PEAPOD

Pneumatically Energized Auto-throttled Pump for a Developmental Upperstage

Critical Design Review

Customer: Special Aerospace Services
Chris Webber and Tim Bulk

The Peas in the Pod

Electronics Lead:
Cesar Galan

Software Lead:
Justin Wilmes

Safety & Testing Lead
Antoine Steiblen

Mechanical Lead:
Kelsey Aldrich

Analysis Lead:
Alan Sanchez

Financial Officer:
Tyler Roth

Manufacturing Lead:
Jason Bass

Project Manager:
Ethan Hollenbach

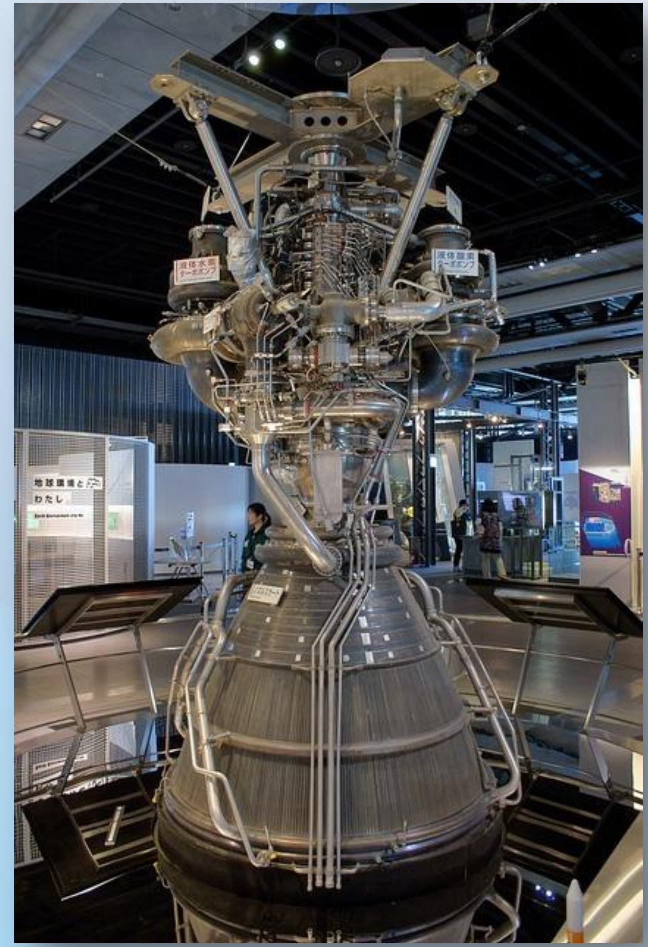
Systems Engineer:
Scott Wurst

Overview

- Project Description
- Design Solution
- Design Requirements and Solution
- Verification and Validation
- Risk Analysis
- Moving Forward
- Q/A

Project Description

Pumps and Their Place in Rocketry


[3]

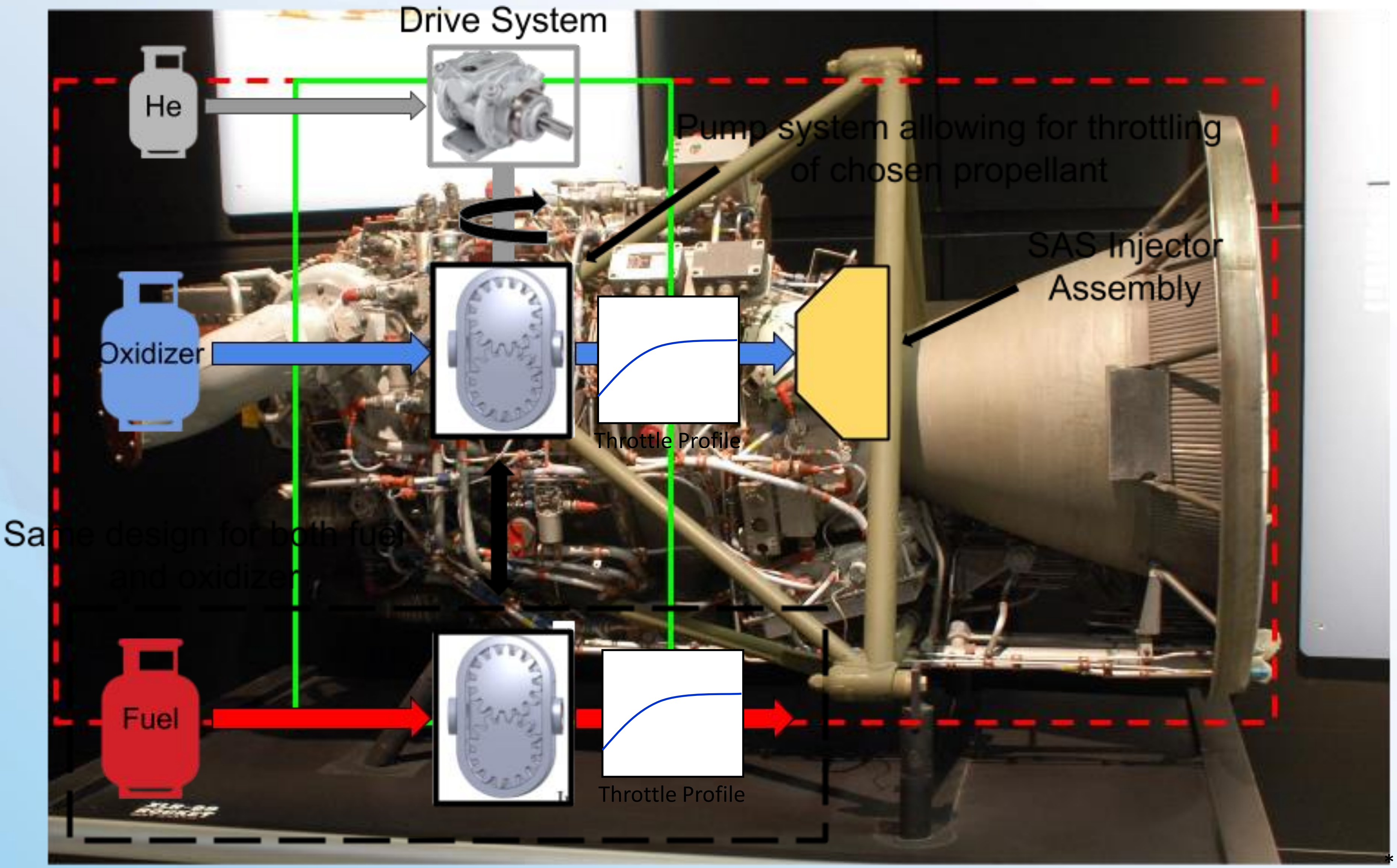
- Deliver propellants to combustor
- Low pressure fuel tanks
- Precise throttling control

Project Motivation

Design and manufacture a pneumatically powered pump system for use on an upper stage rocket engine or lander.

- Proof of concept pump system for hypergolic propellants
- 10%-100% throttleability
- Pneumatically powered

Concept of Operations



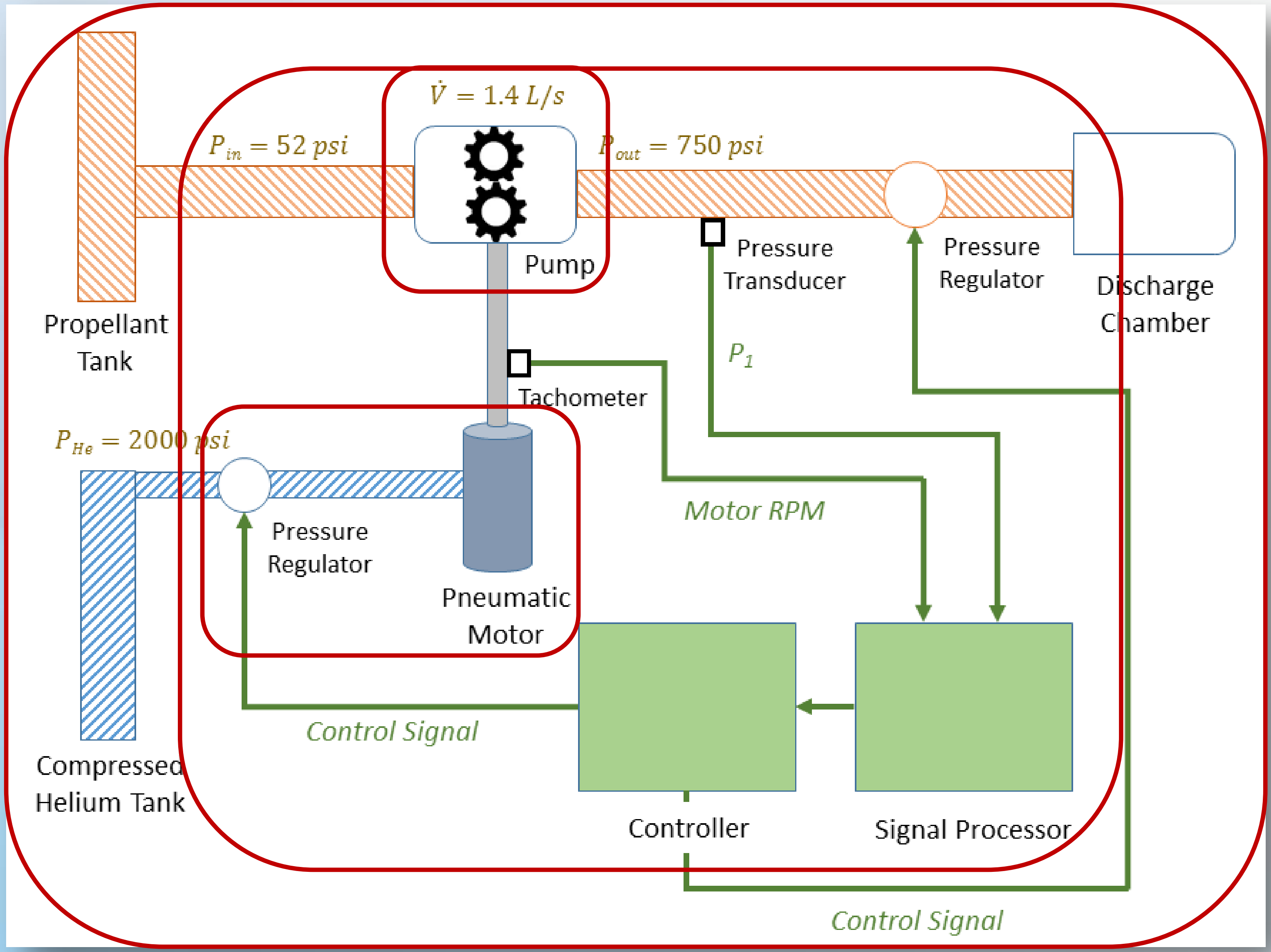
*Reference 11

Levels of Success

Level	Functional Success	Performance Success	Functional Requirement
1	• Pneumatic power • Digital control • Meets safety requirements	• 750 ± 15 psi outlet pressure • Structural FOS 2.5 • 120 seconds of operation • 75% efficiency of pump at full throttle	• **FR1** – System is pneumatically driven • **FR7** - FOS of 2.5 • **FR8** – 75% efficiency at full throttle • **FR3** – Pump outlet is at 750 ± 15 PSI
2	• Propellant stream throttling • All level 1 requirements	• 10-100% throttleability • 0-100% throttle in 2 seconds • All level 1 requirements	• **FR2** – Pump system is throttleable • **FR4** – Pump system can run through throttle profile • **FR5** – Pump is restartable
3	• Hypergolic compatible • All level 1 and 2 requirements	• 0-100% throttle in 1 second • All level 1 and 2 requirements	• **FR6** – System is built to hypergolic standards

Design Solution

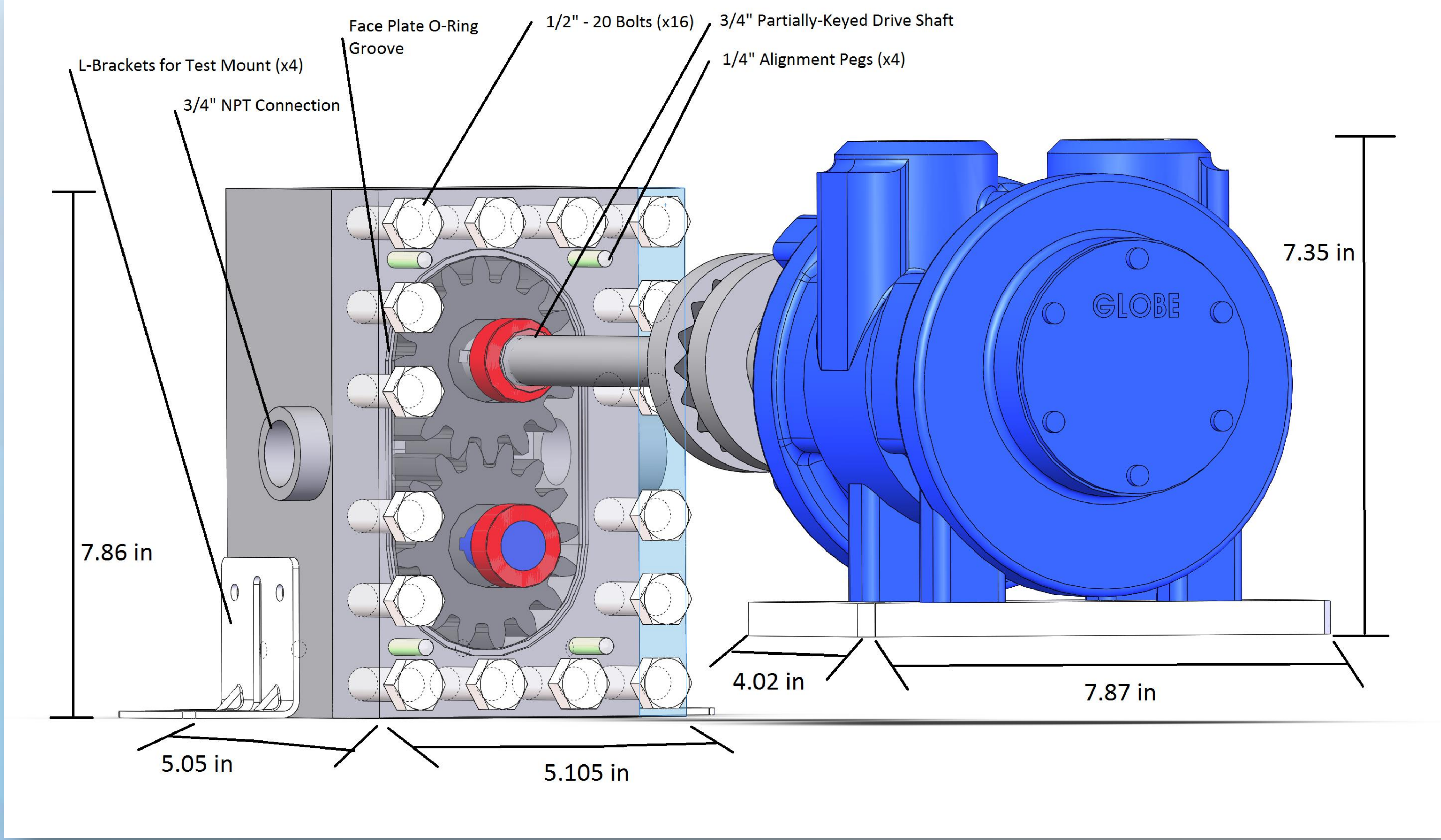
Functional Block Diagram



Subsystems

1. Pump
2. Drive System
3. Control
4. Test

PEAPOD Pump and Drive System



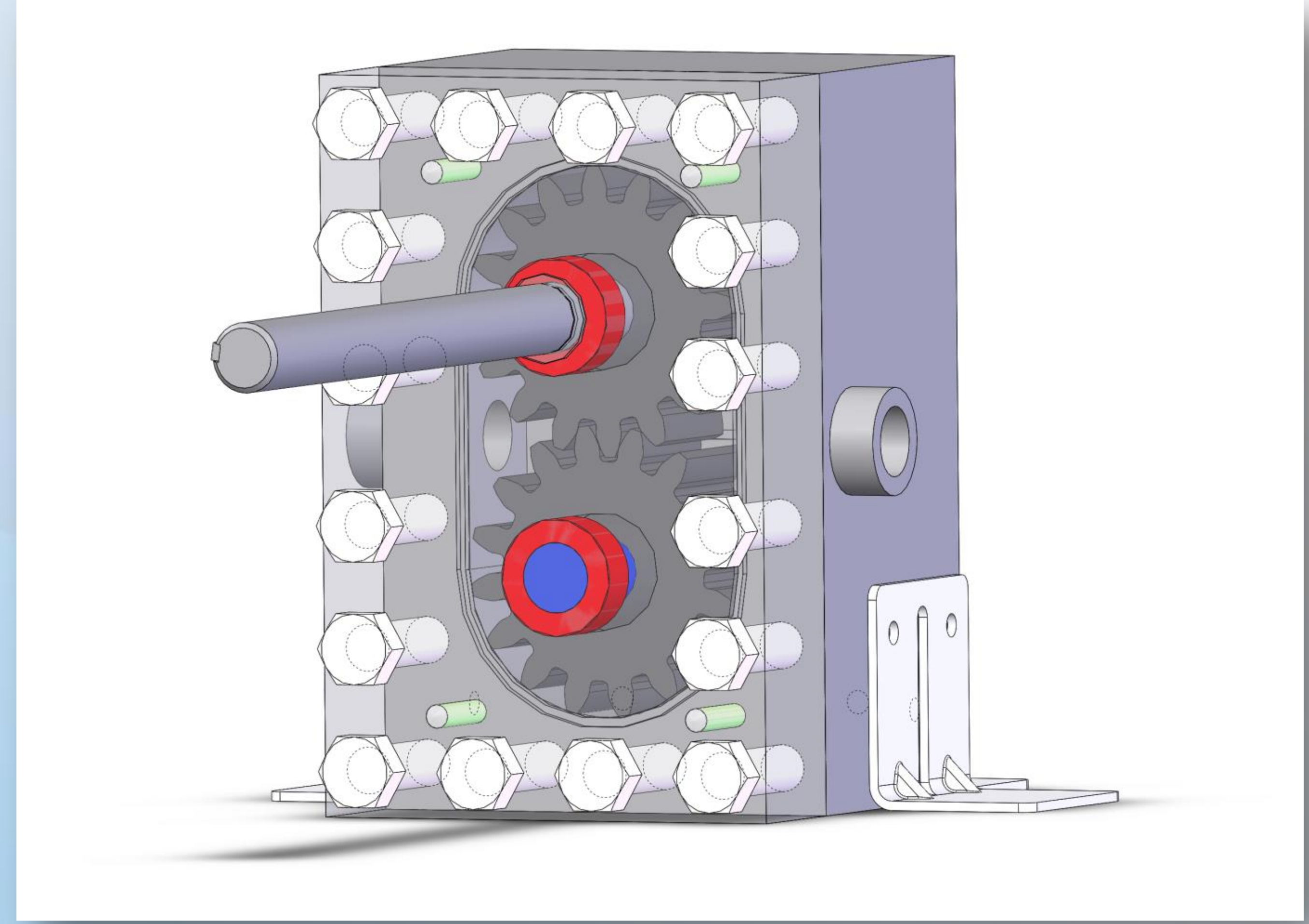
Critical Project Elements

Critical Project Elements	Associated Subsystem(s)
Develop a functioning pump	Pump
Meet efficiency requirements	Pump
Correct acquisition of pressure, RPM, and mass flow rate	Control
Developing throttling capabilities (10-100%)	Pump, Drive System, Control
Safe operation of pump and drive system	Test
Budgetary restrictions	All

