Hybrid Oxidizer Tank Filling and Dynamics

Team #3

April 25, 2020

Advisor:

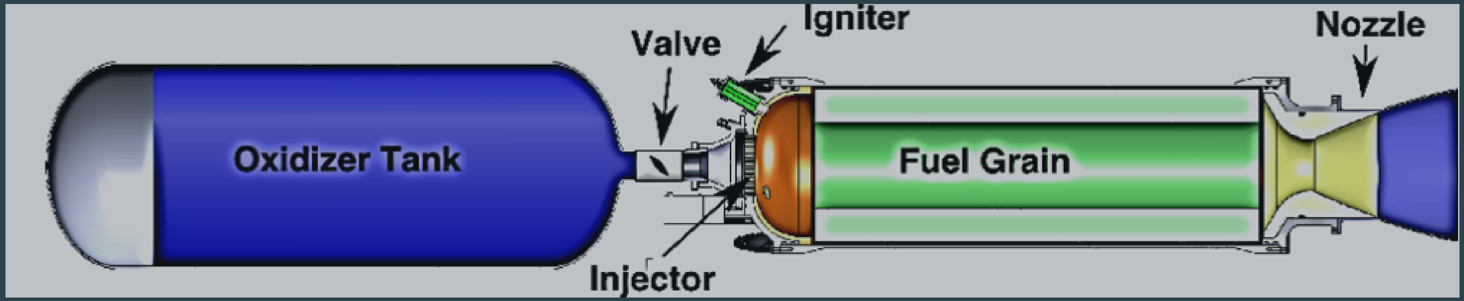
Dr. Jeffrey Santner

Agenda

- Introduction
- Python Simulations
- ANSYS Simulations
- Structural Design & Analysis
- Control Systems
- Conclusion

Introduction

- Sub-unit of the Eagle Rocketry SEDS Club at Cal State LA
  - Aerospace centric club researching rocket engines: Hybrid
  - SEDS: Students for Exploration and Development of Space



Objectives

- Remotely transfer 15kg of nitrous oxide from a commercially purchased vessel
- Create a testing structure for the nitrous oxide pressure vessel which can double as a launch pad
- Predict the time taken for the filling process

Meet the Team

Orifiel Ortiz

- Computational Fluid Analyst

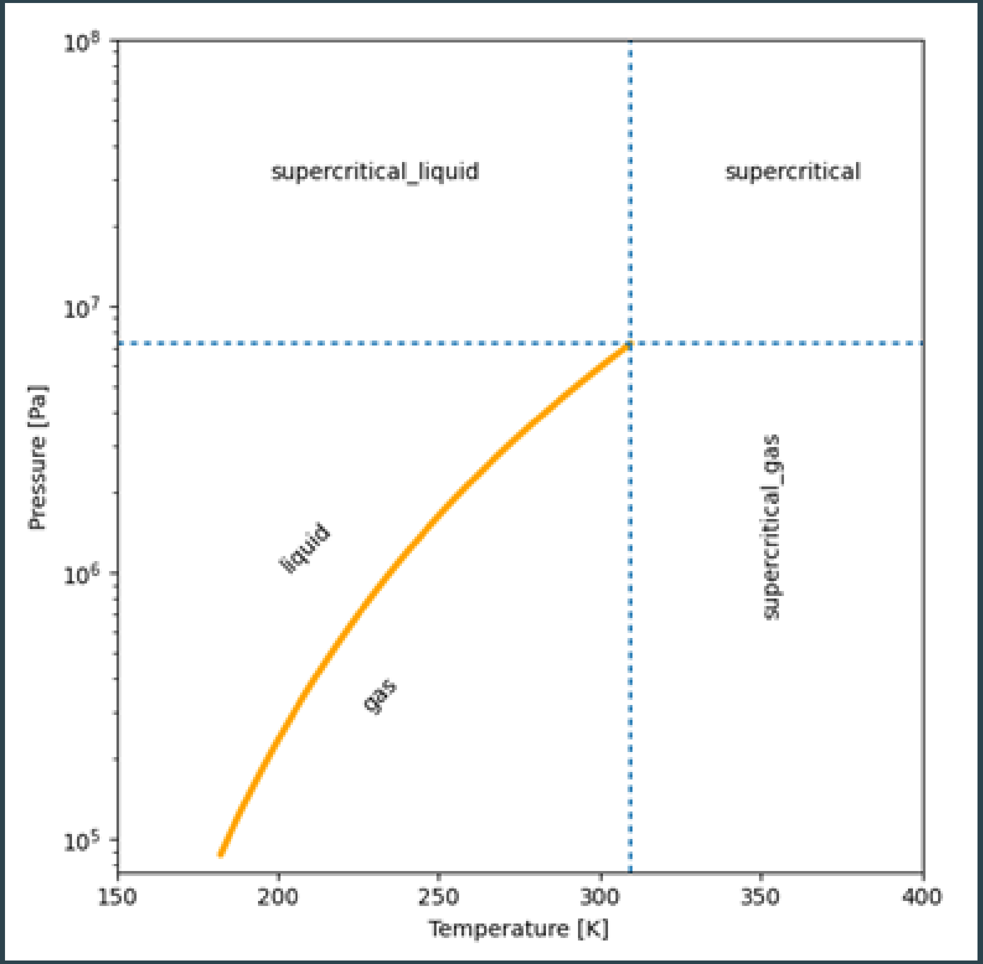
Python Simulations

Model Overview

- Based on a modified Equilibrium Model. [1]

Limitations:

- CoolProp cannot compute thermodynamic properties when the fluid is supercritical
- CoolProp cannot calculate N_2O thermal conductivity or viscosity at any temperature or pressure



Thermal Conductivity and Viscosity

- Supercritical Thermal Conductivity is calculated from tables published by Richter and Sage. [2]

Validity range:

$$277.59K\ -444.26K$$

$$101.33kPa\ -34.47\ MPa$$

- Supercritical Viscosity is calculated from work by Takashi et. al. [3]

Validity range:

$$298.15K\ -398.15K$$

$$102.50kPa\ -5.50MPa$$

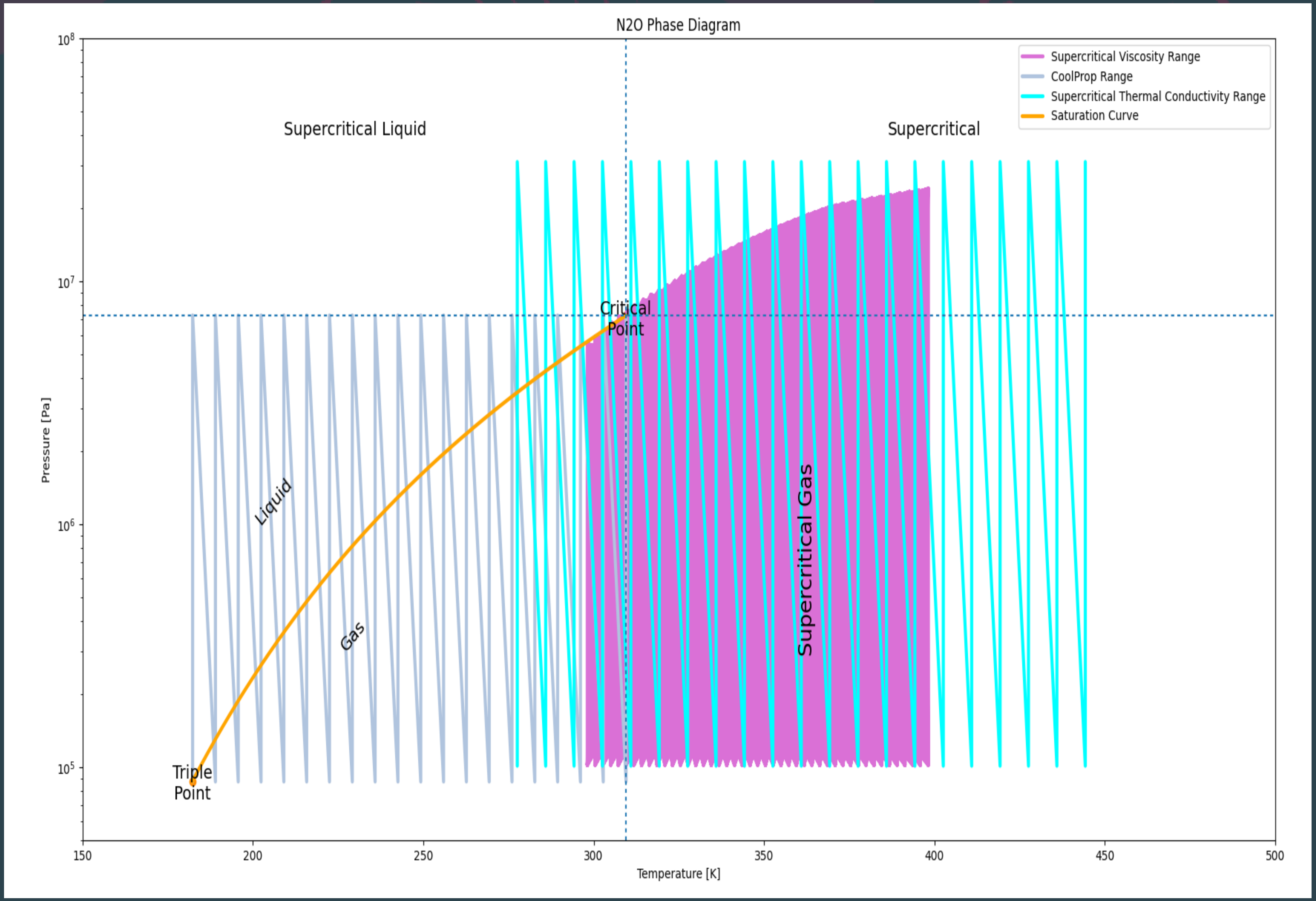
Thermal Conductivity and Viscosity

- Saturation values calculated from equations published by ESDU. [4]

Validity range:

$$182.33K \ - 309.57K$$

$$87.3kPa \ - 7.24MPa$$



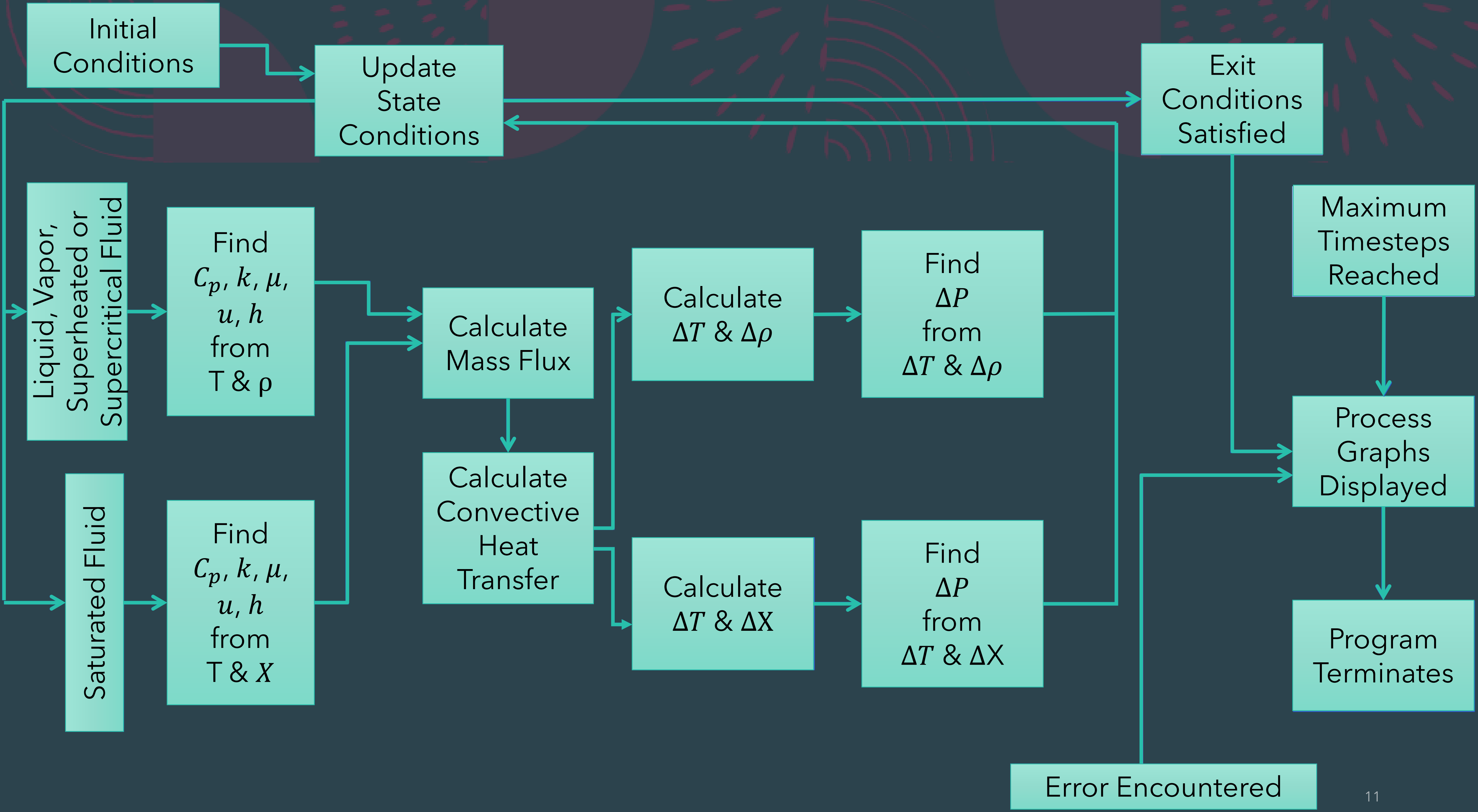
Solution

- Helmholtz Functional Equations using temperature and density as the two known supercritical fluid states. [5]

$$\alpha(\delta,\tau) = \boxed{\alpha^0(\delta,\tau)} + \boxed{\alpha^r(\delta,\tau)}$$

- $\alpha(\delta,\tau)$ = Helmholtz Energy
- δ = normalized density
- τ = normalized temperature

- Other fluid properties can be calculated through the First Law of Thermodynamics, with a known Helmholtz Energy



Initial Conditions

Update State Conditions

Exit Conditions Satisfied

Liquid, Vapor, Superheated or Supercritical Fluid

Find $C_p, k, \mu,$ u, h from T & ρ

Saturated Fluid

Find $C_p, k, \mu,$ u, h from T & X

Calculate Mass Flux

Calculate Convective Heat Transfer

Calculate ΔT & $\Delta\rho$

Find ΔP from ΔT & $\Delta\rho$

Calculate ΔT & ΔX

Find ΔP from ΔT & ΔX

Maximum Timesteps Reached

Process Graphs Displayed

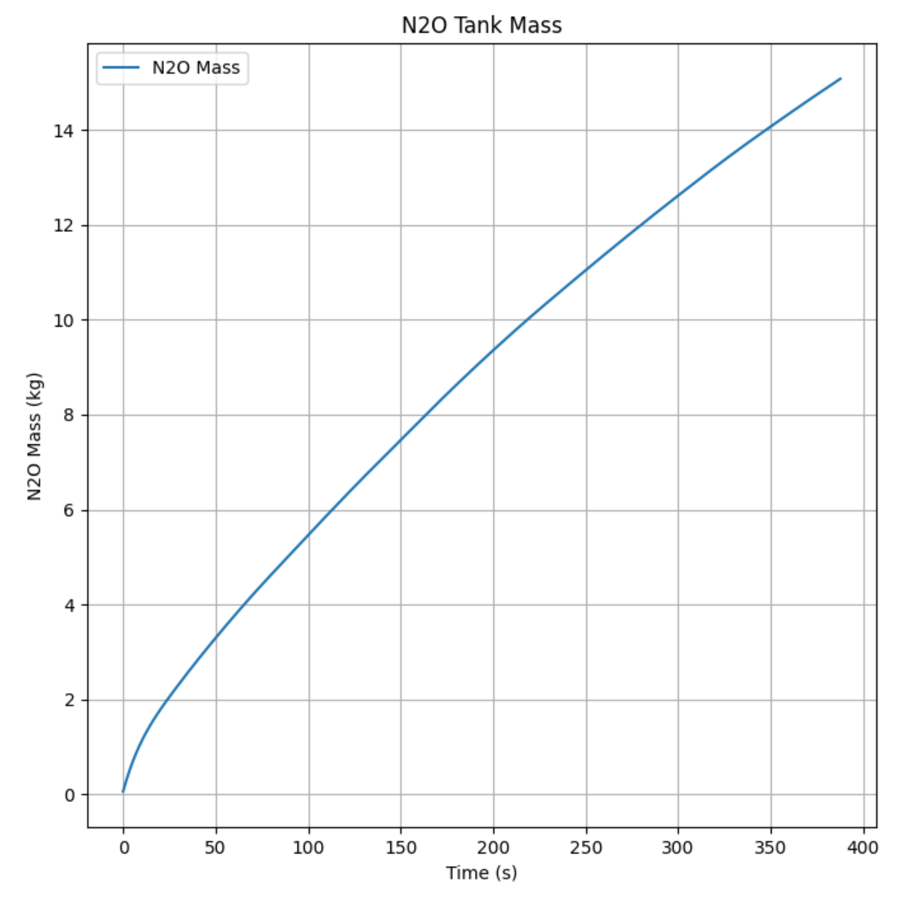
Program Terminates

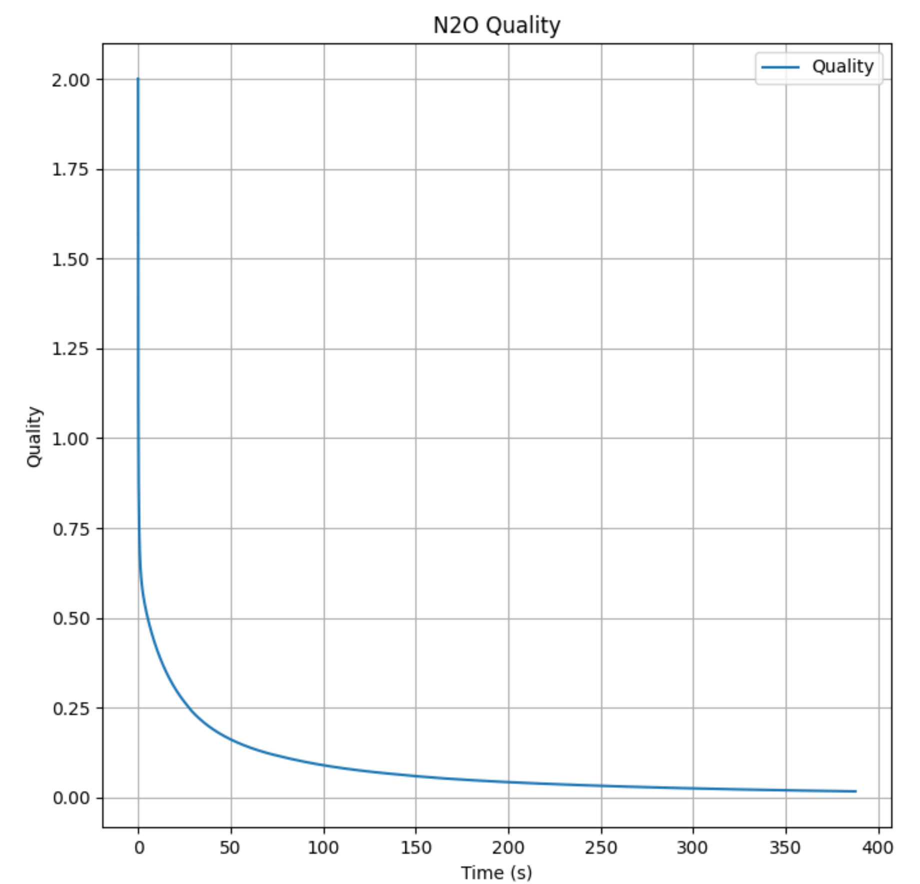
Error Encountered

Boundary Conditions

- Initial/Atmospheric Temperature: $298K$
- Initial Pressure: air at $101.33\ kPa$
- Tank Length: $1.27\ m\ (50\ in)$
- Tank Inner Diameter: $152.4\ mm\ (6\ in)$
- Source Tank Pressure: $689.48\ kPa\ (1000\ Psi)$
- Total Tank Mass: $15kg$

