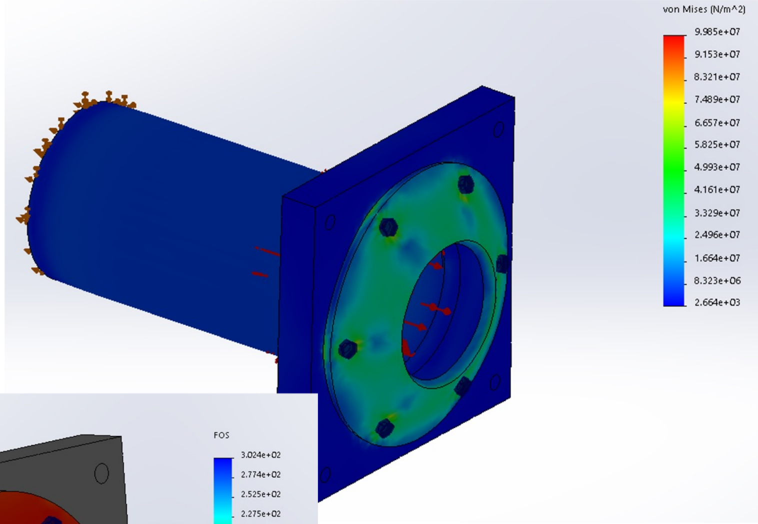
Combustion Chamber FEA

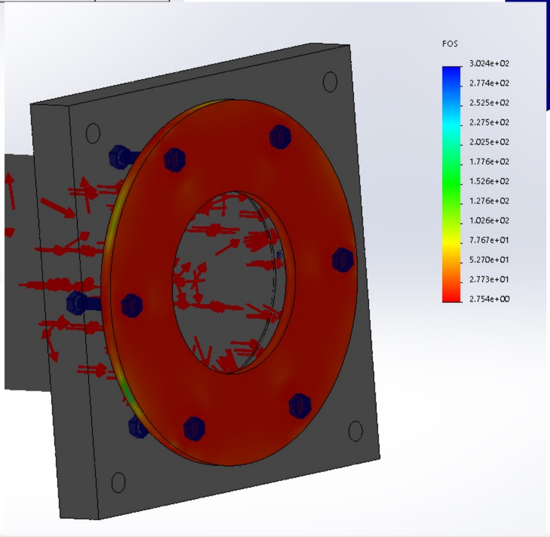
Pressure load: 150 psi
Bolt connection: 1/2-13
Mesh: element size 0.36 inch, # of elements 75000

Max $\sigma_{von\text{-}mises}$ = 100 MPa

Axial force in bolts: 3 kN

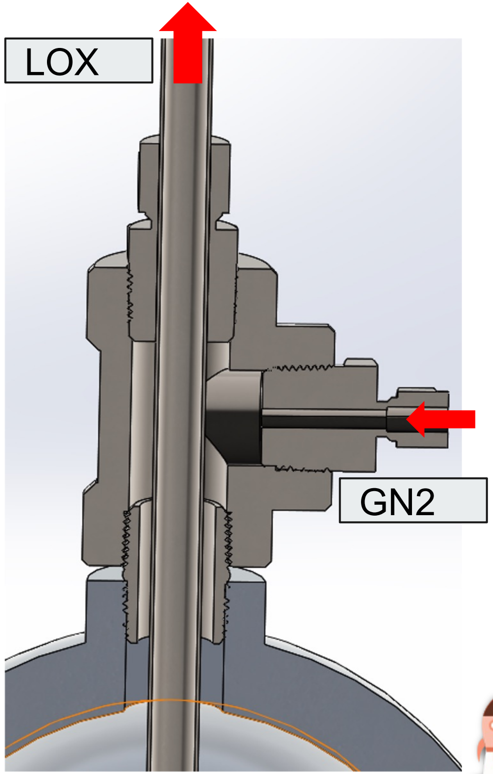






Min FS = 2.75 at 150 psi

LOx Run Tank



Rated Working Pressure: 3000 psi

Tank Material: Al 6061 - T6

Tank Thread: 3/4 - 14 NPSM

Compatibility with LOX

- According to NASA guidelines, Al 6061-T6 is compatible for LOX storage containers, but not piping
- According to Air force test data at cryo LOX temperatures
    - Yield strength increases 120%
    - Dimensional area decreases 0.4% due to thermal contraction

An off the shelf load cell will be used for fill measurement

Main Injector - Material

Material: Inconel 718 (DMLS Printed)

- Precipitation-hardening Nickel-Base superalloy
- High strength in either annealed or aged condition
- Highly oxidation resistant
- Retains relatively high strength from cryo to over 1000 C
- Poor machining characteristics
- Offered by Protolabs and 3D systems

DMLS Limitations

- Minimum feature size 0.38mm (0.015”)
- Max overhang angle approx. 45°
- Max horizontal circular cross section ⌀8mm

Main Injector - Interfaces & Envelope

Combustion Chamber: Radial seal - 2x size 240 O-rings (⅛” Cross Section)

- Axially clamped by flange plate & tie rods
- Radial seal needs less preload than face seal, and chamber wall will see small strain

Igniter: ½”-20 UNF thread with size 115 O-ring face seal

- Easy to interchange igniter & injector designs
- Avoids wear & leak paths of NPT fittings
- O-ring gland can be printed into injector

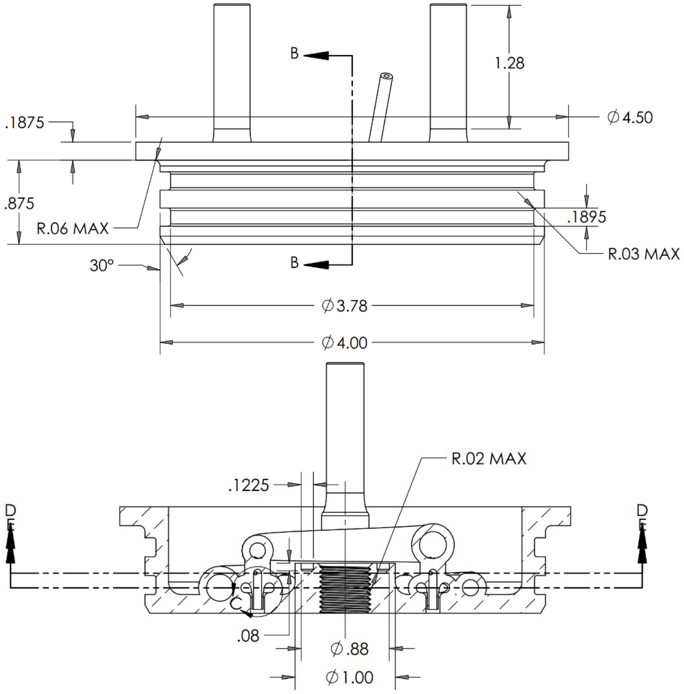
Feed System: 2x 0.375” tube ends printed into injector

- Use ⅜” Swagelok fittings to adapt or directly connect to main valves

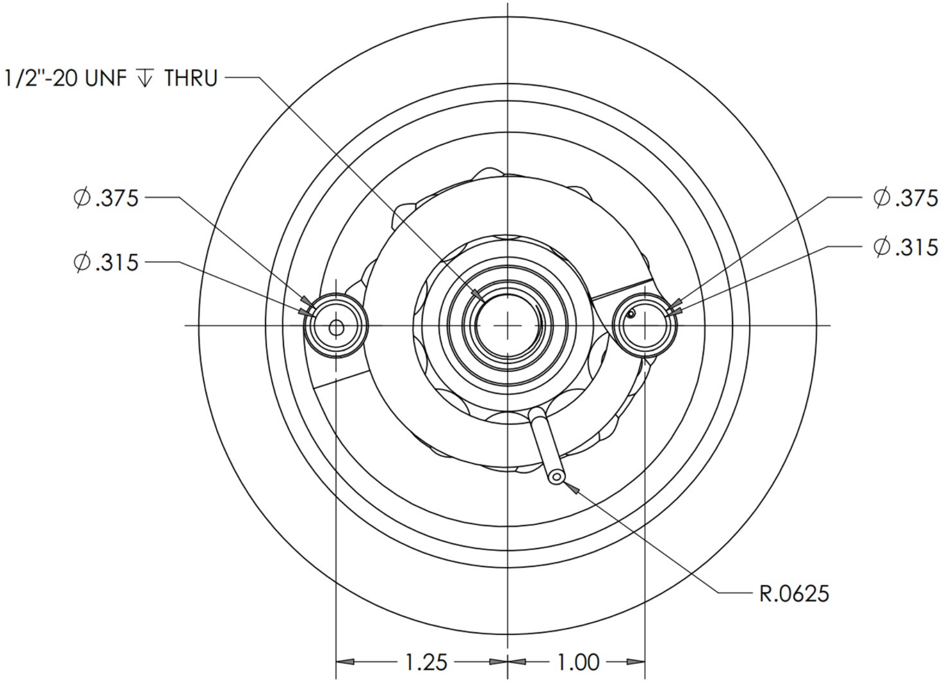
Chamber Pressure Measurement (PTMC)

- ⅛” tube end printed into injector
- Use Swagelok-¼” FNPT adapter to connect pressure transducer

Main Injector - Interfaces & Envelope



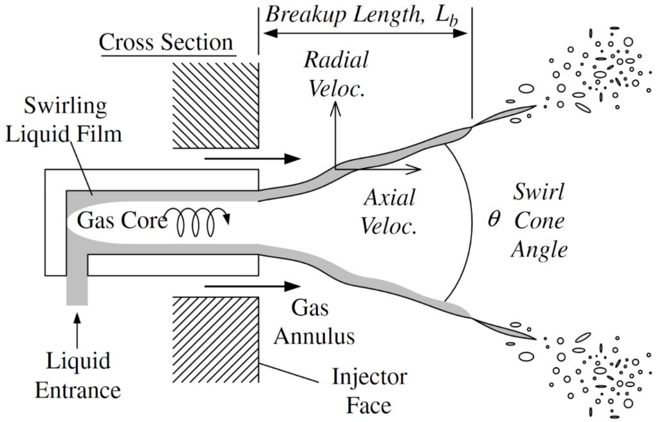
SECTION B-B



Main Injector - Elements

Liquid-Center Coaxial Swirl Elements
- Gas impinges axially on liquid spray cone
- Good mixing of unlike-phase propellants
- Liquid-Liquid swirl used on many liquid-propellant engines

Element Sizing
- Flow conditions at manifold inlet from simulation
  - Fuel: 24 bar, 240 K
  - LOx: 20 bar, 140 K
- Target 10 bar outlet, Pc
- 10 elements nominally (arbitrary)
- Fuel Orifice: 1.91E-5 m^2
  - Assumed Cv 0.6, including manifolds (plate orifice)
- LOx Orifice: 1.27E-5m^2
  - Assumed Cv 0.9, including manifolds



Liquid-Center Coaxial Swirl Element [1]

[1] Im, Ji-Hyuk, et al. "Comparative study of spray characteristics of gas-centered and liquid-centered swirl coaxial injectors." *Journal of Propulsion and Power* 26.6 (2010): 1196-1204.