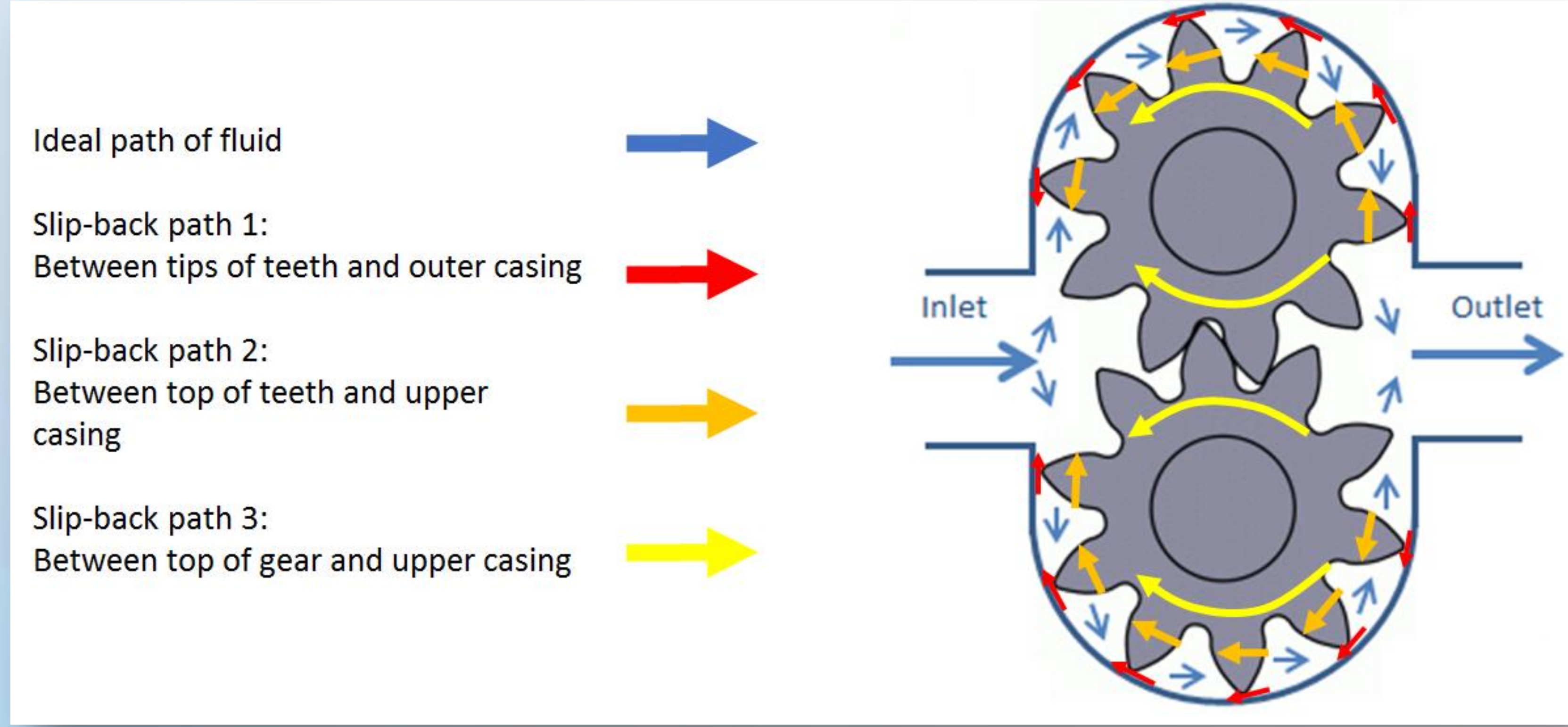
Key Subsystems

- The Pump
  - Fluid Analysis
- The Drive System
  - Required Performance Specifications
  - System Level Efficiency Analysis
  - Simulated Throttle Profile
  - Mechanical Analysis
- Control System
  - Software
  - Electronics

Pump Design and Functionality



Gear Pump Efficiency



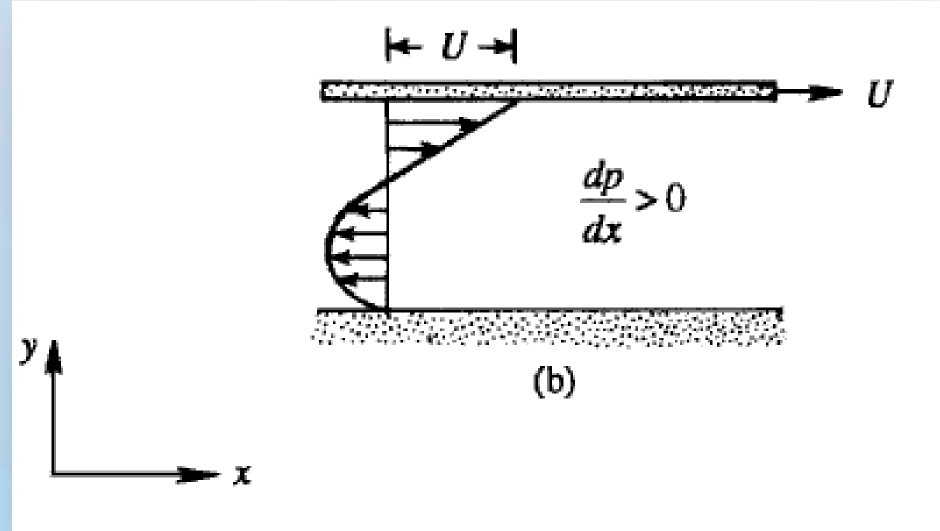
Volumetric Efficiency:

$$e_v = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}} = 1 - \frac{\dot{m}_{slip_1} + \dot{m}_{slip_2} + \dot{m}_{slip_3}}{\dot{m}_{ideal}}$$

Total Efficiency:

$$e = e_m * e_v$$

Couette-Poiseuille Flow



Volumetric flow per unit width of channel

$$\frac{Q}{w} = \int_0^h u dy = U\frac{h}{2}\left[1 - \frac{h^2}{6\mu U}\frac{dp}{dx}\right]$$

- Slip-back paths 1, 2, and 3 can be described by the Couette-Poiseuille equations where the pressure gradient is adverse
- Couette (moving plate) term is 2 orders of magnitude smaller, so this loss contribution is **negligible** (less than 1% error introduced)
- Slip-back path 3 is more complicated and more assumptions must be made

Volumetric Losses

$$\dot{m}_{ideal} = \frac{\rho \omega w D^2 (9n - 2.35))}{16n^2}$$

$$\dot{m}_{slip_1} = \frac{\rho h_{tip}^3 w \Delta P_1}{12\mu L_{tip}}$$

$$\dot{m}_{slip_2} = \frac{3\rho h_{top}^3 D}{16 n\mu} \frac{\Delta P_2}{L_{top}}$$

$$\dot{m}_{slip_3} = \frac{\pi \rho h_{top}^3 \Delta P_3}{32\mu}$$

ρ - density of fluid

ω - gear angular velocity

μ - dynamic viscosity of fluid

w - face width of gear

D - pitch diameter of gear

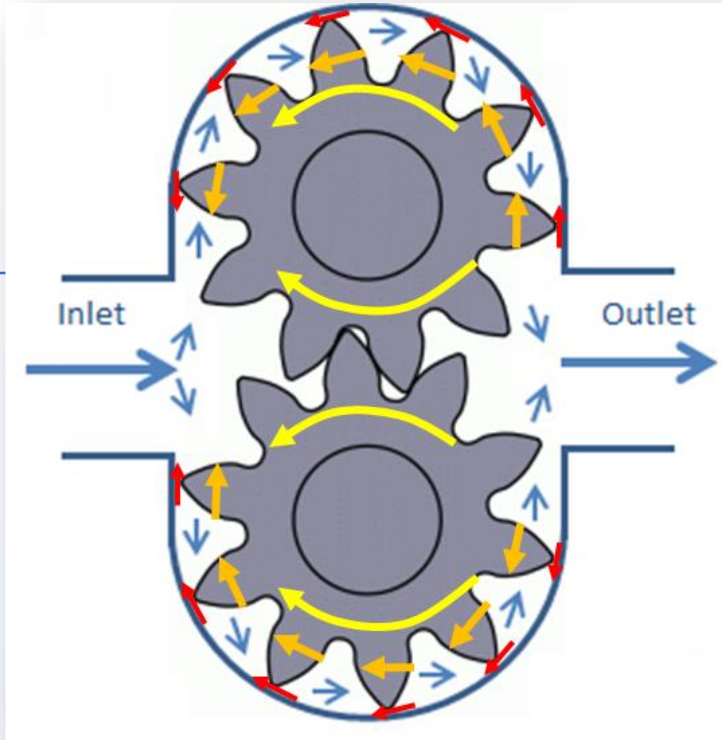
n - number of teeth

h_{tip} - clearance between tooth tip and outer housing

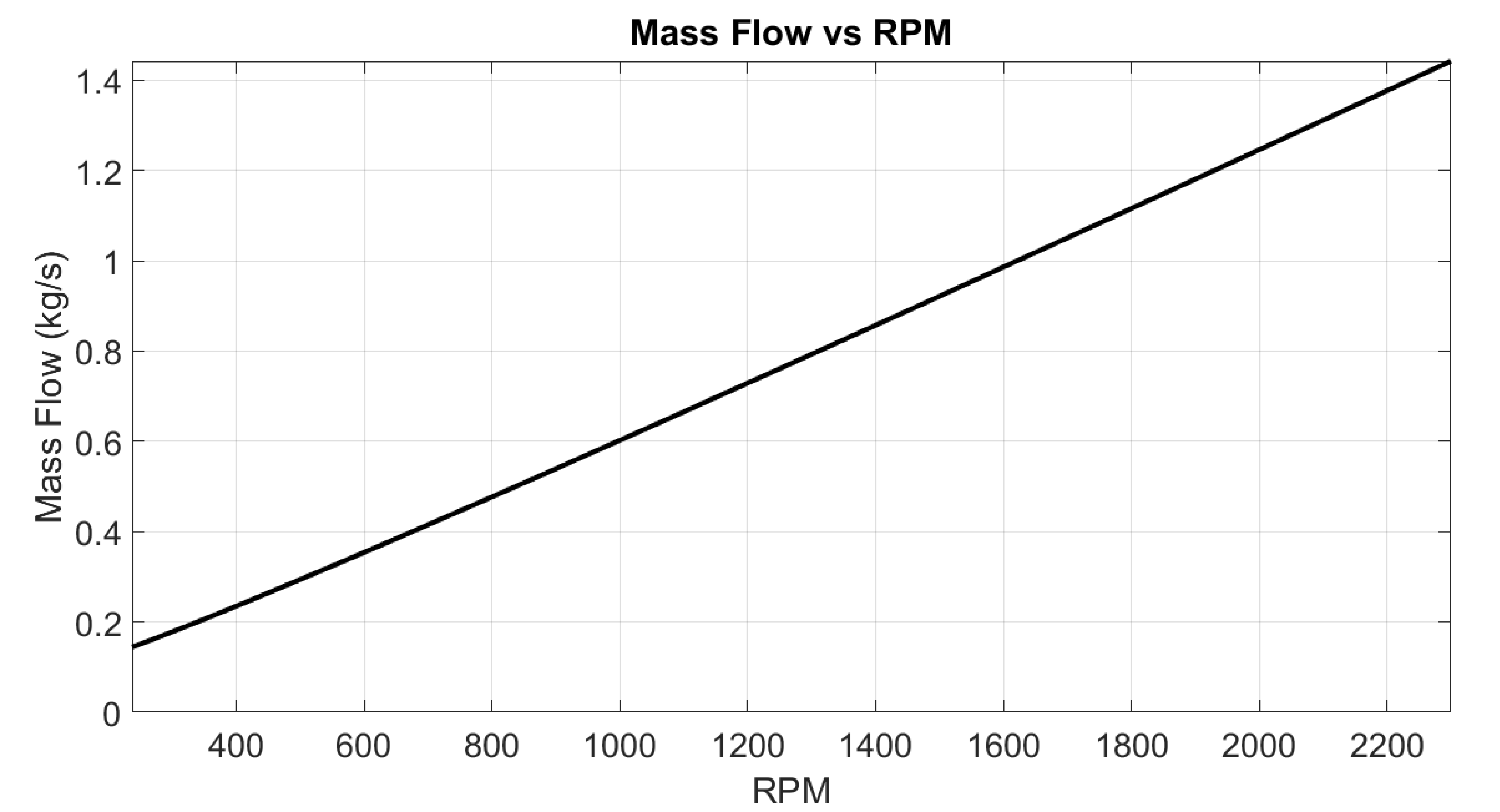
h_{top} - clearance between tooth/gear top and upper housing