m & X





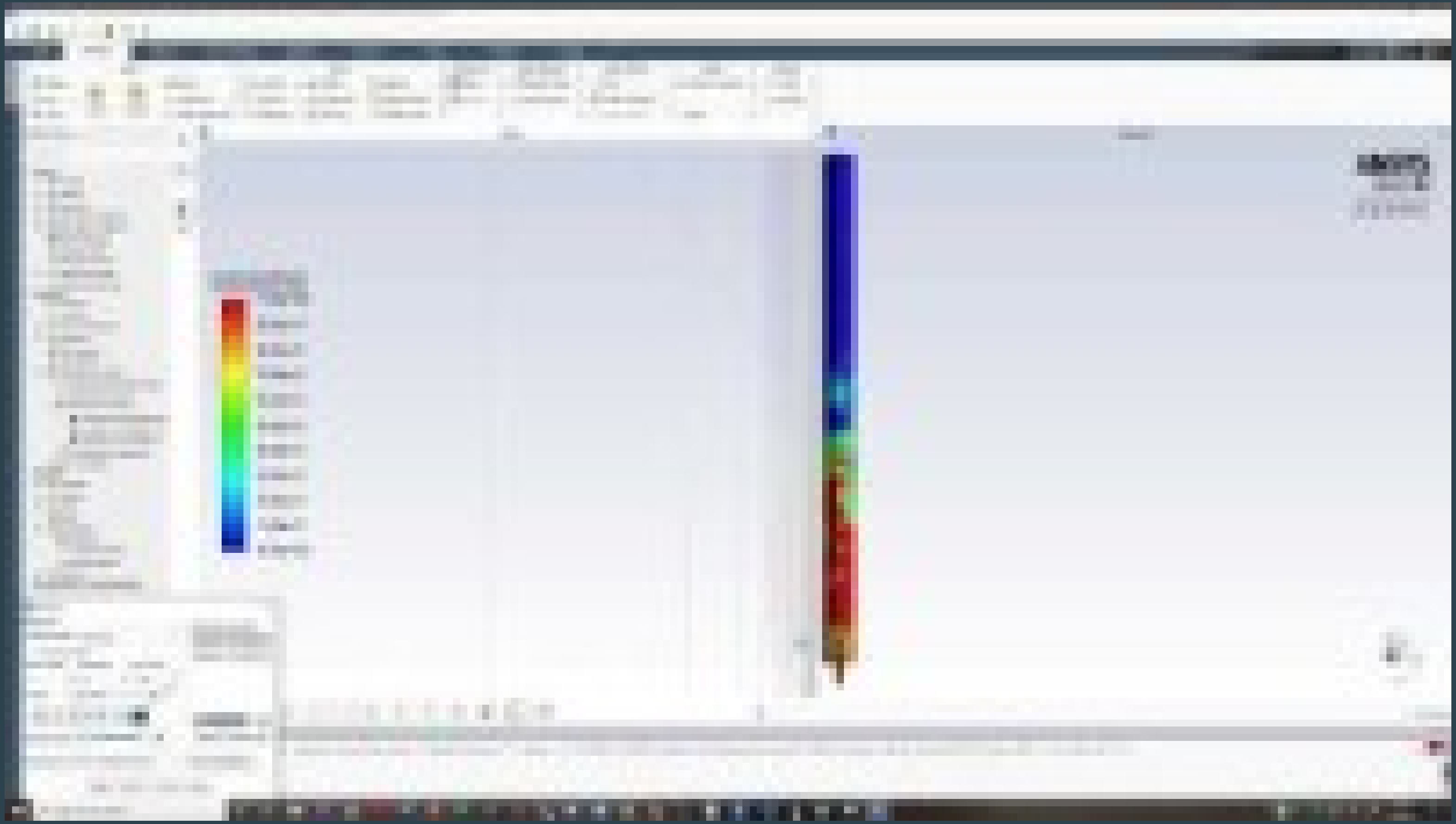
Note: If X > 1, N_2O superheated

Miguel Romero

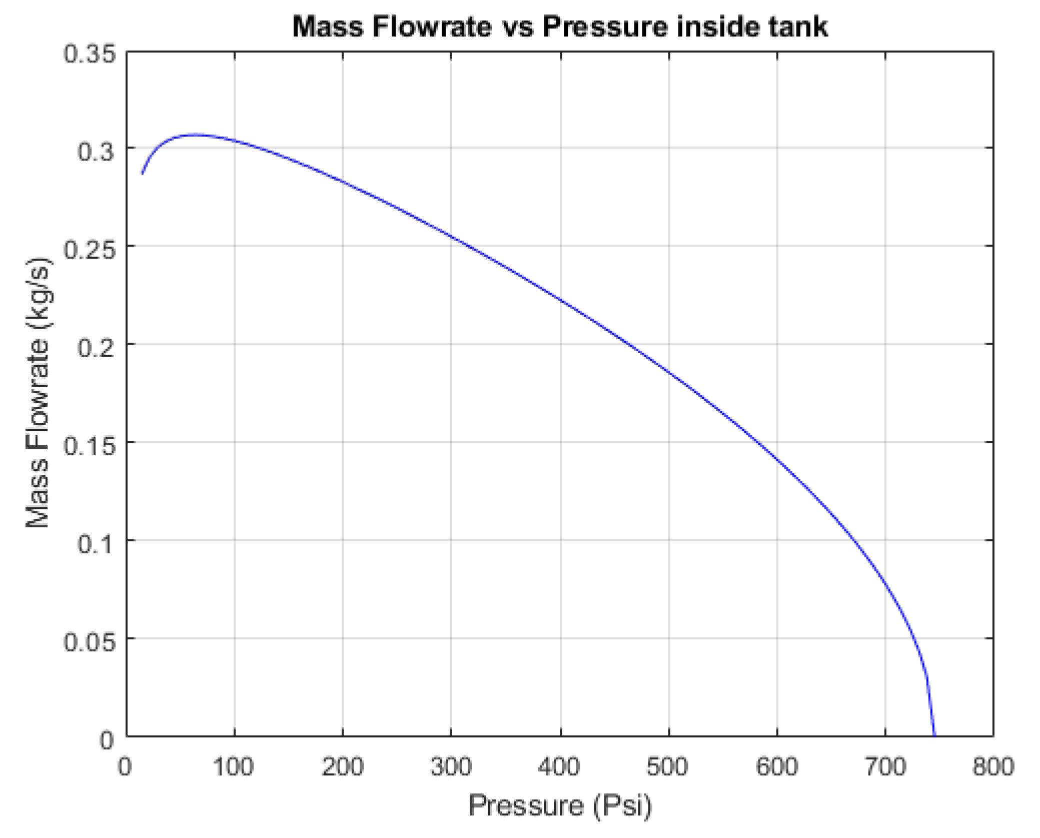
- Pressure Vessel Fluid Analyst

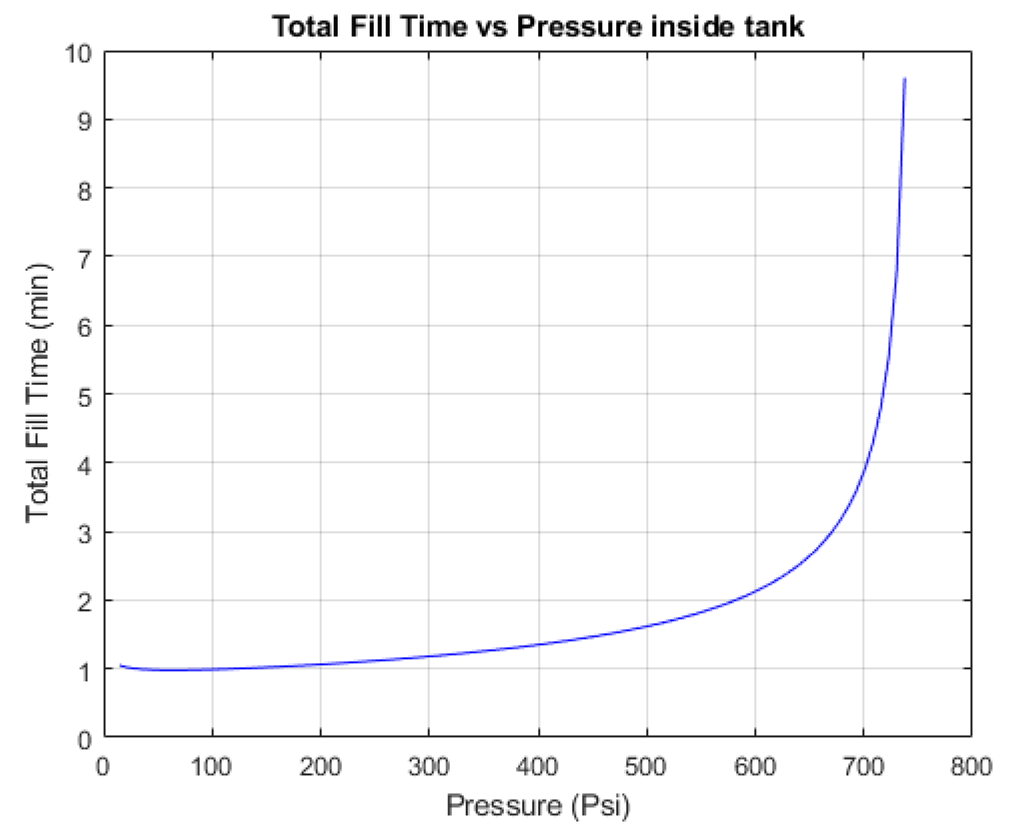
Ansys Pressure Vessel Simulations

Oxidizer Tank Filling



MATLAB

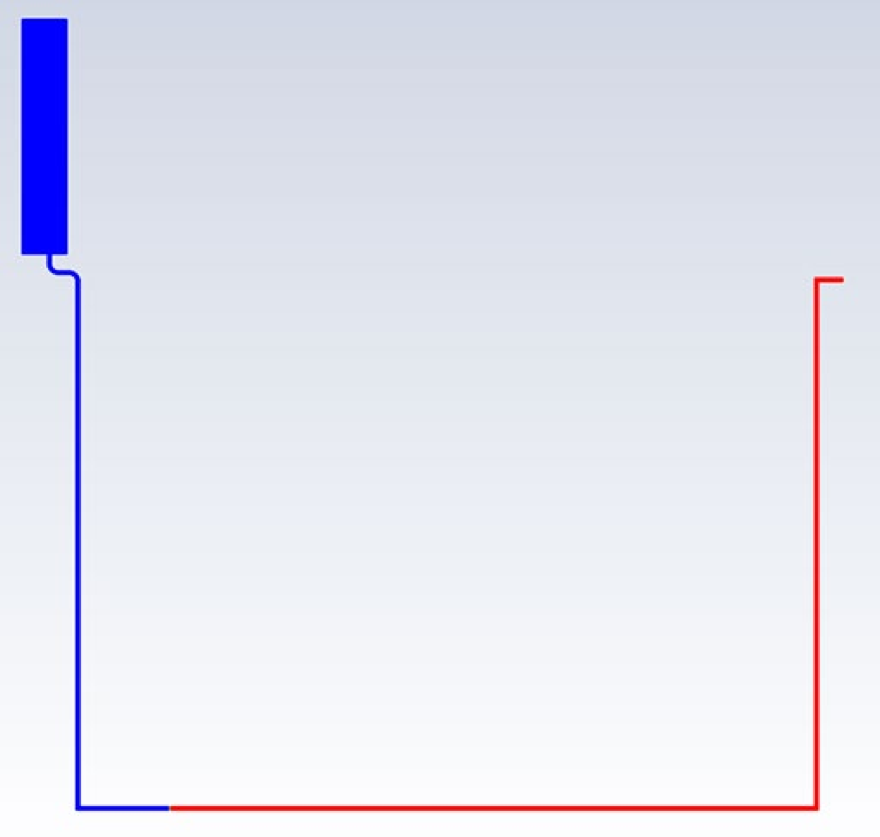

Mass Flowrate vs Pressure inside tank
Mass Flowrate (kg/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Pressure (Psi)
0
100
200
300
400
500
600
700
800

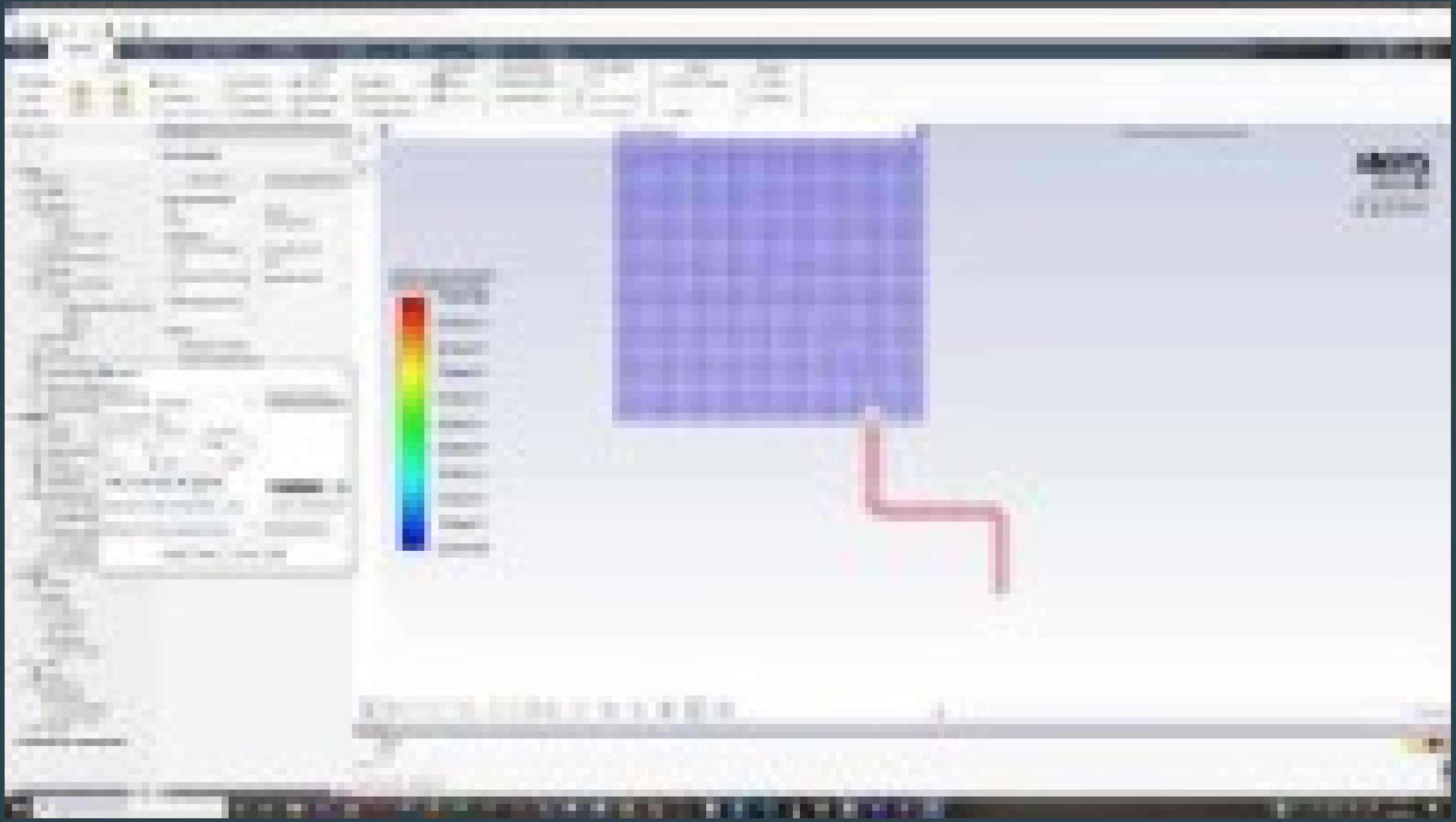

Total Fill Time vs Pressure inside tank
Total Fill Time (min)
10
9
8
7
6
5
4
3
2
1
0
Pressure (Psi)
0
100
200
300
400
500
600
700
800

Ground Fill System

- Inlet diameter to Oxidizer Tank: 0.25in
- Inner diameter of piping system is 0.25in
- Going to open the source tank at varying pressures to slow down the filling time

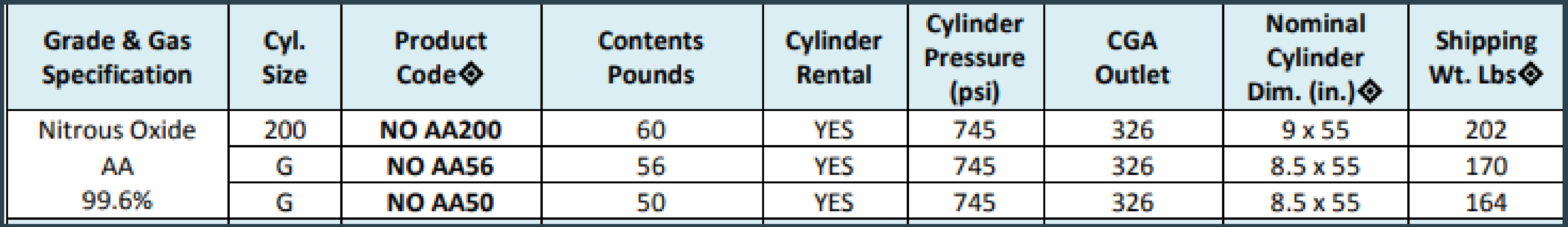
Ground Fill System





Mass Requirements

- Do we have enough N20 to fill the tank and for the ground system piping?
  - N2O mass system = 28kg
  - N2O source tank = 27kg
  - 2 source tanks from vendor



