CROSS

CRyogenic Orbital Siphoning System

Presented by The College of New Jersey

NASA Human Lander Challenge 2024-25

Meet the Team

Dr. Mohammed Alabsi: Project Advisor

Mohamed Eladawy: Project Manager / Applied Thermodynamics

Vaishnavi Adusumilli: Team Manager / Mechanical Design

Kyle Luis: Webmaster / Fluid Modeling & Design

Pierce Rubenstein: Treasurer / Control Systems

Project Deliverables and Constraints

Solution Requirements

- A design of a cryogenic fluid transfer process
- Have minimal mechanical components
- Have thermal insulation from radiative sources
- Provide boil-off mitigation/management

Environmental Constraints

- Zero gravity conditions
- Surface tension dominated environment
- Launch survivability
- Longevity of 10 months in outer space

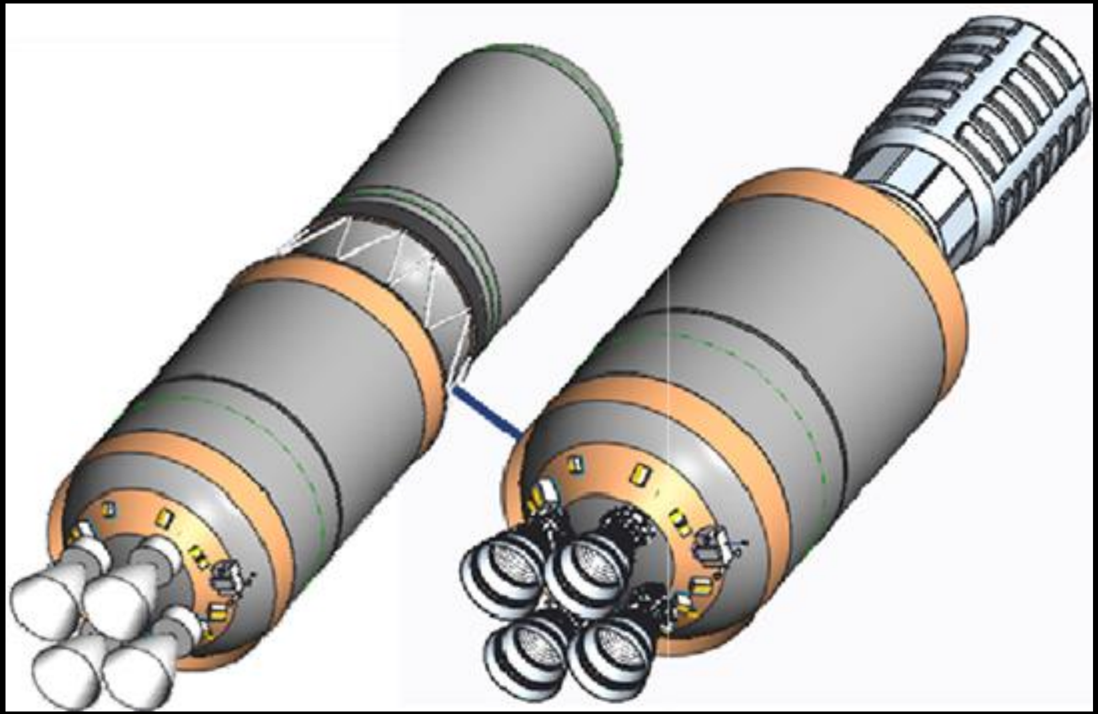


FIGURE 1: Distributed Launch Transfer Concept[1]

[1]B. Kutter, E. Monda, C. Wenner, & N. Rhys. (2015). Distributed Launch - Enabling Beyond LEO Missions. https://uploads.tapatalk-cdn.com/files-186/Distributed-Launch-2015.pdf

Primary Challenges

Surface Tension Dominated Environment

Current Propellant Management Devices (PMDs)

- Bladders and Diaphragms: tank size and material limitation
- Vanes: limited to small demand flow
- Sponges : high system mass and small volume application
- Pistons: leakage at piston rings and low EE
- Screen LAD: low reliability and high manufacture cost

Current Issues

- Adhesion To Unwanted Surfaces
- Low Expulsion Efficiency (EE)
- Bond Number Effects (Bo)

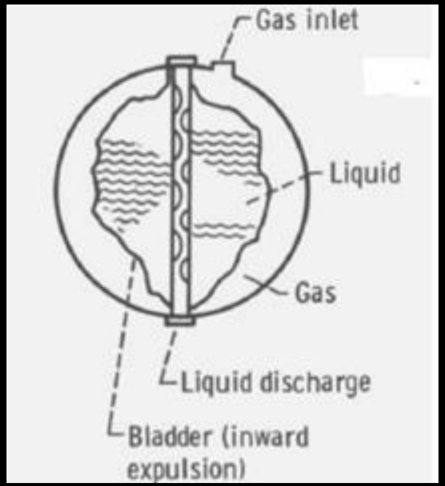


FIGURE 2: Bladder PMD Schematic[2]

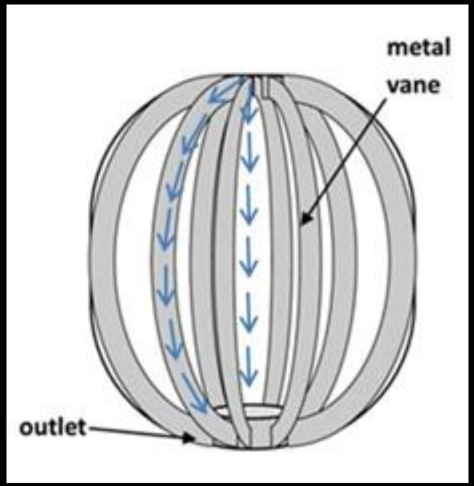


FIGURE 3: Vane PMD Schematic[2]

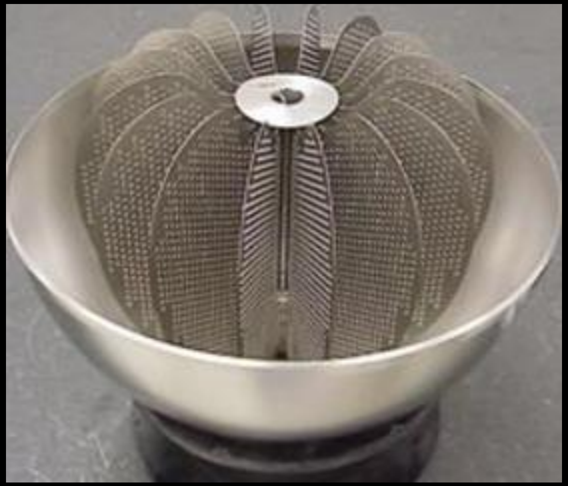


FIGURE 4: Example of Sponge PMD[2]

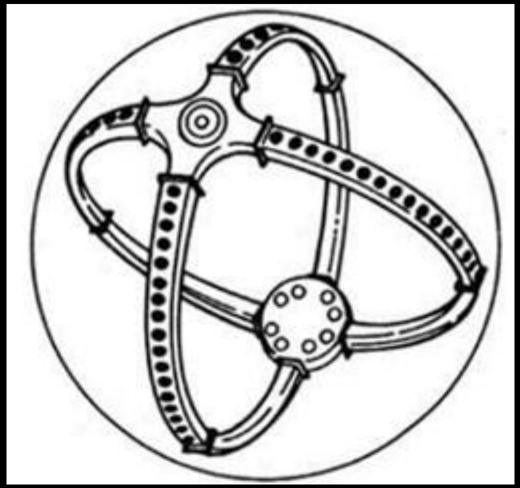


FIGURE 5: Screen LAD Schematic[2]

[2]Hartwig, J. W. (2016). A detailed historical review of propellant management… https://ntrs.nasa.gov/. https://ntrs.nasa.gov/api/citations/20170000667/downloads/20170000667.pdf

Primary Challenges

Long Term Storage in Microgravity Conditions

Current Boil-off Management

- Autogenous pressurization
- Helium pressurization

Current Issues

- Vapor pressure risk due to boil-off
- Low expulsion efficiency
- Short storage term
- Propellant contamination
- Helium as a limited resource

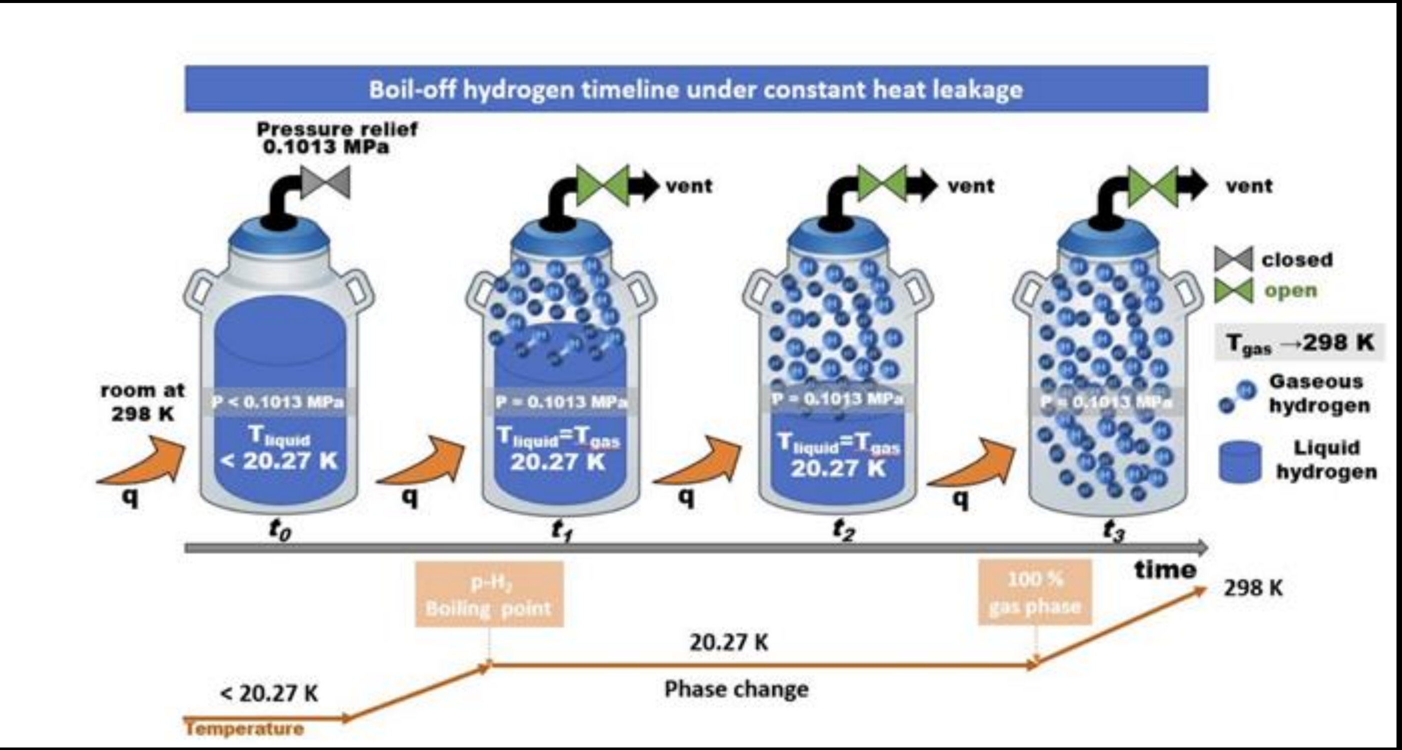


FIGURE 6: Example of Propellant Boil-Off In A Closed System[3]