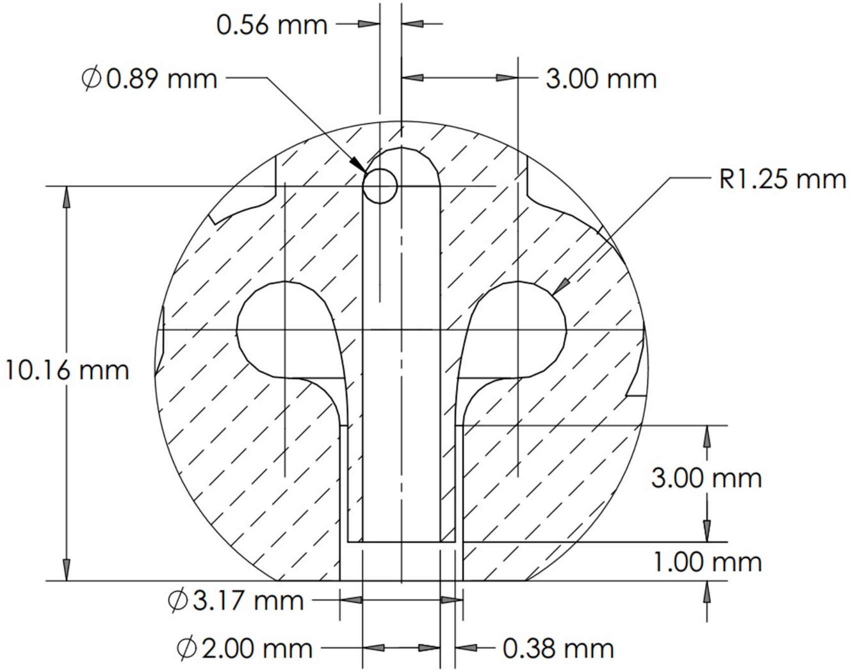
Main Injector - Elements

LOx Element

- 2x Tangential inlets ⌀0.89mm (net ⌀1.27mm)
- “LOx Post” shared outlet ⌀2mm
- Inlets tangent to outlet, ⊥ to outlet axis

Fuel Element:

- Single annular orifice, ID 2.76mm, OD 3.17mm
  - Protolabs: min. wall thickness 0.381mm
- ⌀2.5mm toroidal manifold for annular orifice
  - Allow deceleration of gas before entering orifice to even flow distribution



Main Injector - Elements (Alternative)

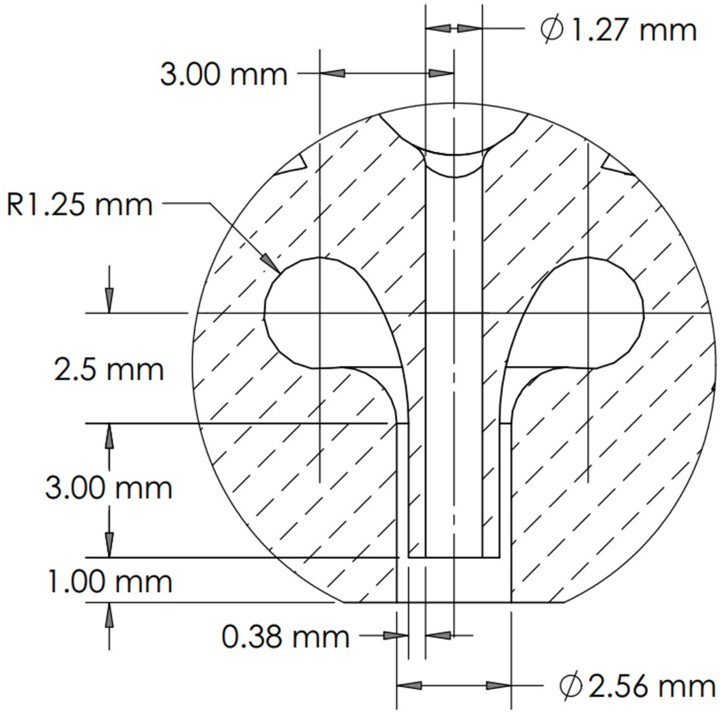
Coaxial Non-Swirl Element (Simpler to print)

LOx Element

- Single ⌀1.27mm “post”
- Direct inlet from LOx manifold

Fuel Element:

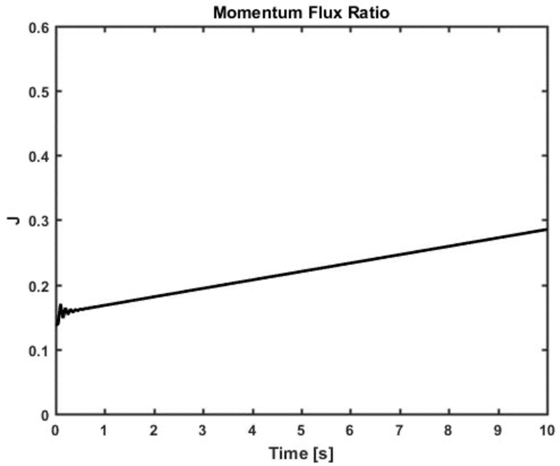
- Single annular orifice, ID 2.03mm, OD 2.56mm
  - Protolabs: min. wall thickness 0.381mm
- ⌀2.5mm toroidal manifold for annular orifice
  - Allow deceleration of gas before entering orifice to even flow distribution

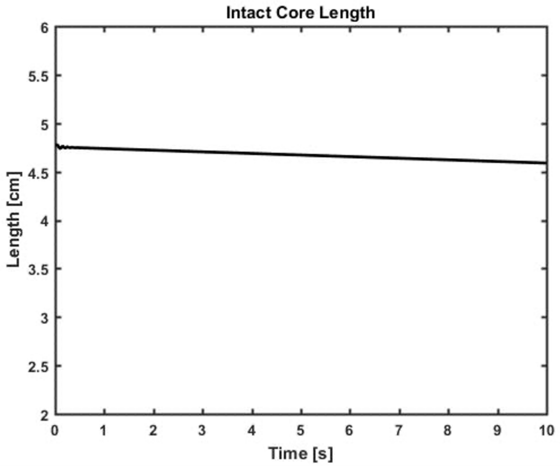


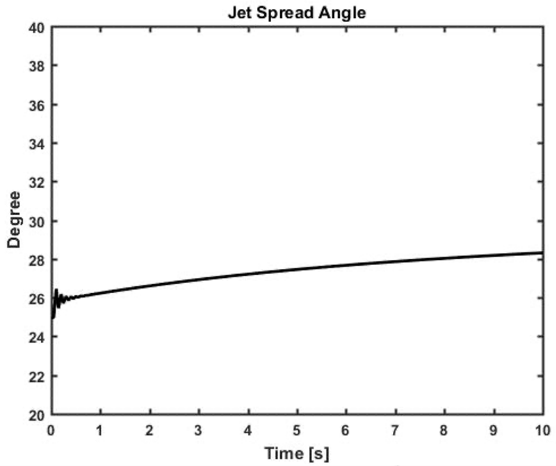
Main Injector - Element Performance Calcs

Estimates for coaxial non-swirl injector

- CH_4 exit area 1e-5 m^2
- Intact core length 4.6 cm
- Spread angle 27.5 deg
- To be updated once feed system pressure drops are better characterized







Main Injector - Manifolding

"Constant Velocity" Manifold Design

- Constant rate of area change ⇒ Constant dynamic pressure (neglecting frictional losses)
  - As propellant is tapped off from manifold, manifold cross-section shrinks to maintain velocity
  - In constant-area manifold, dynamic pressure is converted to static as distance through manifold increases
- Element inlets tap off perpendicular to manifold
  - Flow into elements is driven by static pressure
  - Maintaining static pressure evens out mass flow
- Taper takes advantage of AM capabilities