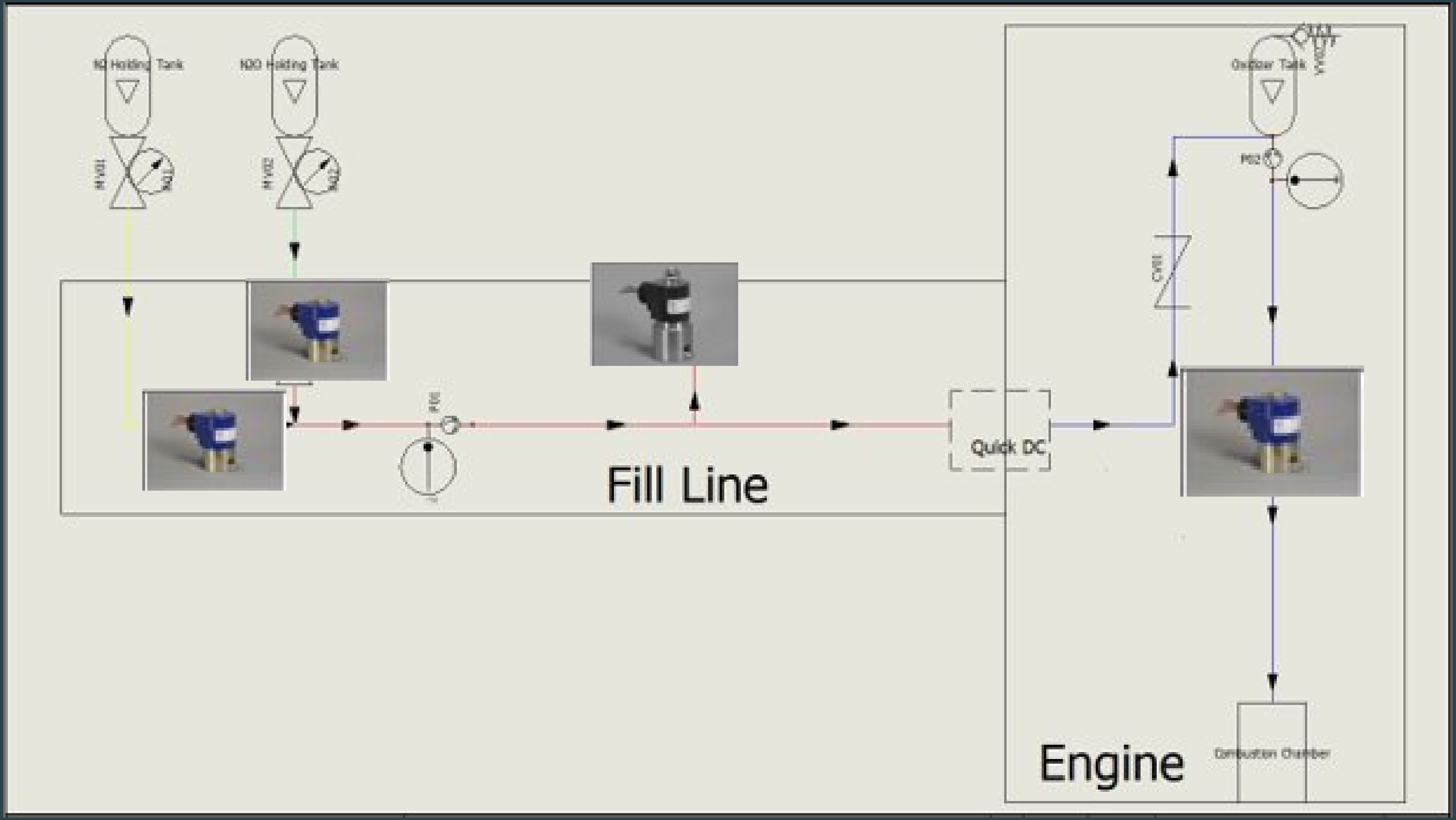
Grade & Gas Specification	Cyl. Size	Product Code◈	Contents Pounds	Cylinder Rental	Cylinder Pressure (psi)	CGA Outlet	Nominal Cylinder Dim. (in.)◈	Shipping Wt. Lbs◈
Nitrous Oxide AA 99.6%	200	**NO AA200**	60	YES	745	326	9 x 55	202
	G	**NO AA56**	56	YES	745	326	8.5 x 55	170
	G	**NO AA50**	50	YES	745	326	8.5 x 55	164

Ansys & Valve Simulations

Amy Moore

- Piping & Valve Fluid Analyst

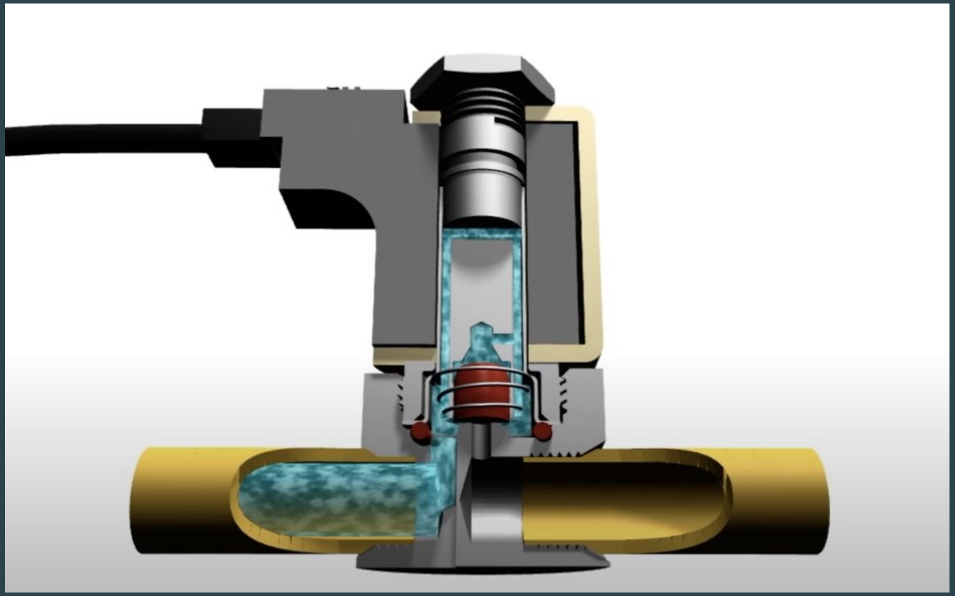
Schematic of Valve Layout

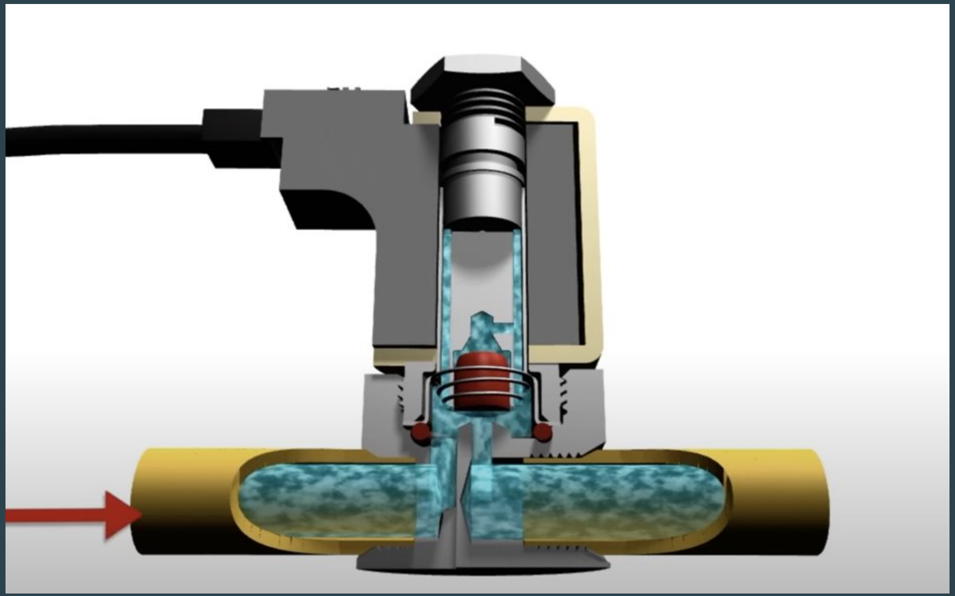


V01-Normally Closed (Blue)
V02-Normally Closed
V03-Normally Open (Gray)
V04-Normally Closed

Valve System Analysis

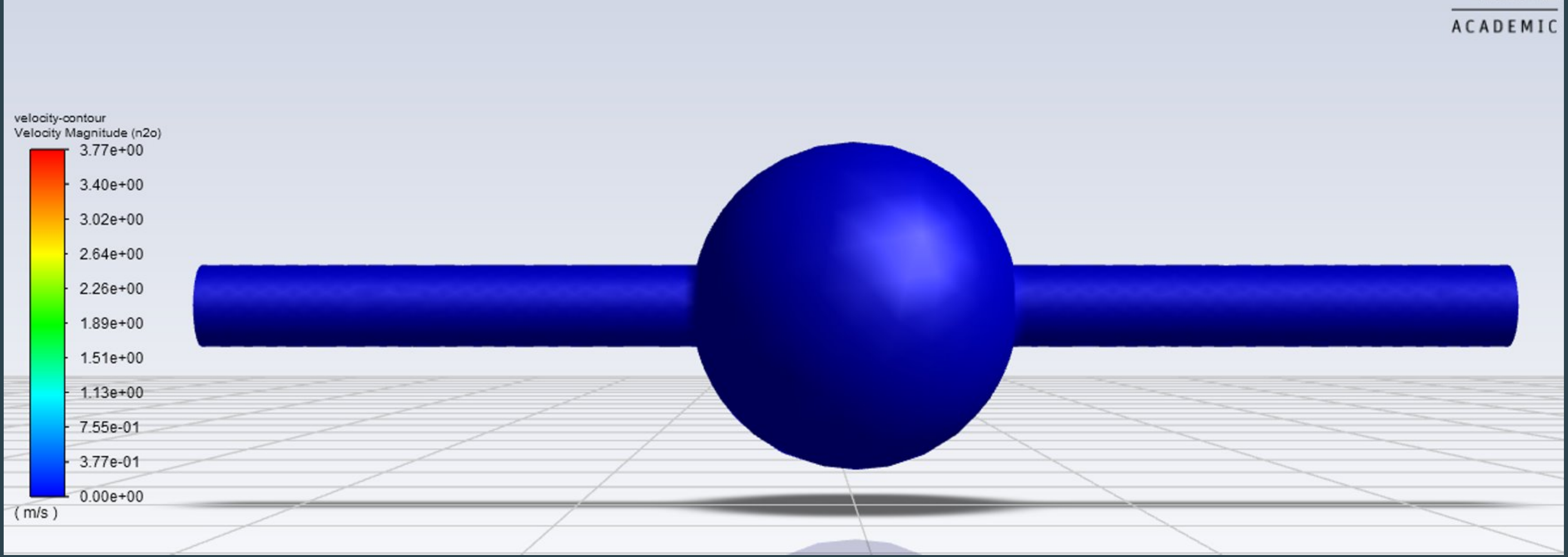
- CFD simulations performed on valves
- ANSYS and SimScale software was implemented
- Valve normally closed tested
- Inner and outer diameter 0.25 in.





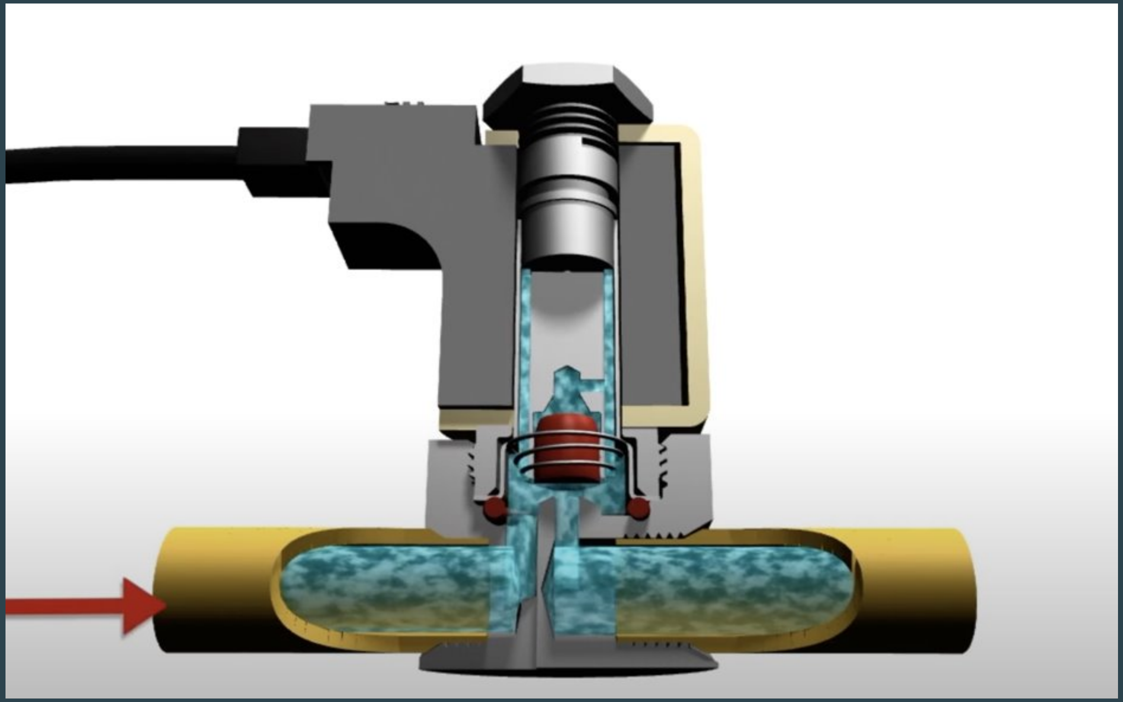
Valve Analysis ANSYS

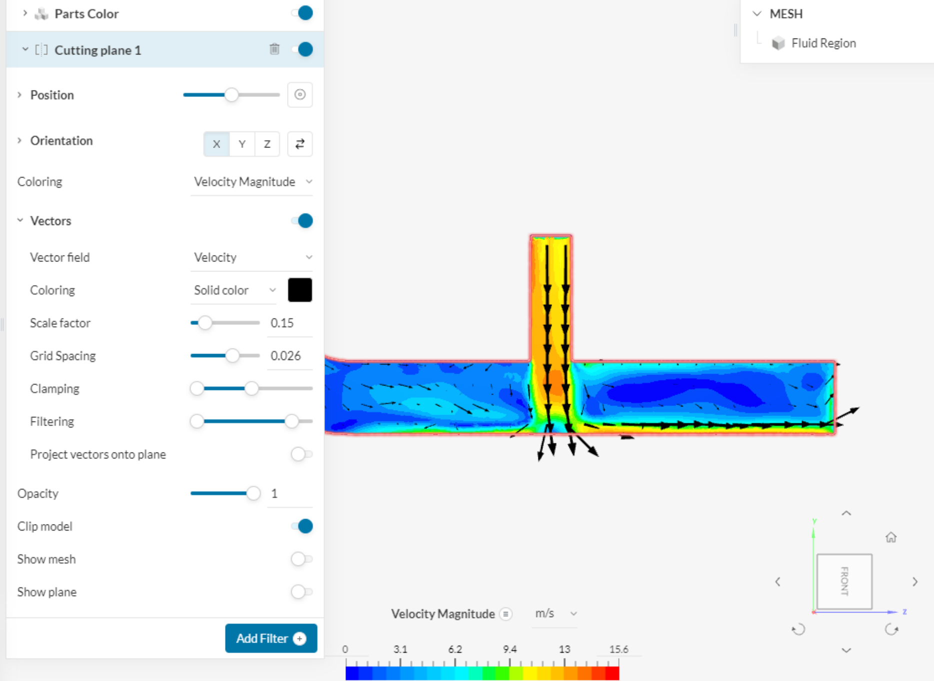
- Velocity entering valve 3.77 m/s
- Mass flow rate entering valve 3 kg/s



Valve Analysis SimScale

- SimScale is a program able to understand CAD models
- Velocity at the stopper region is 9 m/s