[3]R. Morales-Ospino, A. Celzard, V. Fierro. Strategies to recover and minimize boil-off losses during liquid hydrogen storage. Renewable and Sustainable Energy Reviews, 2023, 182, pp.113360. ff10.1016/j.rser.2023.113360ff. ffhal-04146246f

CROSS Design: System Overview

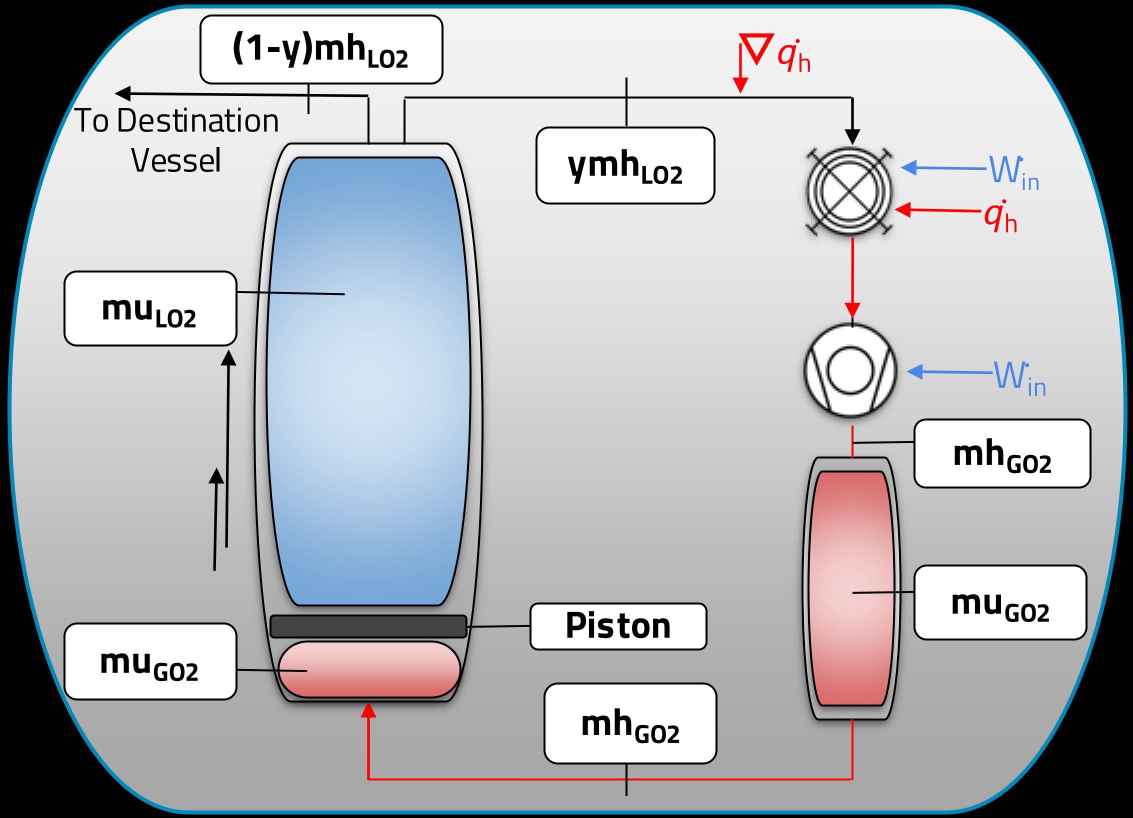
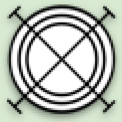
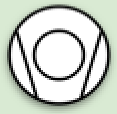


Figure 7: CVAPS Schematic Diagram

Definitions	
h	Specific enthalpy
u	Specific thermal energy
m	Mass
y	Mass fraction
W	Power
$\dot{q}$	Heat transfer rate
∇	Gradient

Key	
	High Energy Heating element
	High Energy Compressor
	Piston
	Low Energy Thermoelectric Heating

CROSS Design: CVAPS Process

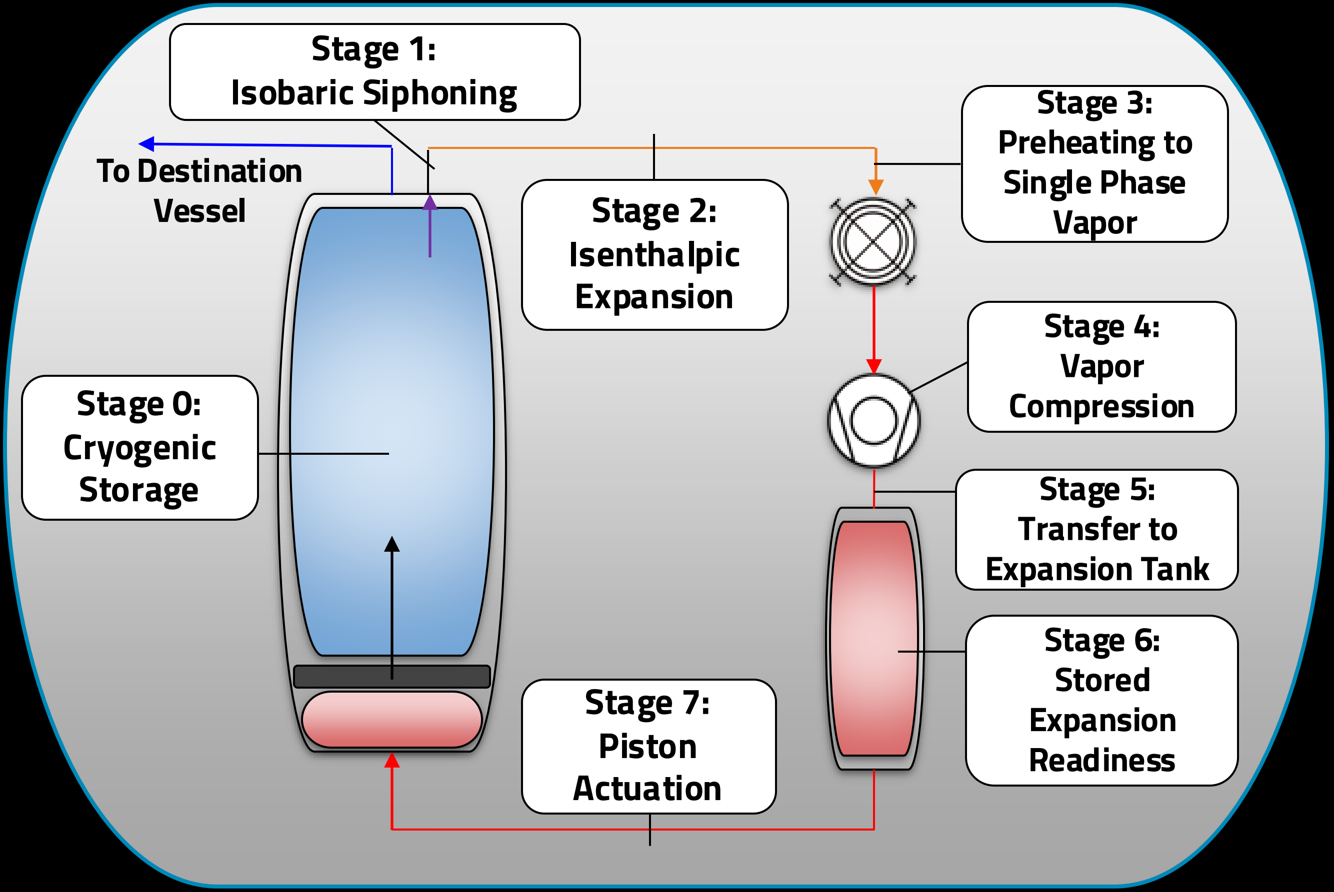


Figure 8: CVAPS Process Diagram

Pressure-Volume Relationships	
Stage 0	P_0, V_0
Stage 1	$P_1 < P_0$, V_1
Stage 2	$P_2 = P_1$, V_1 $\Delta h = 0$ (throttling)
Stage 3	$P_3 > P_4$, V_3
Stage 4	$P_4 V_4^{\gamma} =$ Constant $\gamma \sim 1.42$
Stage 5	$P_5 = P_4$, V_5
Stage 6	$P_6 < P_5$, $V_6 = V_5$
Stage 7	$P_7 < P_6$, V_7

CROSS Design: Flow and Phase Control

Phase Separation:

- Siphoning Loop to Isolate Phases
- Centrifugal Cyclonic Separator

Flow Stabilization Features:

- Hydrophobic Membranes in Lines
- Single Phase Pump

Automation and Feedback

- Pressure Sensing in Main Storage Units
- Automated Valve Control for System Response
- Maintains Boil-off During Storage
- Reduces Manual Intervention and Error

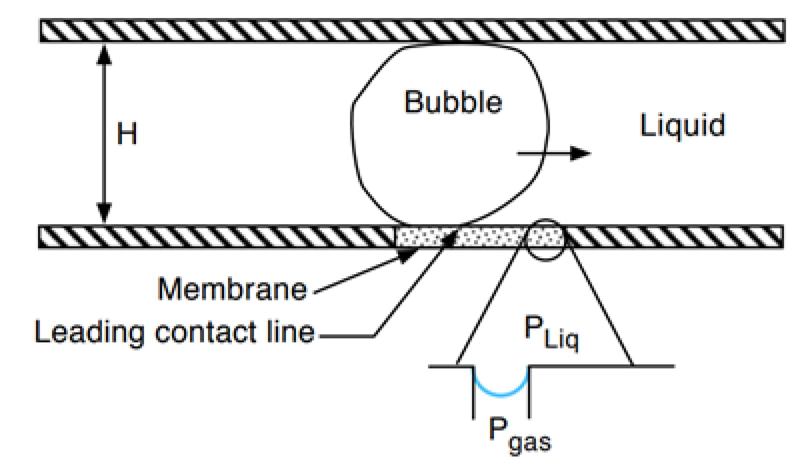


Figure 9: Gas Bubble Passing By a Membrane[4]