Manifold Sizing

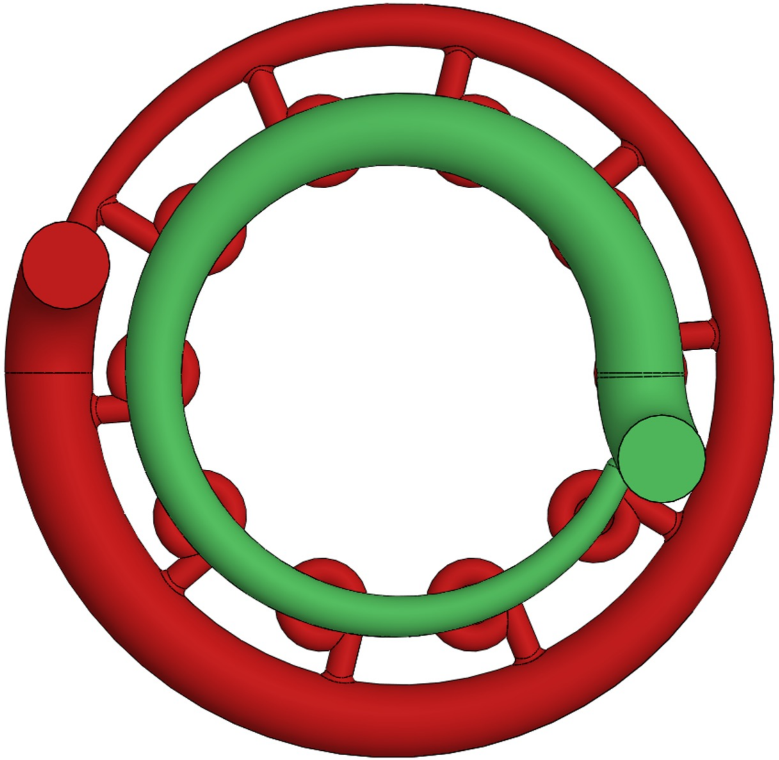
- 8mm max. unsupported circular cross-section ~2e-4 m^2
- Order of magnitude larger than orifice areas
- Methane manifold velocity: ~120 m/s
  - Feed system sim code must be updated to include frictional losses
- Liquid Oxygen manifold velocity: ~5.6 m/s

Main Injector - Manifolding

Green: Liquid Oxygen

Red: Methane

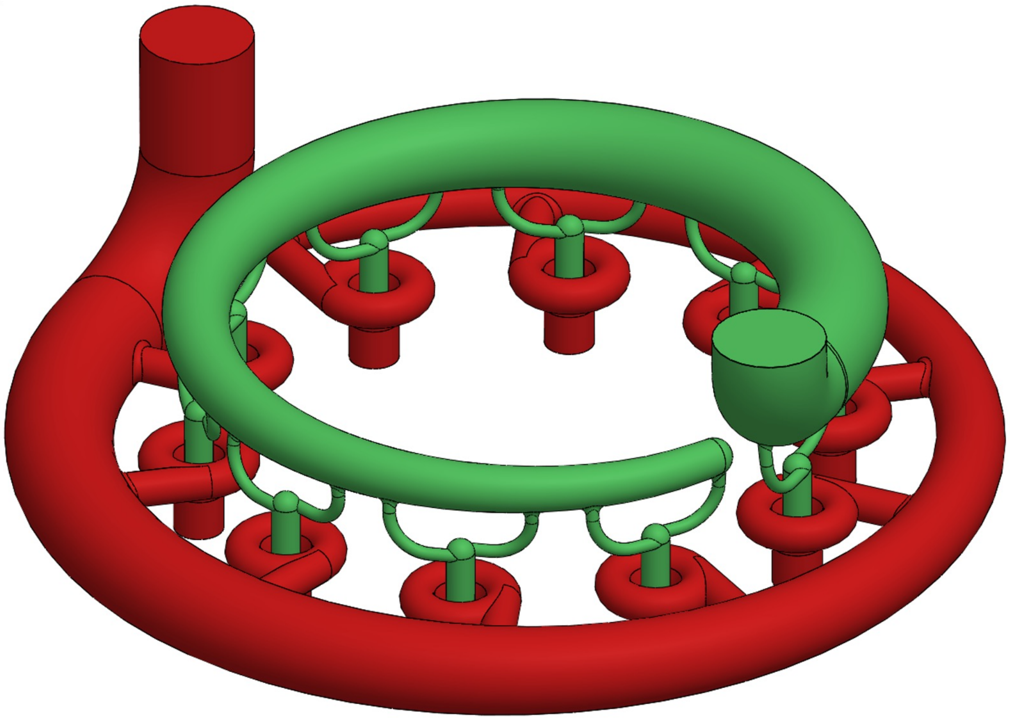
Tangential inlets for fuel elements are intended to even out mass flow around annulus, i.e. prevent higher mass flow near inlets



Main Injector - Manifolding

Green: Liquid Oxygen

Red: Methane



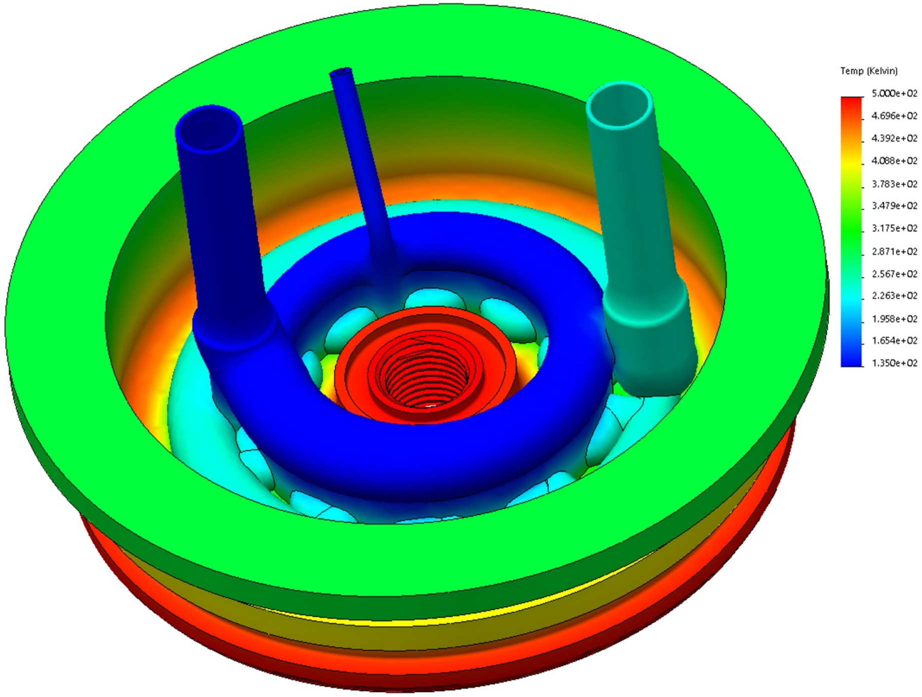
Main Injector - FEA

Thermal Analysis

- All faces contacting LOx assigned 135 K
- All faces contacting CH4 assigned 244 K
- Chamber face & igniter body contacts assigned 500 K (arbitrary)

Static FEA

- LOx & Fuel manifolds assigned 40 bar pressure
- Chamber face & PTMC tap-off assigned 10 bar pressure (up to second O-ring gland on injector)
- Supported with elastic supports on faces contacting chamber wall & retaining flange
- Igniter attachment & fittings neglected

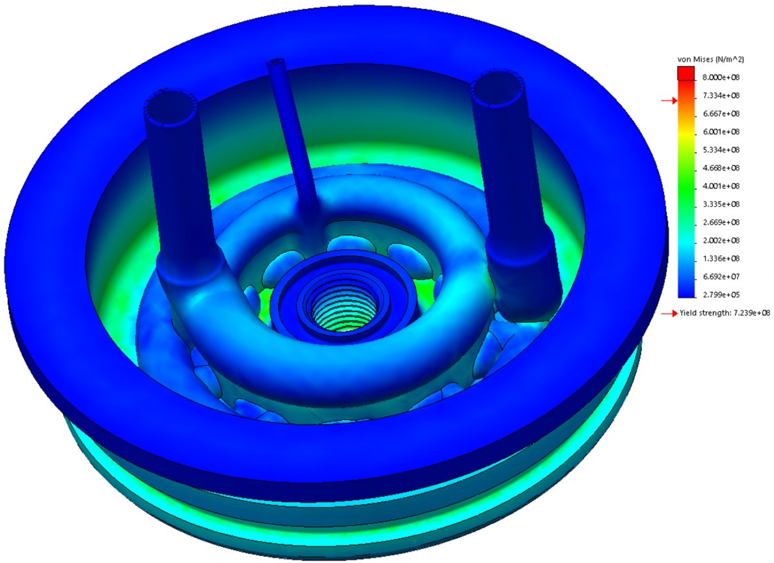


Thermal Analysis Results

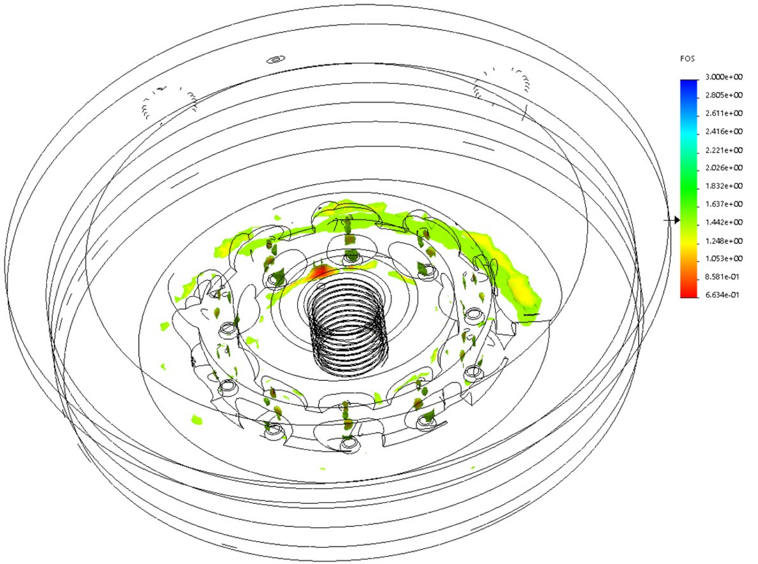
Main Injector - FEA

Some surface yielding in fuel manifold, but no through-thickness yield

With slight refinement, design will certainly survive low-cycle fatigue from testing