Cutting plane 1

Orientation: X

Coloring: Velocity Magnitude

Vectors

Vector field: Velocity

Coloring: Solid color

Scale factor: 0.15

Grid Spacing: 0.026

Opacity: 1

Clip model ●

Show mesh ○

Show plane ○

Project vectors onto plane ○

Base Structure Analysis

Vicente Estrada

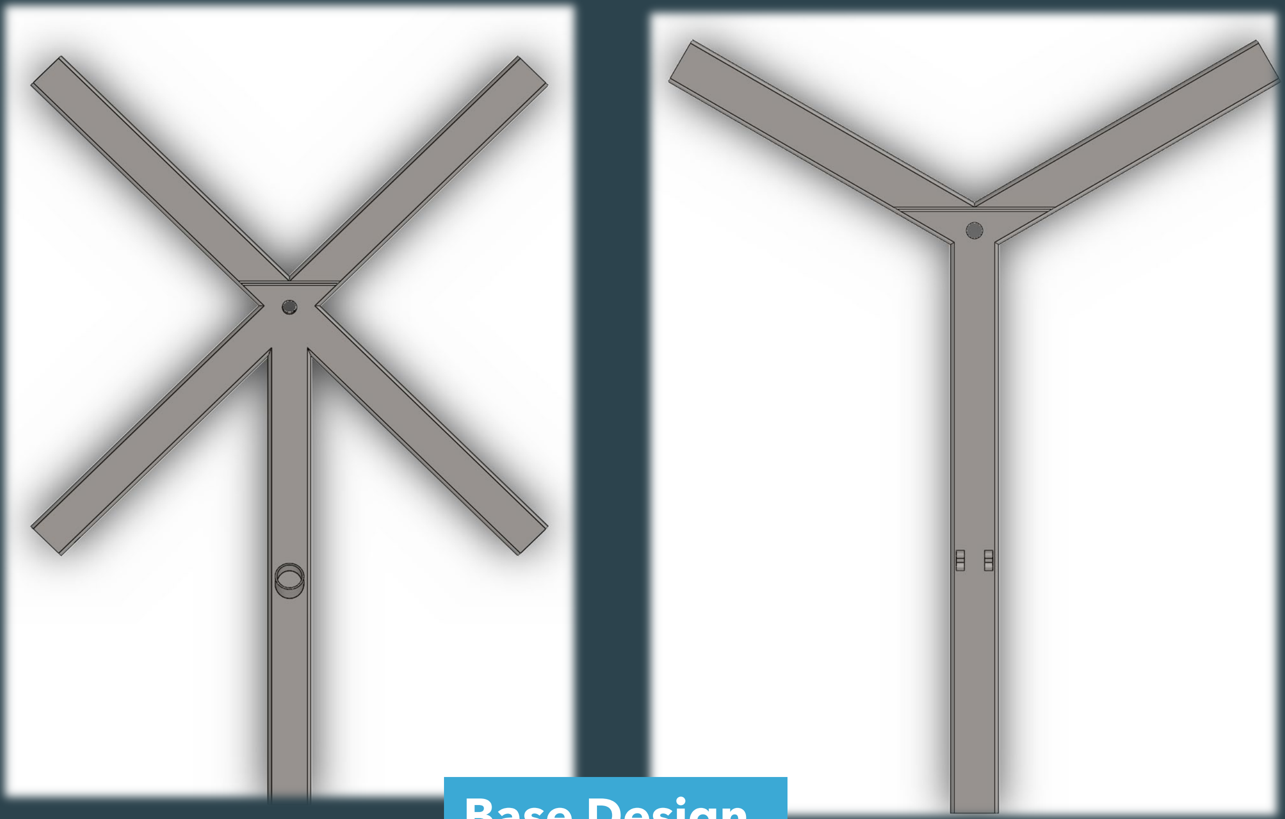
- Structural Designer & Analyst

Base Structure

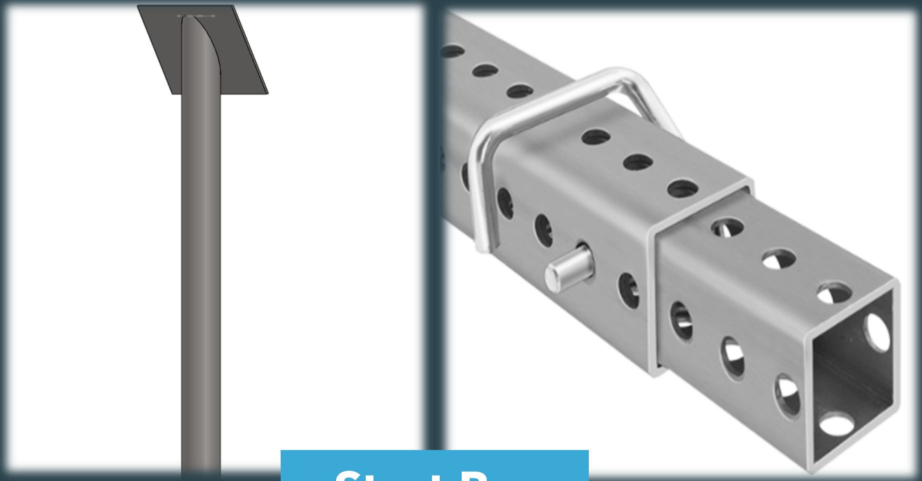
Revision 2

Final Revision

Major Changes

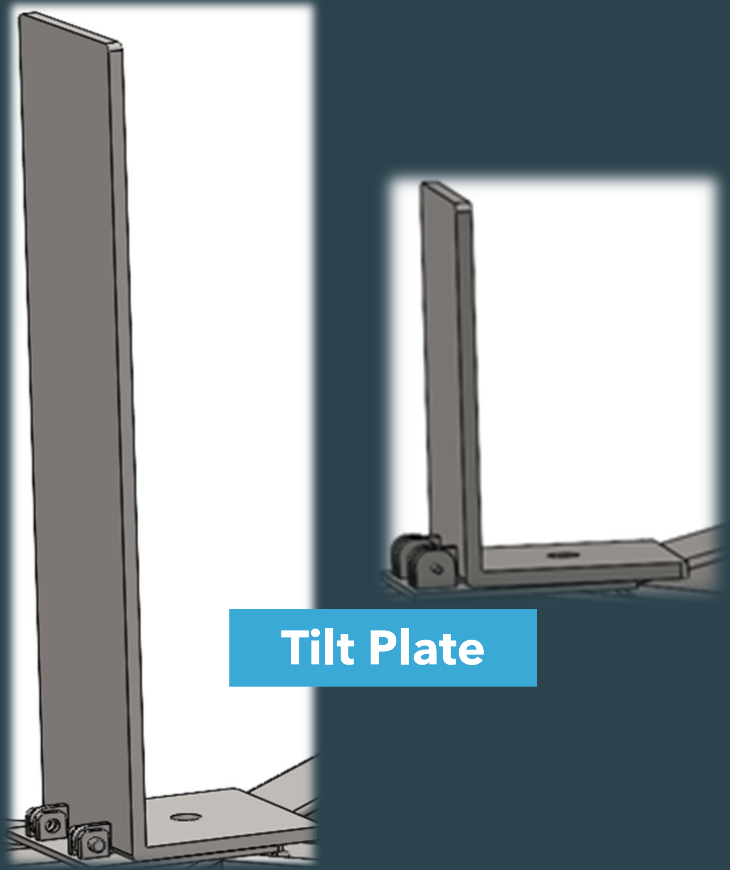


Base Design

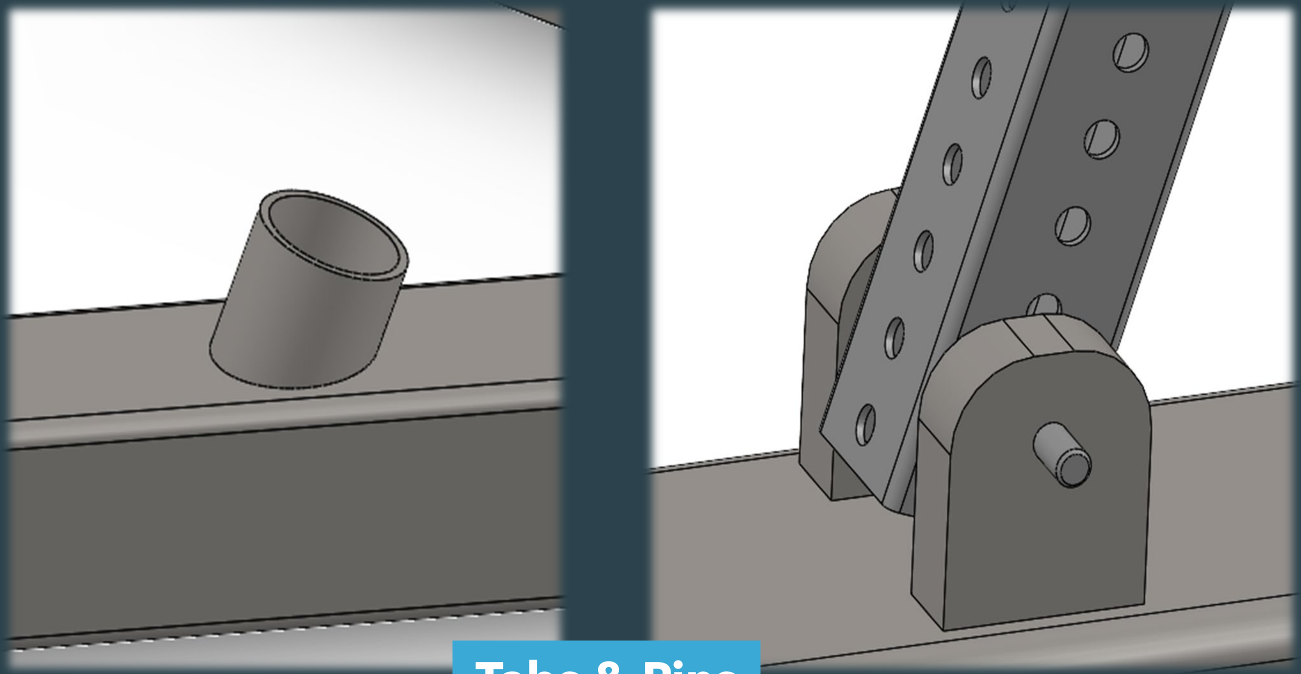


Strut Bar

Major Changes



Tilt Plate



Tabs & Pins

Hand Calculations

$$W_T = 284.78N$$

$$F_T = 2500N$$

$$\Sigma F_y: 0 = R_s Cos(68) + R_y + F_T - W_T$$

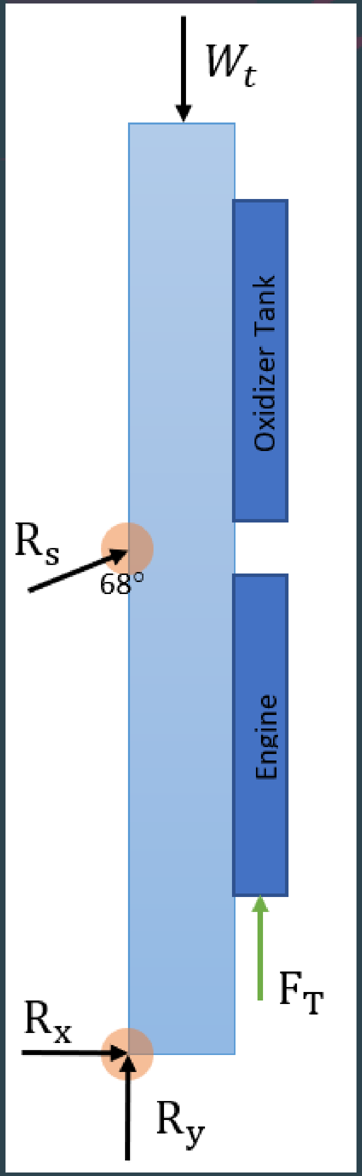
$$\Sigma F_x: 0 = R_s Sin(68) + R_x$$

$$\Sigma M: 0 = (0.3048m)F_T - (2.231m)R_s Sin(68) - 21.7Nm$$

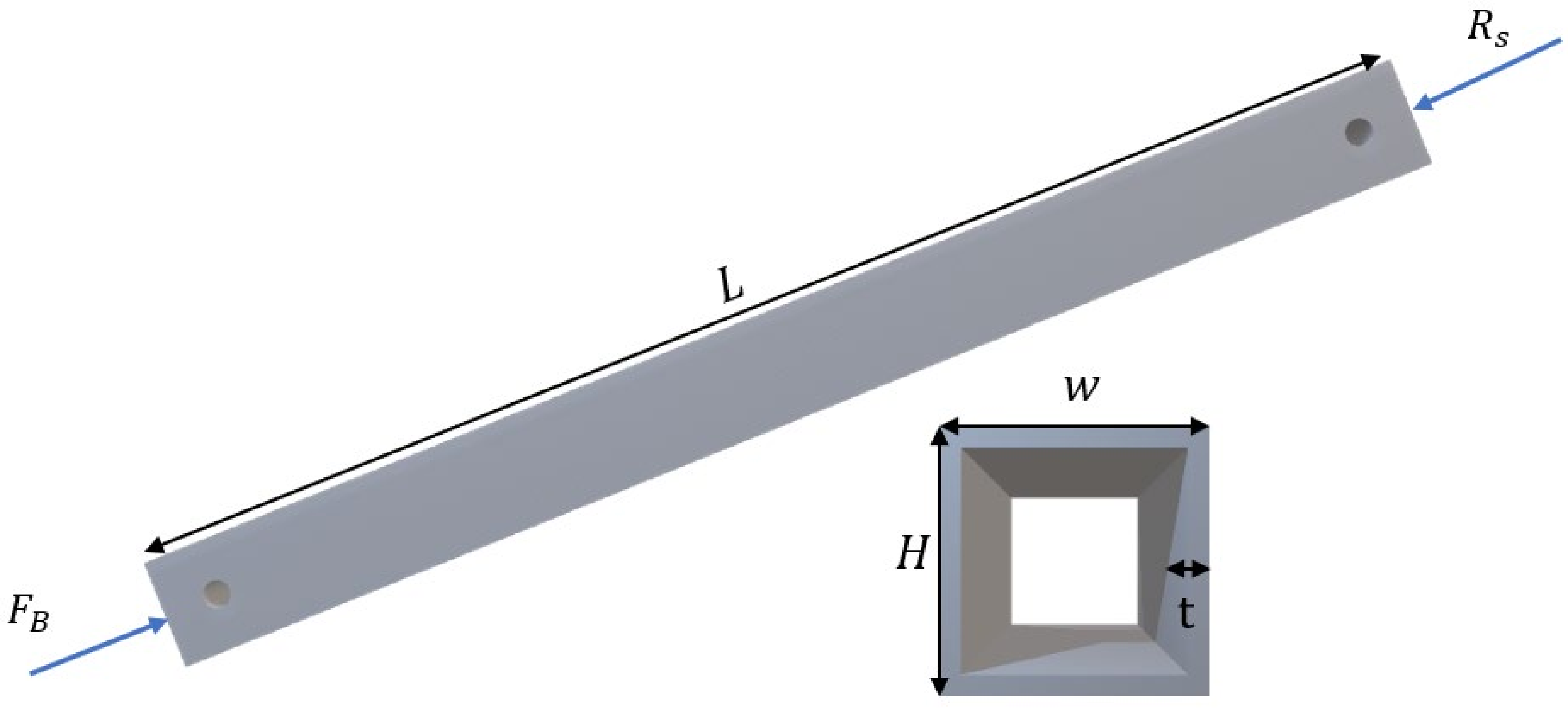
$$R_y = -2349.28N$$

$$R_x = -331.82N$$

$$R\_s = 357.88N$$



Hand Calculations



$L = 2.4384\,m$

$H = w = 0.0635m$

$t = 2.67X10^{-3}m$

$k = 1$

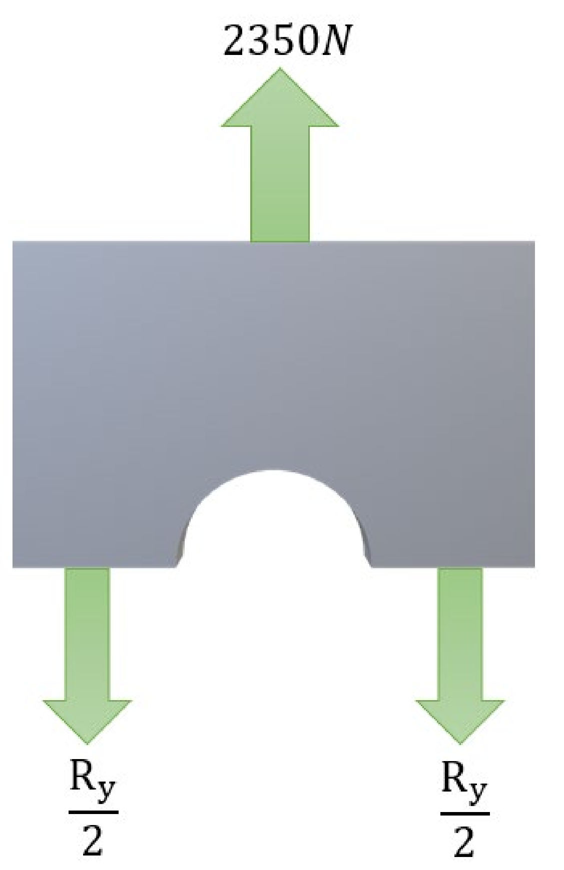
$E = 200\ GPa$

$I = 39.9X10^{-7}m^4$

$P_{cr} = 127.83\ kN$

$$R < P_{cr}$$

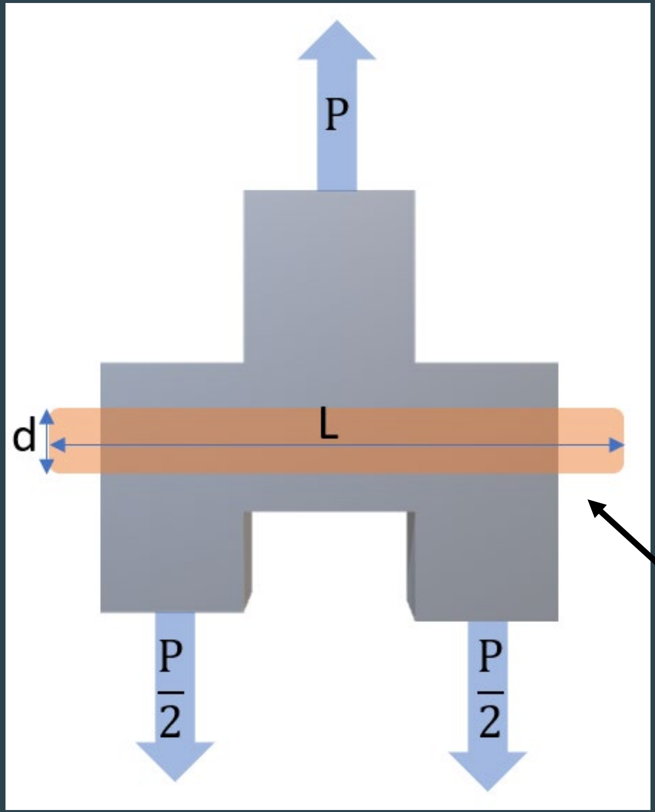
Hand Calculations



$$\sigma_Y = 206\,MPa$$

$$\sigma = 2.33\,MPa$$

$$\sigma_Y > \sigma$$



Stainless Steel Pin

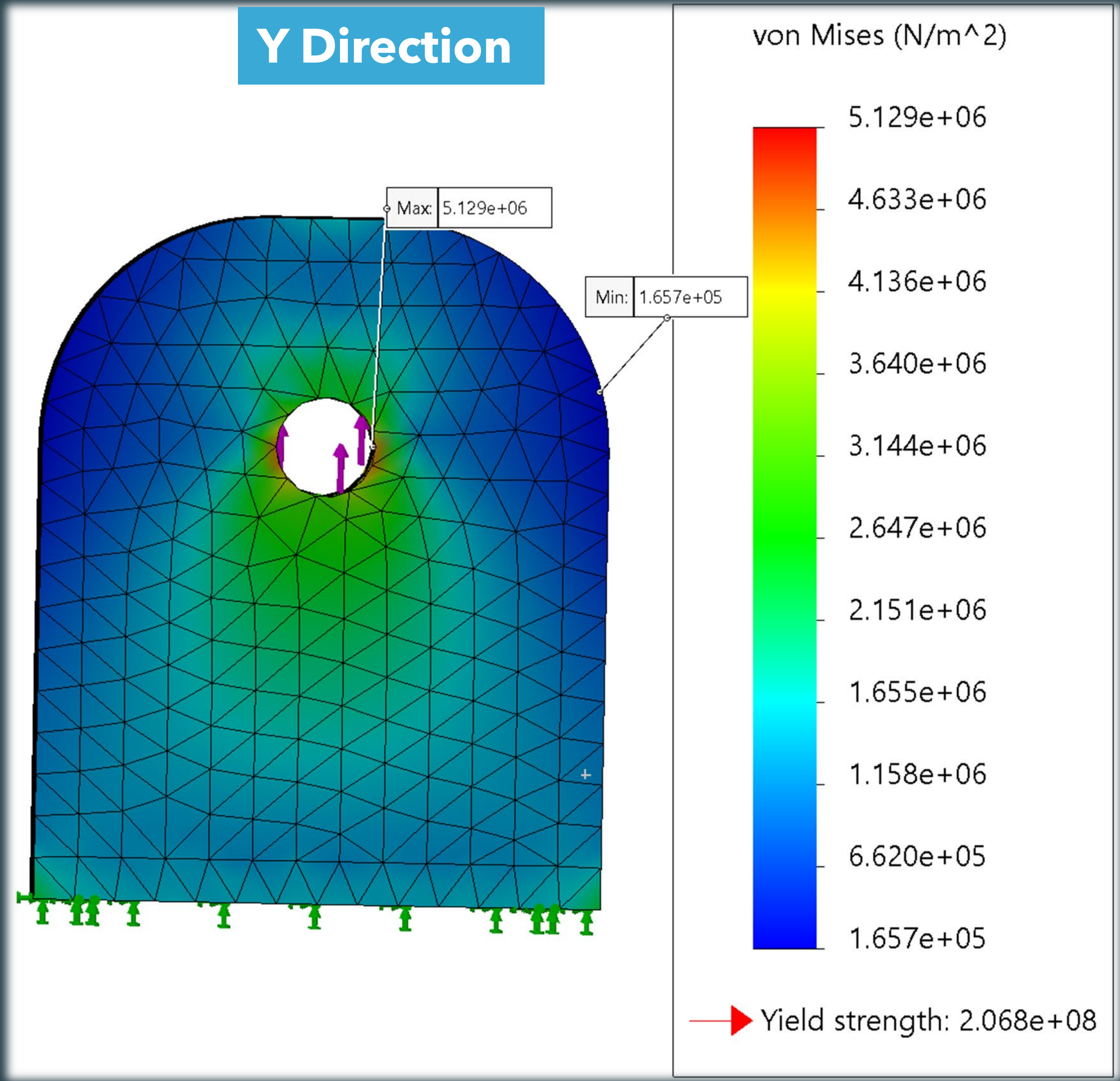