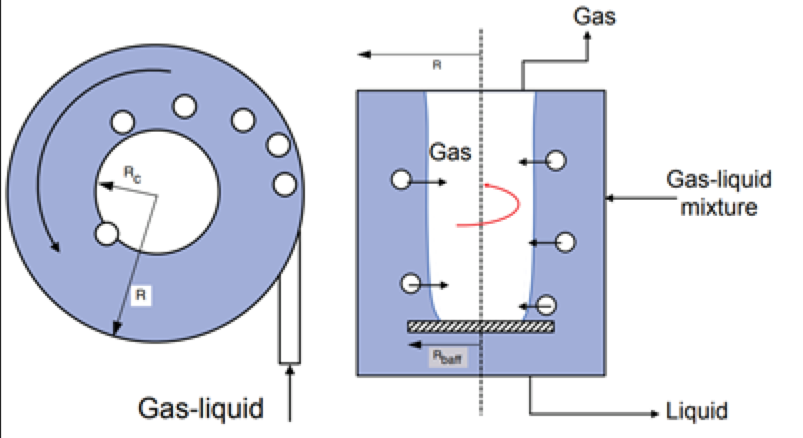


Figure 10: Schematic Of A Cyclonic Separator[4]

[4]Balasubramaniam, R., Ramé, E., & Motil, B. J. (2019). Microgravity liquid-gas two-phase flow: Review of pressure drop and heat transfer correlations and guidelines for equipment operability (NASA/TM–2019-220147). National Aeronautics and Space Administration. https://ntrs.nasa.gov/api/citations/20190001795/downloads/20190001795.pdf

Concept of Operations

Stage 1: Storage

- CROSS pre-pressurized before installation to payload vehicle
- Valve minimally opened for limited flow of propellant to CVAPS
- CROSS stays pressurized over time

Stage 2: Coupling

- Signals from the destination vessel are sent to the instrument system
- Automated couplers activate between destination vessel and CROSS

Stage 3: Transfer Begins

- Valve opens further to allow increased flow to CVAPS
- Increased rate of vaporization heightens gas pressure
- Piston begins to move in the direction of the exit point

Stage 4: Transfer Ends

- Pressure equalizes at the end of piston stroke
- Cross is now filled with gas
- Destination vessel supply is now fully replenished
- CROSS disengages from destination vessel

Figure 11: CROSS Concept of Operations Graphic

PULSE: Overview

Objective

- Total gaseous mass needed for transfer and storage
- Time required for complete transfer
- Data collection of both phases for more accurate analyses
- Validate the piston based storage for cryogenic fluids

Methodology

Gaseous mass flow based on pressure differential

- Knowns: density and volume of gas
- Unknown: mass of gas required for complete transfer
- Maintain cryogenic conditions through vacuum

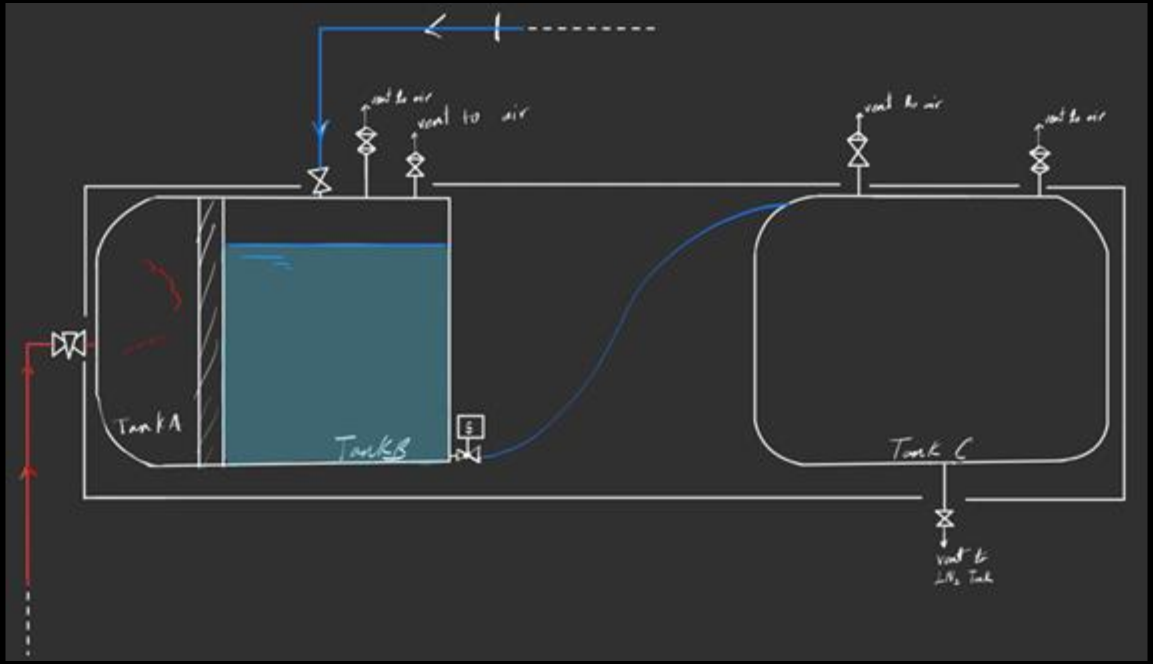


FIGURE 12: Theoretical Concept Transfer Process

PULSE: Apparatus Schematic Diagram

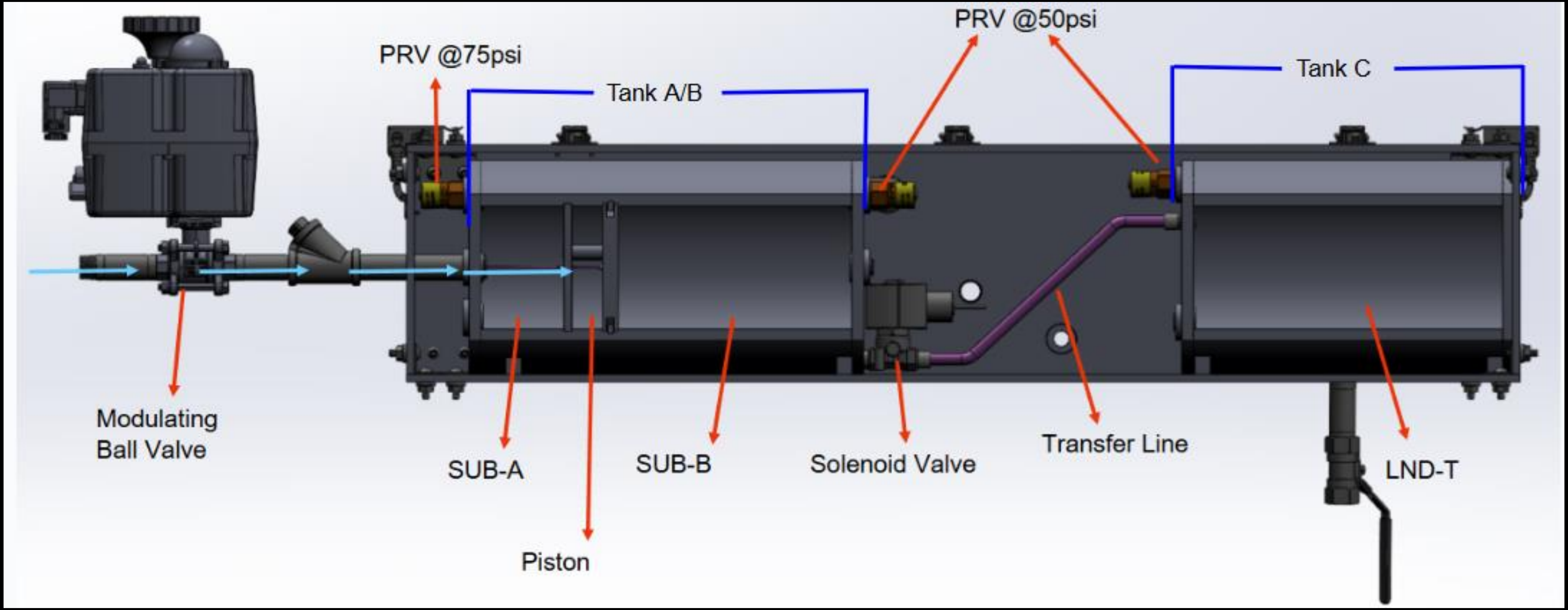


FIGURE 13: PULSE Apparatus Diagram

Piston: Manufacturing: Piston

Thermal Expansion Analysis (6061-T651 Al):

- Nominal[5] : 14 µin/in-°F
- Measured: 22.67µin/in-°F

Prototypes:

- 3D printed PLA, 6.5" diameter
- 3D printed ABS Plastic, 6.5" diameter
- Machined Acrylic, 6.43" diameter

Ring Iterations:

- Bronze Core and PTFE Wear Ring Stock
- Rubber Core and FEP Plastic
- Solid PTFE Plastic rings (6.25"- 6.5")

Final Dimensions:

6.355" overall diameter with 6 solid PTFE rings

FIGURE 14: Various Piston Prototypes

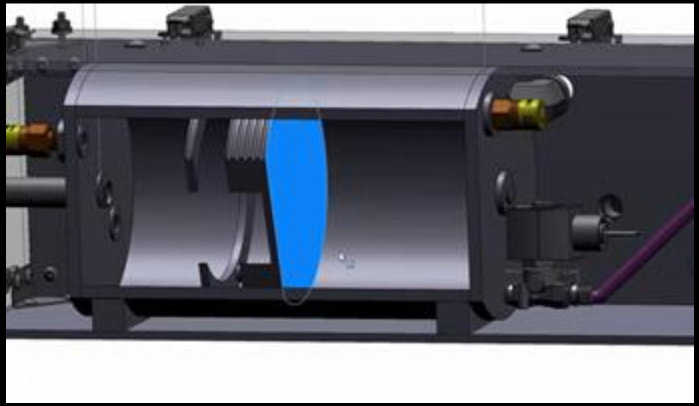


FIGURE 15: Theoretical Concept of Transfer Process

FIGURE 16: Final Piston Iteration

[5]MatWeb. (2025). Aluminum 6061-T6; 6061-T651 – Material datasheet. MatWeb. Retrieved June 20, 2025, from https://www.matweb.com/search/DataSheet.aspx?MatGUID=b8d536e0b9b54bd7b69e4124d8f1d20a

Tanks: Manufacturing & Analysis

Tank A/B

- **Material:** Custom Hydraulic Cylinder
- **Safety Factor:** 2.46 (75 psi at -400 °F)
- **Max Deflection:** 0.0039 in. at face

Tank C

- **Material:** Modified Oxygen Tank
- **Safety Factor:** 7.1 (50 psi at -400 °F)
- **Max Deflection:** 0.0012 in. at face