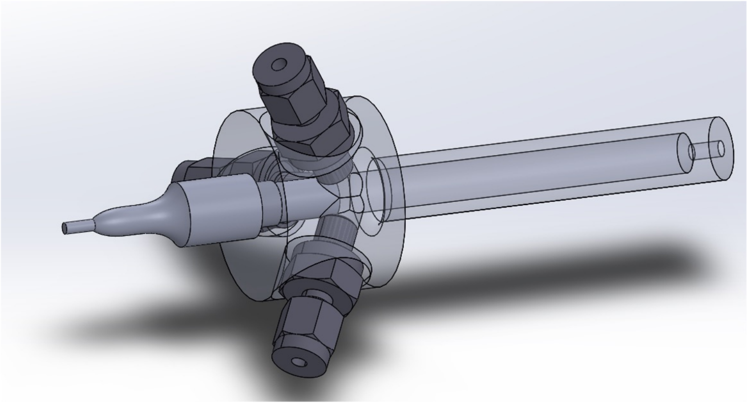
Von Mises Stress Criterion

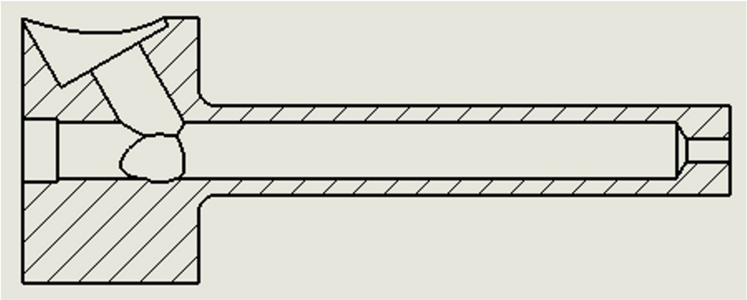


Factor of Safety (All regions with FSy < 1.5)

Igniter - Overview

Oxidizer	Gaseous Oxygen
Fuel	Gaseous Methane
Chamber Pressure	13.8 bar (~200 psia)
Throat Diameter	1/8 in
Chamber Diameter	7 mm (spark plug thread ID)
O/F Ratio	4.5
Ox Mass Flow Rate	0.005 kg/s
Fuel Mass Flow Rate	0.0011 kg.s
Chamber Temp	3463 K
Material	Inconel 718
Safety Factor	>15
Chamber Length	3 in
L*	14.58
Contraction Ratio	4.86





Interfaces

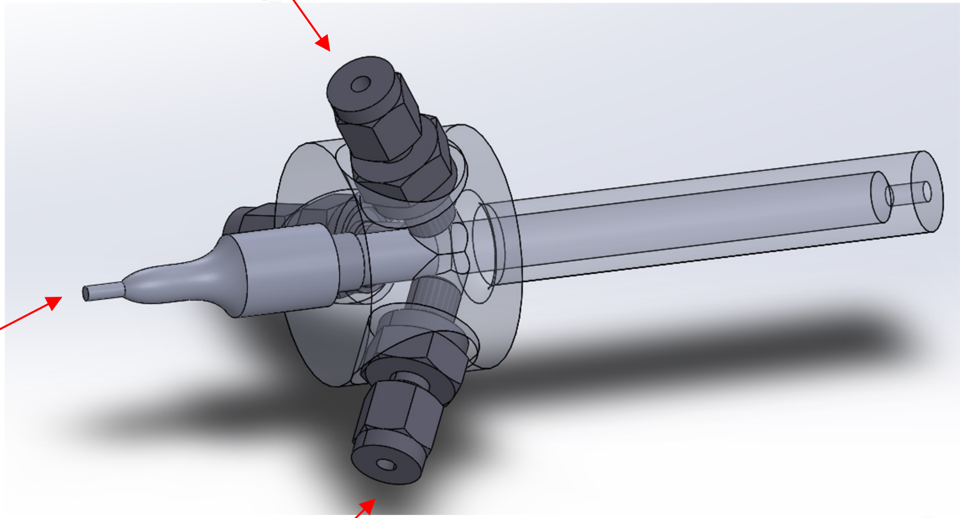
ector, o-ring face seal

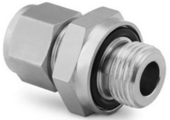
a single component

ennox orifices

Ox Orifice	1.76 mm
Fuel Orifice	0.99 mm
Impinge angle	120 degrees

Pressure transducer
(attached via tube)





Igniter - Spark Plug

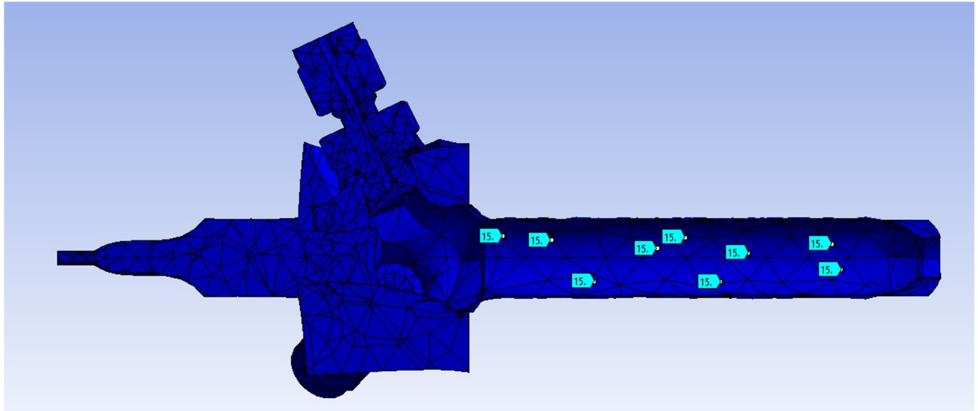
NGK surface discharge spark plug

ACDelco ignition coil (7-24 Vdc)

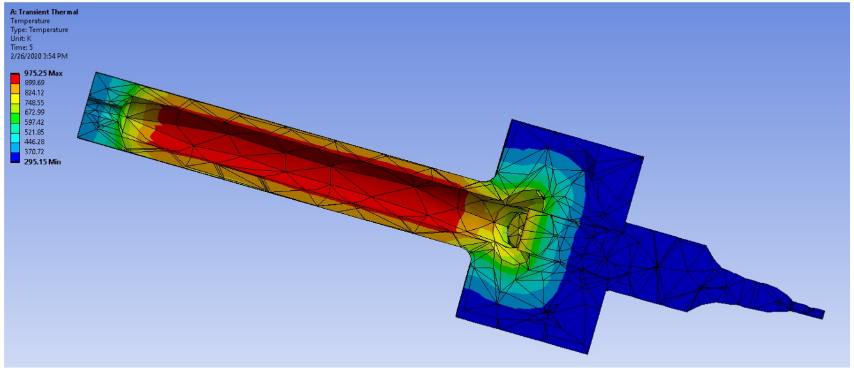
ACDelco spark plug wire

Aptiv connectors

Igniter - FEA



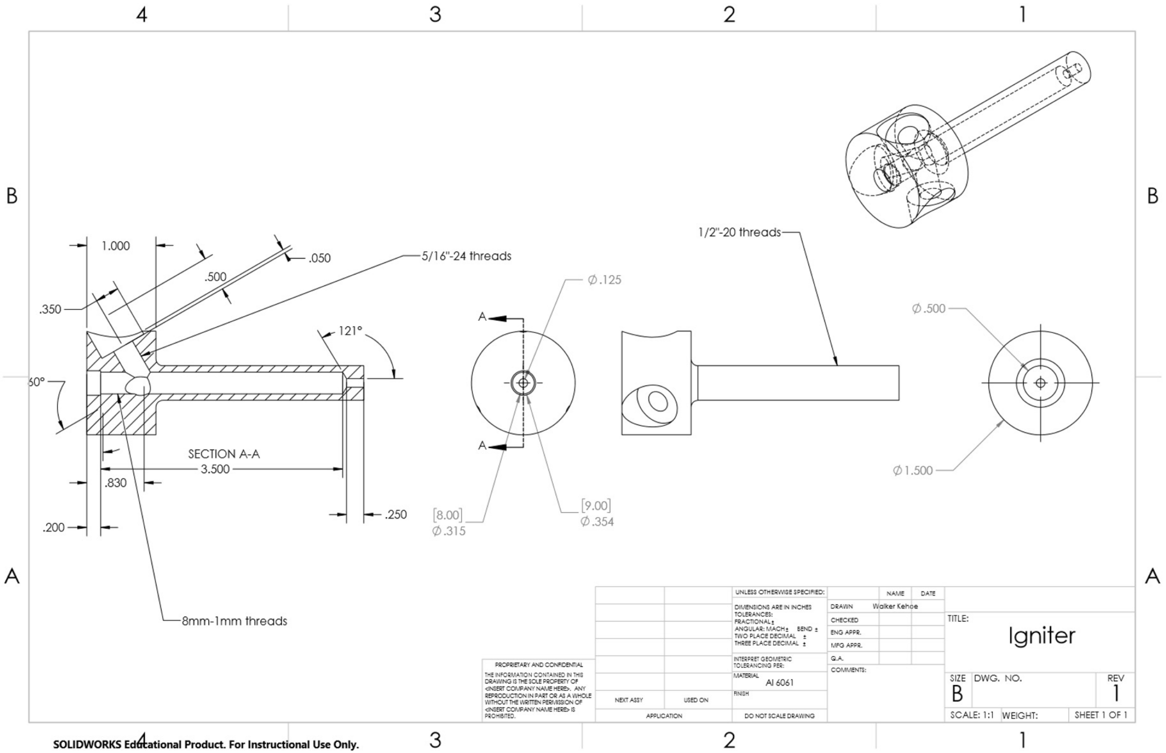
Pressure: Safety Factor > 15



Temperature after 5 seconds

- Heat transfer coeff of 500 W/m^2-K (needs to be refined)
- Igniter will most likely run for much less than 5 seconds