$$P = R_y$$

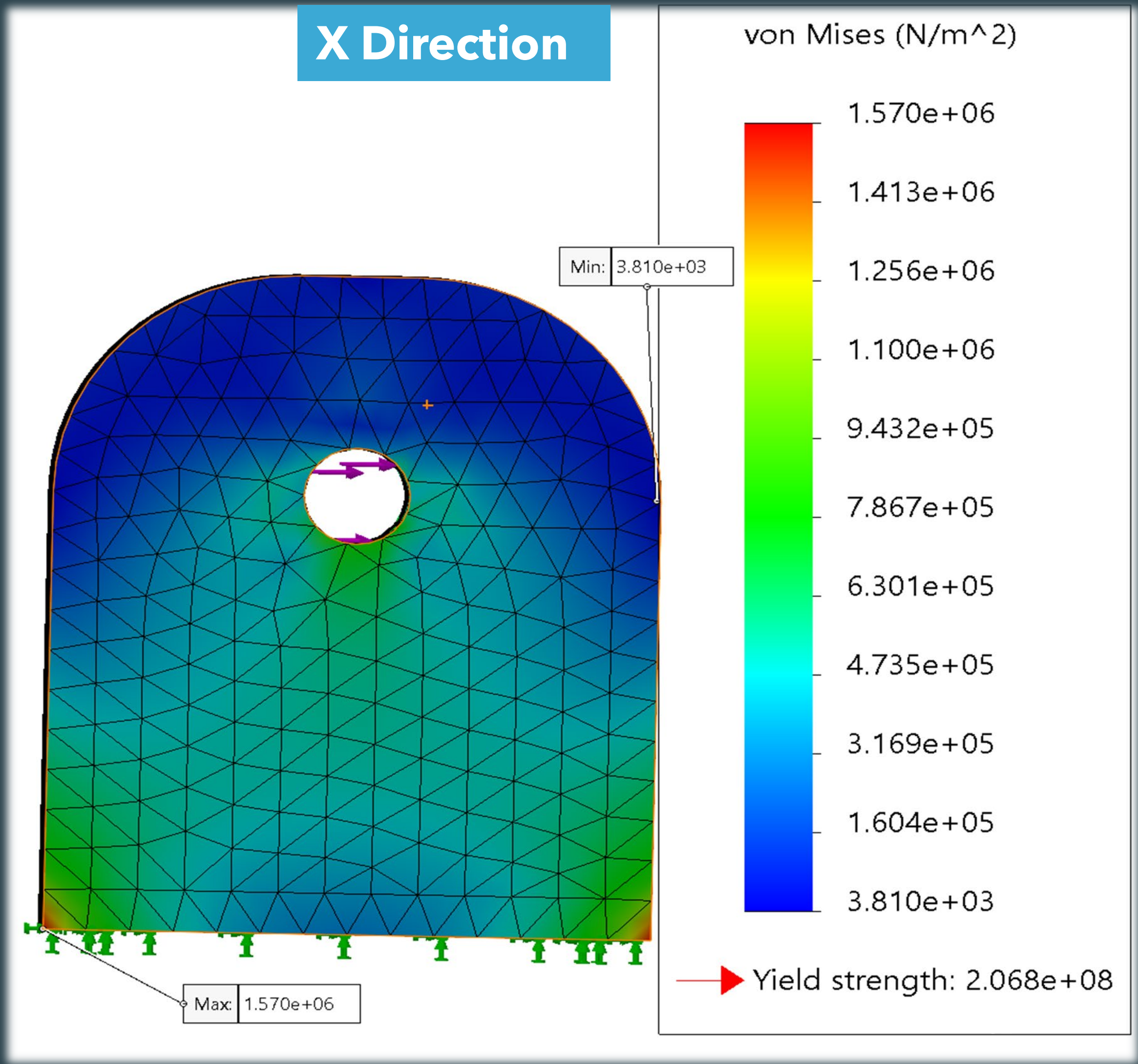
$$\tau_U = 66278.5N$$

$$L = 0.127m$$

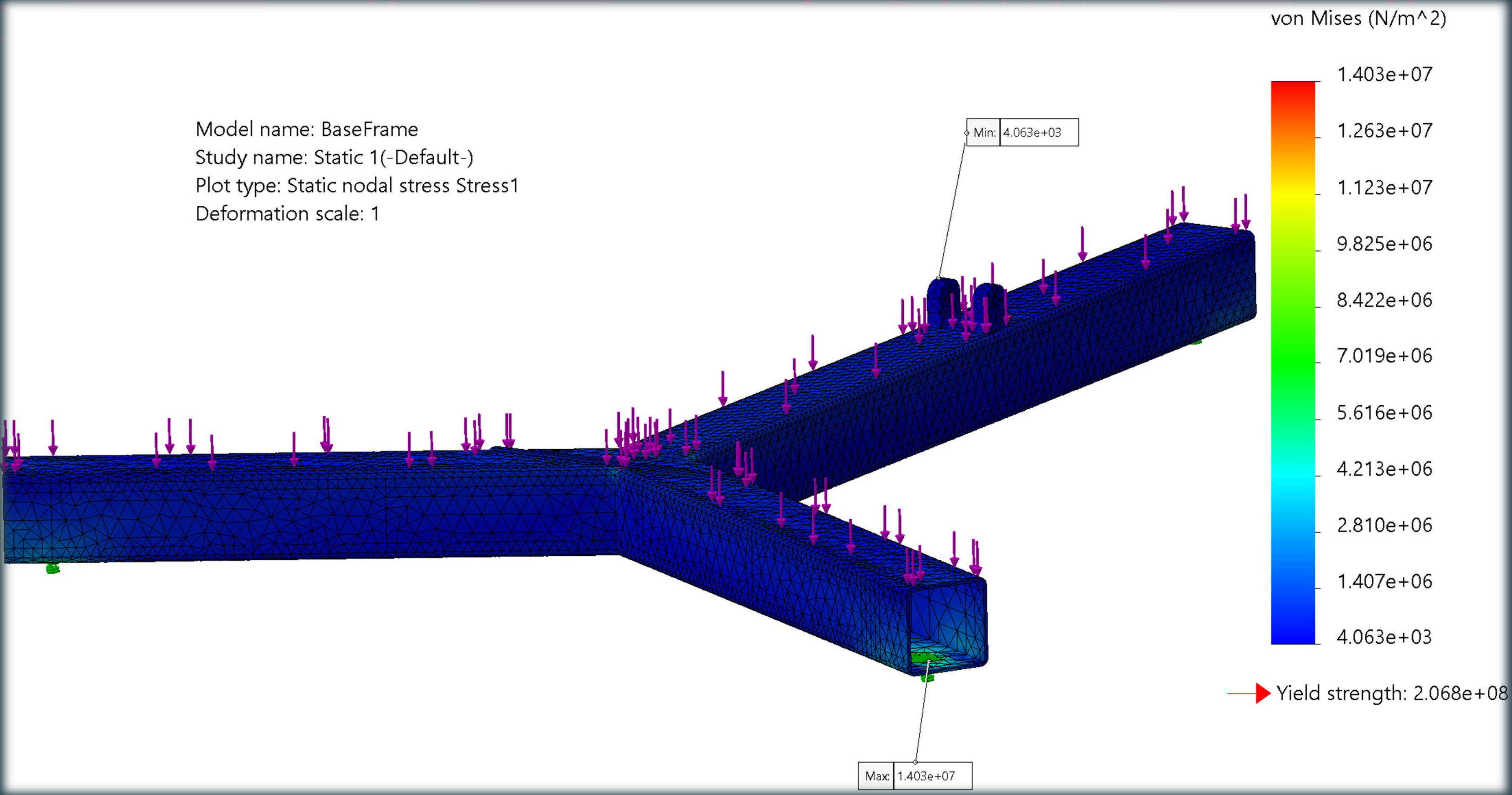
$$d = 0.4375m$$

FEA


Y Direction
von Mises (N/m^2)
5.129e+06
4.633e+06
4.136e+06
3.640e+06
3.144e+06
2.647e+06
2.151e+06
1.655e+06
1.158e+06
6.620e+05
1.657e+05
Max: 5.129e+06
Min: 1.657e+05
Yield strength: 2.068e+08

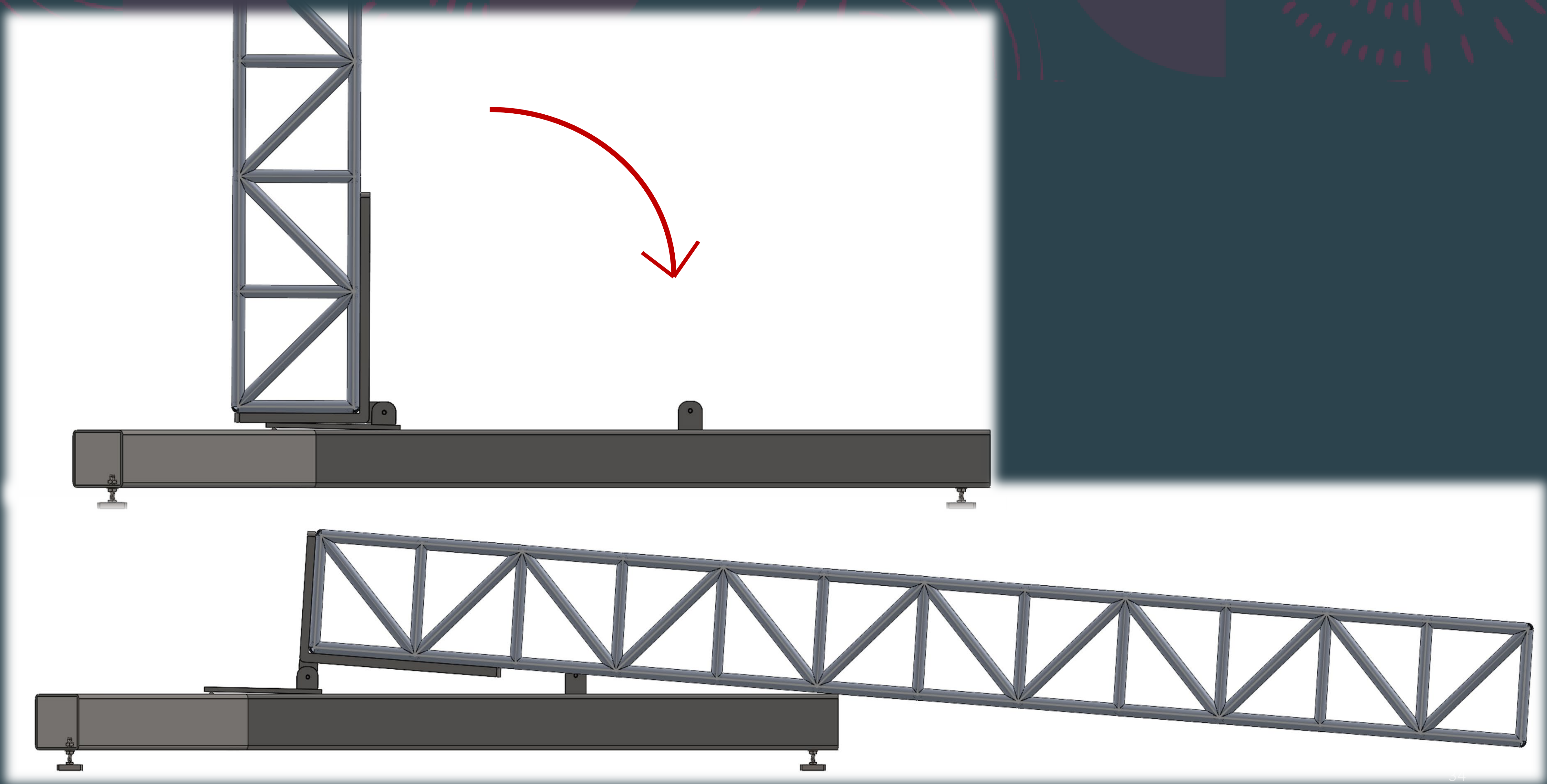

X Direction
von Mises (N/m^2)
1.570e+06
1.413e+06
1.256e+06
1.100e+06
9.432e+05
7.867e+05
6.301e+05
4.735e+05
3.169e+05
1.604e+05
3.810e+03
Min: 3.810e+03
Max: 1.570e+06
Yield strength: 2.068e+08

FEA



Model name: BaseFrame
Study name: Static 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Transportation/Mounting Assembly



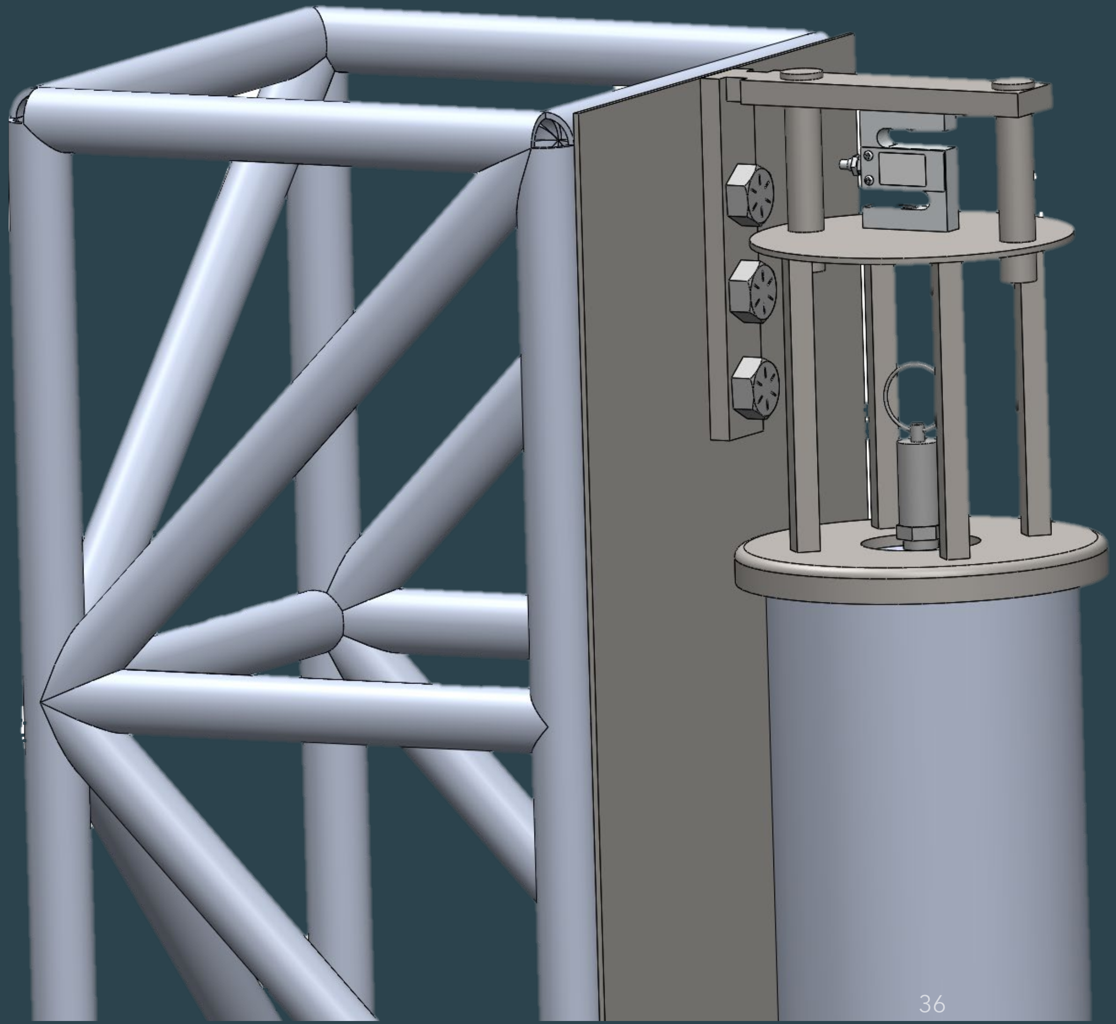
Test Stand Analysis

Alex Guilbaud

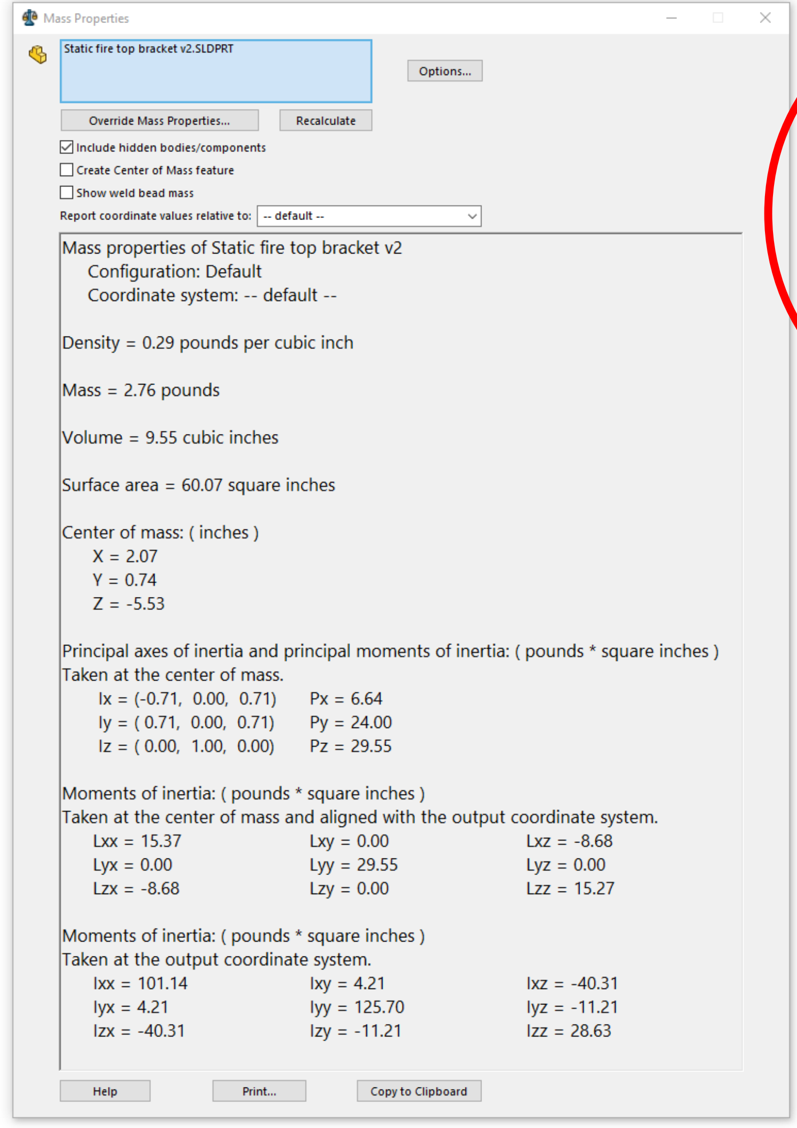
- Structural Designer & Analyst

Mechanical Force Analysis

- Concern:
  - Original bracket has potential to fail
- Resolve:
  - Calculate bending stresses and conduct FEA; determine if true



Mechanical Force Analysis



Static fire top bracket v2.SLDPRT

☑ Include hidden bodies/components
☐ Create Center of Mass feature
☐ Show weld bead mass

Report coordinate values relative to: -- default --

Mass properties of Static fire top bracket v2
Configuration: Default
Coordinate system: -- default --