L_{tip} - length of tooth tip

L_{top} - length across tooth at pitch diameter

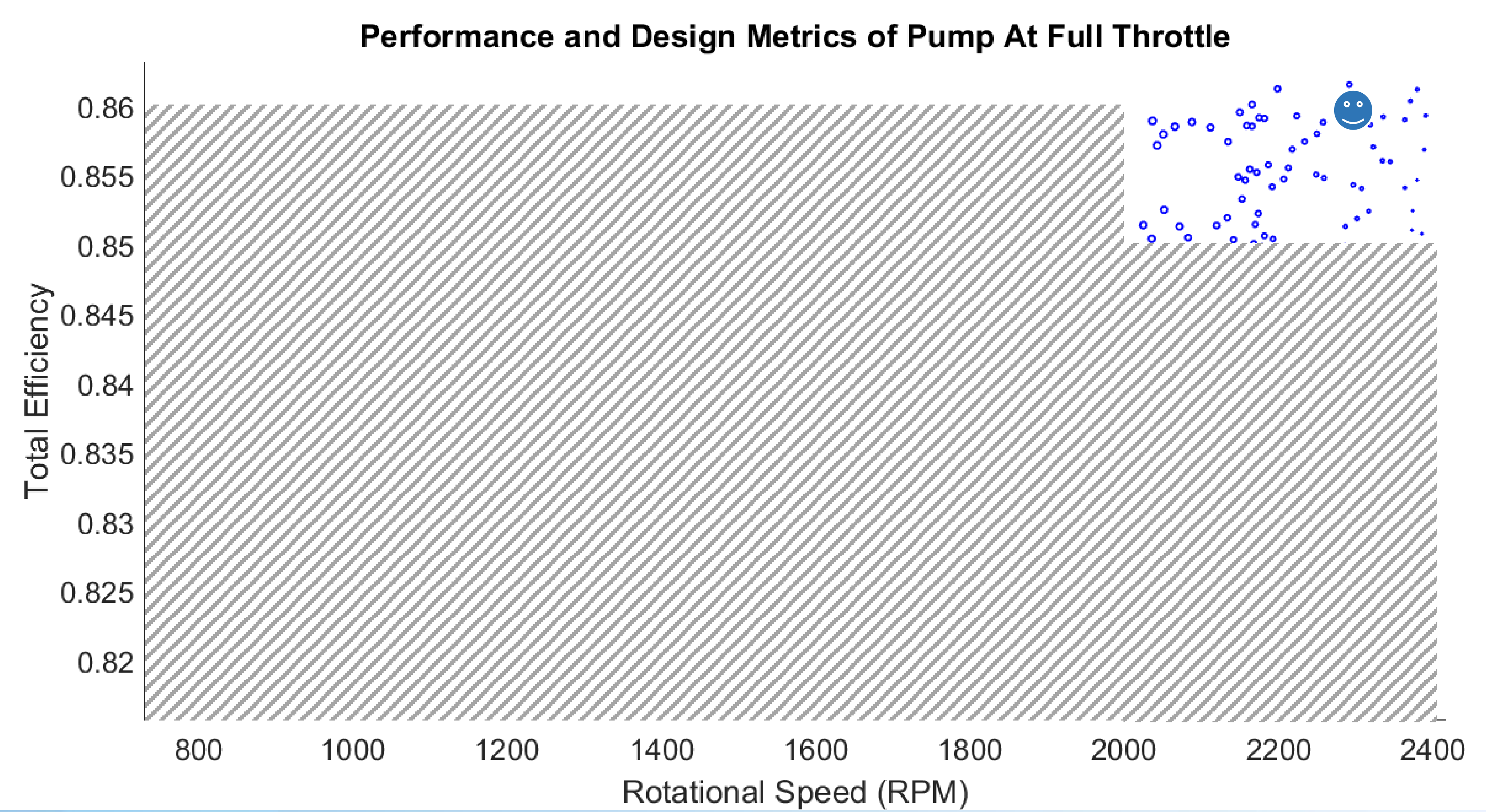


Resultant Mass Flow



Project Description | The Design | Verification & Validation | Moving Forward

Possible Gear Designs



Design Selection

Performance Parameters

- P_{out} = 750 psi
- ṁ= 1.4 kg/s
- $RPM_{fullthrottle}$ = 2300 RPM
- e = 85.77%

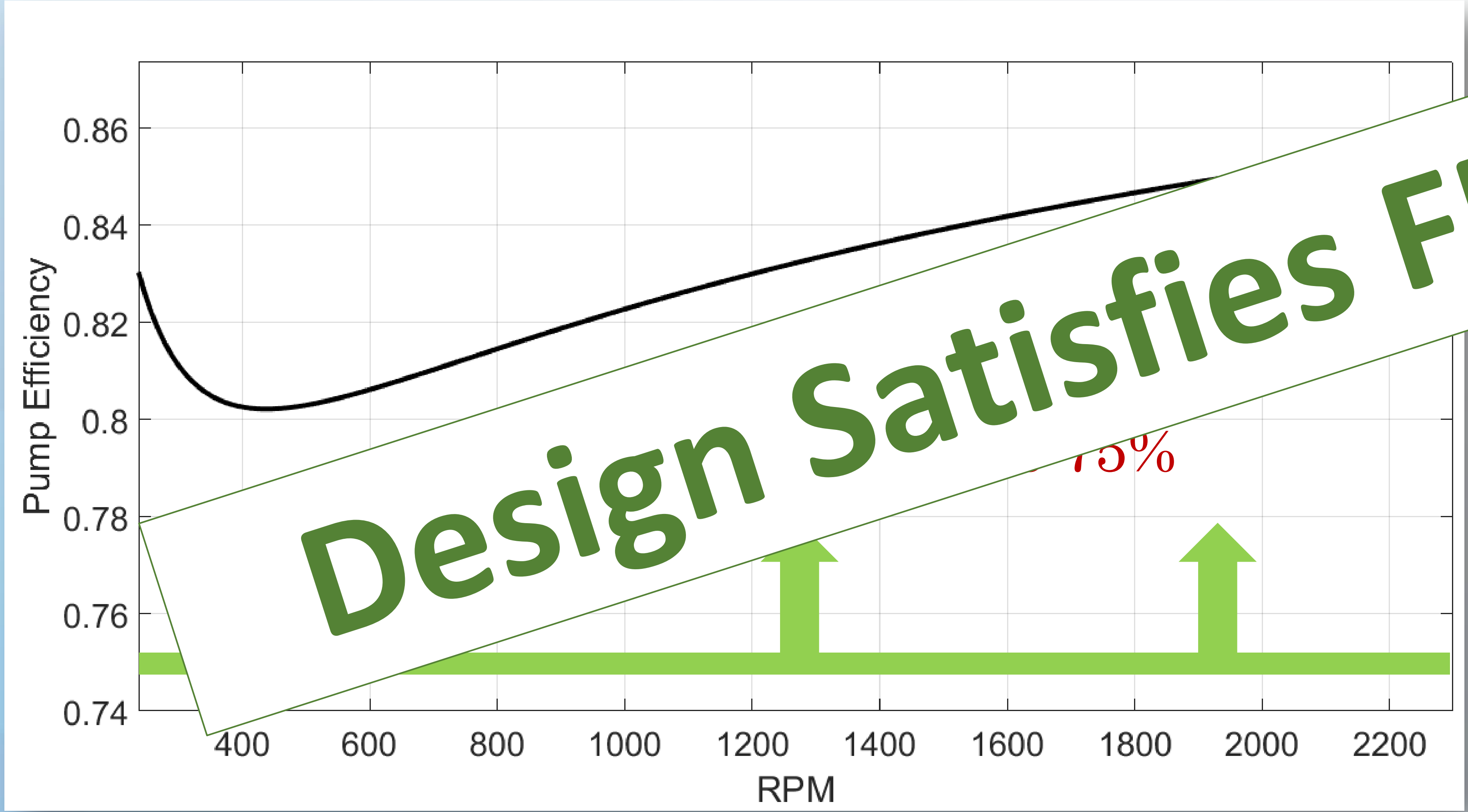
Mec

– 0.002”

er Teeth – 0.002”

Design Satisfies FR3, FR8

Pump Efficiency



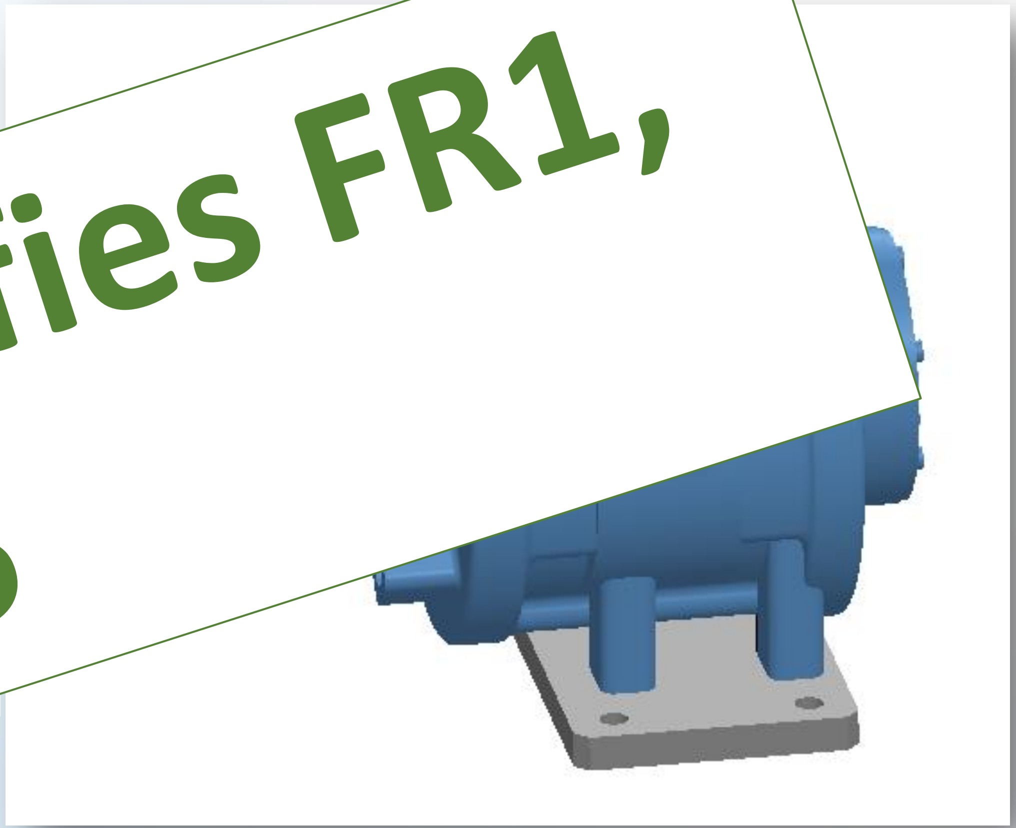
Design Satisfies FR8

- ottle = 2300 RPM
- n = 16
- w = 1.5000"
- D_{pitch} = 2.75555"
- D_{outer} = 3.1000"
- e = 85.66%

Drive System Choice

- Globe Benelux VA10J
- Will be purchased

Derived Requirements	Drive [illegible]
2300 RP[illegible]	[illegible]
31.[illegible]	[illegible]
7.48[illegible]	[illegible]



Design Satisfies FR1, FR5

Material Margins

- FOS of 2.5

Component	Fatigue Margin	Material Failure Margin	Displace
Gears (teeth)	0.06	[illegible]	[illegible]
Housing Walls	N/A	[illegible]	[illegible]
Housing B[illegible]	[illegible]	[illegible]	NA
[illegible]	[illegible]	[illegible]	2.00E-04"
[illegible]	[illegible]	0.02	NA
[illegible]	0.23	0.52	NA
[illegible]way	0.11	0.32	NA
Drive Shaft	0.12	0.45	7.00E-01 °

$$margin = \frac{Allowable}{FOS * Maximum} - 1$$

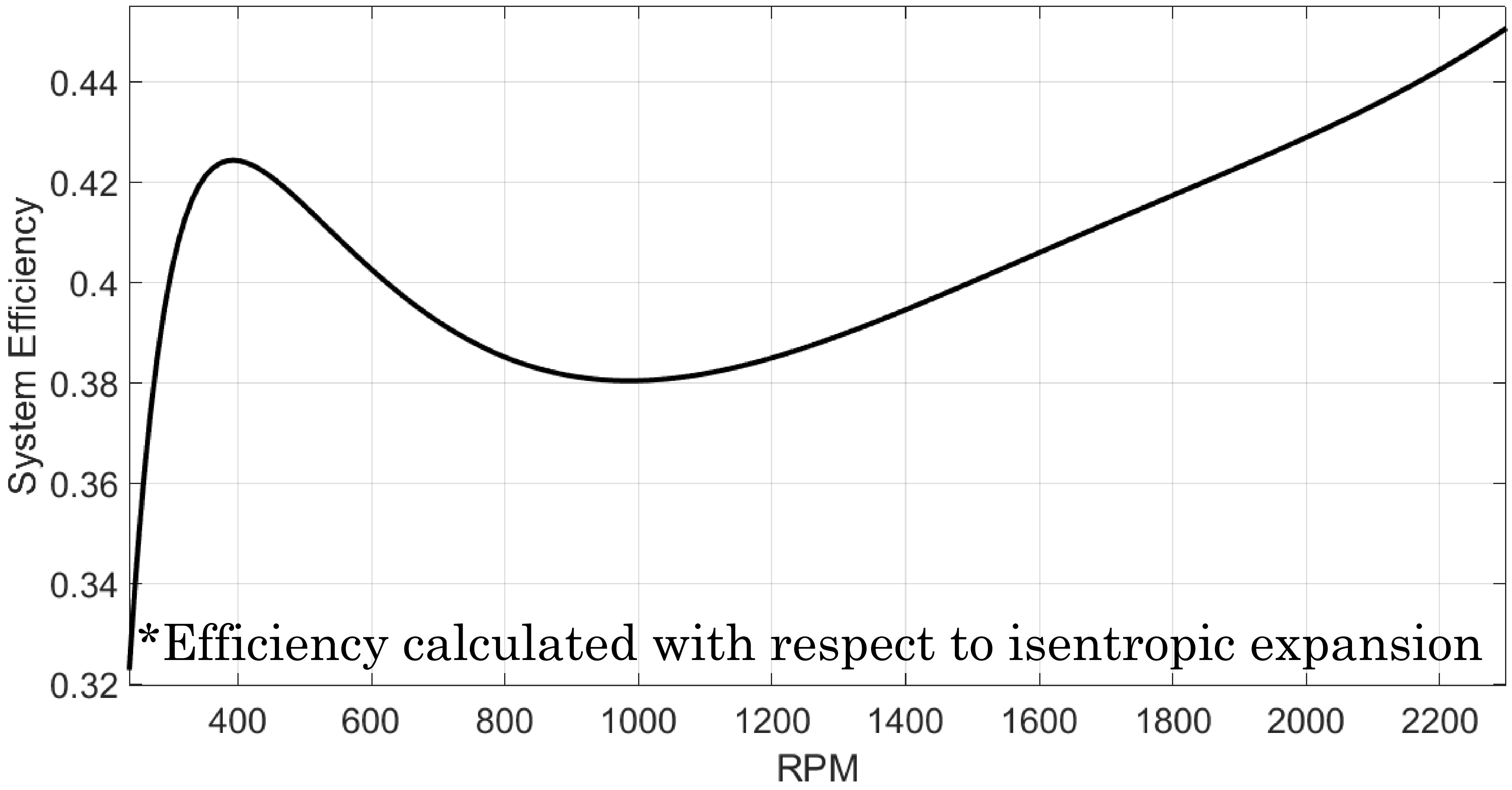
Design Satisfies FR7

Material Compatibility

Component	Material	Hypergolic Compatibility
Gears	17-4 PH Stainless Steel	NTO & UDMH C [D2-113073-1, S moistu
Housing	Stainless Steel 304	
Bearings	Stai	H Compatible -1, Sect. 22.3.3, 26.3.2][1]
K		NTO & UDMH Compatible [D2-113073-1, Sect. 22.3.3, 26.3.2][1]
	s Steel 303	NTO & UDMH Compatible [D2-113073-1, Sect. 22.3.3, 26.3.2][1]
Seals	EPDM	UDMH Compatible Not Compatible with NTO[2] [D2-113073-1, Sect. 26.3.2][1]

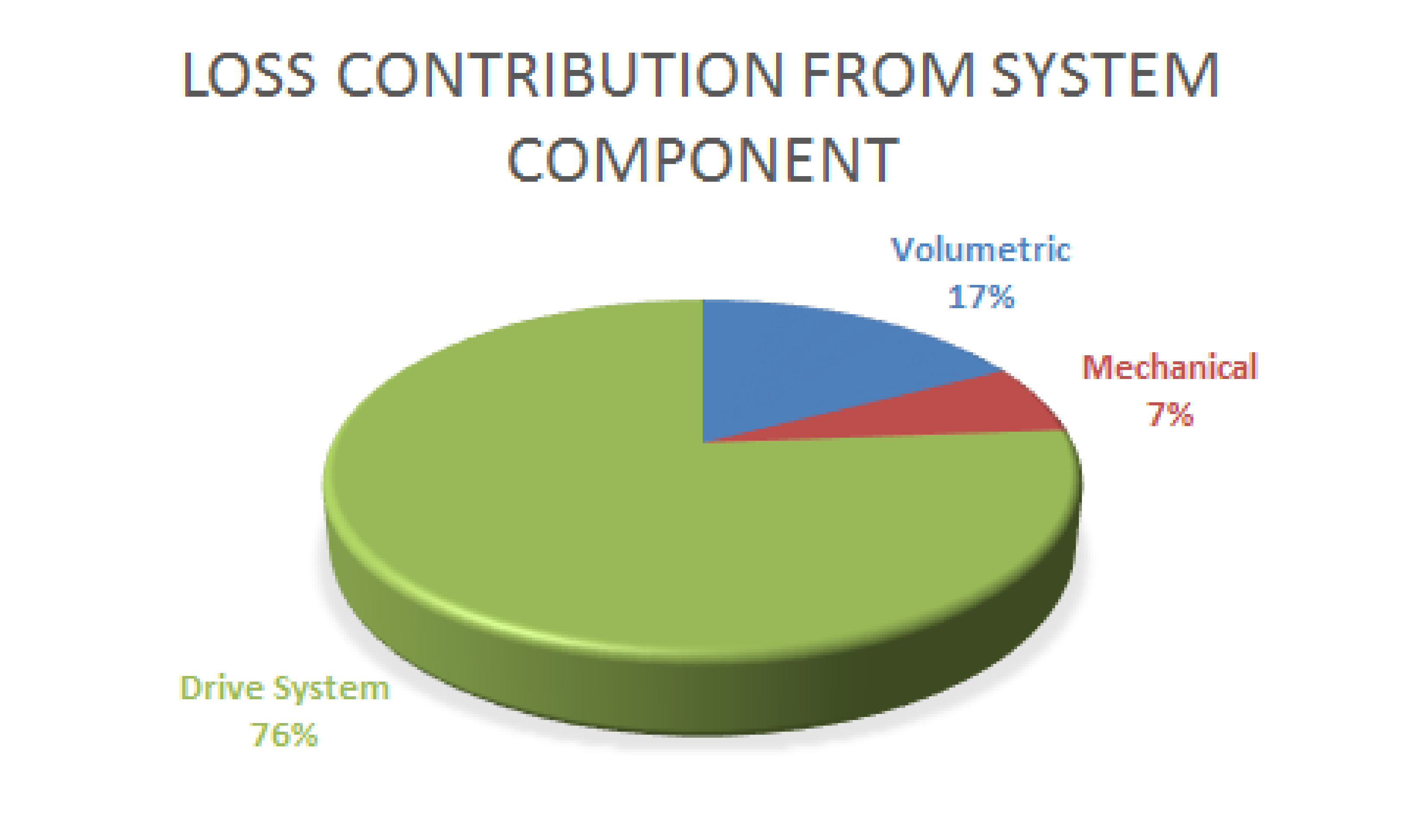
Design Satisfies FR6

System Efficiency



- Using Water
- VA10J Drive System
- $\dot{m}$= 1.4 kg/s
- $RPM_{fullthrottle}$ = 2300 RPM
- n = 16
- w = 1.5000"
- D_{pitch} = 2.75555"
- D_{outer} = 3.1000"
- e = 85.66%