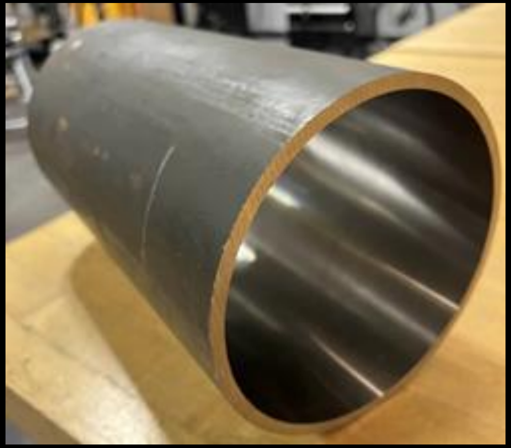


FIGURE 17: Hydraulic Cylinder used for Tank A/B

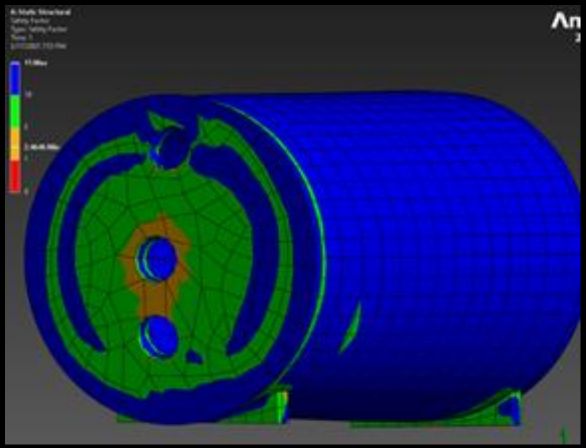


FIGURE 18: Hydraulic cylinder ANSYS safety factor analysis

FIGURE 19: Oxygen Medical Tank used for Tank C

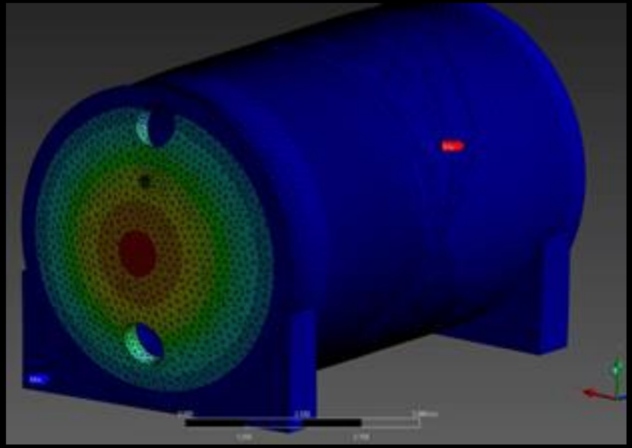


FIGURE 20: Oxygen Tank ANSYS safety factor analysis

Tank Heads: Manufacturing & Analysis

Materials and Components

- Custom 3/16" AISI 1026 Steel Gussets
- SS 304 Welded Bungs and Fasteners
- 3/8" Diameter SS Connecting Rods

Analysis Results

- Maximum Deformation: 0.00047 inches
- Maximum Stress: 38,431 psi
- Safety Factor: 1.55

FIGURE 21: Tank A Manufactured Head

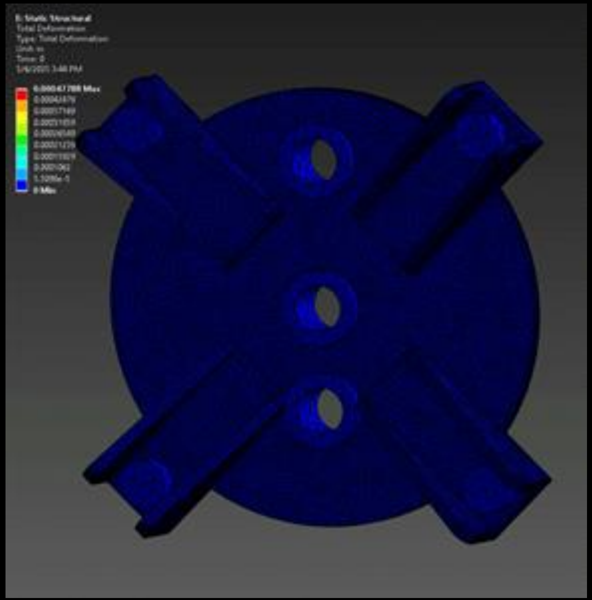


FIGURE 22: Deformation Analysis

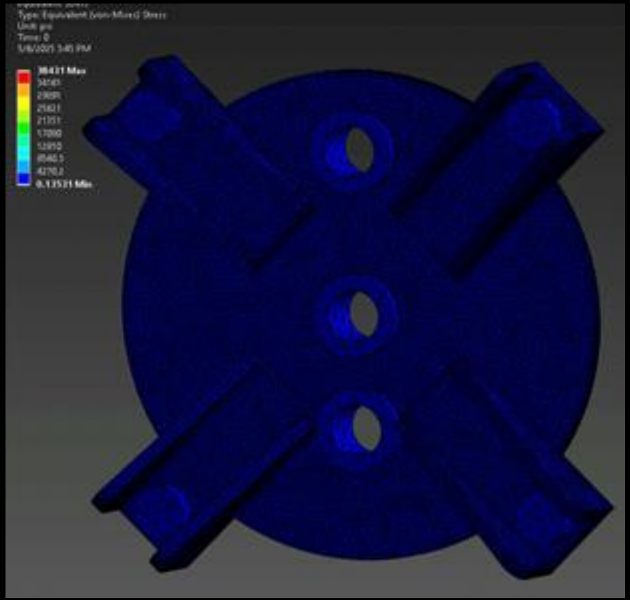


FIGURE 23: Maximum Stress Analysis

Vacuum Chamber: Manufacturing

Materials:

- G-10 Garolite Boards
- Re-Machined Latches
- Silicone Rubber Gaskets and Bolt Washers
- ¼" Thick Acrylic Observation Panel
- Aluminum Based Mylar Sheets





Figures 24-28: Vacuum Chamber Manufacturing

Vacuum Chamber: Thermal Analysis

Heat Leak Analysis

1 Minute

- Maximum Temperature: 117.57 K
- Maximum Heat Leak Rate: 3 W at Exit

4 Minute

- Maximum Temperature: 154.81 K
- Maximum Heat Leak Rate: 9.8 W at Exit

Vacuum Pressure Analysis

7 PSI

- Max Deformation: 0.24 in
- Safety Factor: 3.5 at 3228.5 PSI

14.7 PSI

- Max Deformation: 0.46 in
- Safety Factor: 1.7 at ~6500 PSI

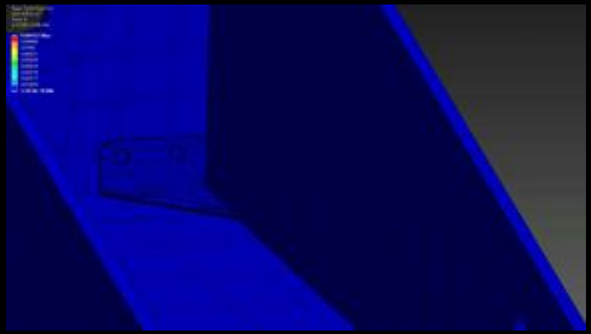


Figure 29: Maximum Heat Leak at Corner Brackets

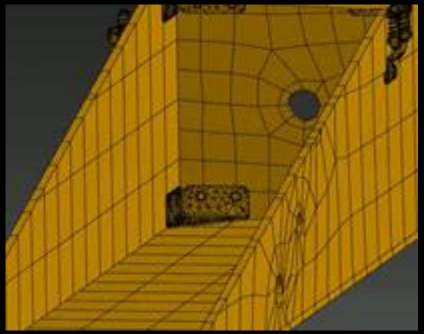
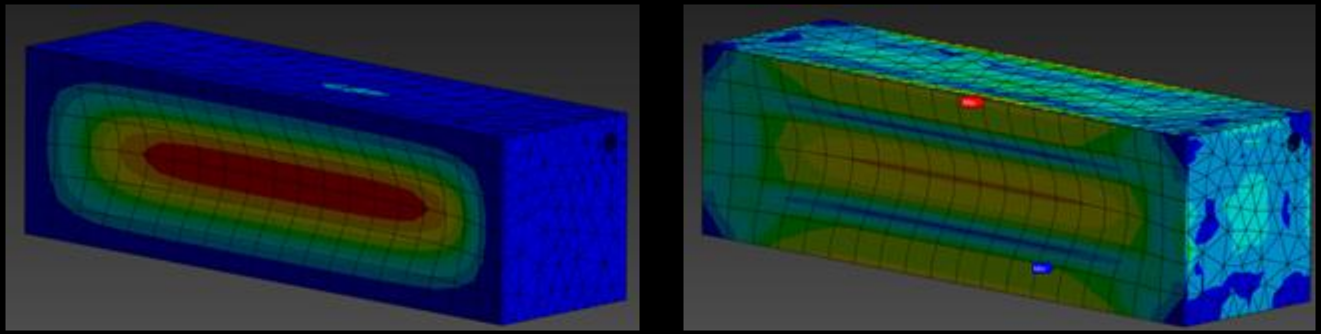


Figure 30: Heat Leak at 4 Minutes



Figures 31-32: Vacuum Chamber Deformation (left) and Maximum Stress (right)

PULSE: Operational Visualization

FIGURE 33: Pulse Testing Process

Controls System: Overview

Sensors

- Strain gauge rosettes to determine tank pressures
- RTDs for assistance with determining pressures
- All signals conditioned prior to data collection

Modulating Valve

- Closed-loop PID control scheme developed to maintain linear pressure increase in gas tank
- Experimental valve flow relationship utilized for accuracy

Code

- Web server configured for remote data viewing and valve control
- Dual-core controller to run micropython code exporting data to files for analysis