Density = 0.29 pounds per cubic inch

Mass = 2.76 pounds

Volume = 9.55 cubic inches

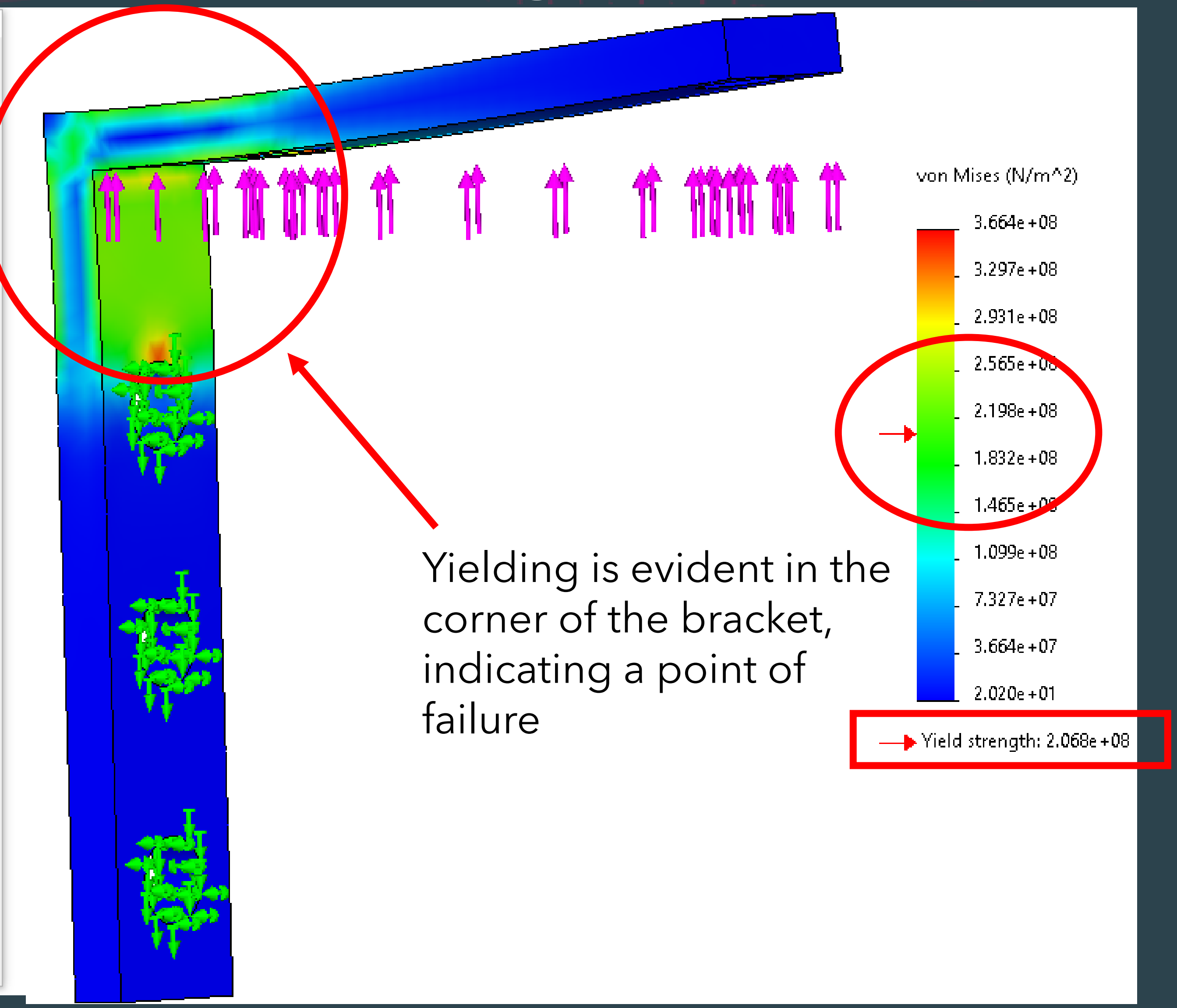
Surface area = 60.07 square inches

Center of mass: (inches)
X = 2.07
Y = 0.74
Z = -5.53

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.
Ix = (-0.71, 0.00, 0.71) Px = 6.64
Iy = (0.71, 0.00, 0.71) Py = 24.00
Iz = (0.00, 1.00, 0.00) Pz = 29.55

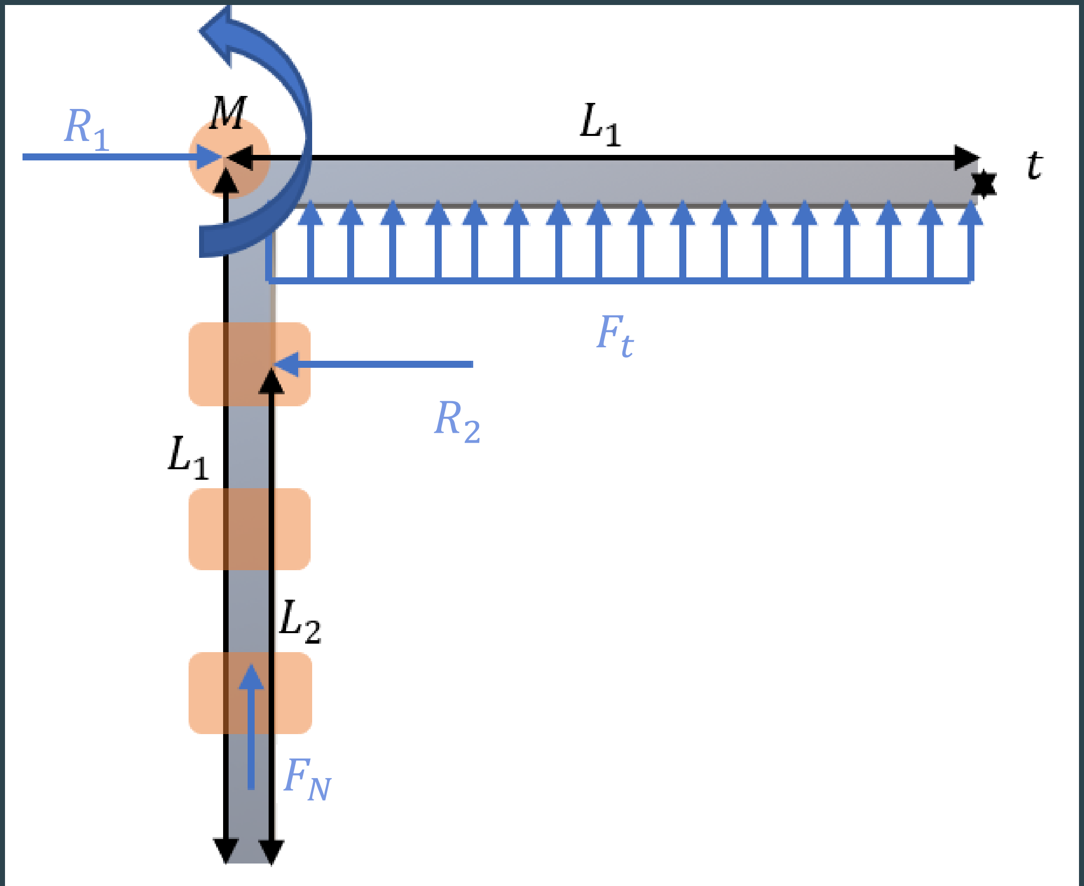
Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 15.37 Lxy = 0.00 Lxz = -8.68
Lyx = 0.00 Lyy = 29.55 Lyz = 0.00
Lzx = -8.68 Lzy = 0.00 Lzz = 15.27

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system.
Ixx = 101.14 Ixy = 4.21 Ixz = -40.31
Iyx = 4.21 Iyy = 125.70 Iyz = -11.21
Izx = -40.31 Izy = -11.21 Izz = 28.63



Yielding is evident in the corner of the bracket, indicating a point of failure

Hand Calculations



$$L_1 = 0.191m$$

$$L_2 = 0.127m$$

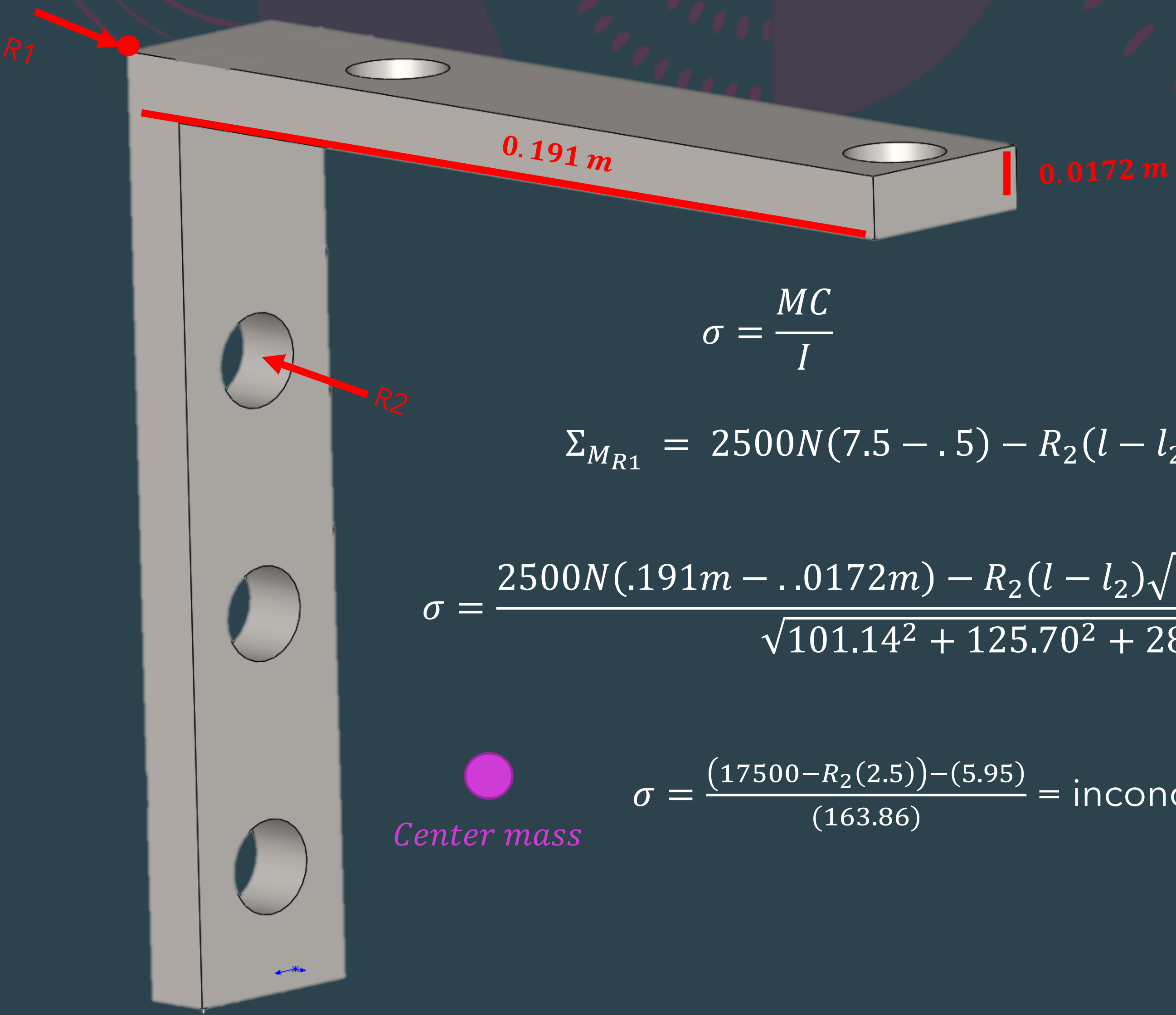
$$t = 0.0127m$$

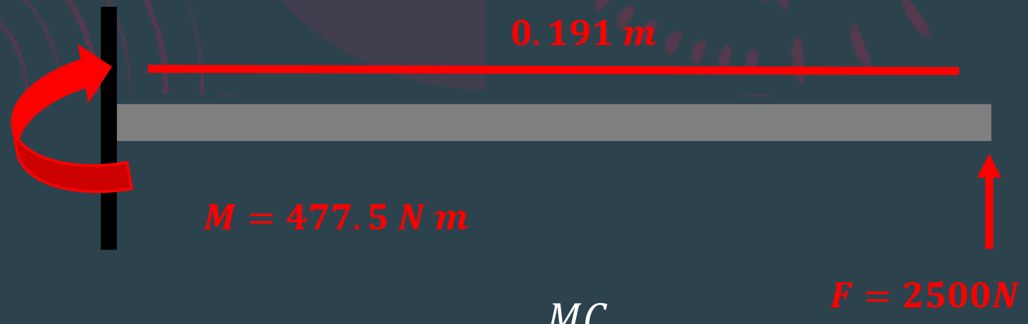
$$F_T = 2500N$$

$$\Sigma F_x: R_1 = R_2$$

$$\Sigma F_y: F_n = -mg + F_T$$

$$\Sigma M_{R_1}: M = 17500Nm - R_2(L_1 - L_2)$$





$$\sigma = \frac{MC}{I}$$

$$\Sigma_{M_{R1}} = 2500N(7.5 - .5) - R_2(l - l_2)$$

$$\sigma = \frac{2500N(.191m - ..0172m) - R_2(l - l_2)\sqrt{(2.07)^2 + .74^2 + 5.53^2}}{\sqrt{101.14^2 + 125.70^2 + 28.63^2}}$$

● *Center mass*

$$\sigma = \frac{(17500 - R_2(2.5)) - (5.95)}{(163.86)} = \text{inconclusive}$$

$$\sigma = \frac{MC}{I}$$

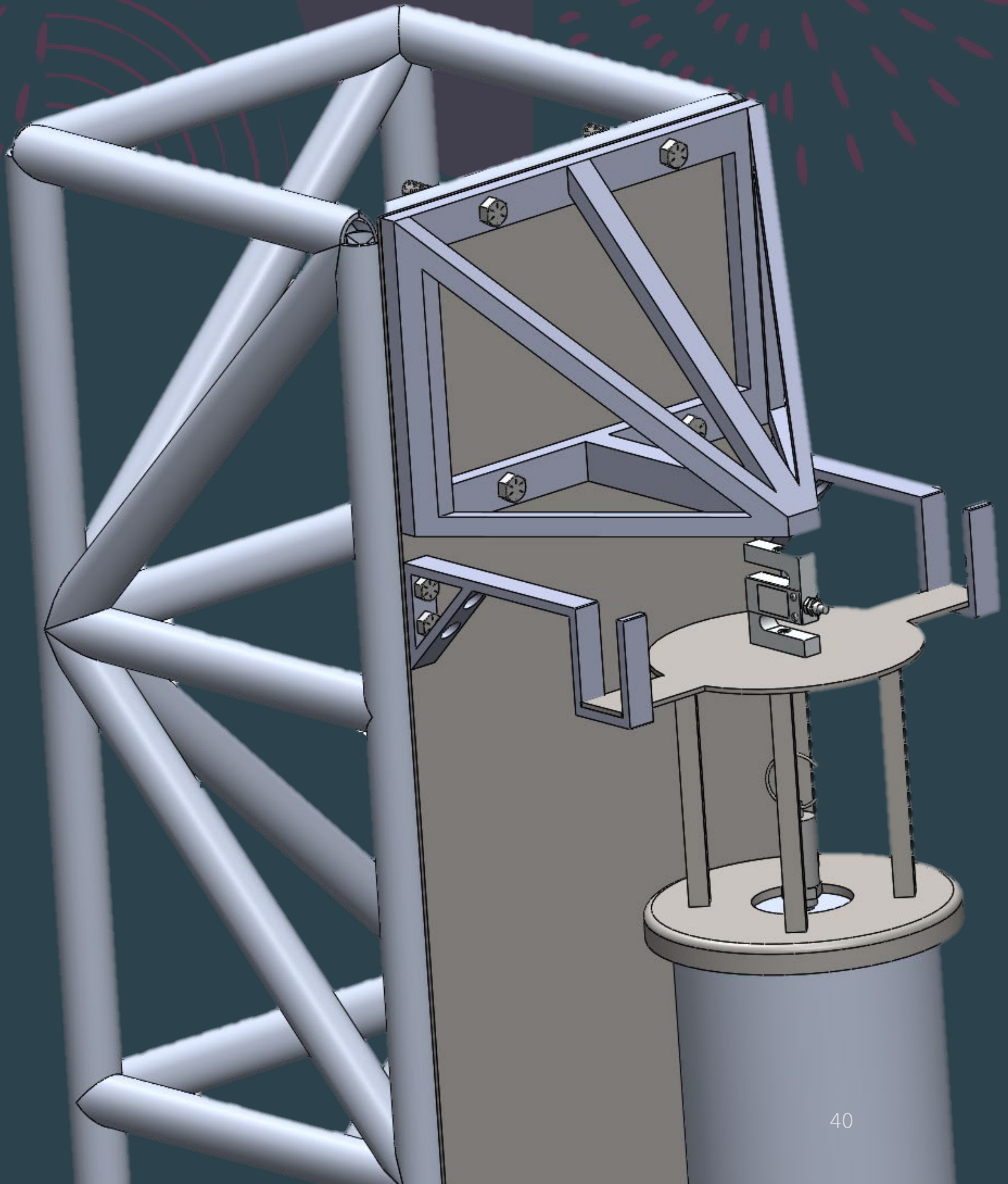
$$I = \frac{B * h^3}{12}$$

$$\sigma = \frac{(477.5\ N * m) * (\frac{.191m}{2})}{\frac{(477.5\ N * m) * (.0172m)^3}{12}}$$

$\sigma = 5.6245 * 10^8 Pa$

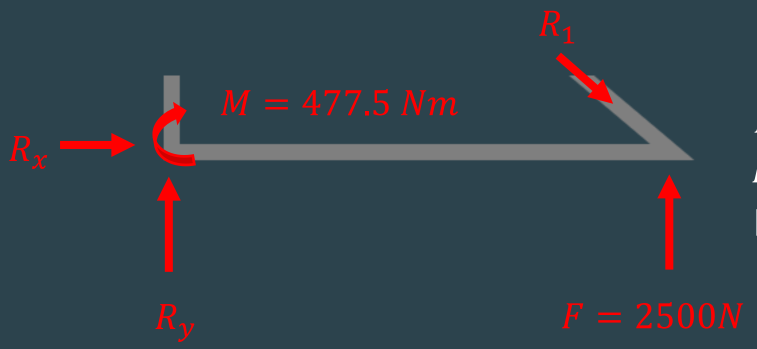
Design Changes

- Evidence of failure present; redesign necessary
- Reinforced truss shape adopted to prevent bending
- Water cut in 4 separate pieces and welded together