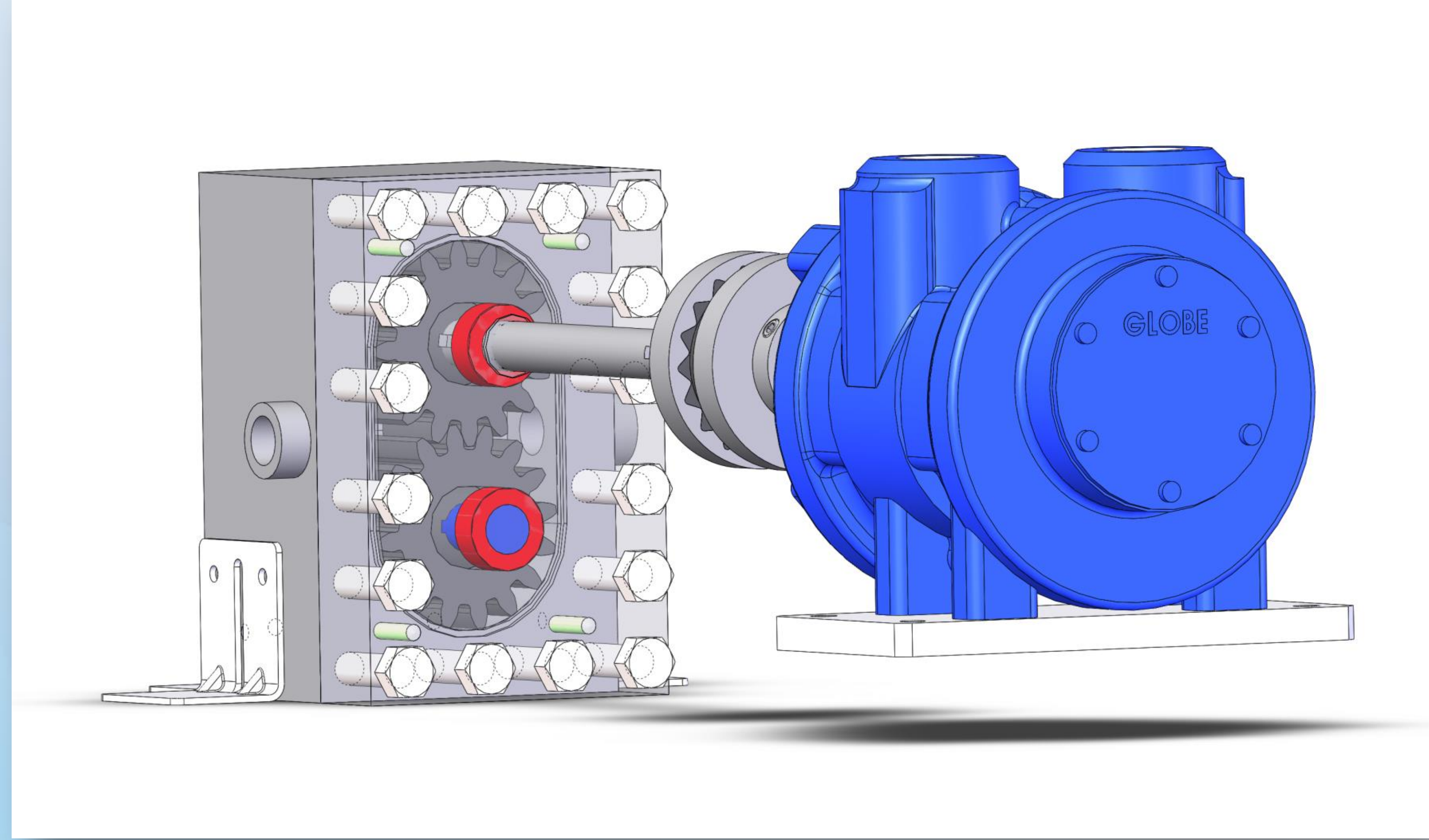
Efficiency Break-down



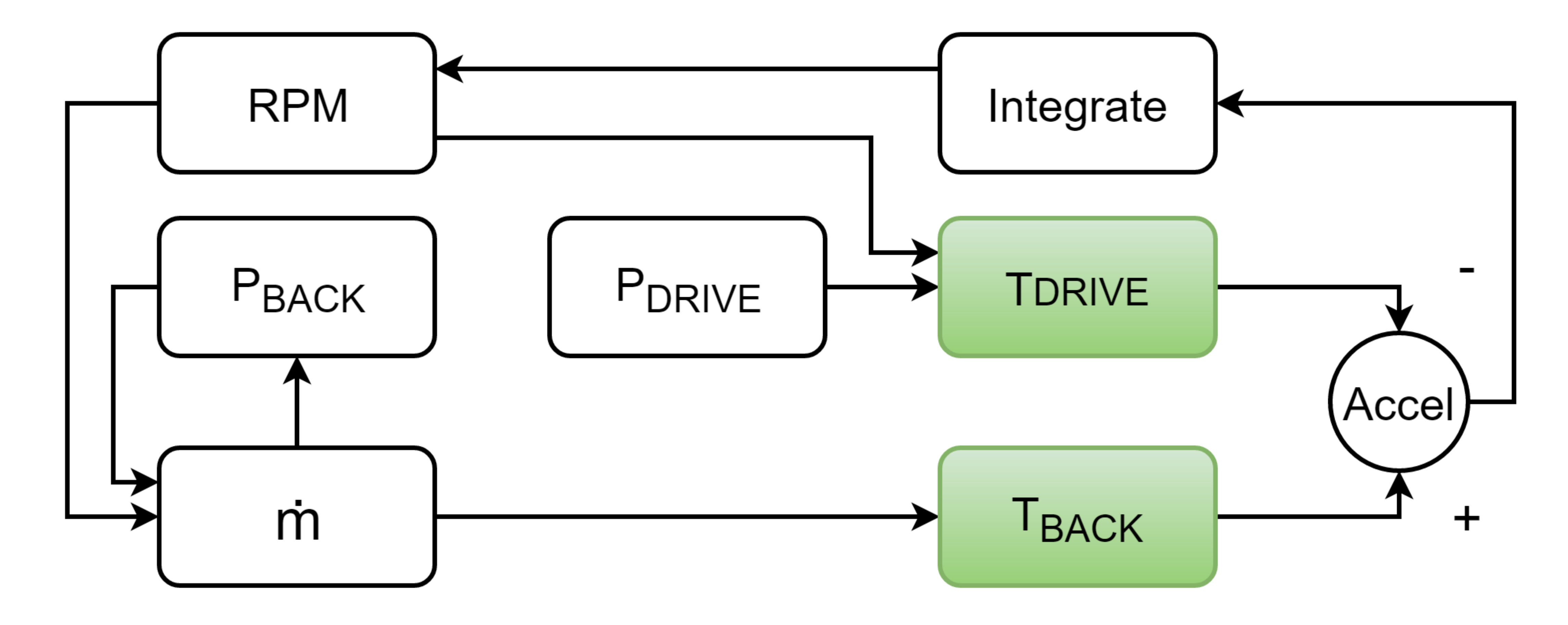
Project Description | The Design | Verification & Validation | Moving Forward