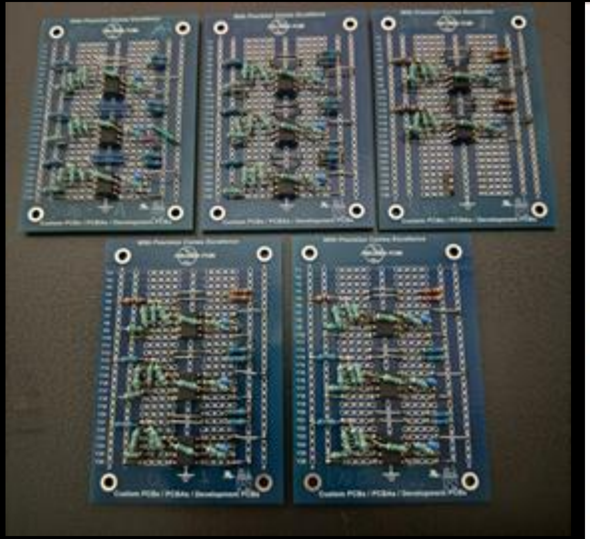


Figure 34: Signal Conditioning Boards

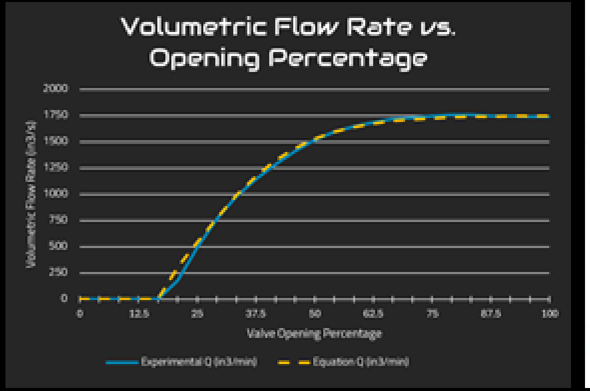


Figure 35: Modulating Valve Flow Relationship Test Data

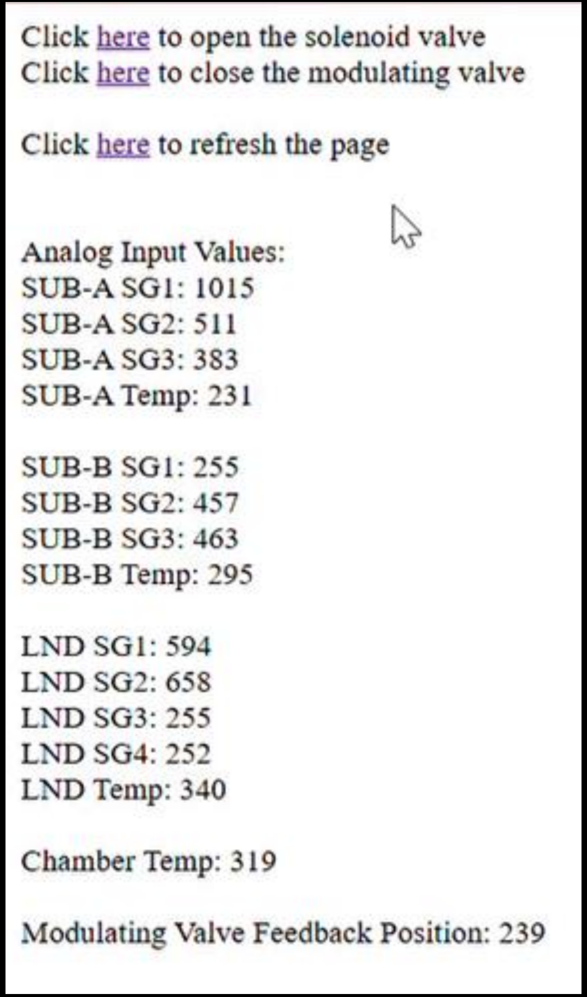


Figure 36: Remote Server Testing

Controls System: Components

- Resistance Temperature Detector
- Strain Rosette
- Valve Power
- Valve Control Signal
- Arduino GIGA R1 WiFi
- MOSFET Transistor

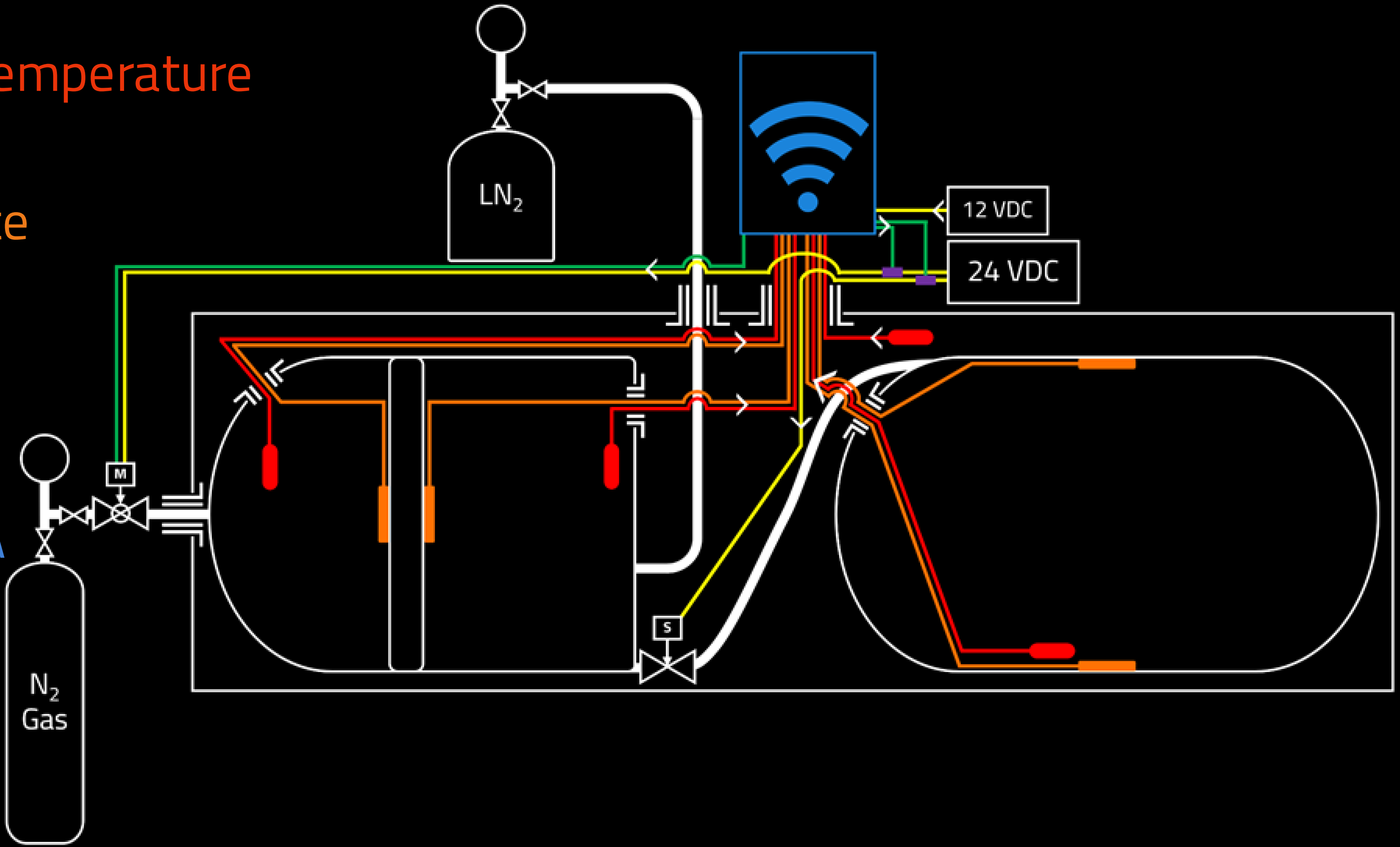


Figure 37: Control System Wire Routing Diagram

Fluid Modeling: Parameter Framework

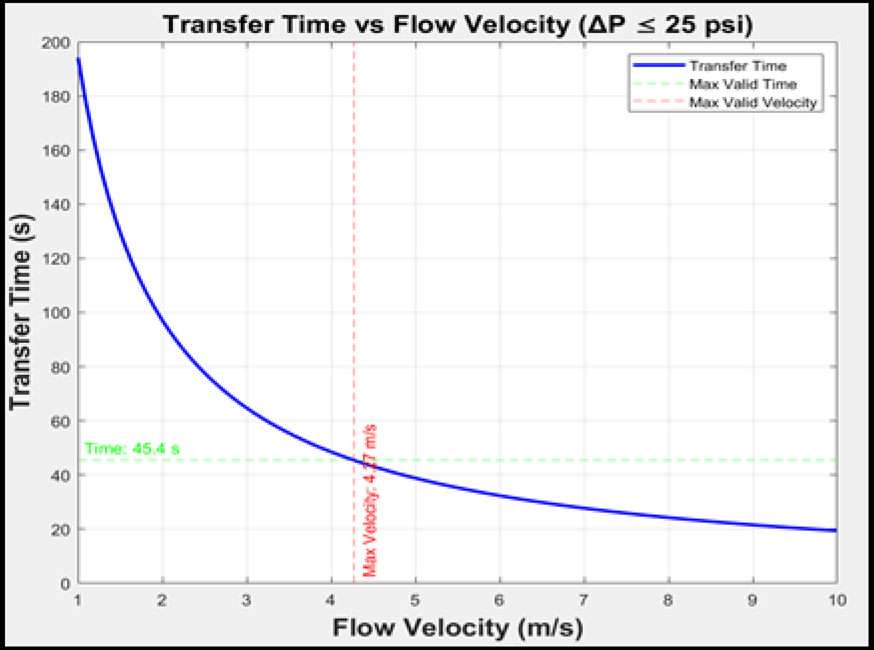


Figure 38: Plotting Transfer Time against Flow Velocity

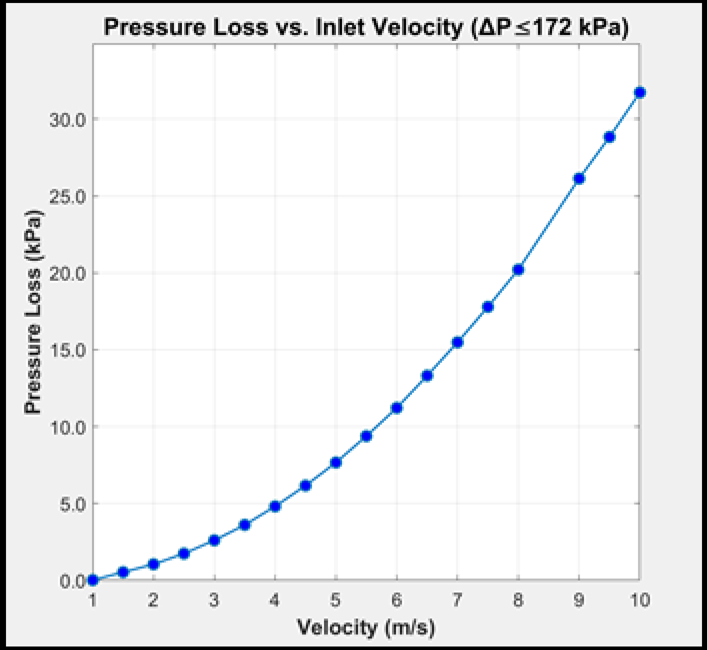


Figure 39 Plotting Pressure Loss against Inlet Velocity

Flow Velocity Determination

- Demonstrates fluid velocity over time within the targeted operational range
- Confirms that ΔP directly influences transfer speed

Pressure Loss Determination

- Pressure loss increases with fluid velocity
- Validates theoretical pressure loss relationships (Darcy-Weisbach Principal)

Fluid Modeling: Validation & Simulation

Parameters

- **Volume of Fluid**: Explicit time formulation
- **Transient:** 0.53 second elapsed time
- **K-Omega model:** Accurate for enclosed flows
- **Iterative Simulation:** 1-10 m/s
- **Total Simulation Time:** ~ 11 hours