Igniter - Engineering Drawing



Cavitating Venturi - Design Specifications

15 degree converging inlet

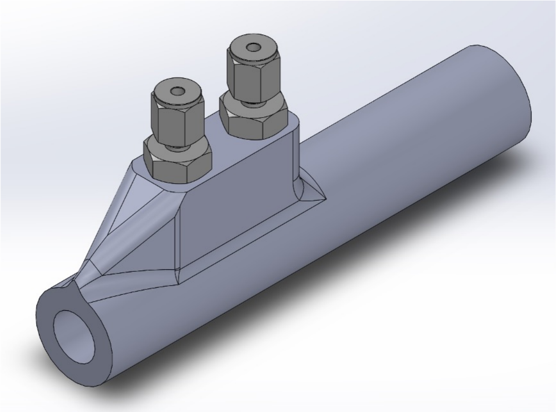
7 degree diverging outlet

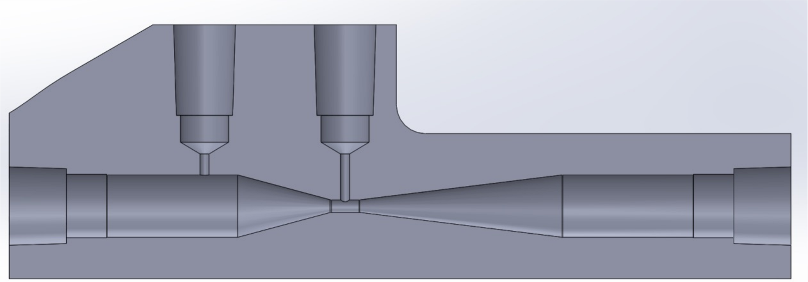
Cp = 0.85

Cd = 0.95

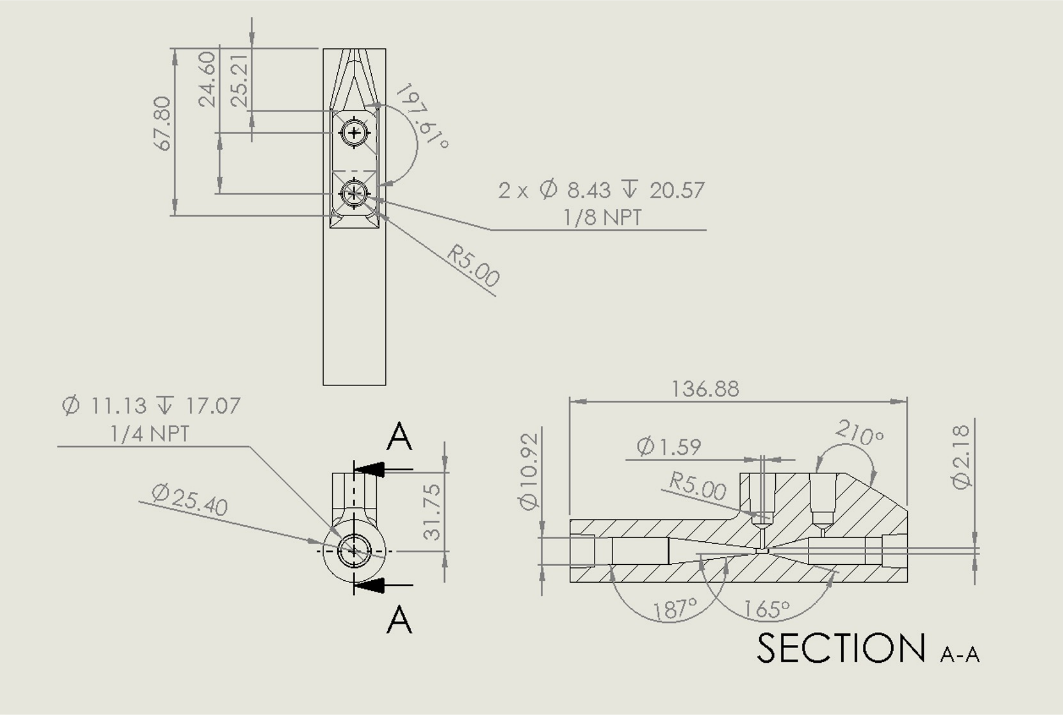
d_th = 2.18 mm

Designed for DMLS from 3D systems

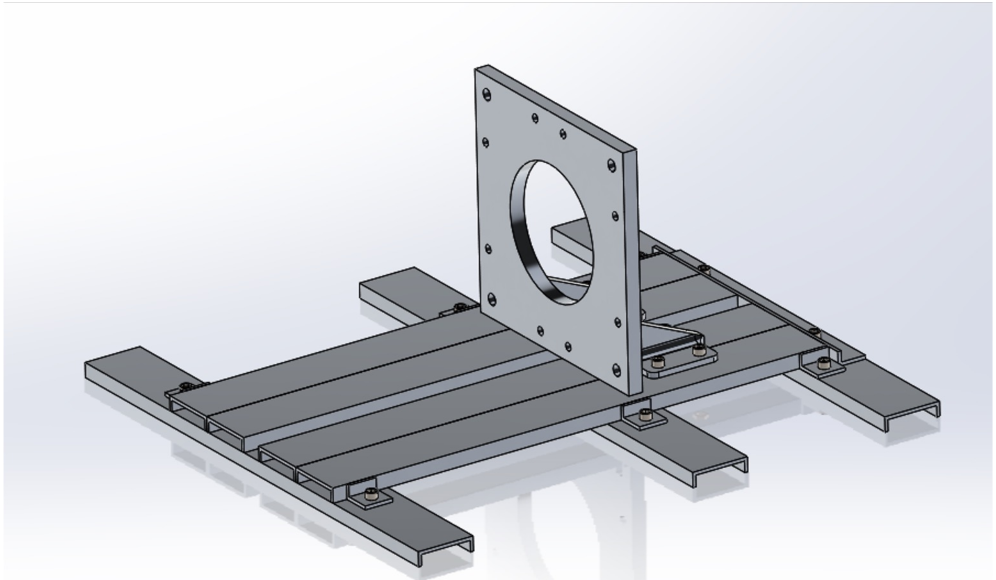


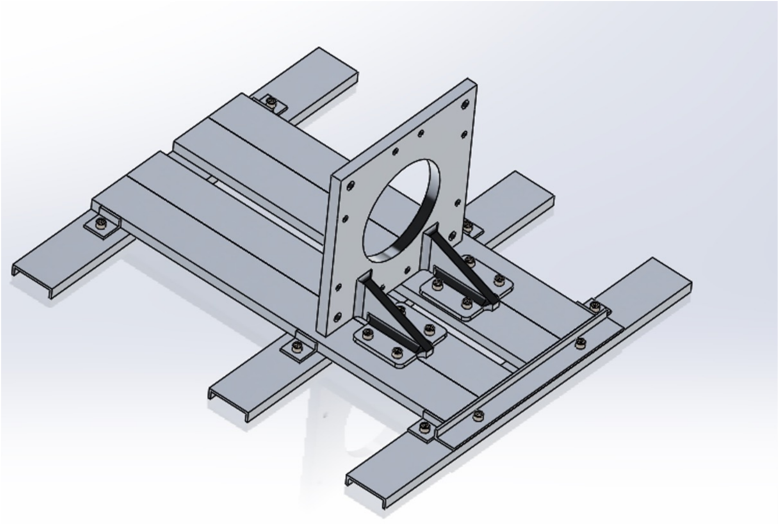


Cavitating Venturi - Engineering Drawings

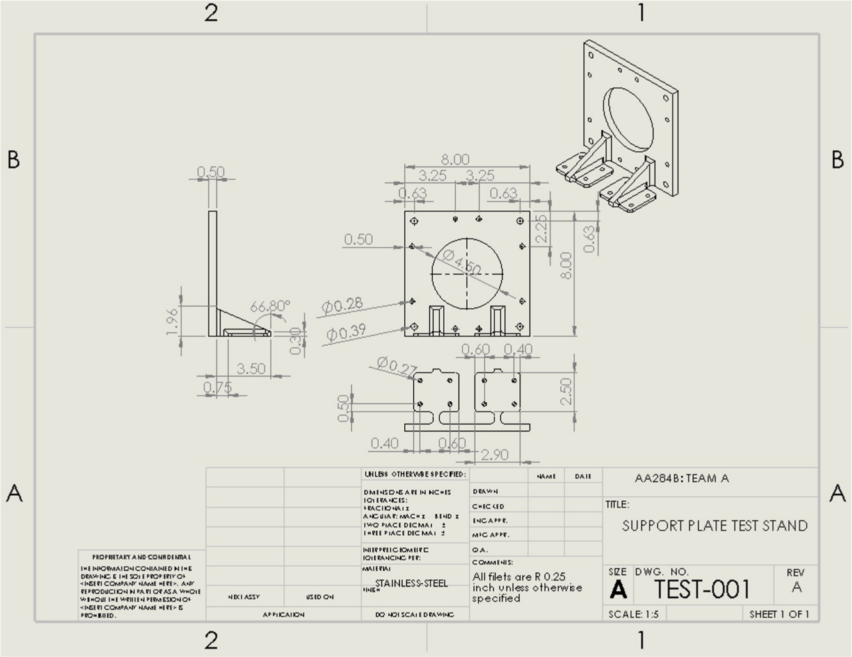


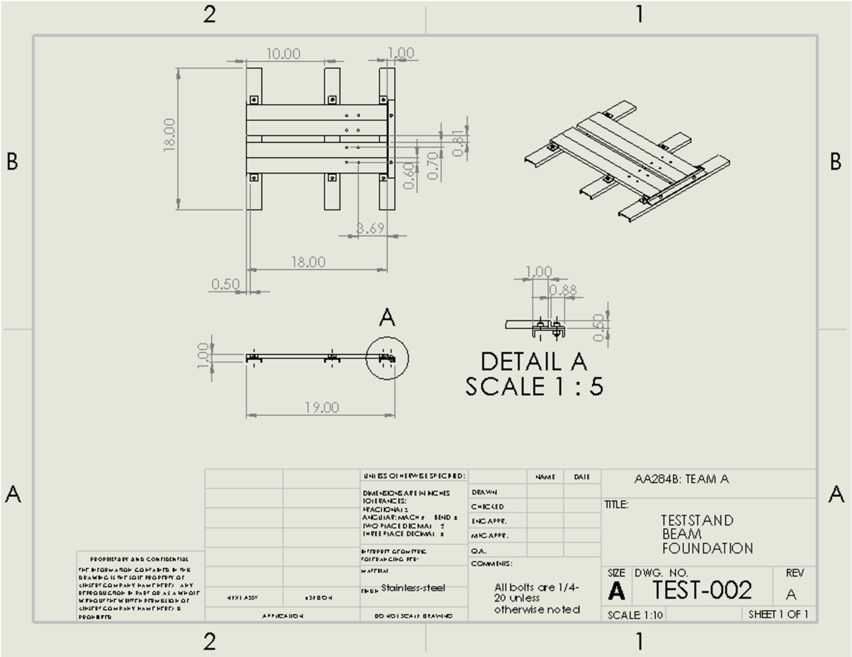
Test Stand





Test Stand


AA284B: TEAM A
TITLE:
SUPPORT PLATE TEST STAND
STAINLESS-STEEL
All fillets are R 0.25 inch unless otherwise specified
SIZE A
DWG. NO. TEST-001
REV A
SCALE: 1:5
SHEET 1 OF 1


DETAIL A
SCALE 1 : 5
AA284B: TEAM A
TITLE:
TESTSTAND BEAM FOUNDATION
Stainless-steel
All bolts are 1/4-20 unless otherwise noted
SIZE A
DWG. NO. TEST-002
REV A
SCALE 1:10
SHEET 1 OF 1

Test Stand

Objective: Design as cheap and simple as possible for the designed loads

Material:

- U-beams and L-beams from Home Depot, standard dimensions, plain steel
- ¼-28 bolts everywhere
- Steel plate, 0.5 inch, easily weldable, total of 4 welds are needed on the support plate, another 12 small welds on the U-beams
- No milling or CNC needed

Test Stand - FEA

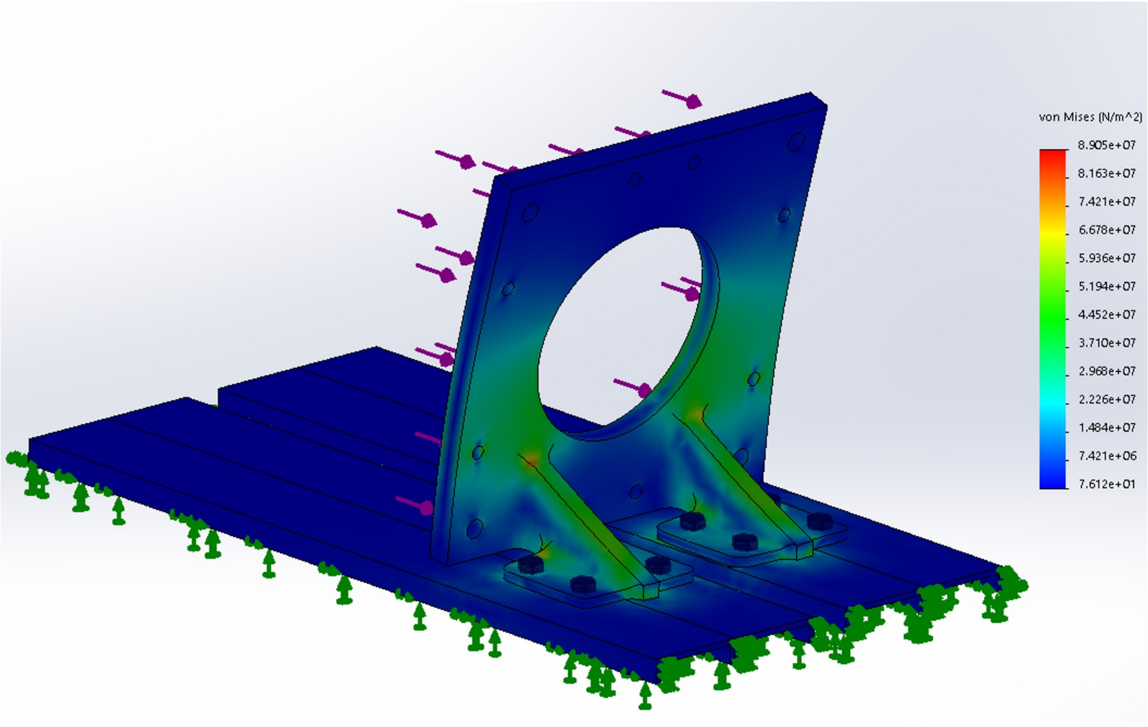