Pump-Drive Compatibility

PEAPOD Pump System

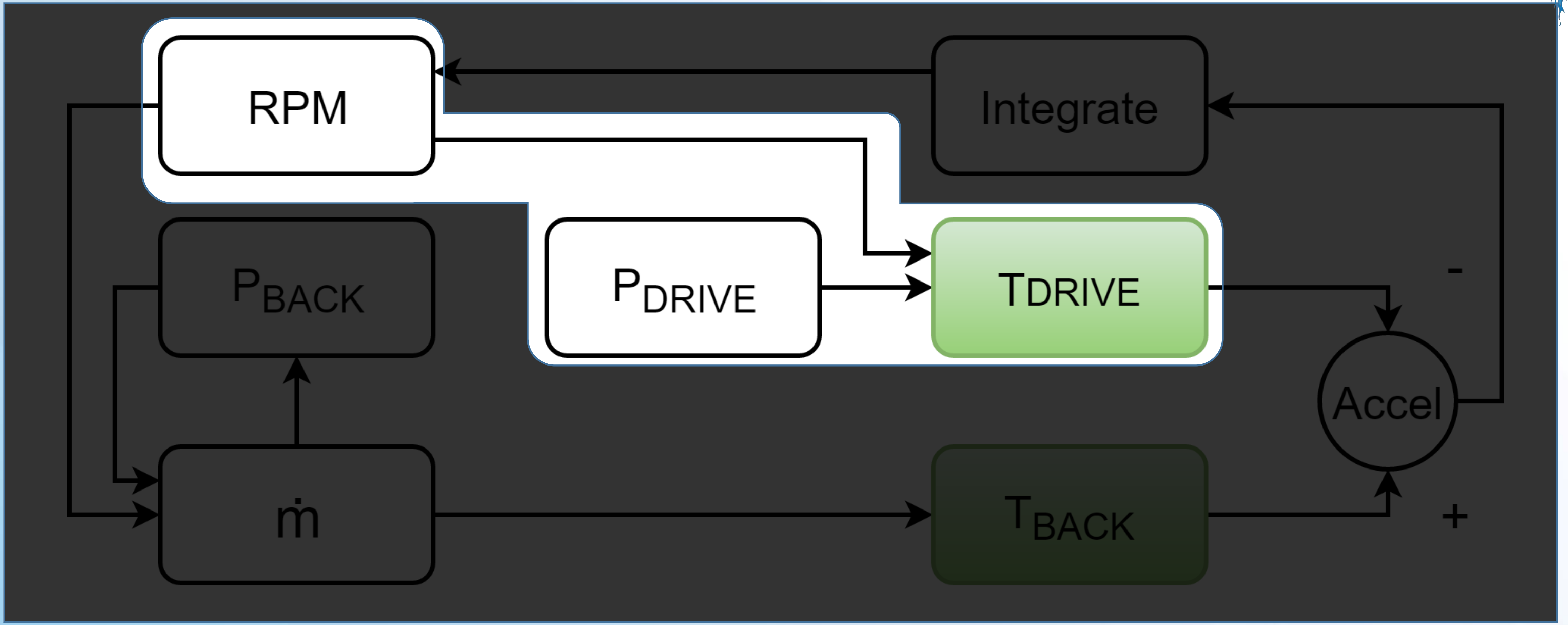


System Modeling

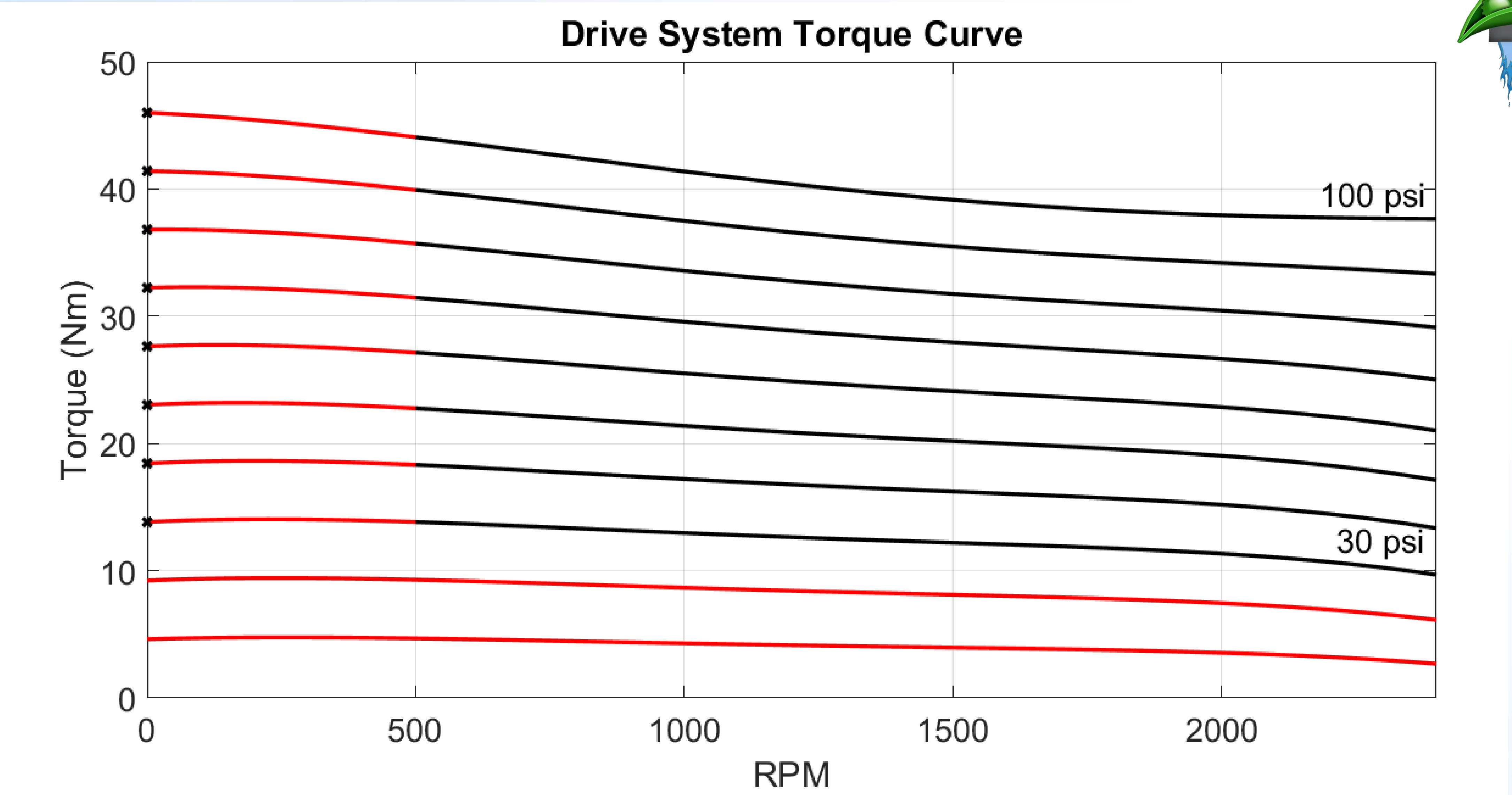


*Used to model torque as a function of RPM

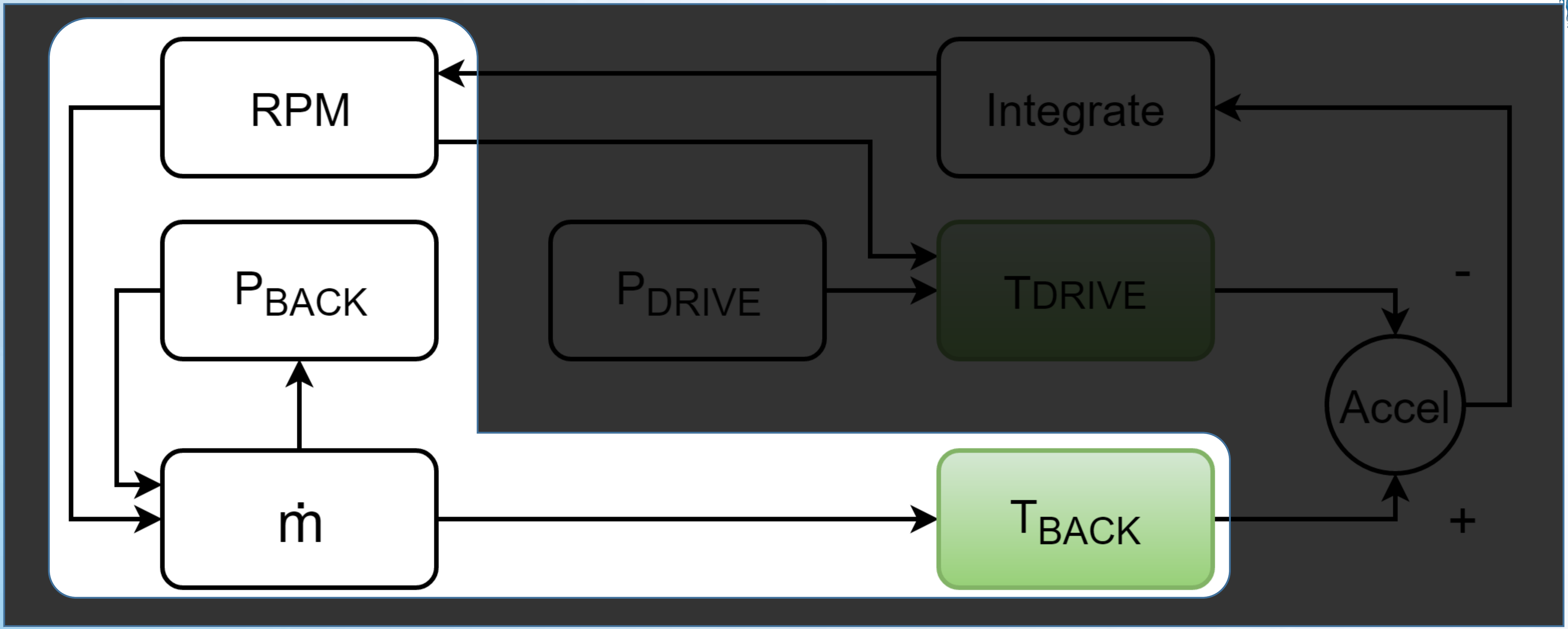
Drive System Modeling



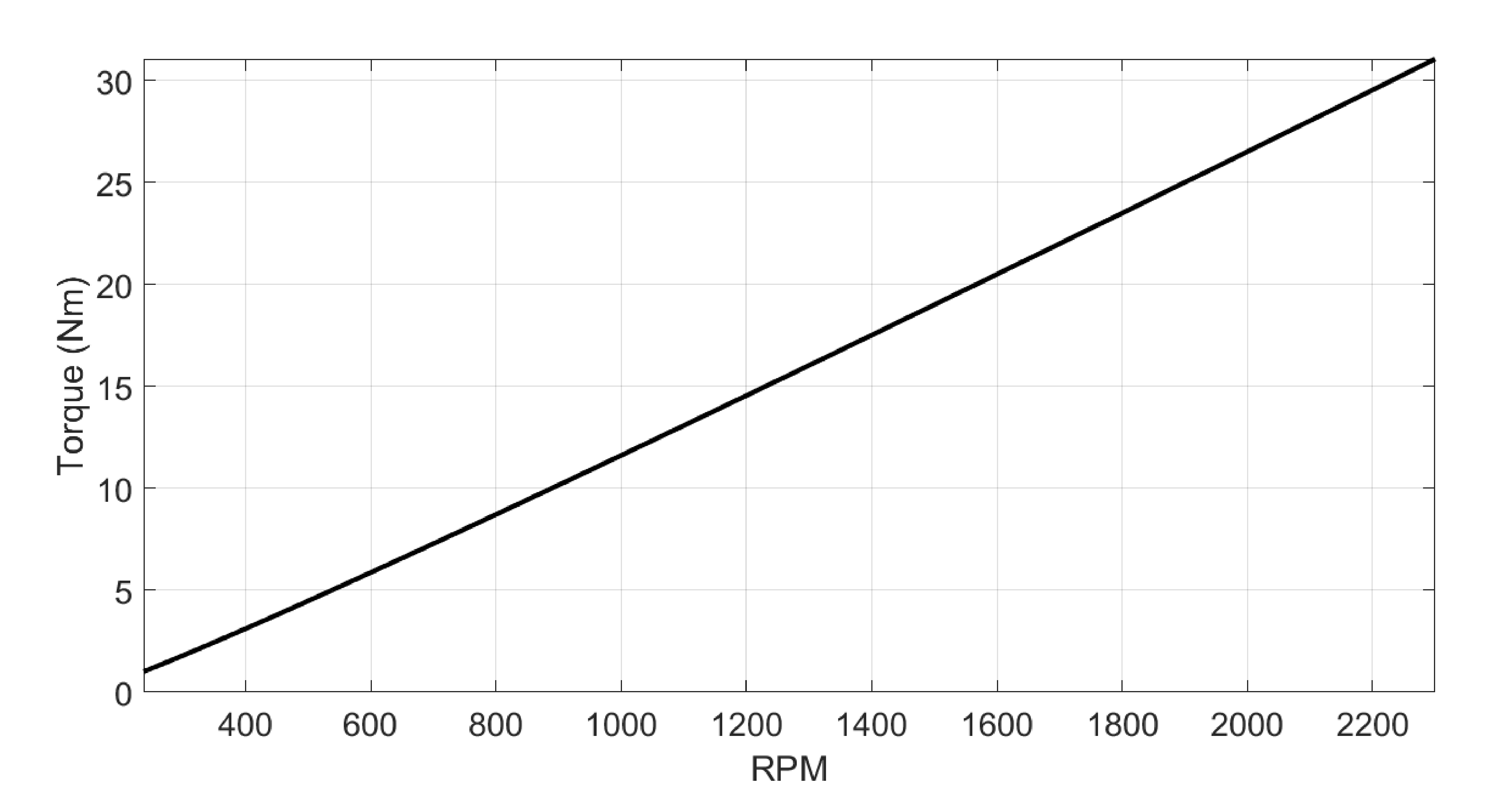
Drive System Modeling



Required Pump Torque

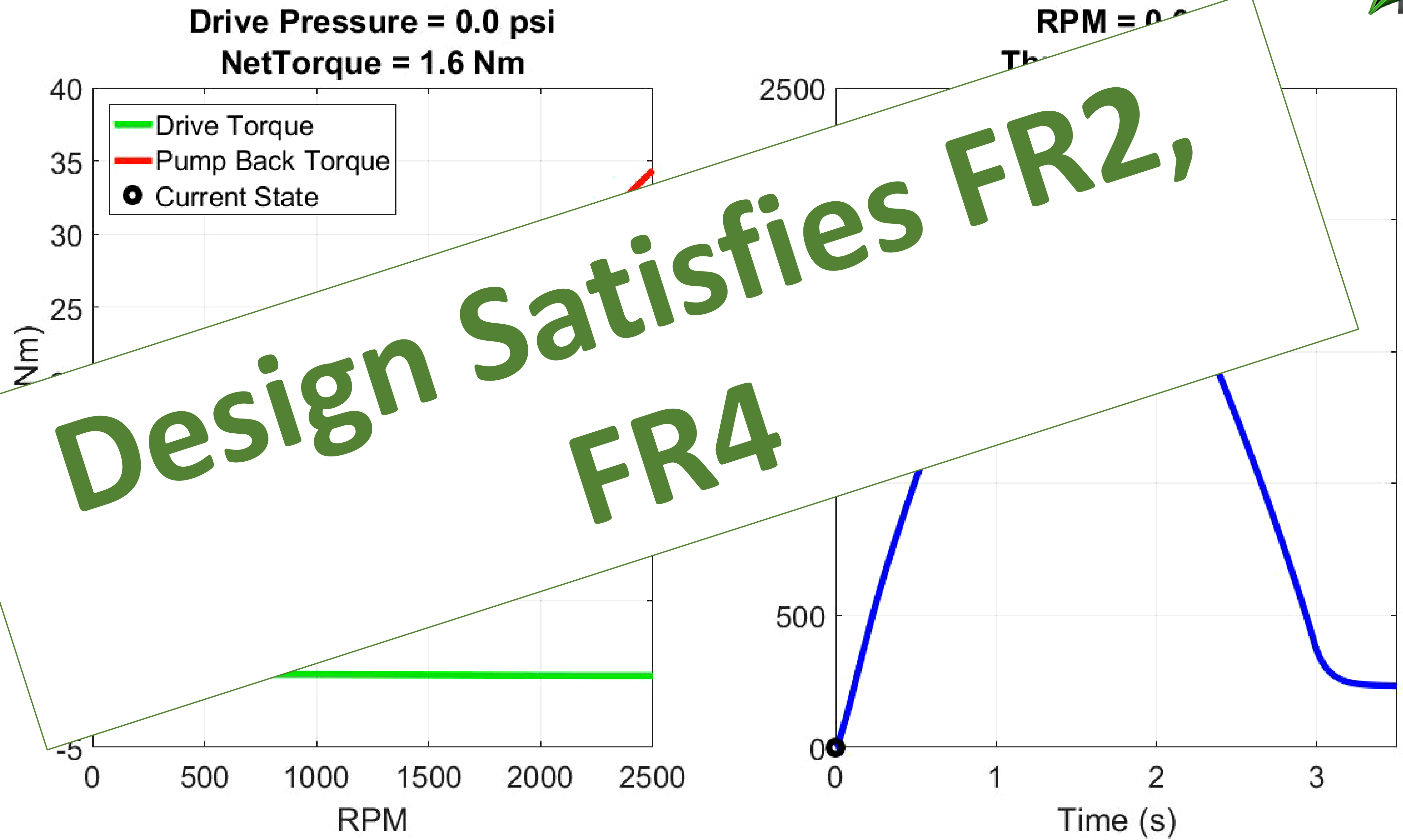


Required Pump Torque



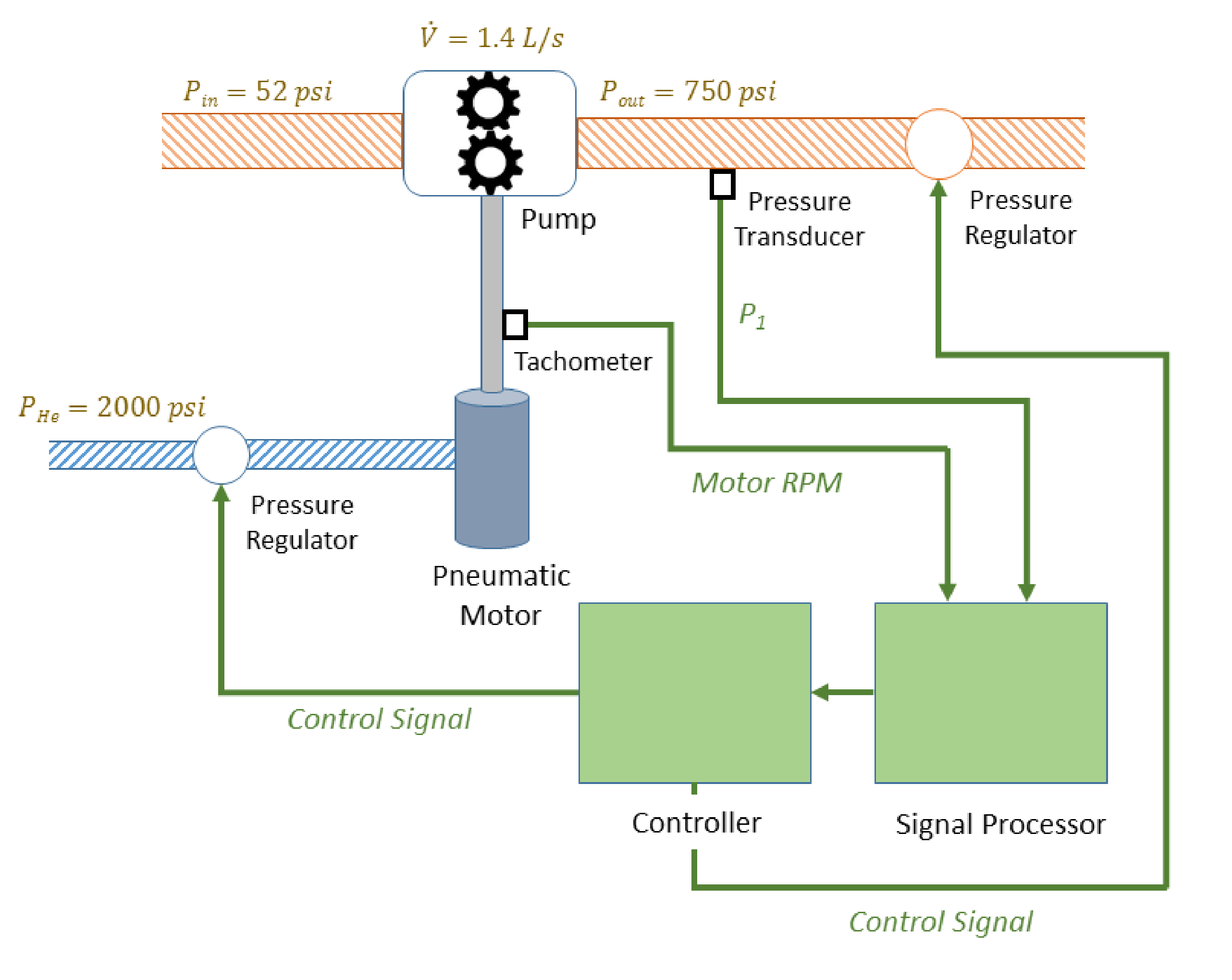
Project Description | The Design | Verification & Validation | Moving Forward

Throttle Profile Simulation



Design Satisfies FR2, FR4

Control System

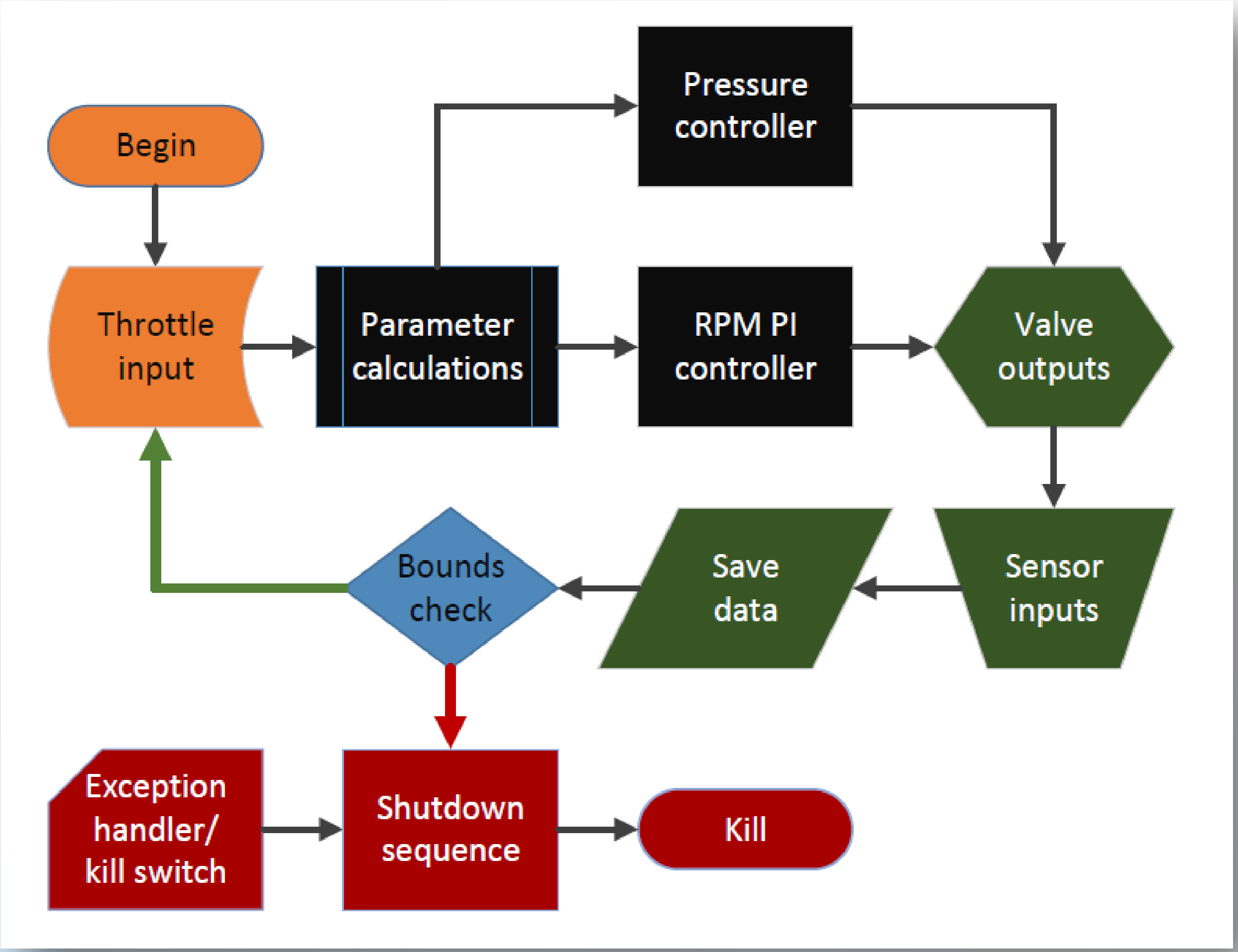


Software Design Requirements

- Interface with user
  - Throttle manipulation
  - User "kill switch"
- Controller
  - Throttle profile
  - Pump control system
- DAQ
  - Data collection and system interface
- Automated safety
  - Exception handling for the DAQ
  - Bounds check sensor returns

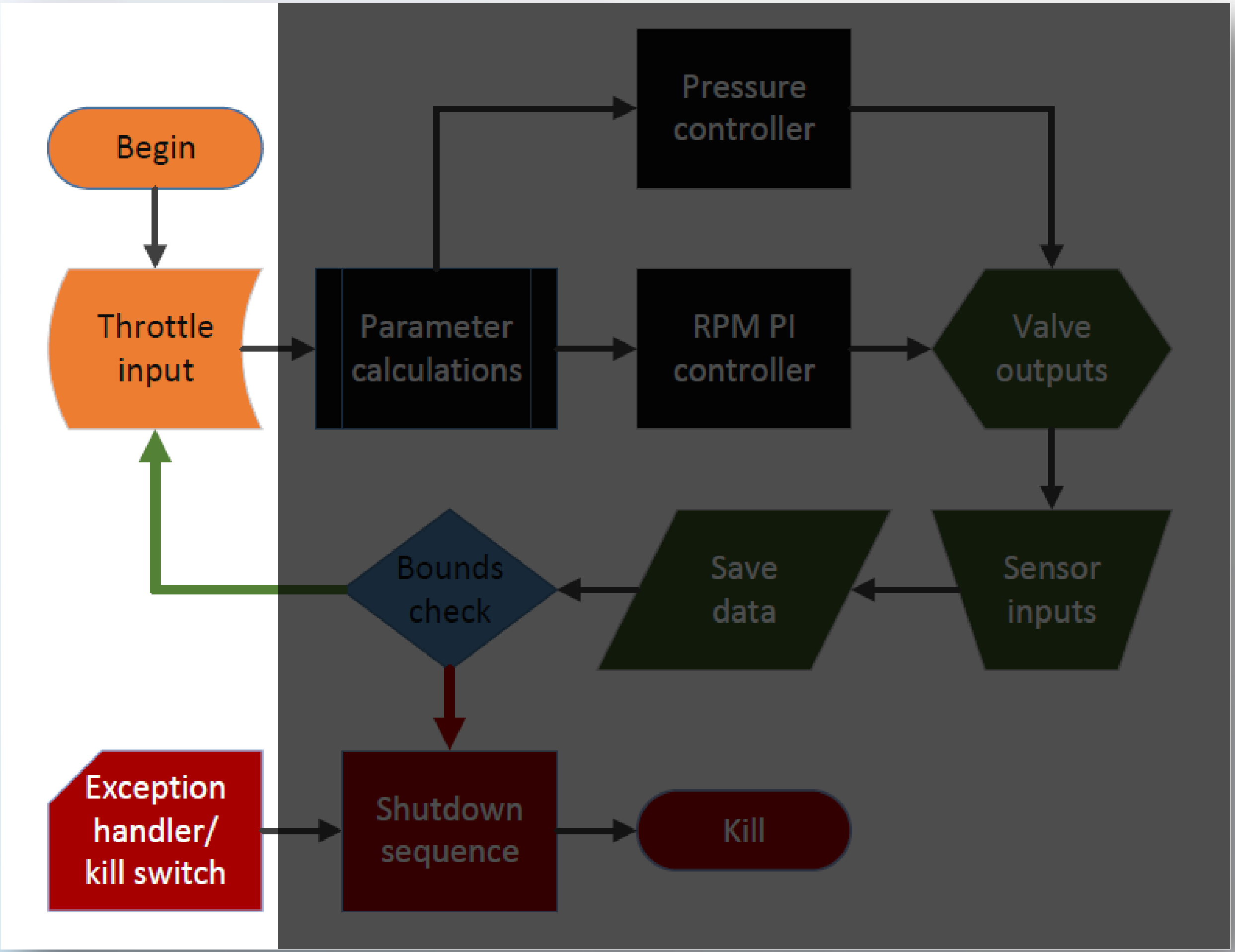
Software Overview

- User interface
- Pump controller
- DAQ - system interface
- Safety - Bounds checking