Data Verification

- **Strain Gauge pressure readings**

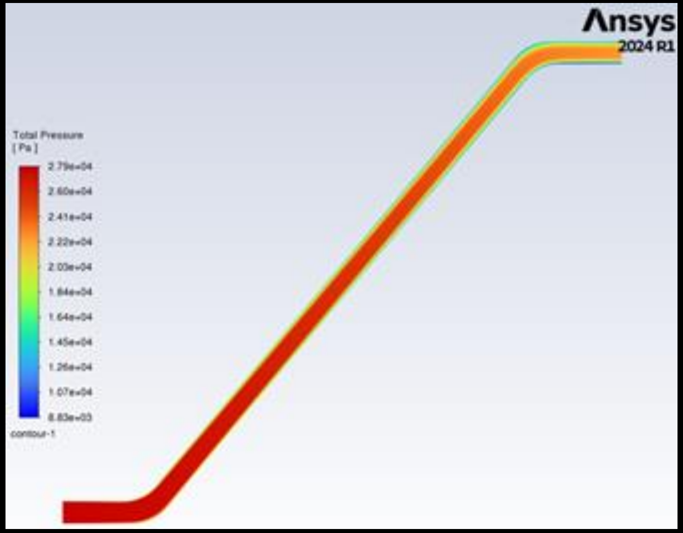


Figure 40: Total Pressure at Fully Developed Flow

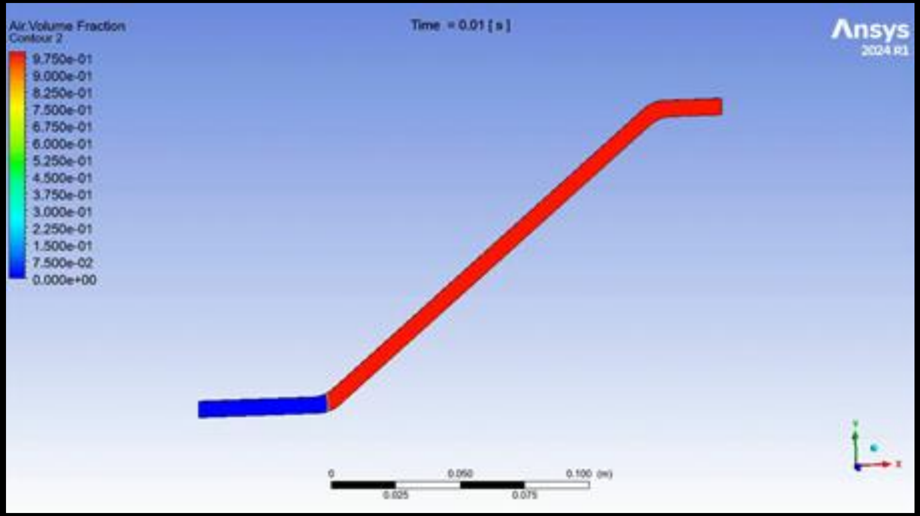


Figure 41: Simulation of Air Volume to Liquid Volume

Validation and Simulation

Destination Behavior

- Turbulence experienced past 0.1 m/s
- Introduction of severe turbulent dissipation at speeds above 5 m/s
- **Total Simulation Time:** ~ 2 Days

Limitations

- Divergent solution methods
- Cluster incompatibility
- Failed UDF implementation on available licensed machines

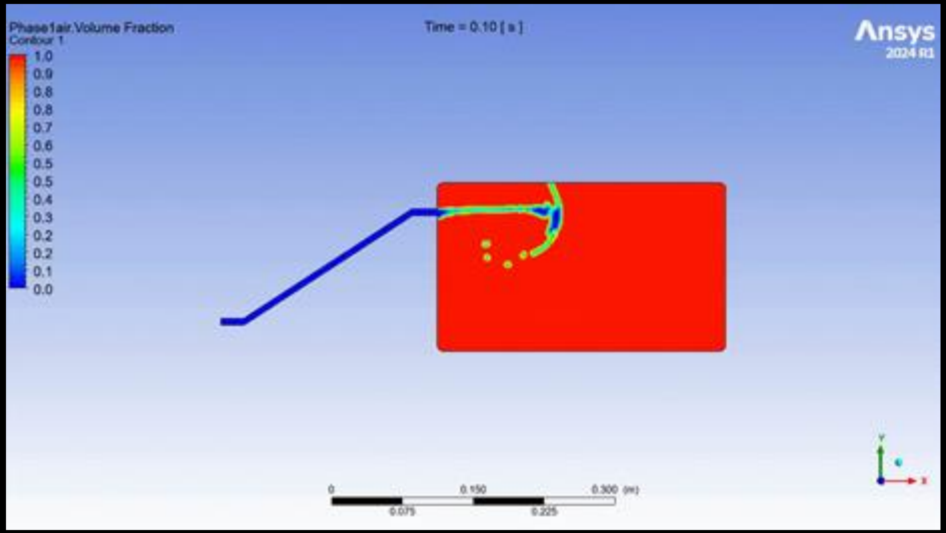


Figure 42: Simulation Model of LN_2 Flowing at 6 m/s

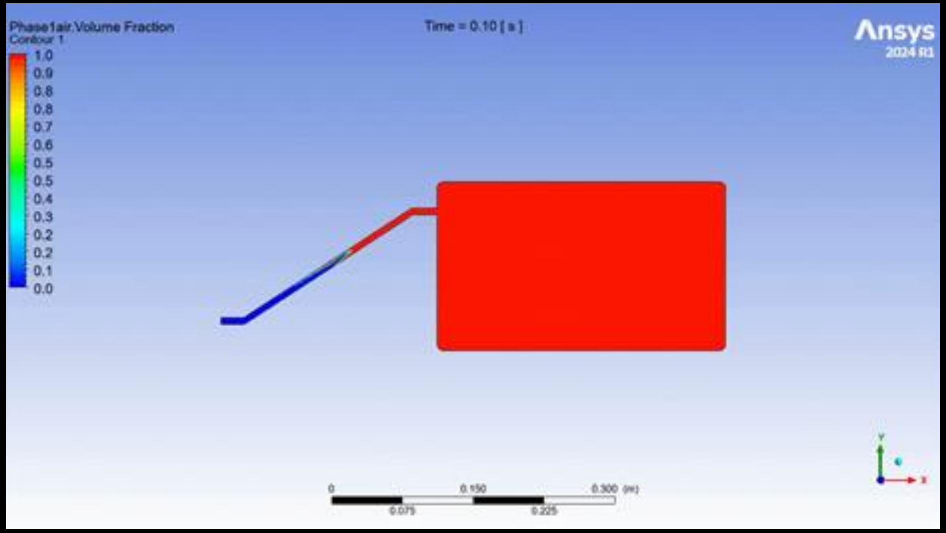


Figure 43: Simulation Model of LN_2 Fill up at 1.5 m/s

PULSE: Risks and Mitigation Plan

Incomplete Piston Seal

- Results in significant propellant contamination and heat leaks from gas portion to storage chamber
- Mitigated in PULSE by using multiple sealing rings
- Mitigation for CROSS with structural webbing and tank outer casing

Piston Misalignment

- Results in piston travel stoppages and potential unsealing
- Mitigated through the addition of an extra “skirt” offset from the main piston to maintain alignment

Two-Phase Flow During Transfer

- Propellant contamination can result in destination vessel engine failure
- Mitigated using siphoning loop and cyclonic separators

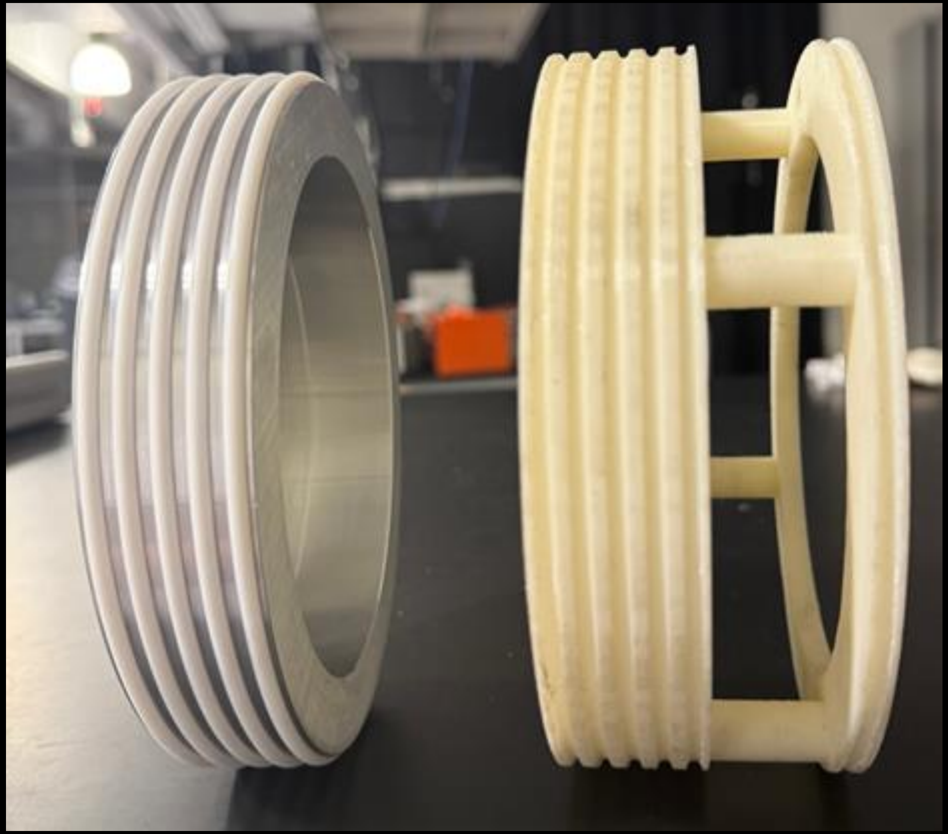


FIGURE 44: Theoretical Concept Transfer Process

CROSS NASA Adoption Timeline – Phase B

PULSE-2

- Advanced CROSS prototype to test CVAPS components and optimal piston design
- Perform ground tests for slosh control, boil-off reduction, and piston sealing
- Perform microgravity fuel transfer tests on board the ISS
- Preliminary Design Review by mid-August 2026