Thrust loads analysis

Load applied: 2kN

8 bolts (¼-20, no pre-load)

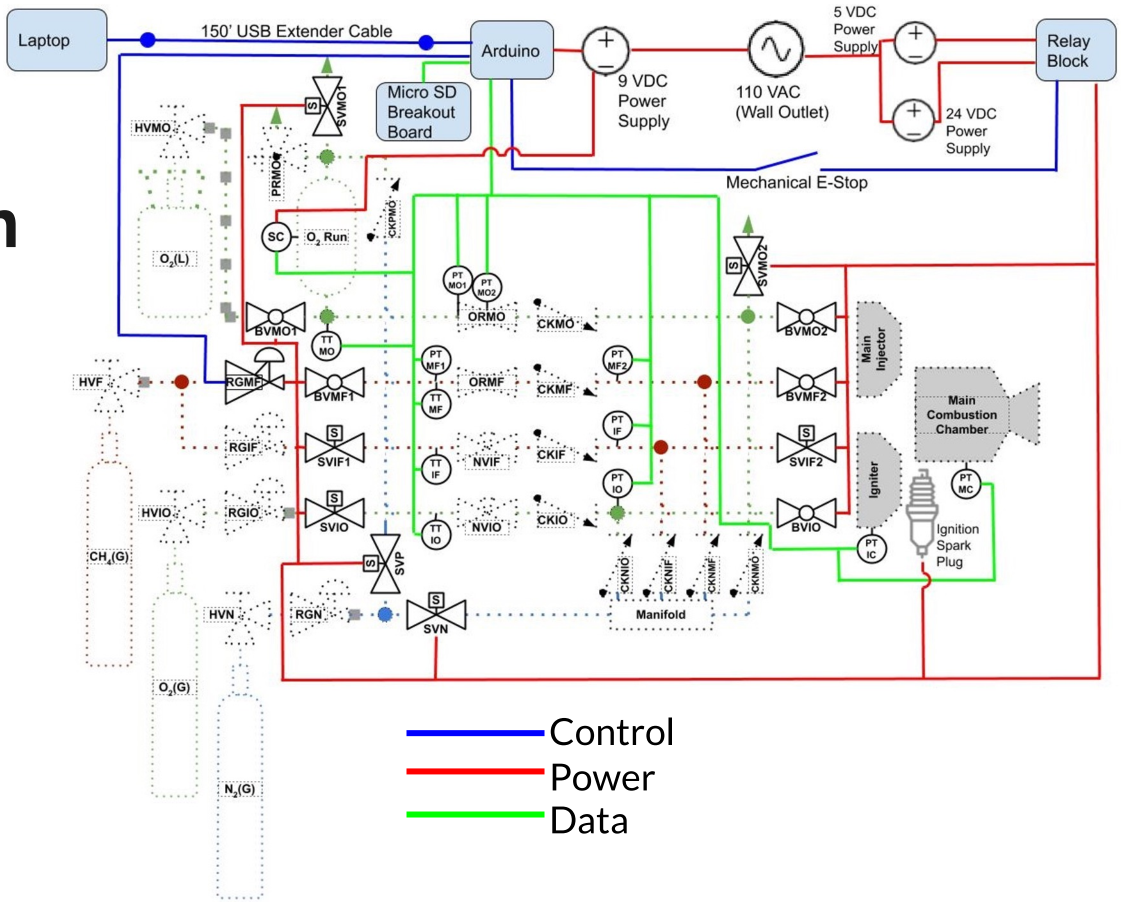
Mesh: element size 0.4 inch, # of elements 15000

Max $\sigma_{von\text{-}mises}$ = 89 MPa



Instrumentation & Control

Instrumentation & Control Diagram



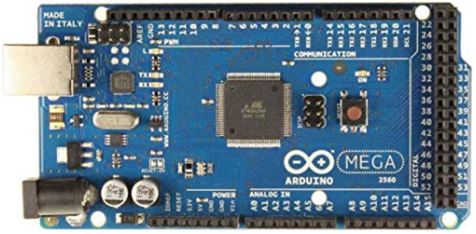
Control Component List

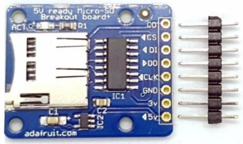
Power
- 24 VDC
- 9 VDC
- 5 VDC

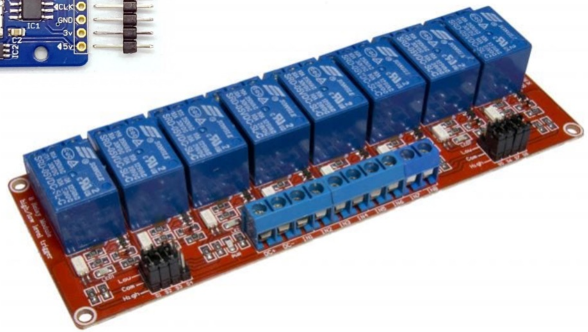
Controller
- Arduino Mega
- Laptop

Data Collection
- Micro SD breakout board
- USB Repeater Cable

Emergency Stop
- Big red button







Control System

- Test sequence stored on Arduino Mega located on the test stand
- USB extension cable allows serial communication to laptop with PySerial
  - Critical data (chamber pressure) plotted in real time
  - Test sequence initiation and other commands sent as character signals to arduino
- Digital valve control commands sent from Arduino to opto-isolated relay block
  - Controls 24 VDC for valves and ignition coil
- Mechanical emergency stop switch interrupts command line between arduino and relay block
  - Long extension cord (approx 300') required for experimenters to access e-stop. Installing switch on the 24 VDC power line would result in high voltage drop
- Oxygen run tank load cell monitored by Arduino