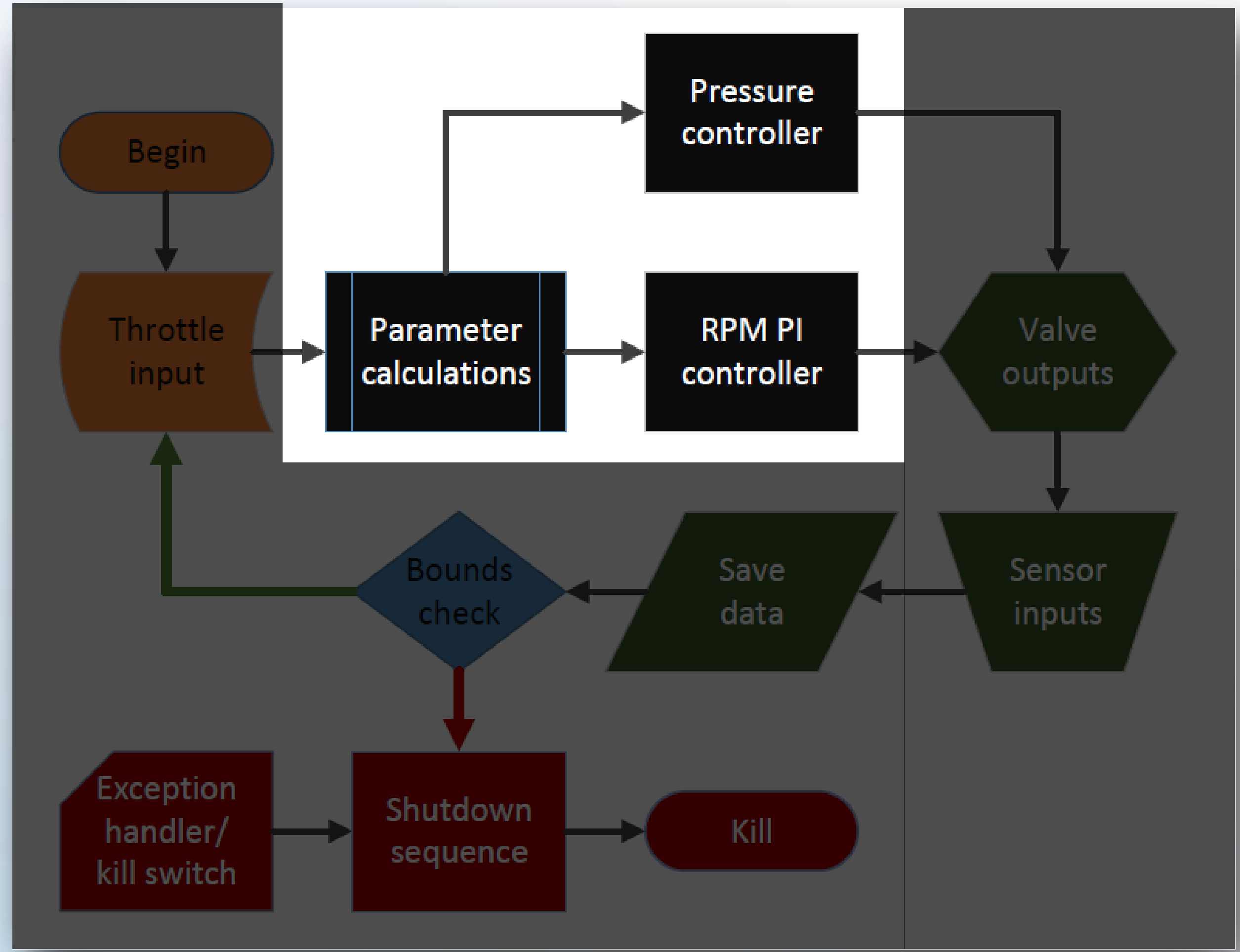
User Interface

- Throttle control
  - Manual control
  - Automatic sequence
- Manual kill switch
- Data viewing



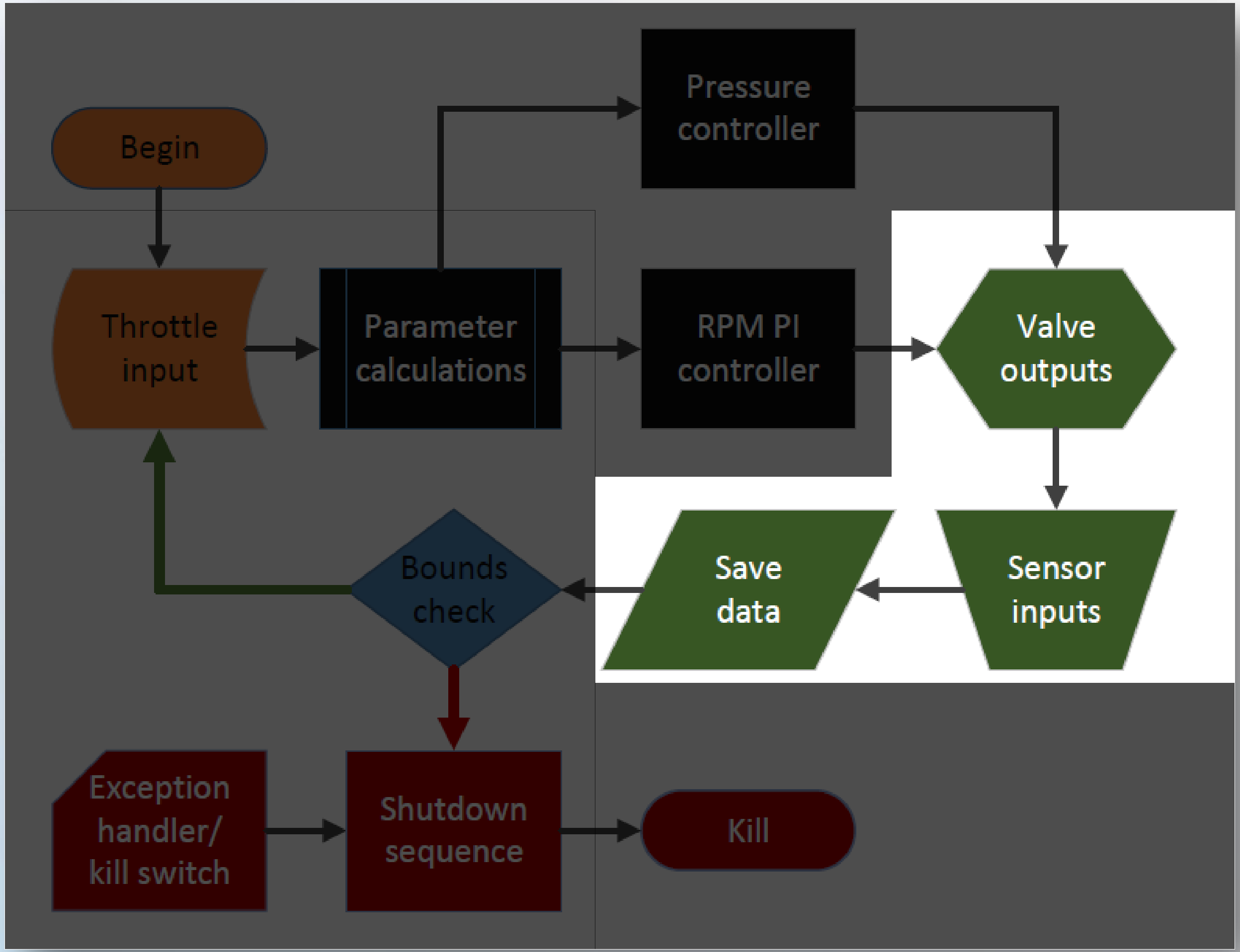
Control

- RPM control
  - Pump controller
  - Valve control law
- Backpressure control



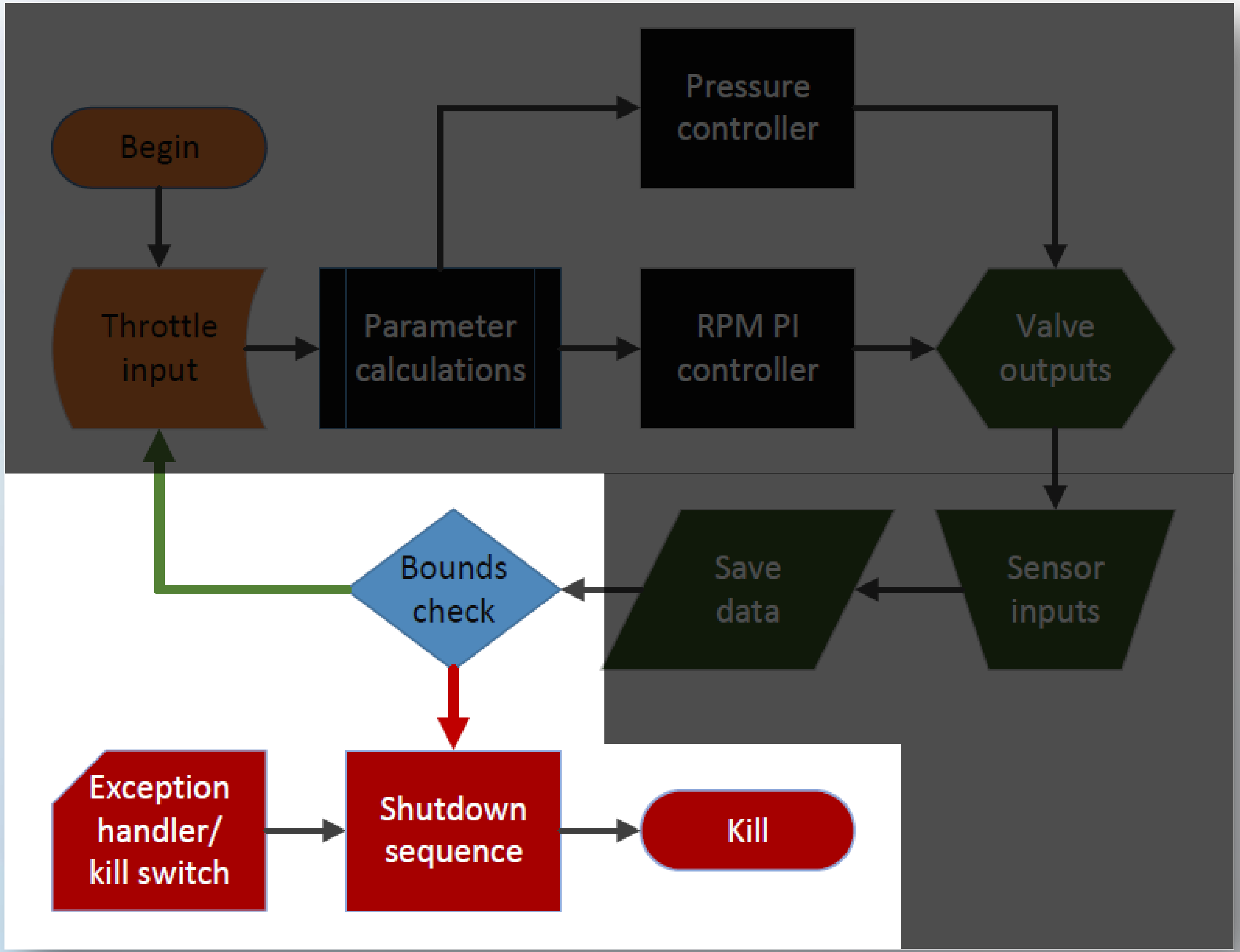
DAQ

- Link between LabView and instruments
  - Control signals
  - Data return



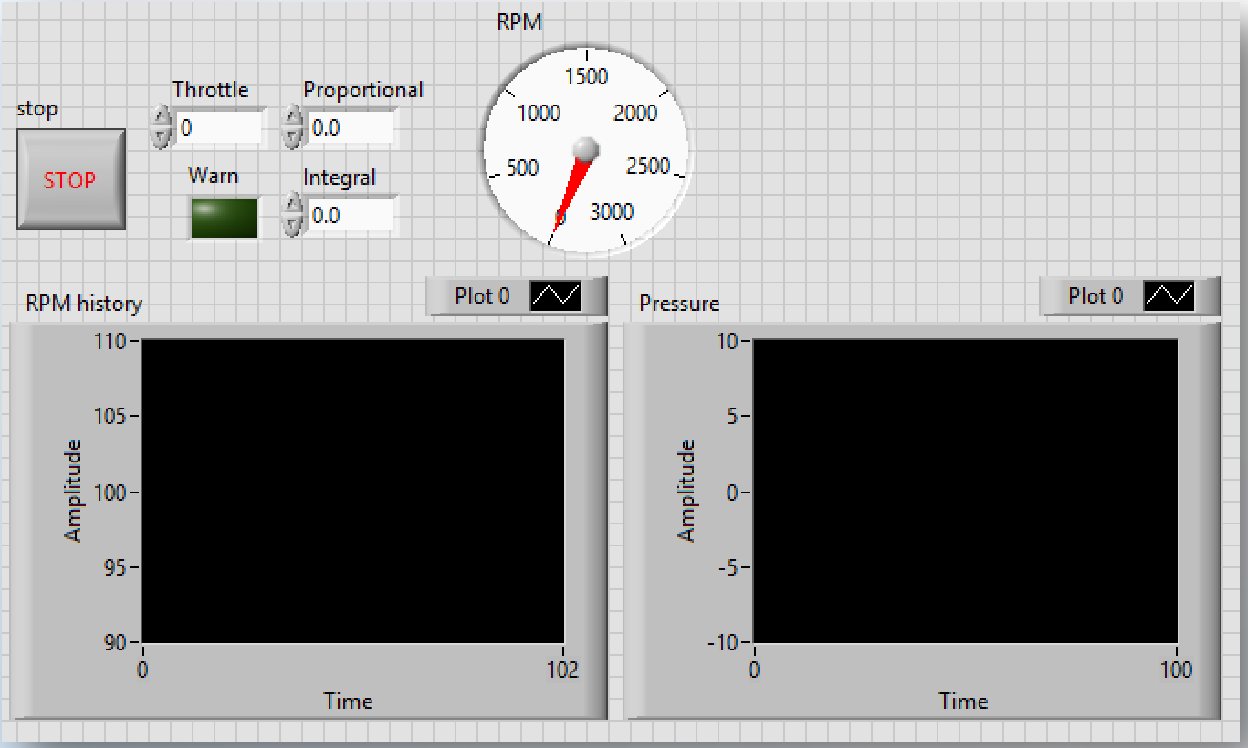
Safety

- Manual override/kill
- DAQ Exception handling
- Bounds check results
  - Automatic kill



LabView User Interface

- Throttle manual input
- PI gain adjustment
- User safety stop
- RPM gauge and history
- Pressure history