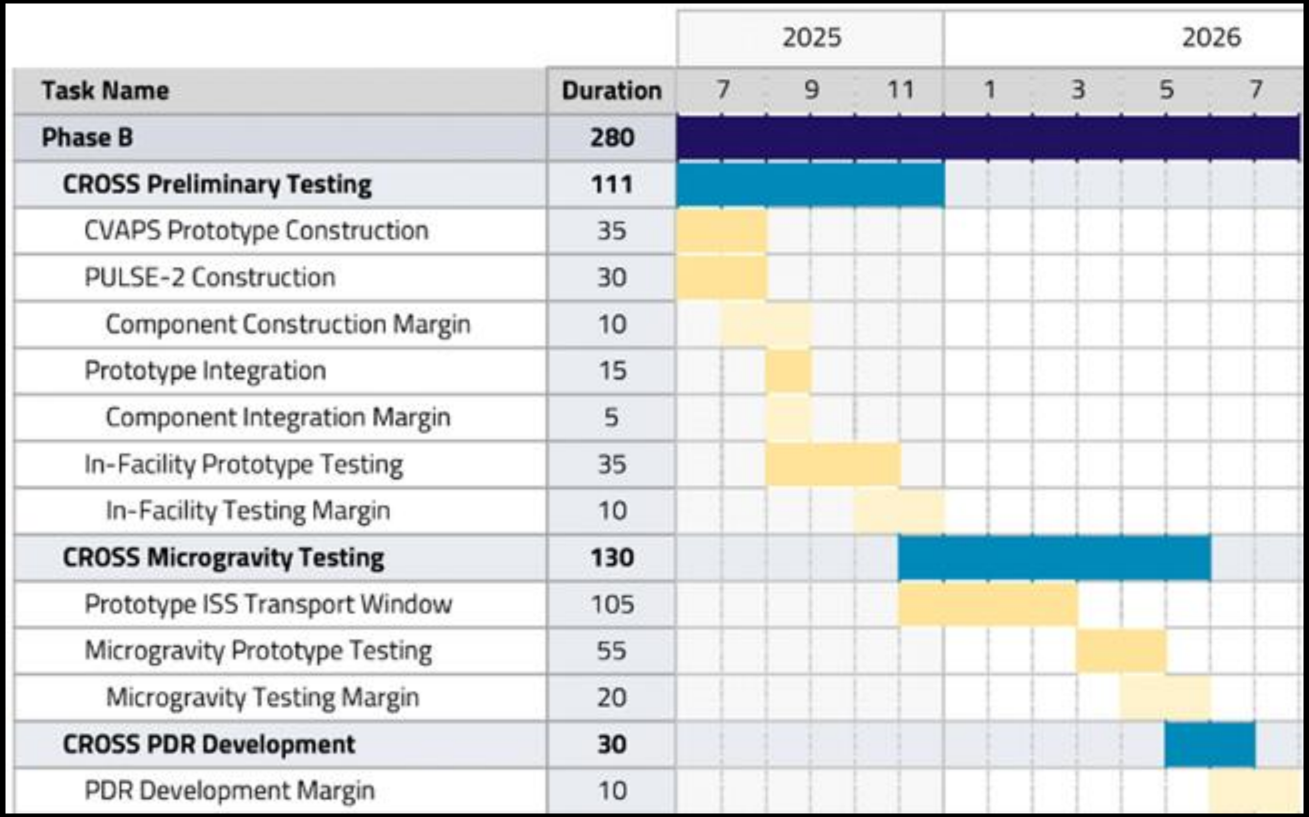


Figure 45: CROSS NASA Adoption Timeline, Phase B

CROSS NASA Adoption Timeline – Phase C/D

Design Finalization

- CVAPS and storage tank optimization based on Phase B testing
- Critical Design Review by mid-January 2027

Manufacturing and SIT

- CVAPS and storage tank to be built simultaneously
- Integration testing performed at JPL's 25-Foot Space Simulator
- Ready for launch delivery June 1st 2028

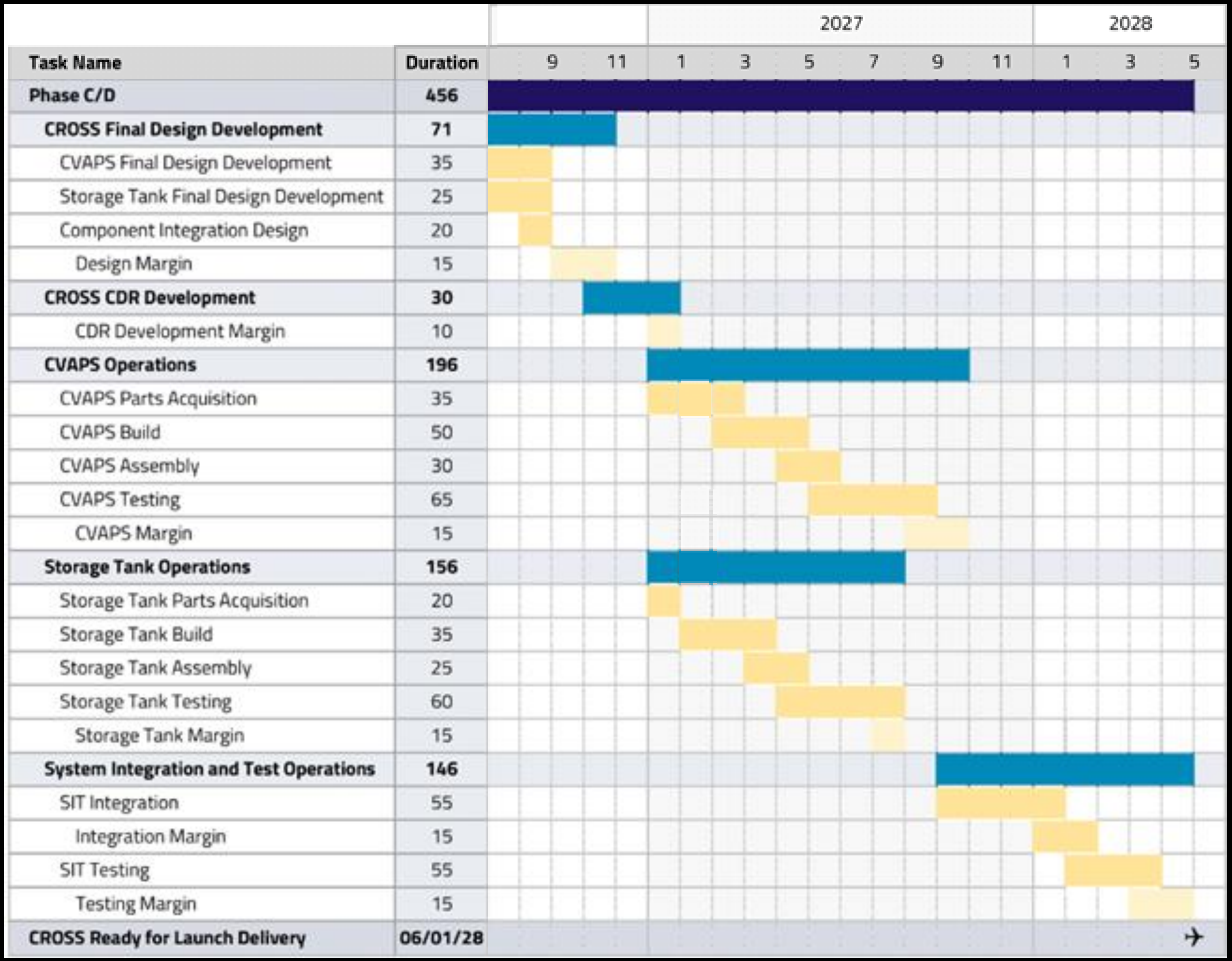


Figure 46: CROSS NASA Adoption Timeline, Phase C/D

Mass Analysis

Component	Material/Basis	Mass
Piston (Solid)	Composite (ρ = 1600 kg/m^3)	21,300 kg (~47,000 lbs)
Piston (Shell, 90% Reduction)	Composite (ρ = 1600 kg/m^3)	2,130 kg (~4,700 lbs)
Inner Tank	7-Series Al Alloy (ρ = 2800 kg/m^3)	2,600 kg (~5,730 lbs)
Outer Skeletal Support	Composite (ρ = 1600 kg/m^3)	374 kg (~824 lbs)
Electronics & Components	Electronics, Thermal lines, Compressors	250 kg (~550 lbs)
Total MLI Insulation	Based on Space Shuttle TPS Scaling	800 kg (~1,760 lbs)
Total Dry Mass (with 1.25 Multiplier for Seams, Fittings, Attachments)		
With Solid Piston (for one propellant system)		31,500 kg (~71,000 lbs)
With Shell Piston (for one propellant system)		7,800 kg (~17,200 lbs)

Cost Analysis

Structures Mass (kg)	Maximum Power (kW)	Electronics Mass (kg)	Thermal Mass (kg)
63,000	400	500	800

CROSS Mechanism Costs	Mechanical Subsystem	Electrical Subsystem	Thermal Subsystem	Software Subsystem
	$16,644,000	$151,000	$40,000	$17,000
Additional Costs	Wrap Costs	Facility Costs	PULSE-2 Costs	Employee Salaries
	$5,498,000	$5,056,000	$1,668,000	$19,800,000

Overall Totals	CROSS Mechanism	Mechanism + Testing	Full Adoption Costs
	$16,852,000	$27,405,000	$48,874,000
Inflation-Adjusted Totals	**$28,678,000**	**$46,638,000**	**$83,172,000**

[6]Megson, T. H. G. (2007). Aircraft structures for engineering students (4th ed.). Elsevier.

[7]National Aeronautics and Space Administration. (2005). External tank thermal protection system (NASA Fact Sheet). NASA Marshall Space Flight Center. https://www.nasa.gov/wp-content/uploads/2016/08/114022main_tps_fs.pdf