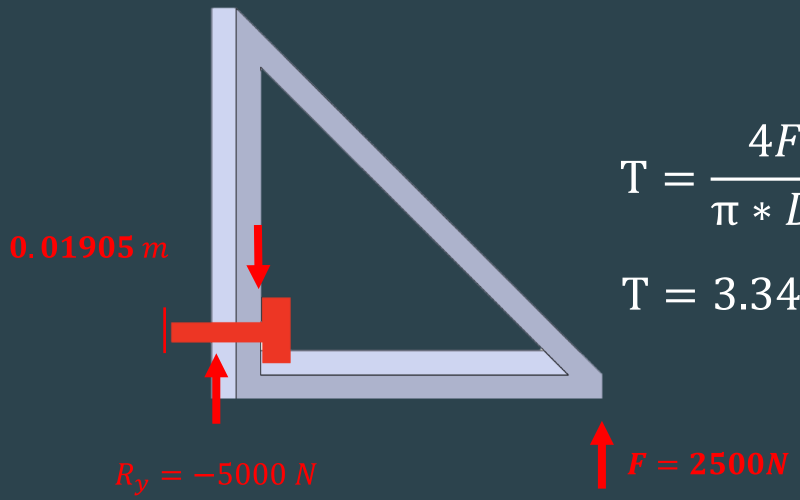


Bracket FEA

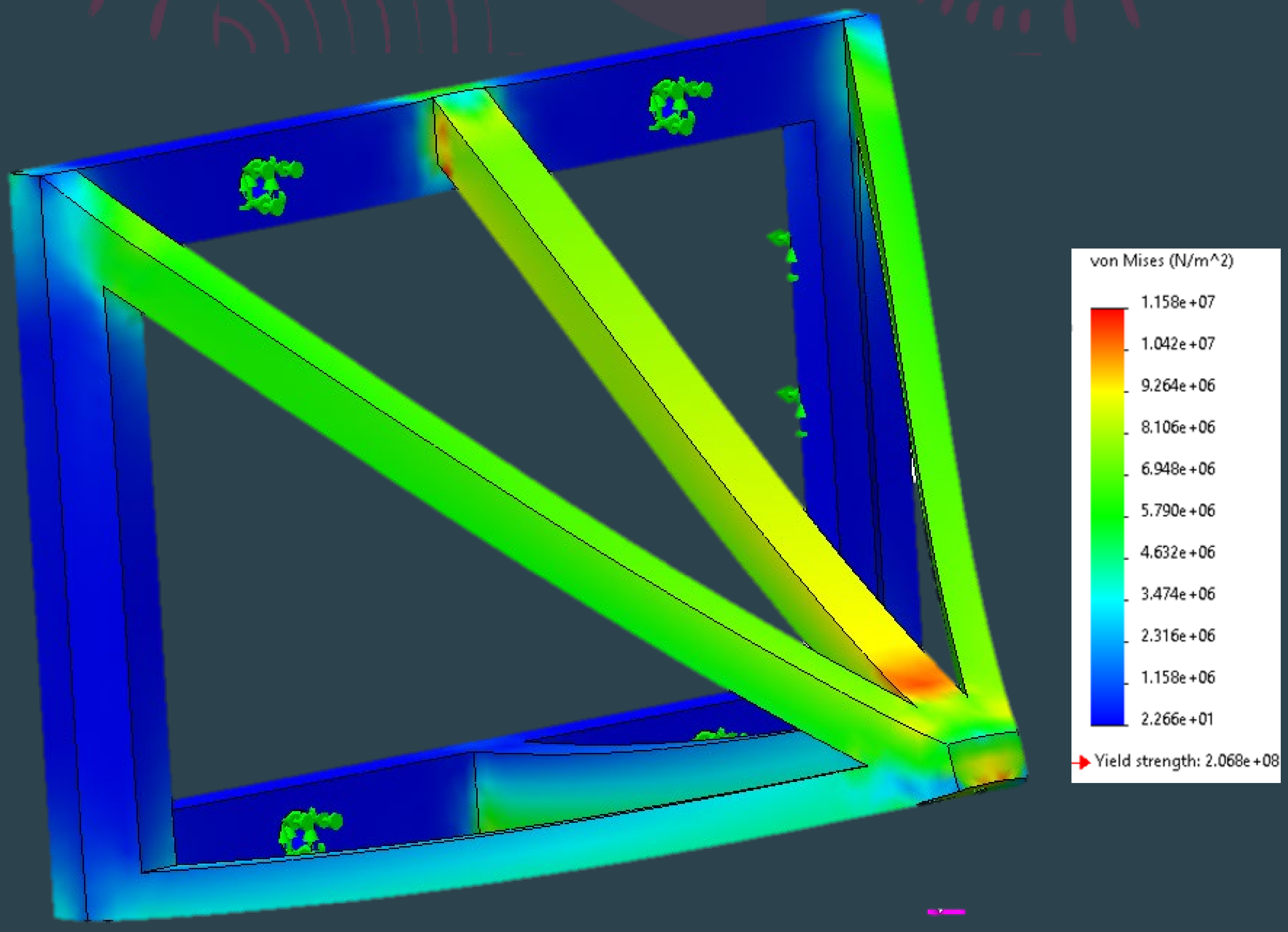
- no yielding is evident with new design
- Same mounting hardware can be used



$$R_1 = 3535.53\ N$$
$$R_y = -5000\ N$$
$$R_x = -2500\ N$$
$$\mathrm{M} = -5.61 * 10^{-4}\ N * m$$



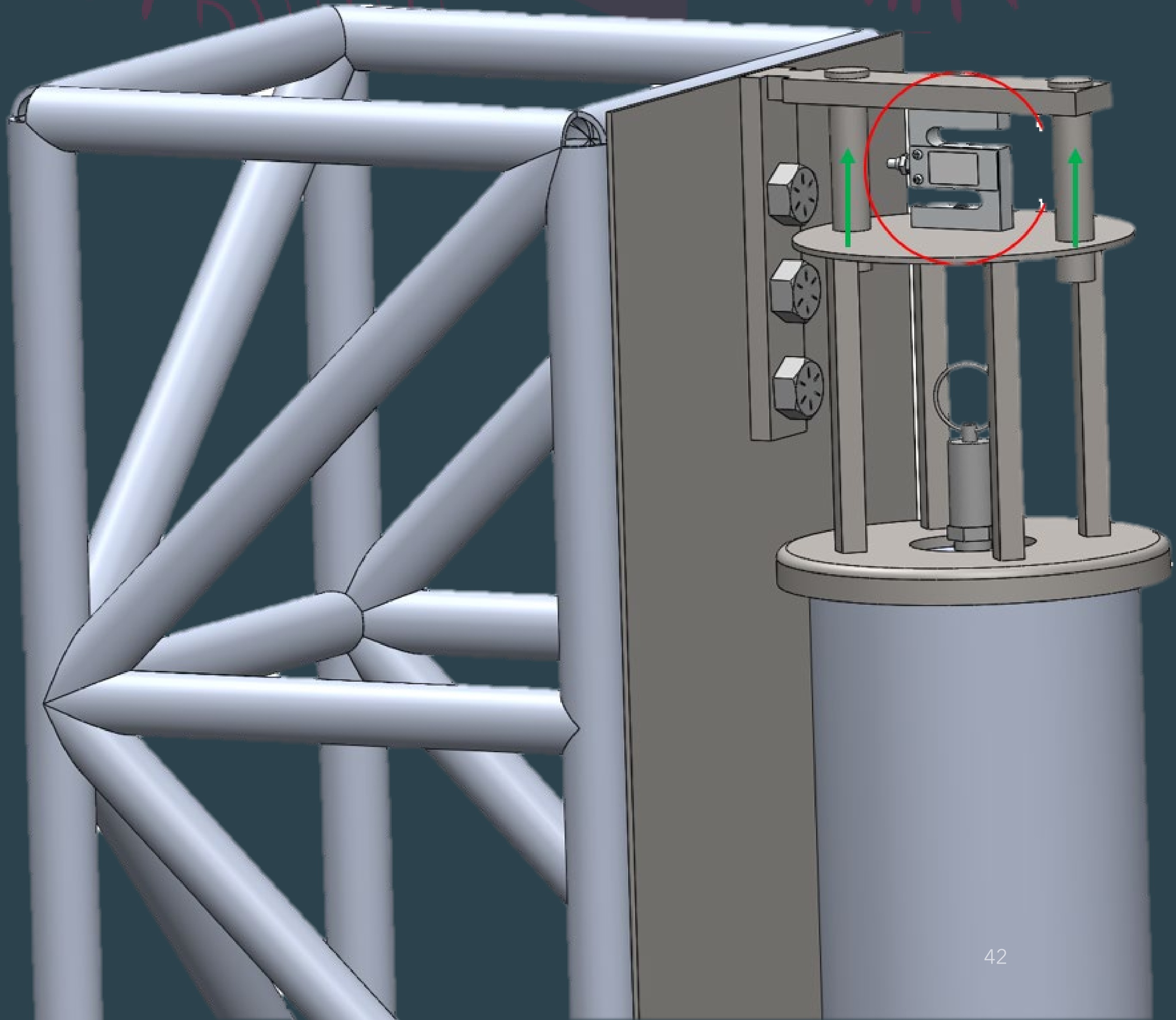
$$\mathrm{T} = \frac{4F}{\pi * D^2}$$
$$\mathrm{T} = 3.34 * 10^5 \frac{N}{m}$$

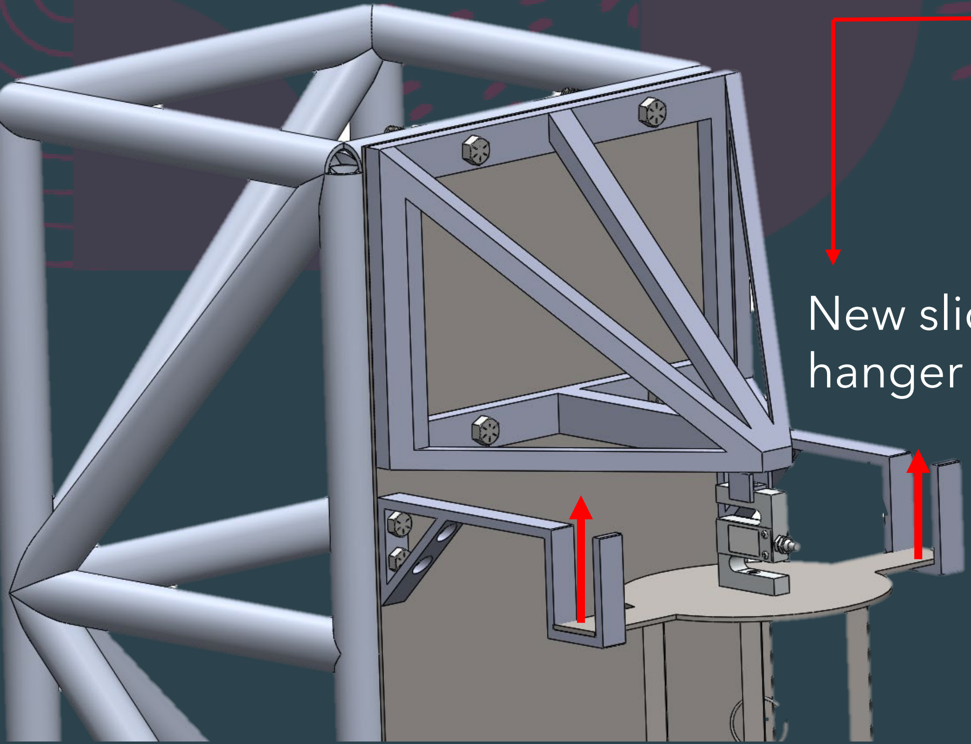


Design changes

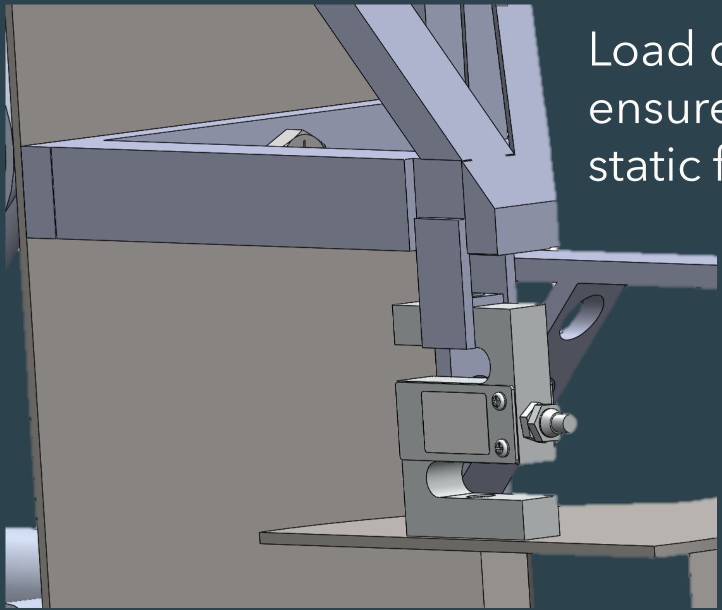
- Original slide system for load cell could bind/stuck during test fire

- Bracket redesign meant redesigning this slide system as well

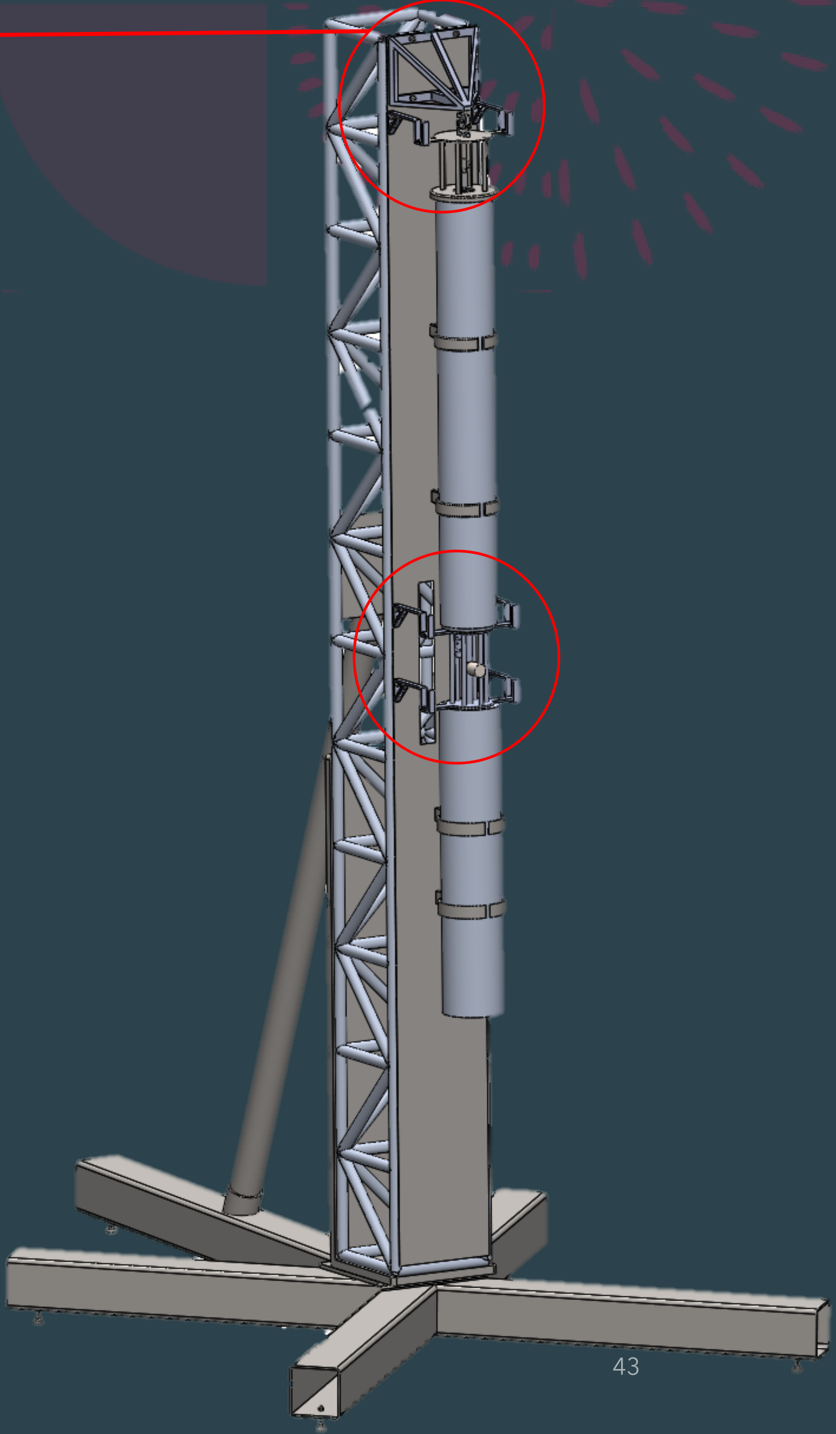




New slide system doubles as a hanger for motor assembly



Load cell is guided with tabs to ensure constant contact with static fire bracket



Controls System

Anthony Urzua

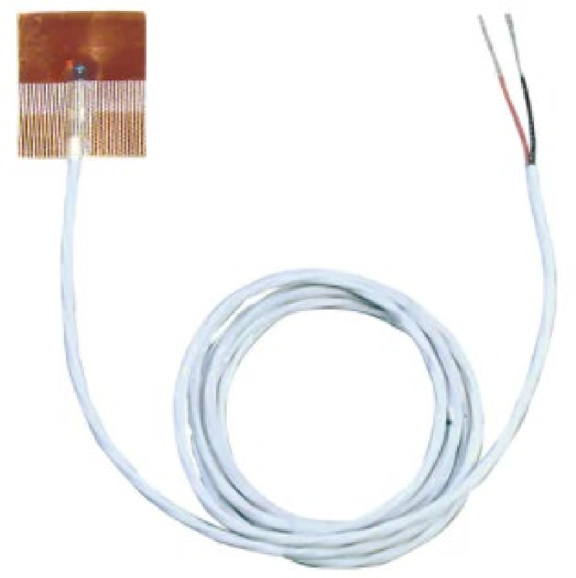
- Controls System Designer

Control System Design

- Design a GUI to allow operators to control the fill, drain, and purging sequencing of the oxidizer tank using LabVIEW and Arduino

Selected Sensors

- Explosion-Proof Industrial Pressure Transducer
- Self-Adhesive Polyimide Fast Response Thermistor Surface Sensor

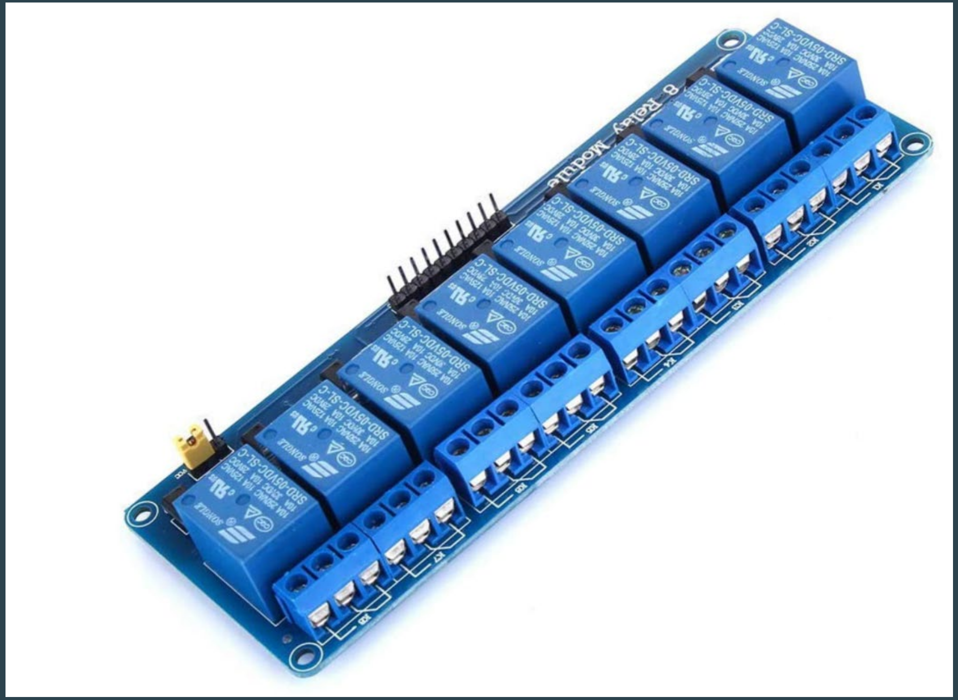


Issues

- Pressure transducer was selected but was not able to be ordered. Could not get a hold of any technical documentation.