Test Operations - LOx Fill & Chill-in

- LOx run tank and feed lines to be insulated by a 0.4 inch thick ceramic fiber insulation blanket and a two-layered aluminium polyethylene film
- Fill procedure:
    - Measure empty run tank weight
    - Run LOx through the feed lines with the solenoid valve open (SVMO2)
    - Close SVMO2 when liquid flow is established through the feed
    - Keep fill valve (BVMO1) open until the weighing scale reads a 5 kg increase in the tank weight
    - Fill N2 through SVP until the pressure transducer reads 1100 psi

Test Operations - Pressurization and Hot-Fire

- N2 gas pressurization system
  - Check valves to prevent backflow of gas into tank
  - Feed N2 to both LOx and CH4 tanks until required pressure is reached
  - Once the test starts, run N2 feed to maintain constant pressure
- Hot-Fire test
  - Check valves are closed and in operation
  - Check pressurized tanks, ensure no leaks
  - Check data acquisition system
  - Push start button to begin test
  - Conduct a 2-second pre-run purge with N2 to purge impurities
  - Open LOx valve to begin oxidizer flow
  - Open the CH4 valves and start the igniter
  - Check the pressure of the combustion chamber, if safe, continue
  - Run test for 5s
  - Close valves and begin engine shutdown
  - Open LOx valve to cool the engine, then use CH4 valve to purge

Emergency Stop Capability

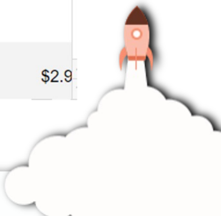
- Shutdown button pressed if pressure readings exceed the maximum allowable values
- Implemented by closing the LOx and CH_4 supply and beginning the purge procedure
- Following ASME protocol

Bill of Materials & Fabrication

BOM Spreadsheet

https://docs.google.com/spreadsheets/d/1Akb-G0P3gi-R2JljckR0jrPFSVN0DPMDoXRMupv_SYY/edit#gid=676738434

	A	B	C	D	E	F	G	H	I	J
1		**Supply Chain Info**								
2	**Item Number**	**Subsystem**	**Category**	**Item**	**Part No.**	**Manufacturer**	**Supplier URL**	**Lead Time Estimate**	**Item Unit**	**Unit Cost**
39	37	Prop Feed	Flow Controls	600 Psi PRV 29430 Series Stainless Steel Relief Valves	PRV29432T600	Rego	http://www.regoproducts.com/cryo/cryogenic-industrial-gas/products/prv-19430.html	6 weeks	each	$61.8
40	38	Prop Feed	Tube/Pipe Fittings	High-Pressure 316 Stainless Steel Pipe Fitting Cross Connector, 3/4 NPT Female	4443K655		https://www.mcmaster.com/4443k655	1 day	each	$78.9
41	39	Prop Feed	Tube/Pipe Fittings	Thick-Wall Stainless Steel Threaded Pipe Nipple Reducer Threaded on Both Ends, 3/4 x 1/4 NPT	2161K13		https://www.mcmaster.com/2161k13	1 day	each	$29.8
42	40	Prop Feed	Tube/Pipe Fittings	High-Pressure 316 Stainless Steel Pipe Fitting Bushing Adapter, 3/4 NPT Male x 1/4 NPT Female	4443K413		https://www.mcmaster.com/4443k413	1 day	each	$11.6
43	41	Prop Feed	Tube/Pipe Fittings	High-Pressure 316 Stainless Steel Pipe Fitting Cross Connector, 1/4 NPT Female	4443K652		https://www.mcmaster.com/4443k652	1 day	each	$43.2
44	42									
45	43	Prop Feed	Tube/Pipe Fittings	Brass Female CGA 540 Nut for High-Pressure Nipple Hose Fitting for Compressed Gas	79215A662		https://www.mcmaster.com/79215a662	1 day	each	$2.9



Total Cost

Running Total

Budgeted	*Purchased*	*Remaining*
5066.45	95.98	4837.57

Subsystem Breakdown

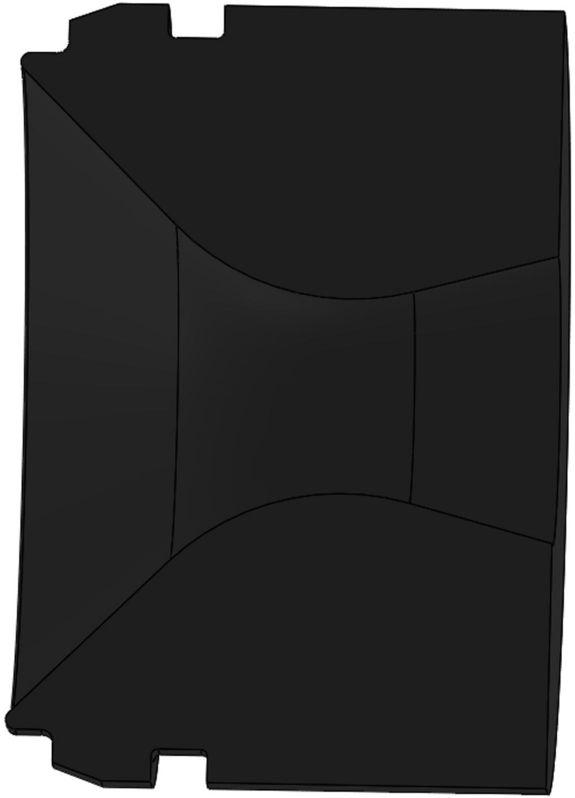
Subsystem	*Budgeted*	*Purchased*
Avionics	534.9	91.86
Igniter/Injector	95.98	95.98
Nozzle/Chamber	23.78	0
Feed	4348.81	0
Test	158.96	0

Component Breakdown

Component	*Budgeted*	*Purchased*
Adhesives/Sealants	0	0
Fasteners	14.81	0
Flow Control	2373.87	0
Instruments	447.22	91.86
Machined Parts	0	0
Metal Stock	144.15	0
Propellant/Gas	315.15	0
Seal Elements	23.78	0
Services	0	0
Tanks	184.95	0
Tubing/Pipe Fittings	1455.25	0
Tubing/Pipes	107.27	0

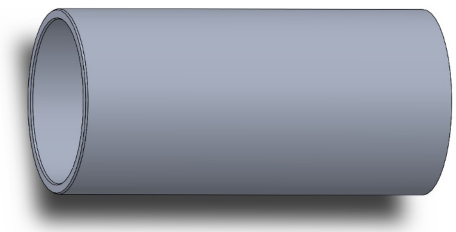
Fabrication - Nozzle

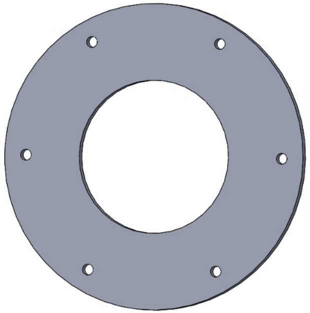
- Nozzle: graphite, conical converging-diverging with one O-ring groove
  - https://etmgraphite.com/
  - Long Beach, can ship to Stanford

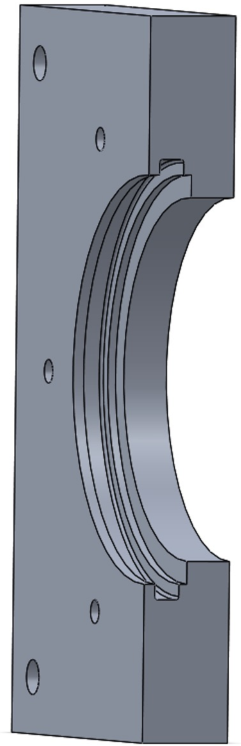


Fabrication - Combustion Chamber

- Aluminum tube: no grooves, easy to machine
  - PRL
- Flange: square w/ circular center, 1” thick Al-6061, ½” deep slot for aluminum tube, O-ring groove in slot, 10 holes (4 tie rods, 6 bolts)
  - Likely too difficult for us to machine ourselves in PRL
- Plate: circular w/ circular center, ¼” thick Al-6061, 6 bolt holes
  - PRL?