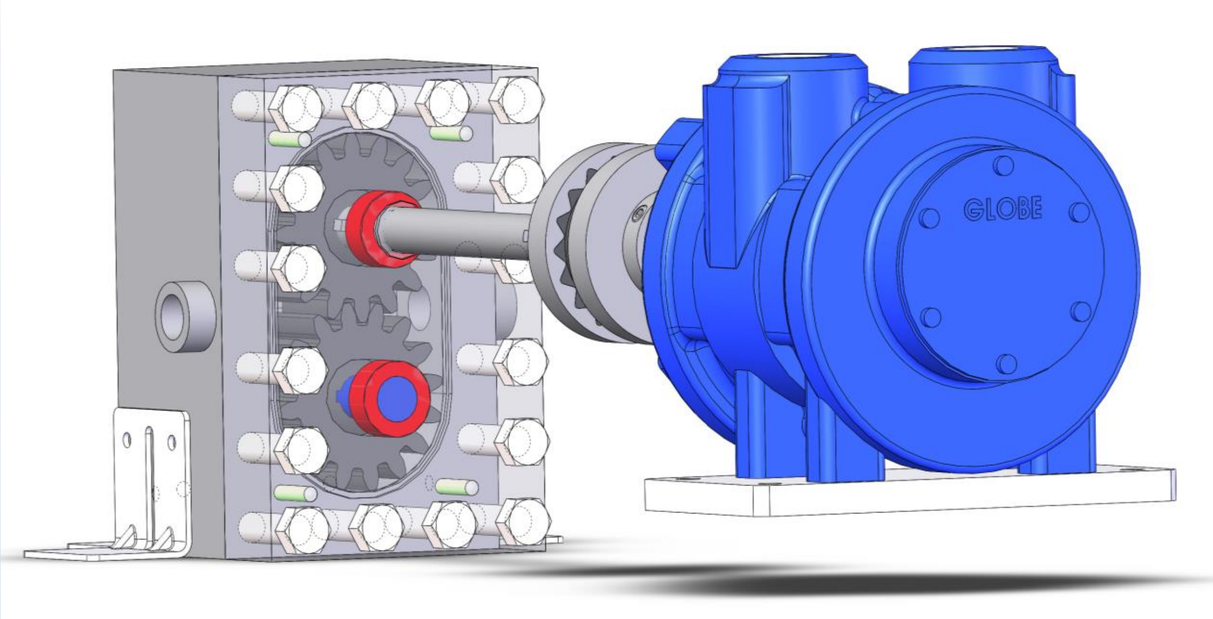


Electronic Requirements

Requirement	Range	Instrument
Regulate drive system input pressure	2-100 psi	Pressure Regulator
Measure pump outlet pressure	50 – 800 psi	Pressure Transducer
Measure pump drive shaft RPM	230 – 2400 RPM	Encoder/Tachometer/ Tachogenerator

Key System Parameters

- Max Required Power = 7.5 kW
- Required Torque = 31 Nm
- RPM = 2300
- Total Efficiency = 85.7%
- Sampling Rate = 6.5 kHz
- Slew Rate = < 2 s
- Volumetric Flow Rate = 1.4 L/s



Verification & Validation

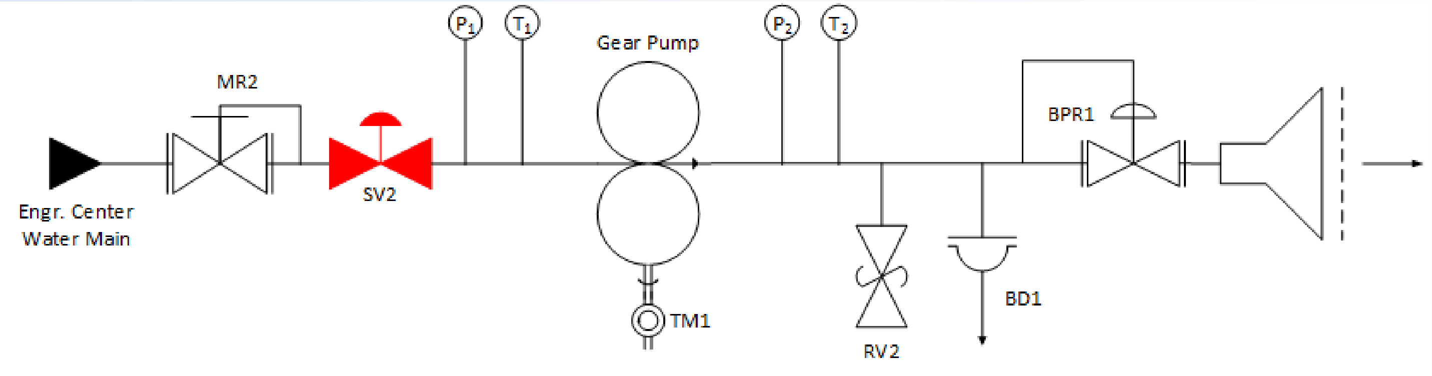
Validation Schedule

Phase 1 – November, December 2016	Phase 2 – January, February 2017	Phase 3 – February, March, April 2017
Simulation & Sensor Testing: • Electronic Pressure regulator design and testing • Electronics Calibration • Mockup Simulations • Testing Location Validation: 1. Water Flow requirements 2. Air Flow requirements	**Subsystem Testing:** • Drive System: air motor testing, feed pressure regulation, solenoid valve operation, start-up and shut-down procedures, emergency cut-off and venting, helium feed verification, measuring component slew rates • Gear Pump System: back pressure regulation, solenoid valve operation	**Full System Testing:** • Motor-Pump coupling and operation • Pump throttling through drive system electronic pressure regulator • Validating system slew rate • Optimization of system control

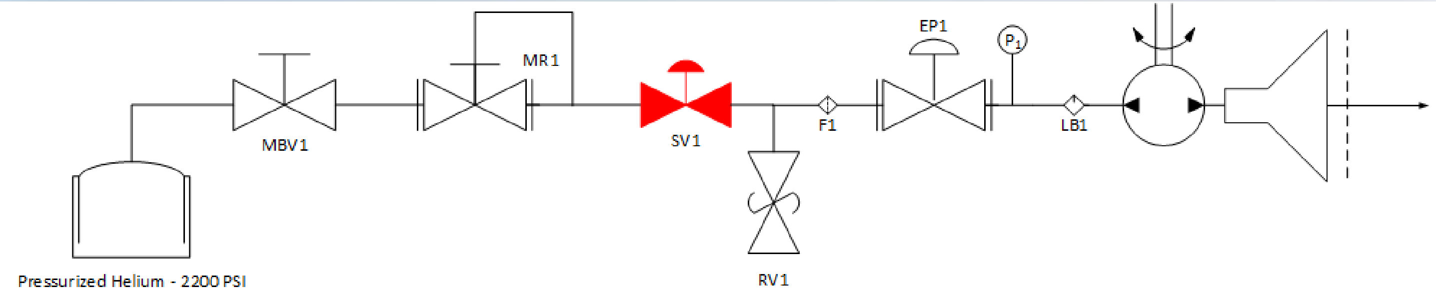
Fluid Schematic

1. Pump System – Including the gear pump and electronic back pressure regulator

Pump



2. Drive system – Including an electronic regulator, air motor and a solenoid valve.



Drive System

Nomenclature

SV = Solenoid Valve
RV = Relief Valve
MBV = Manual Ball Valve
MR = Manual Regulator
EP = Electronic Pressure Regulator
BPR = Back Pressure Regulator
TM = Tachometer
BD = Burst Disk
LB = Lubricator
F = Air Filter
P = Pressure Transducer
T = Temperature Sensor

Fluid Schematic

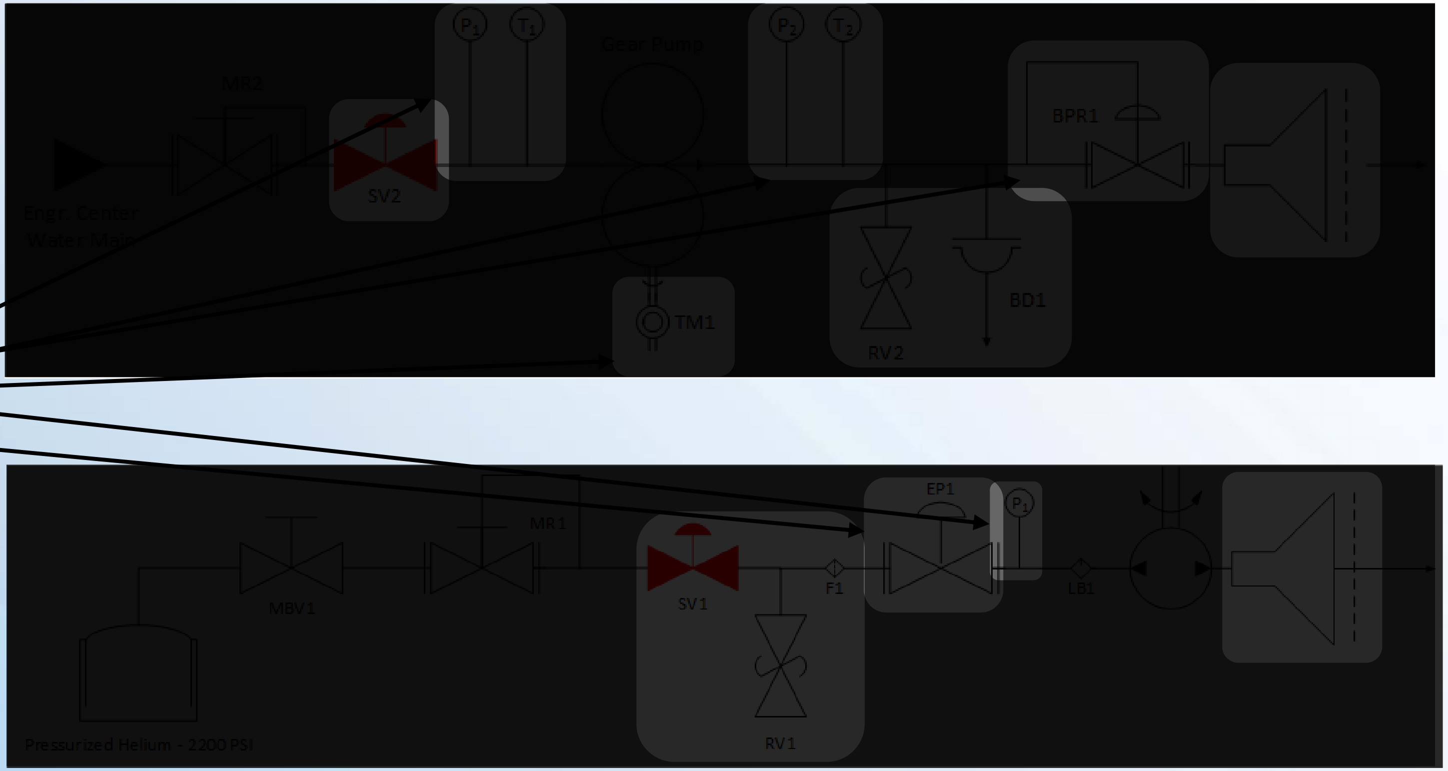
Testing will focus on the following two systems:

1. Drive system – Including an air motor and a solenoid valve
2. Pump System – Including the gear pump, electronic back pressure regulator

During the pump operation, both the electronic feed system pressure regulator and the pump back pressure regulator are controlled to the commanded pump throttle settings

An electronic pressure regulator and temperature sensors monitor the system

Both systems are equipped with relief valves and vents as well as having normally closed solenoid valves



Nomenclature

SV = Solenoid Valve
RV = Relief Valve
MBV = Manual Ball Valve
MR = Manual Regulator
EP = Electronic Pressure Regulator
BPR = Back Pressure Regulator
BD = Burst Disk
LB = Lubricator
F = Air Filter
P = Pressure Transducer
T = Temperature Sensor

Instrumentation

Instrument	Part #	Specifications	Resolution & Sampling Rate
Pressure Regulator (EP1)	Parker R119-08CG/M2	1"NPT to ¼"NPT 400 cfm 0 to 125 psi	3 psig – Fulfills Reqs.
Pressure Transducer (P1)	Omega PX309-5KG5V	¼"NPT 0-5000 psig	0.08 psig – Fulfills Reqs.
Piezo Pressure Transducer (P2)	PCB 113B24	¼" NPT 0 to 1000 psig	0.02 psig & 1kHz - Fulfills Reqs.
Thermocouples (T1, T2)	Omega TC-T	¾" NPT T Type	1kHz Sample rate
Solenoid Valve – Water (SV1)	Omega SV173	¾"NPT	-
Solenoid Valve – Helium (SV2)	Omega SV172	½"NPT	-
Back Pressure Regulator (BPR1)	Equilibar BDM12S	Max pressure Rating 150 Cv range from.1 14.3 Port Size 1/8	-
Tachometer (TM1)	ABQ A2108	100-6000 RPM Needs a mounting rig & calibration	30 RPM & Analog – Fulfills Reqs

Sensor Sampling

Instrument	Number of channels used	Minimum sampling rate
Pressure Transducer	1	1 kHz
Piezo Pressure Transducer	1	2.2 kHz
Thermocouple	2	1 kHz
Tachometer	1	1.5 kHz
Total	5	5.7 kS/s

Sensor Sampling

NI DAQ specs

- 8 analog inputs
- Sample frequency 50kS/s
- Using 5 channels: 10kS/s/ch
- Worst case: 4 times above the highest minimum sampling rate

Sensor Error Stack-up

Instrument	Error in %
Pressure Transducer	.01 %
Tachometer	0.0015 %
DAQ	0.0015 %
Total	.023 %

Total error will translate to ± 10^{-4} kg/s for mass flow rate

Final Testing

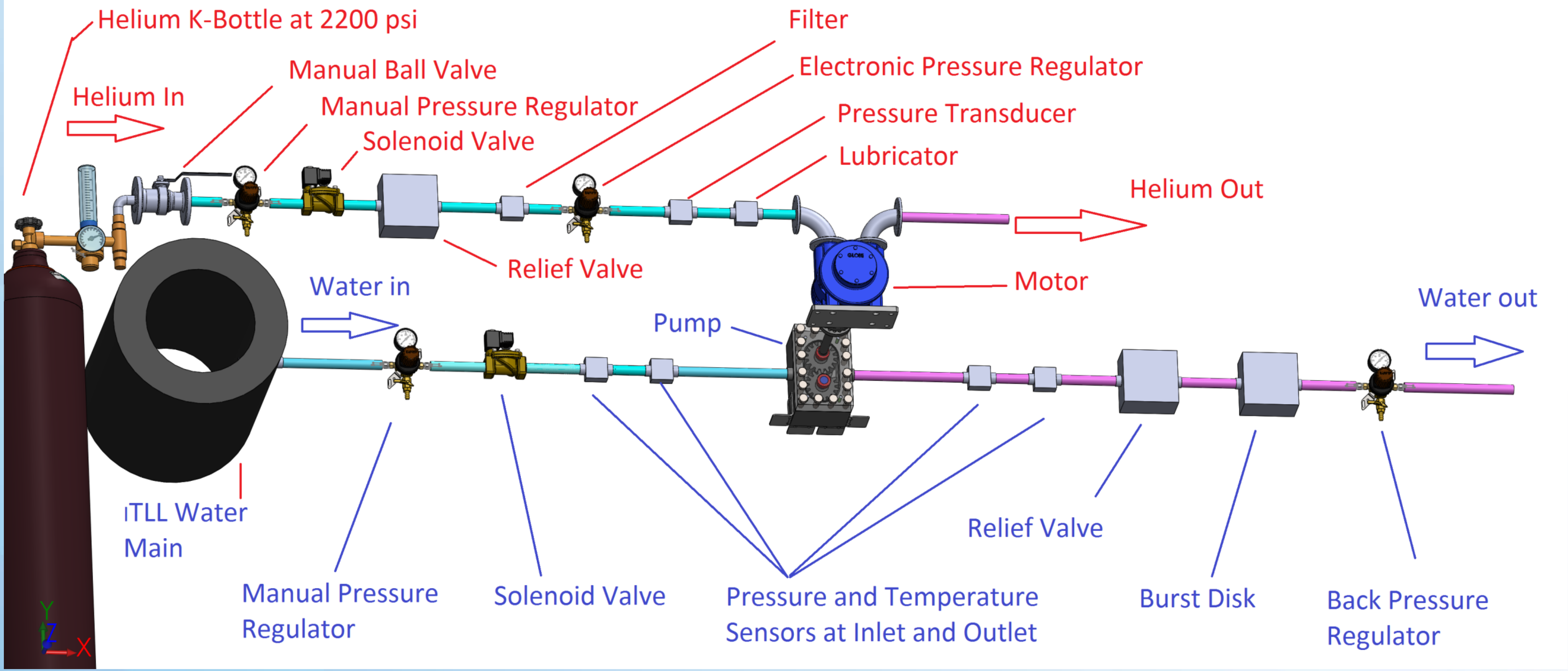
Full scale testing to be conducted*	Key Results to be Obtained	Validation of Functional Reqs.*
Max/min throttle tests (10 - 100% Throttle)	Pump performance: slew rate, control overshoot	FR2, FR7
Throttle profiles(using helium)	Response to throttle profiles, control stability	FR1, FR4
Steady throttle tests	Mass flow rate, back pressure, efficiency, fluctuation magnitude	FR3, FR8
System startup and shutdown, including emergency shutdown	Iterate shutdown procedures, optimize restart-ability	FR5

*All tests will be conducted with **one pump and water**

*See slides 85-87 for list and description of Functional and Derived Reqs.