Additional Hardware

- 6 V Battery
- 8-Channel 5V DC Relay Module Control Board



Current Block Diagram


Startup

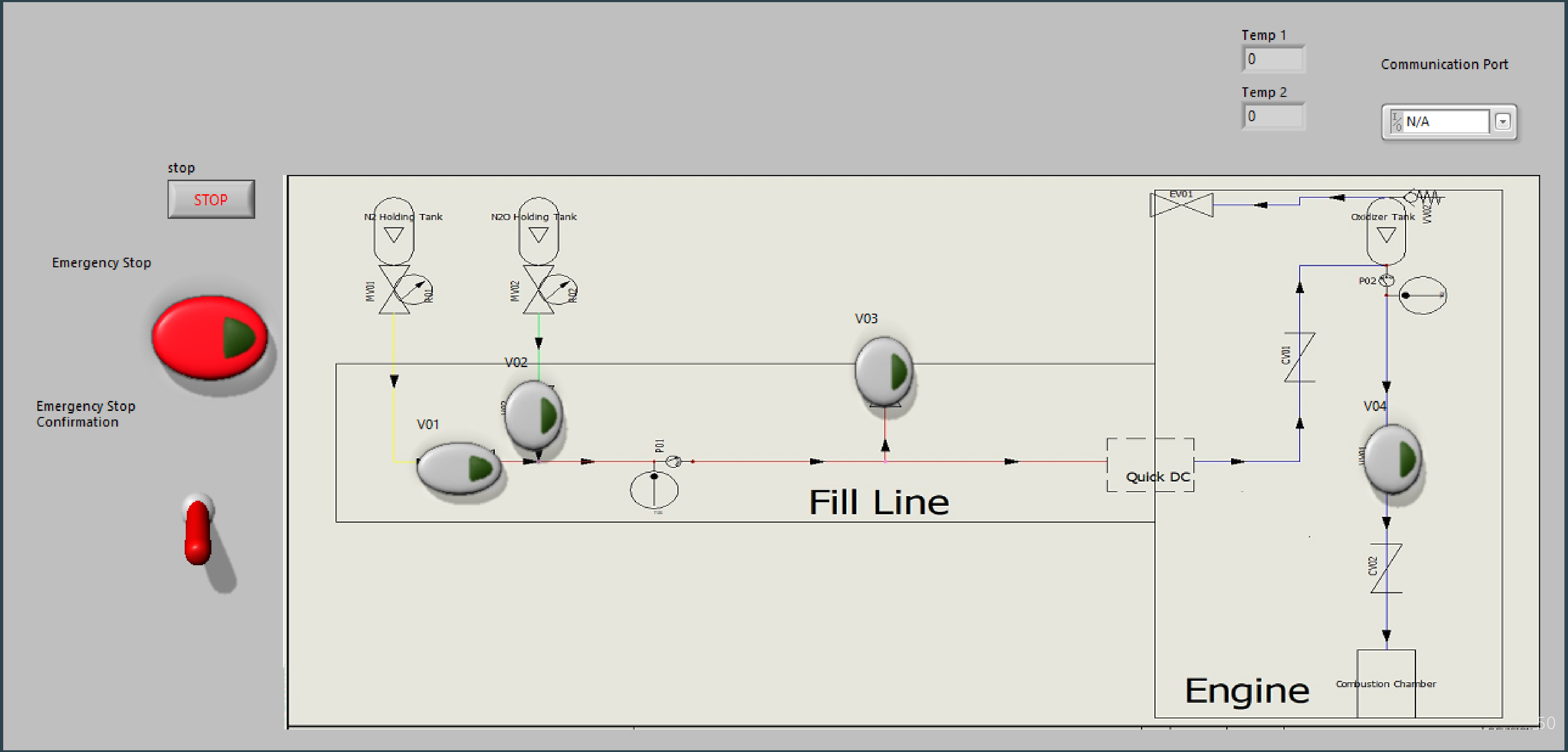
Purge

Begin Filling Sequence

Monitor temperature

Vent

Front Pannel

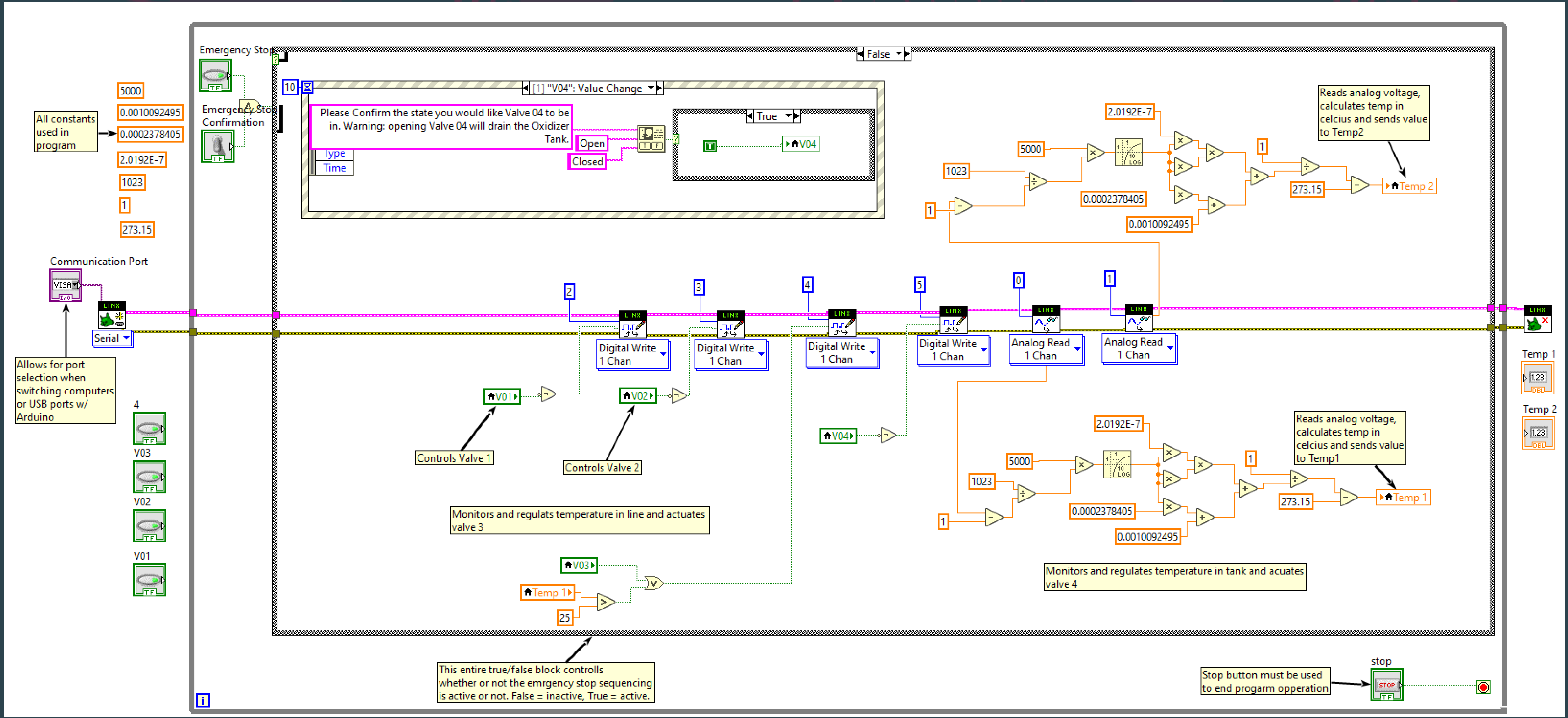


Temp 1: 0

Temp 2: 0

Communication Port: N/A

Block Diagram



All constants used in program

Allows for port selection when switching computers or USB ports w/ Arduino

Please Confirm the state you would like Valve 04 to be in. Warning: opening Valve 04 will drain the Oxidizer Tank.

Reads analog voltage, calculates temp in celcius and sends value to Temp2

Reads analog voltage, calculates temp in celcius and sends value to Temp1

Controls Valve 1

Controls Valve 2

Monitors and regulats temperature in line and actuates valve 3

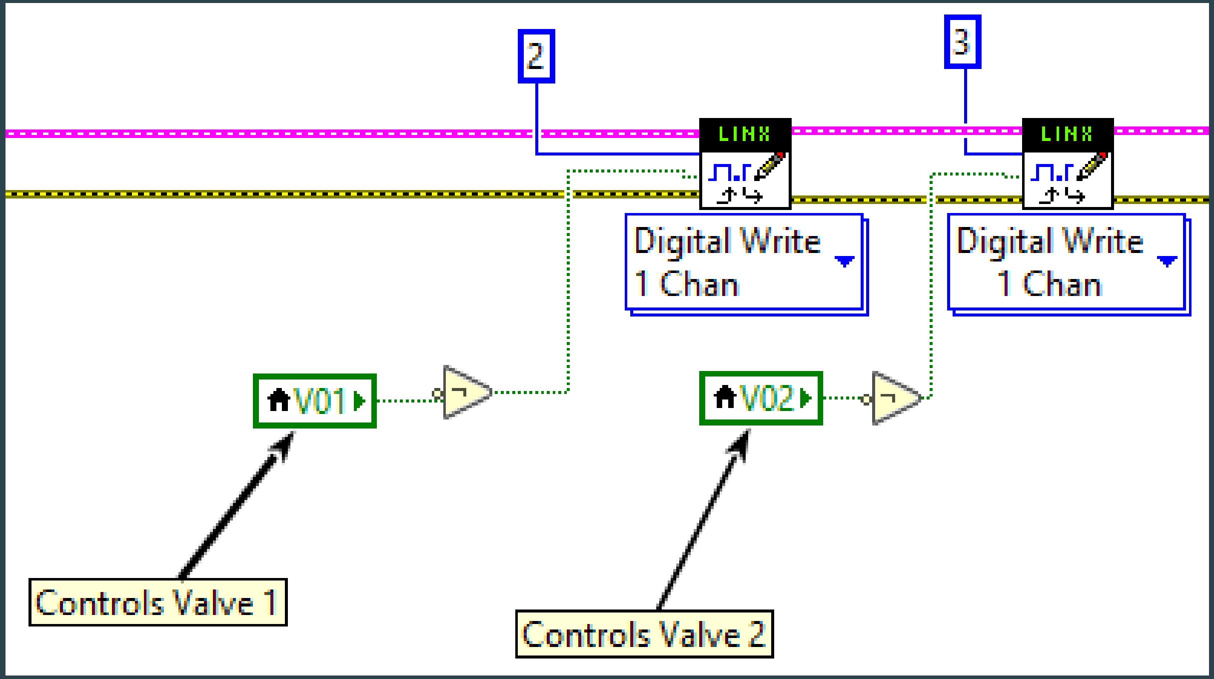
Monitors and regulates temperature in tank and acuates valve 4

This entire true/false block controlls whether or not the emrgency stop sequencing is active or not. False = inactive, True = active.

Stop button must be used to end progarm opperation

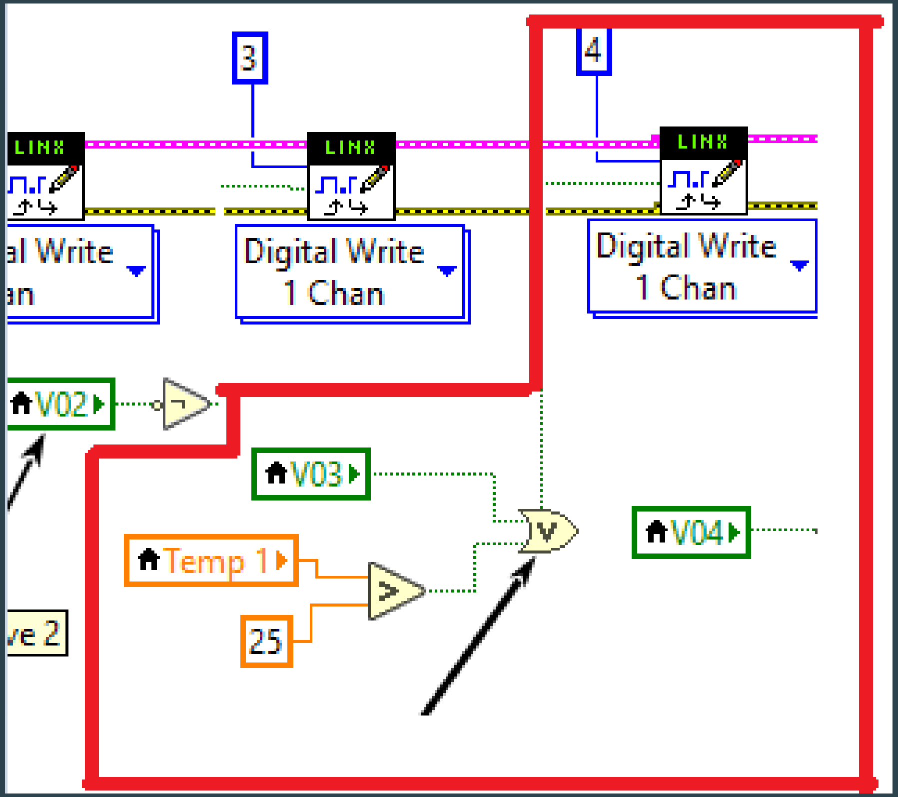
Valve actuation logic

Normally Closed:

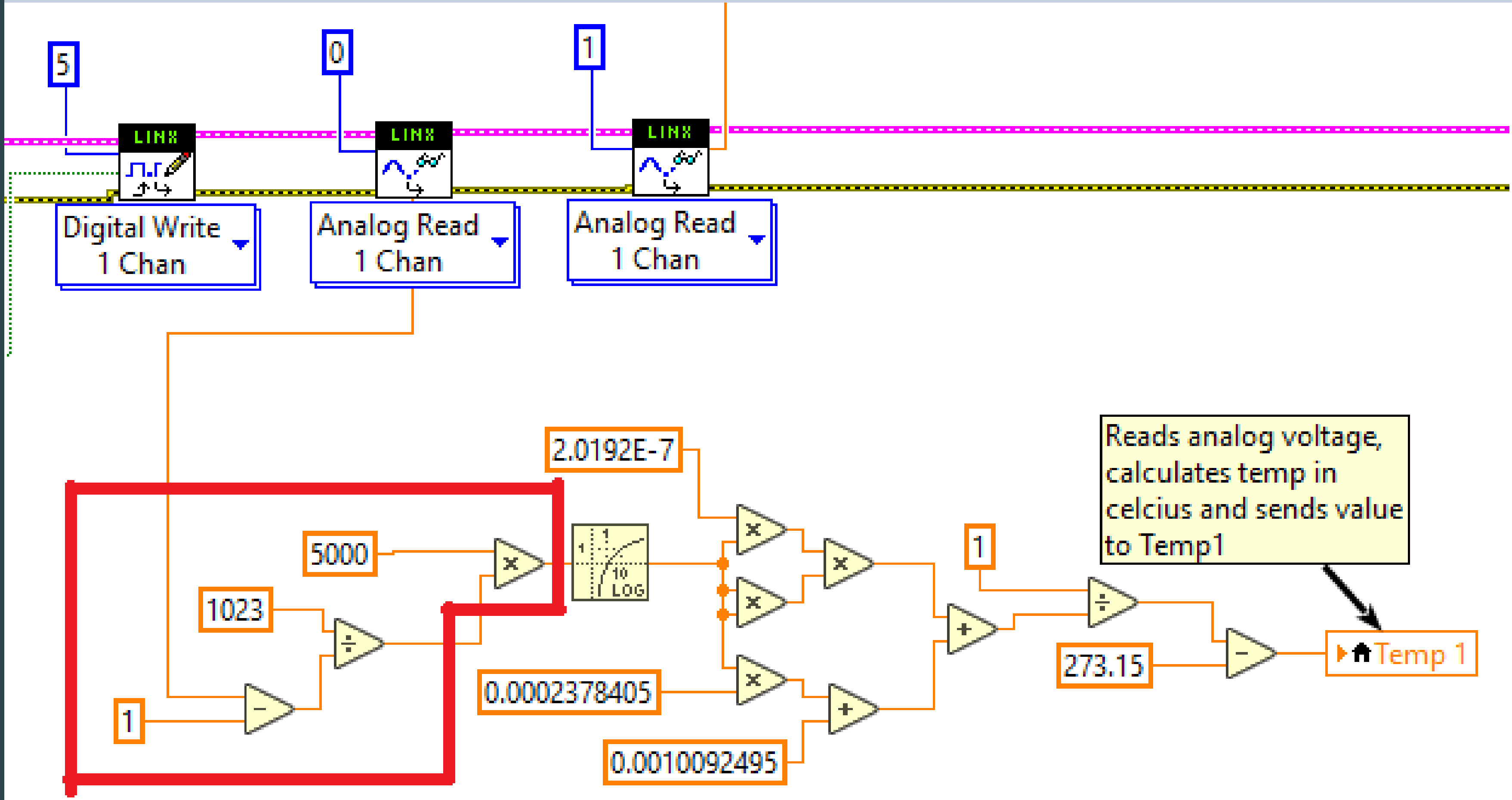


Valve Actuation logic

Normally Open:

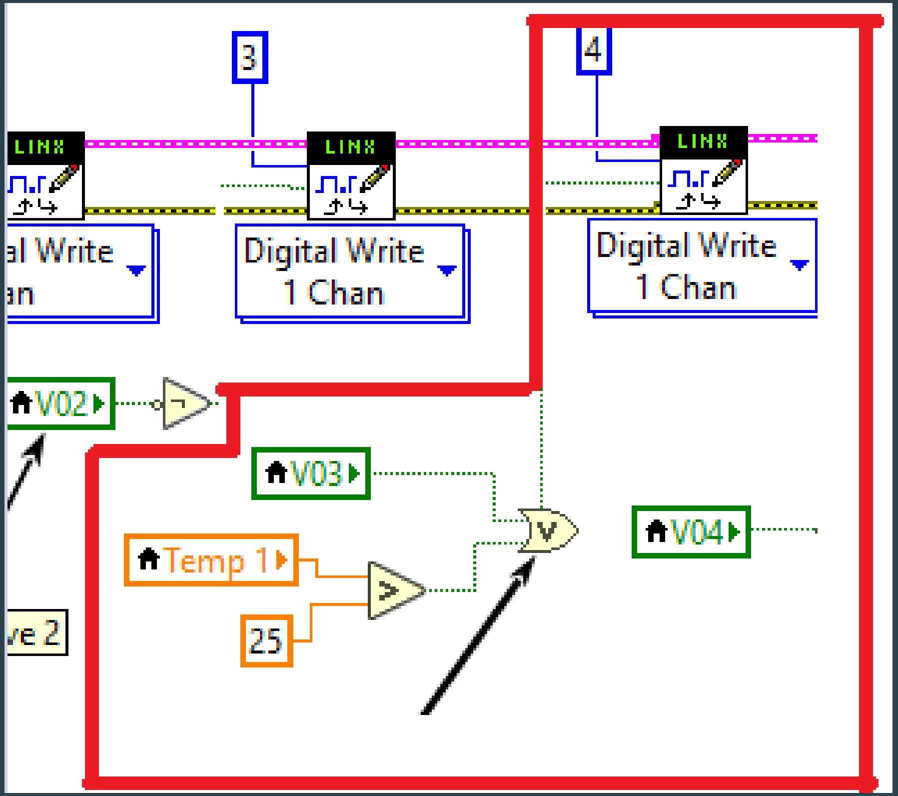


Temperature Calculation



Reads analog voltage, calculates temp in celcius and sends value to Temp1

Temperature Regulation



Truth Table:

Temp	Valve controller	Temp || Valve	Valve Position
0	0	0	Closed
0	1	1	Open
1	0	1	Open
1	1	1	Open

In Conclusion

- Python and ANSYS total times are within 2 minutes of each other.
- Valve losses increase total fill time.
- Structural designs reduce manufacturing complexity.
- Structure can withstand static fire forces.
- Controls system allows process to be done autonomously.

Thank you!

- Dr. Santner
- ERSEDS
- GC Valves
- EMJ Metals
- College of ECST

References

[1] J. E. Zimmerman, B. S. Waxman, B. J. Cantwell and G. G. Zilliac, "Review and Evaluation of Models for Self-Pressurizing Propellant Tank Dynamics," in *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, San Jose, 2013.

[2] N. G. Richter and B. H. Sage, "Thermal Conductivity of Fluids. Nitrous Oxide," *Journal of Chemical & Engineering Data,* vol. 8, no. 2, pp. 221-225, 1963.

[3] M. Takahashi, N. Shibasaki-Kitakawa, C. Yokoyama and S. Takahashi, "Viscosity of Gaseous Nitrous Oxide from 298.15 K to 398.15 K at Pressures up to 25 MPa," *Journal of Chemical & Engineering Data,* vol. 41, no. 6, pp. 1495-1498, 1996.

[4] ESDU, "Thermophysical properties of nitrous oxide," *ESDU Series on Physical Data, Chemical Engineering,* September 1991.

[5] E. W. Lemmon and R. Span, "Short Fundamental Equations of State for 20 Industrial Fluids," *Journal of Chemical Engineering Data,* vol. 51, no. 3, pp. 785-850, 2006.