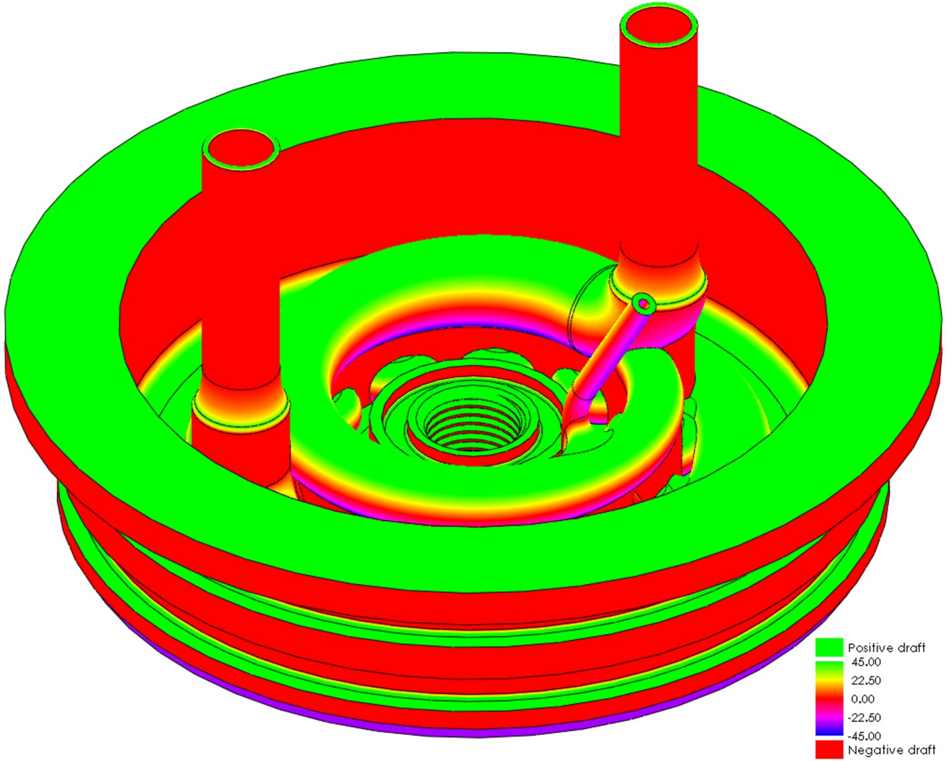
Fabrication - Main Injector

DMLS by 3D Systems or Protolabs

- In discussion with both about sponsorship
- Journal/Conference paper on project
- If not, can likely purchase (~$1500)

Overhang Angle Analysis

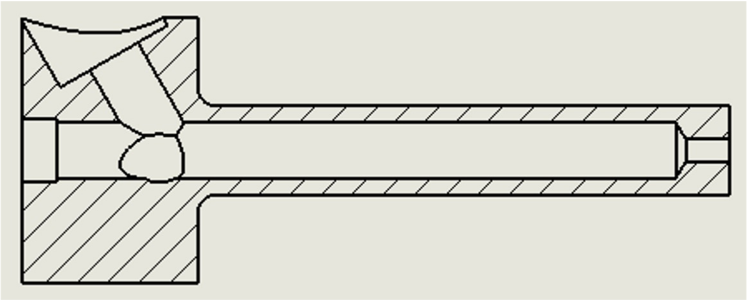
- Steepest exterior overhangs are on LOx manifold, ~55°, but are small enough area to print
- O-ring glands on exterior can be supported & post-machined
- Internal geometry stays below 4mm roof radius



Fabrication - Igniter

Iterative process:

- Machine out of 316L stainless steel in PRL
- Loop: test & redesign (if necessary)
- DMLS for final design using Inconel 718
    - Sponsorship by 3D Systems or Protolabs
    - Stretch goal: incorporate into injector as a single component



Fabrication - Test Stand

- All components can be bought with minimal lead time from Home Depot and McMaster
- Small standard steel welding job
- Estimated time to completion: 1 week
- Only uncertainty: Mounting holes in parking lot are not useable anymore

Sourcing - Cryo Flow Controls

Ball Valves

- Triad ¼” NPT ball valves
  - $399 with student discount
  - April 8th delivery date

Solenoid Relief Valves

- Gems D-Cryo Series Solenoid Valve
  - $167
  - 25 day lead time

Run Tank Scale

- Parcel Scale from Ebay ($100)

Check Valves

- Checkall ⅜” NPT check valve
  - $82.55
  - $42 extra for Oxygen cleaned
  - 3 day lead

Cavitating Venturi

- Printed with 3D systems
  - Lead time unknown

Sourcing - Lab Components Available at Stanford

Methane (main)	Tescom pressure regulator
	1/4 in Swagelok ball valve
	MSP Pressure transducer (2)
	3/8 in Swagelok ball valve
LOx (main)	GP Pressure transducer (2)
Methane (igniter)	Victor regulator CGA 350 (Greg?)
	Parker solenoid valve
	MSP Pressure transducer
GOx (igniter)	Victor regulator CGA 540
	MSP Pressure transducer
	1/4 in Swagelok ball valve
N2 (purge)	Victor regulator CGA 580
	Parker solenoid valve (2)

Sourcing - Combustion Chamber Phenolic

- Accurate Plastics
  - https://accurateplastics.acculam.com/item/c-ce-canvas-phenolic-laminates/phenolfab-trade-c-ce-laminate-tube/fbgt3-5004-000n

Sourcing - Fittings

https://docs.google.com/spreadsheets/d/1Akb-G0P3gi-R2JIjckR0jrPFSVN0DPMDoXRMupv_SYY/edit?usp=sharing

- Sourced through McMaster-Carr and Swagelock
- End decision will be made before purchasing based on price

Test Plan

Test Plan

Subsystem tests

- Igniter test (needs to re-ignite for this mission)
  - Test igniter under operating conditions
    - Determine ignition timing, test control software, size of igniter throat
  - Series of tests
    - Ignite the igniter propellant in open air
    - Ignite in near vacuum under appropriate temperature conditions
    - Measure pressure rise in combustion chamber with no oxidizer flow
- Hydro testing of pressure vessels
  - Manufacture components tested to 1.5 MAWP, holding pressure for 10 min
  - Fill test component with water
  - Procedure
    - Seal off pressure vessel except for a single entry port
    - Fill the vessel with deionized water
    - Orient the chamber to eliminate the presence of trapped air
    - Use a hydraulic pump cart to bring it up to a pre-determined test pressure
    - Hold pressure for an amount of time and visually inspect for leaks

Test Plan

Subsystem tests

- Cold flow test
    - Confirm that oxidizer mass rate matches the design objective
    - Load rocket with oxidizer and vent, no igniter installed
    - Resize injector holes to tune oxidizer mass flow rate
    - Procedure
        - Setup air feed supply
- Avionics startup, data acquisition, shutdown

Full system test

- Single (5 second) burn
- 2 burns back-to-back
- Three burns back-to-back

Backup Slides

LOx Tank - NASA Guidelines

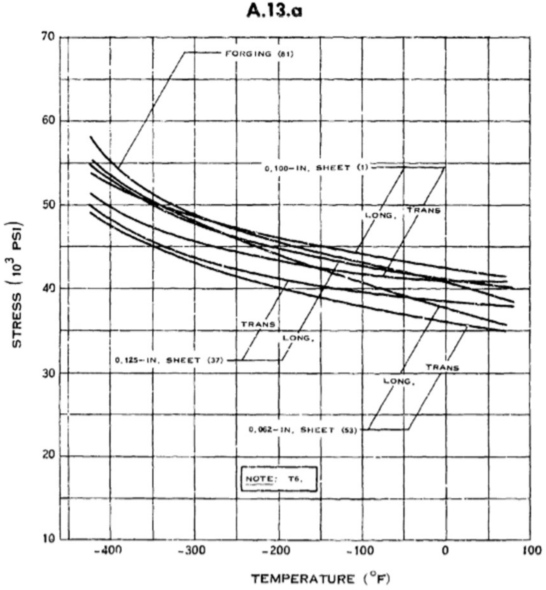
(4) In mechanical impact tests conducted at NASA WSTF, aluminum 6061-T6 did not ignite. Tests were conducted with specimens of several diameters and thickness in LOX and GOX at pressure of 69 MPa (10 000 psia). Sample contamination demonstrated the sensitivity of metals to ignite because of mechanical impact. Aluminum 6061-T6's susceptibility to ignition by mechanical impact increased when it was contaminated with cutting oil, motor lubricating oil, or toolmaker's dye (Sprenger 1975).

National Aeronautics and Space Administration

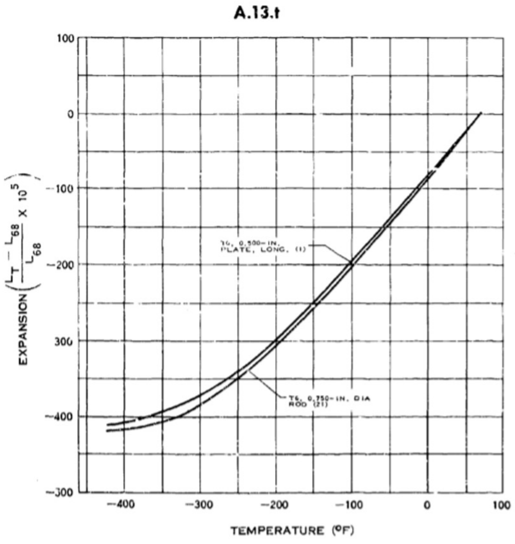
SAFETY STANDARD FOR OXYGEN AND OXYGEN SYSTEMS

Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation

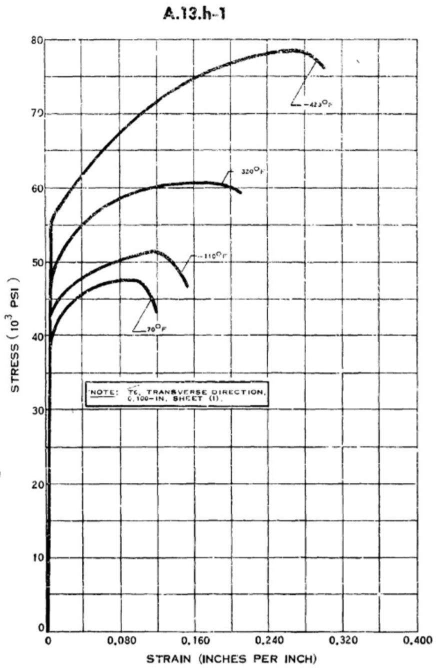
LOx Tank - Airforce Data



YIELD STRENGTH OF 6061 ALUMINUM



THERMAL EXPANSION OF 6061 ALUMINUM



STRESS-STRAIN DIAGRAM FOR 6061 ALUMINUM
284

LOx System Insulation

Details on insulator material & assembly method for run tank & feedline