Cost Analysis Breakdown

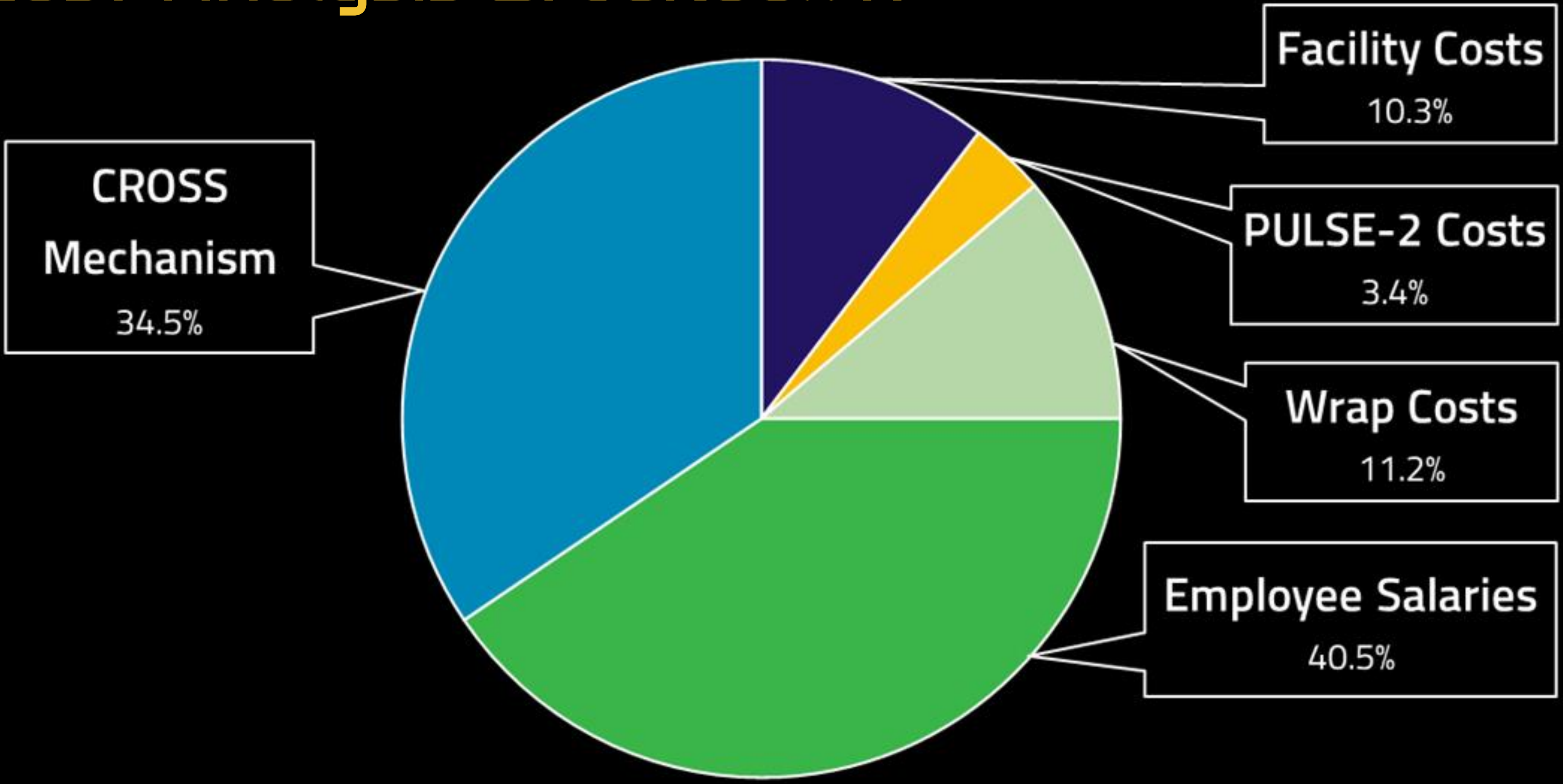


Figure 47: CROSS NASA Adoption Budget Breakdown Pie Chart

CROSS: Principal Outcomes

Long-Term Propellant Storage

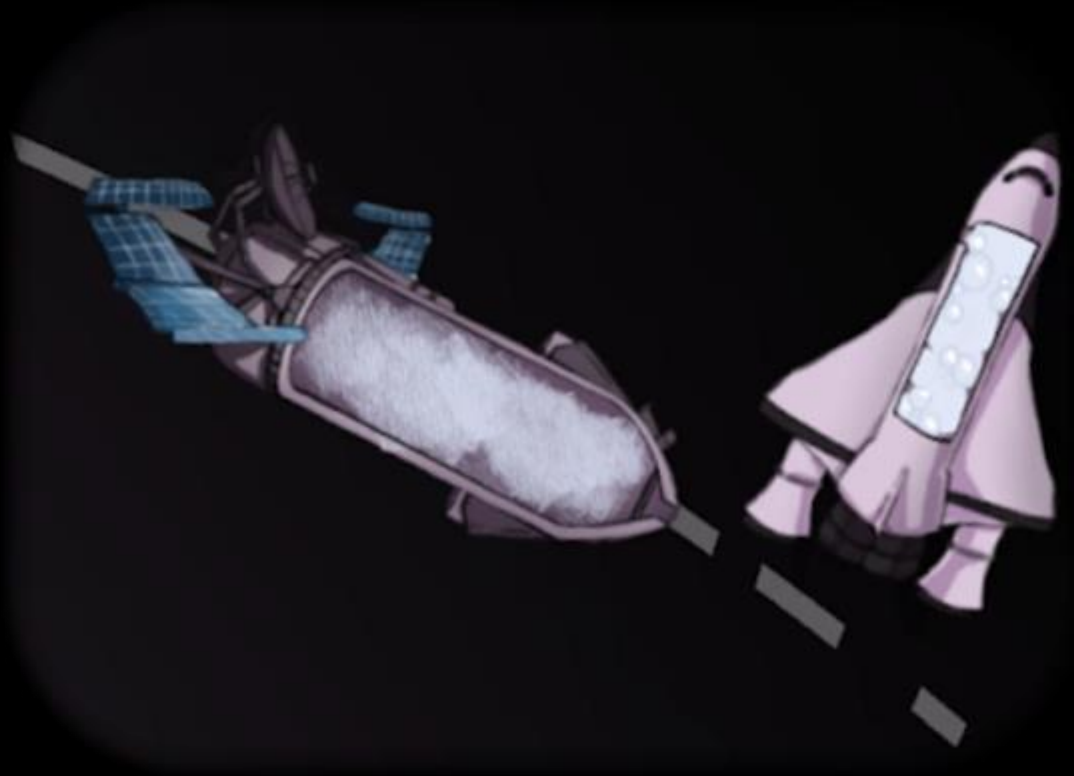
- Controlled boil-off of cryogenic fuel using CVAPS to provide pressure stabilization
- Piston within storage tank to reduce fuel contamination

Microgravity Propellant Transfer

- Piston expulsion device allows for acceleration and orientation independent transfer capabilities
- Autogenous pressurization methods further reduces potential fuel contamination

Additional CROSS Benefits

- Adjustable storage volume provides slosh reduction
- Reduces mission reliance on Helium, a dwindling resource



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- **Professor Bijan Sepahpour**
  - Professor and Project Coordinator, Mechanical Engineering Dept, TCNJ
- **Dr. Anthony Lau**
  - Professor, Biomedical Engineering Dept, TCNJ
- **Dr. Ardeshir Tabrizi**
  - Assistant Professor, Mechanical Engineering Dept, TCNJ
- **Mr. Brian Wittreich**
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- **Mr. Joseph Zanetti**
  - Resident Machinist Supervisor, TCNJ
- **Arthur E. Farmer Machinists**
  - Hydraulic Components, Trenton, NJ
- **Mr. Alex Diblasio**
  - Owner of Ratwerks LLC and Consulting Engineer
- **NJ Space Grant Consortium**

Questions???

Appendix Slides

Controls System: Valves

Testing

- Developed an experimental relationship between valve position and flow rate utilizing Edibon hydraulic mechanism
- Determined valve cutoff and operational windows

Next Steps

- Test position-flow relationship with Nitrogen gas
- Install valve and test piston pressurization

Figure 39: Valve Testing Setup

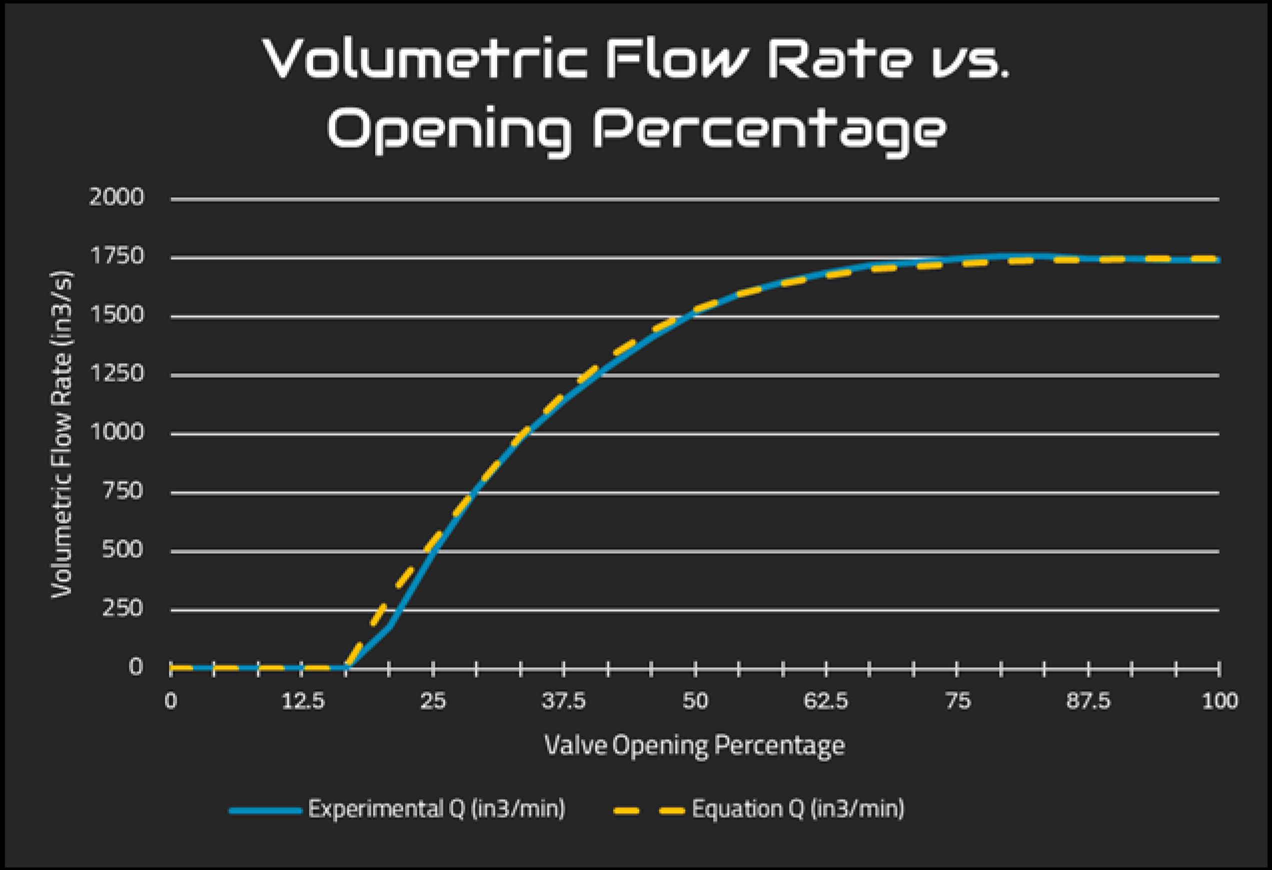

Figure 40: H_2O Flow Rate vs Valve Position Chart

Fluids Transfer: Components

GN$_2$ Connection

- Secure connection between a CGA 295 regulator to the modulating valve

LN$_2$ Connection

- Connection between a VALGLO ⅜″ valve to ½″ NPT Elbow

Vacuum Chamber Connection

- Connection between the Fieldpiece VP67 Pump to Vacuum Chamber

Transfer Line

- Connection between Tank B to the Solenoid to Tank C

Figure 26: Vacuum Chamber to Apparatus layout

Figure 27: Transfer Line Layout