FR6 validated by adherence to Boeing D2-113073-1

Preliminary CAD Design: Full System



Risks and Risk Mitigation

Risks

- 61 possible risks identified
  - Including individual component failure modes
- Evaluated these risks against:
  - Cost
  - Schedule
  - Technical
  - Safety
- Identified Top 5 Risks
  - Mitigation plans were developed

Risk - Top 5

1. Tolerance Stack-up Does Not Meet Project Requirements
2. Driveshaft Seal Failure/Leakage
3. Electronic Back Pressure Regulator Failure
4. Electronic Helium Pressure Regulator Failure
5. Over Budget Due to Component Purchases

Risk Matrix

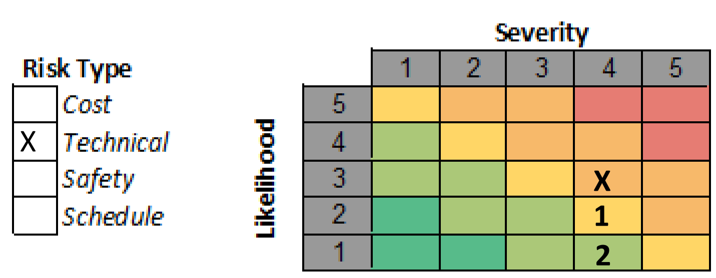
Additive Risk Matrix		Severity					
			1	2	3	4	5
		Cost	Minimal or no impact	<1% of budget to replace	<5% of budget to replace	<10% of budget to replace	>10% of budget to replace
		Schedule	Minimal or no impact	Additional activities required but able to meet key deadlines (few hrs - 1d)	Minor schedule slip; will miss internal deadline (1d - 3d)	Critical path affected (+3d)	Cannot achieve milestone
		Technical	Minimal or no impact	Minor performance shortfall, same approach retained	Moderate performance shortfall, but work arounds available	Unacceptable, but work arounds available	Unacceptable; no alternatives exist
		Safety	Minimal or no impact	Could result in: injury or occupational illness not resulting in a lost work day	Could result in: injury or occupational illness resulting in one or more lost work day(s)	Could result in: permanent partial disability,injuries or occupational illness	Could result in: death or permanent total disability
Likelihood			1	2	3	4	5
5	Near certainty >95%	5					
4	Highly Likely >65%	4					
3	Likely >35%	3					
2	Low likelihood <35%	2					
1	Not likely <10%	1					

Project Description | The Design | Verification & Validation | Moving Forward

Risk Mitigation

Risk: Tolerance Stack-up Does Not Meet Project Requirements

Description of Risk: If the tolerance stack-up does not meet requirements, then components may have to be re-adjusted to meet requirements, or they may have to be re-manufactured.



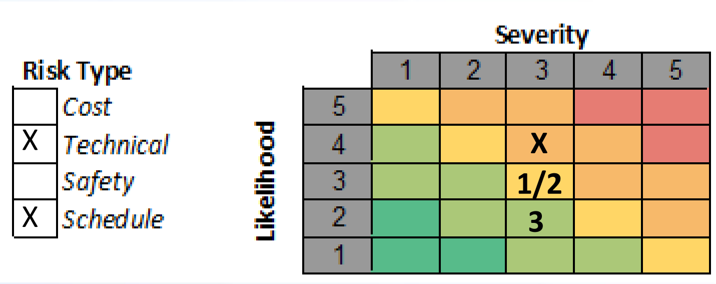
Risk Reduction Plan

Action/Event	Success Criteria	Risk level if successful
1. Speak with the manufacturer on the importance of meeting the specific tolerances	Communication is well received by the customer	Medium
2. Quality inspection of components following manufacturing	Inspection of components yields parts within clearance requirements	Medium - Low

Risk Mitigation

Risk: Driveshaft Seal Failure/Leakage

Description of Risk: If the driveshaft seals leak, then the seals may be required to be remade or an alternative seal is required to be manufactured.



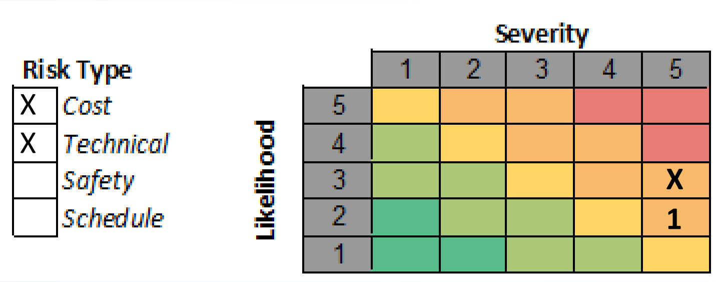
Risk Reduction Plan

Action/Event	Success Criteria	Risk level if successful
1. Inspect seals for quality upon receipt	Seals are void of defect upon receipt	Medium
2. Ensure seals are properly fitted and secured when testing	Seals are in working order and are fitted according to design specifications	Medium
3. Continually inspect seals after each test	Seals show no signs of wear upon completion of tests	Medium - Low

Risk Mitigation

Risk: Electronic Back Pressure Regulator Failure

Description of Risk: If the electronic back pressure regulator fails to operate, then a new regulator must be purchased or the control system/algorithm has to be re-designed.



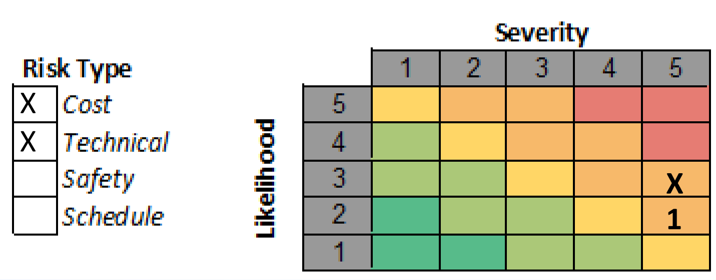
Risk Reduction Plan

Action/Event	Success Criteria	Risk level if successful
1. The outlet conditions are readily monitored to not exceed the component specifications	Pressure and voltage are monitored to not exceed the component specifications	Medium - High

Risk Mitigation

Risk: Electronic Helium Pressure Regulator Failure

Description of Risk: If the electronic helium pressure regulator fails to operate to the needed requirements, then a new pressure regulator is required to be purchased.



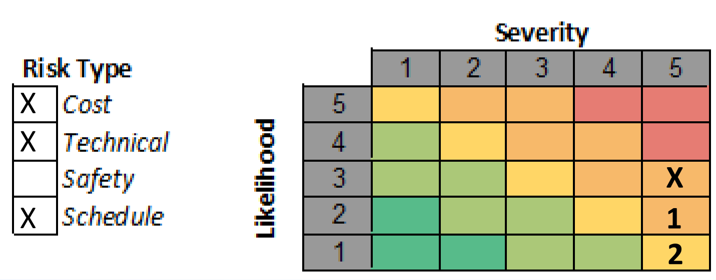
Risk Reduction Plan

Action/Event	Success Criteria	Risk level if successful
1. The helium feed system is monitored and designed as not to exceed the component specifications before the electronic regulator	Pressure and voltage are monitored to not exceed the component specifications	Medium - High

Risk Mitigation

Risk: Over Budget Due to Component Purchases

Description of Risk: If the project is over budget due to purchasing required components, then the system/component may be required to be re-designed, or the quality of components may need be reduced.



Risk Reduction Plan

Action/Event	Success Criteria	Risk level if successful
1. Create and continually update a detailed budget	Budget continues to stay below allotted amount	Medium - High
2. Look for avenues to purchase/borrow parts at discounted rates		Medium

Moving Forward

Work Breakdown Structure

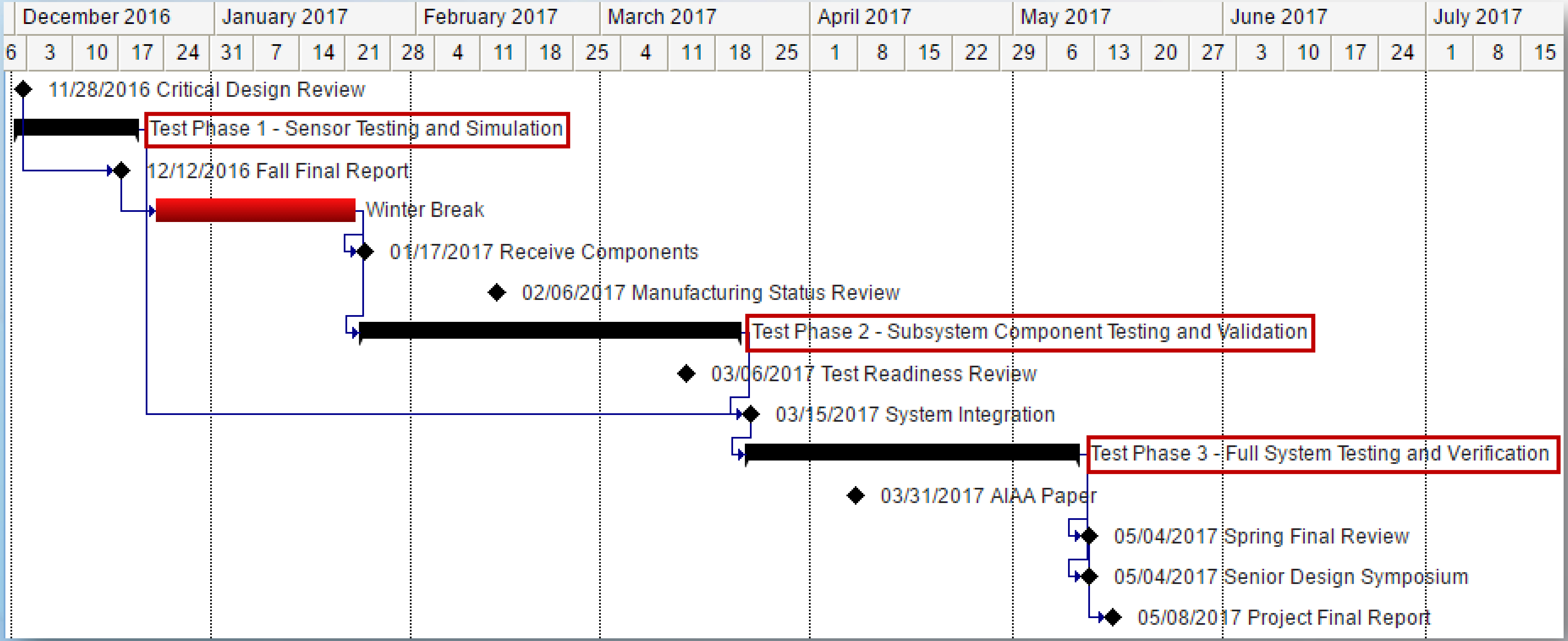
PEAPOD – SAS Senior Design Project

- **Deliverables**
  - PDD
  - CDD
  - PDR
  - CDR
  - FFR
  - MSR
  - TRR
  - SFR
  - PFR
  - SDS
  - AIAA
- **Management**
  - Requirements
  - Risk Matrix
  - Risk Analysis
  - WBS/WP
  - Scheduling
  - Budget
  - Acquire Components
- **Manufacturing & Design**
  - CAD Model
  - Efficiency Model
  - Optimization
  - Acquire Drive System Specs
  - Acquire Valving Specs
  - Manufacture
- **Software**
  - Design Control Schematic
  - Develop LABView GUI
  - Merge Control Algorithm & LABView
  - Data Acquisition
  - Test the Control System
- **Electronics & Sensors**
  - Acquire Electronics Specs
  - Electronics Error Stack-up
  - Signal Conditioning
  - Integrate Electronics
  - Electronic Systems Test
- **Integration/ Testing**
  - ID H2O Source
  - Test Plan
  - Obtain He
  - Component Testing
  - Safety Plan
  - System Integration
  - System Testing

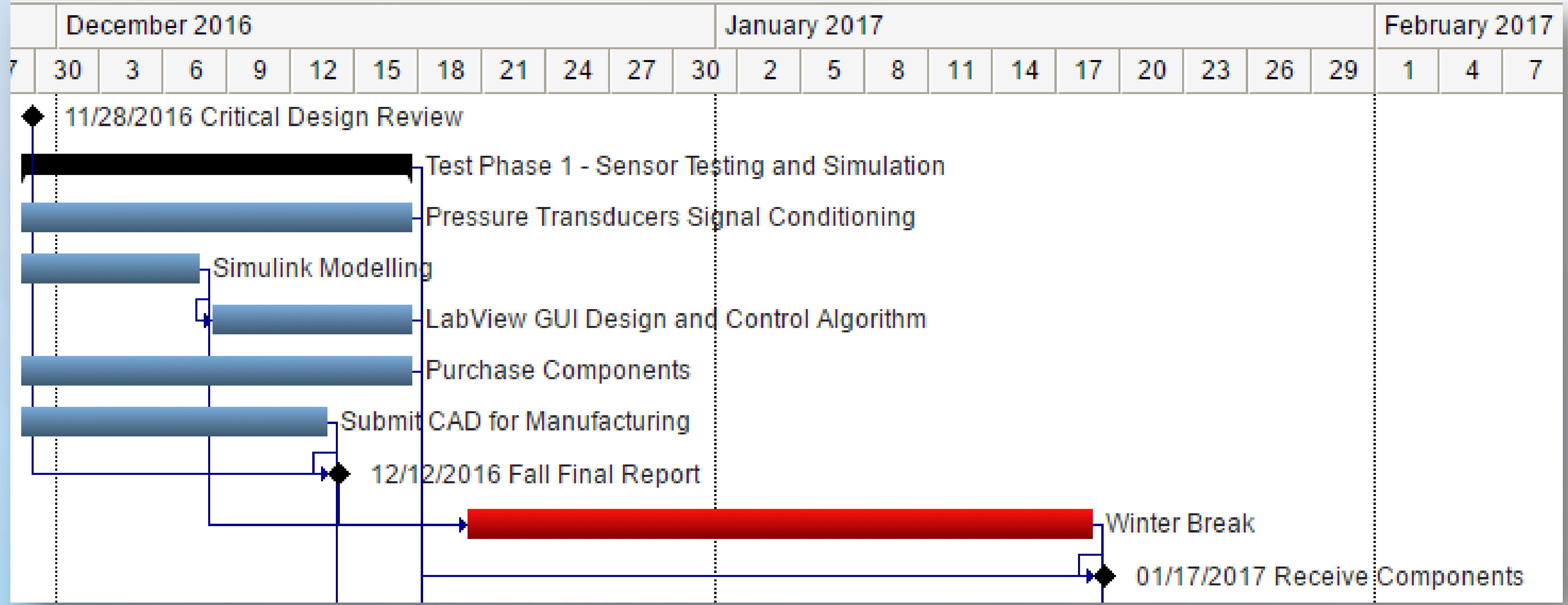
Completed
Not Completed

Work Plan/Schedule

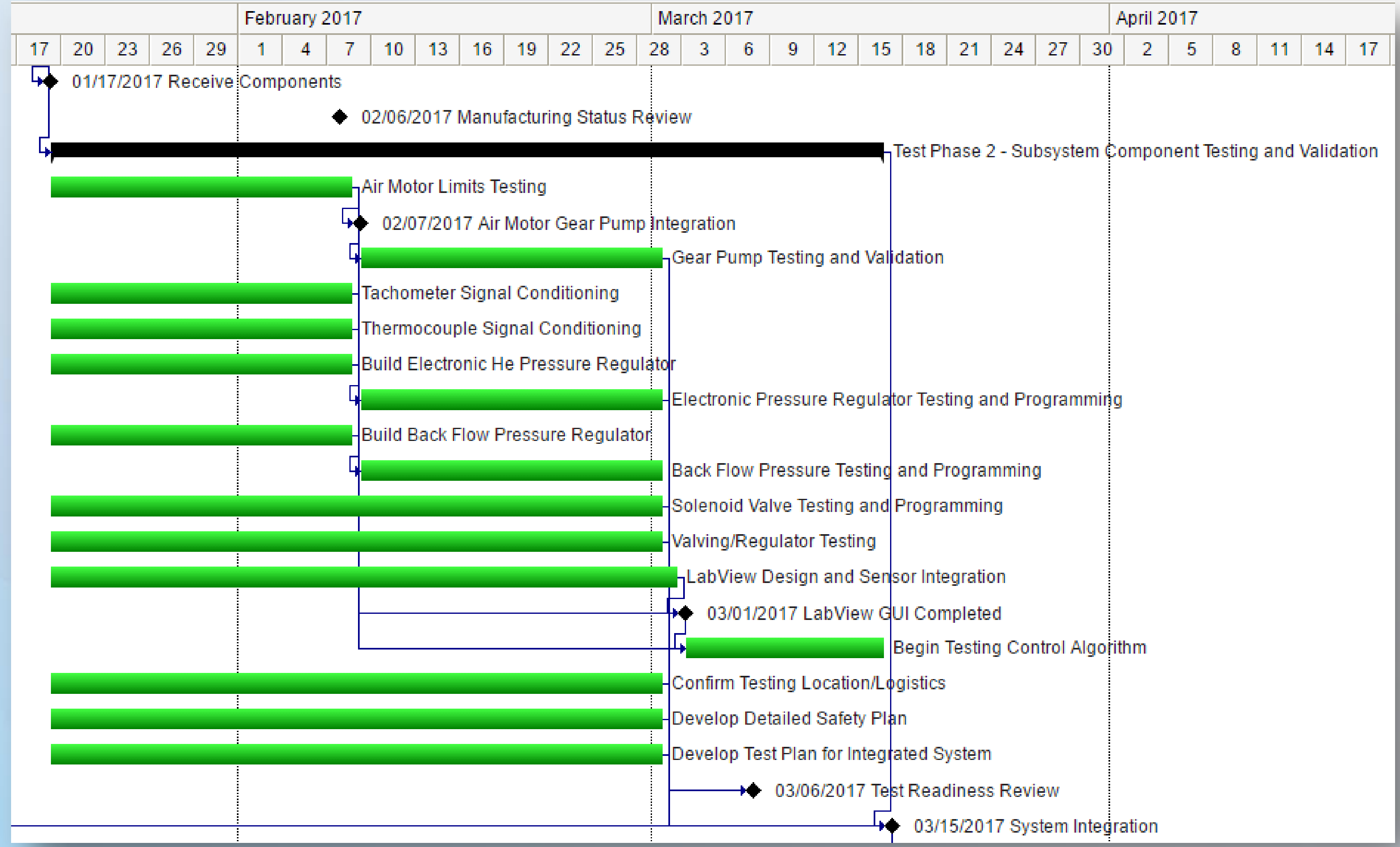
3 Testing Phases



Test Phase 1 – Sensor Testing & Simulation

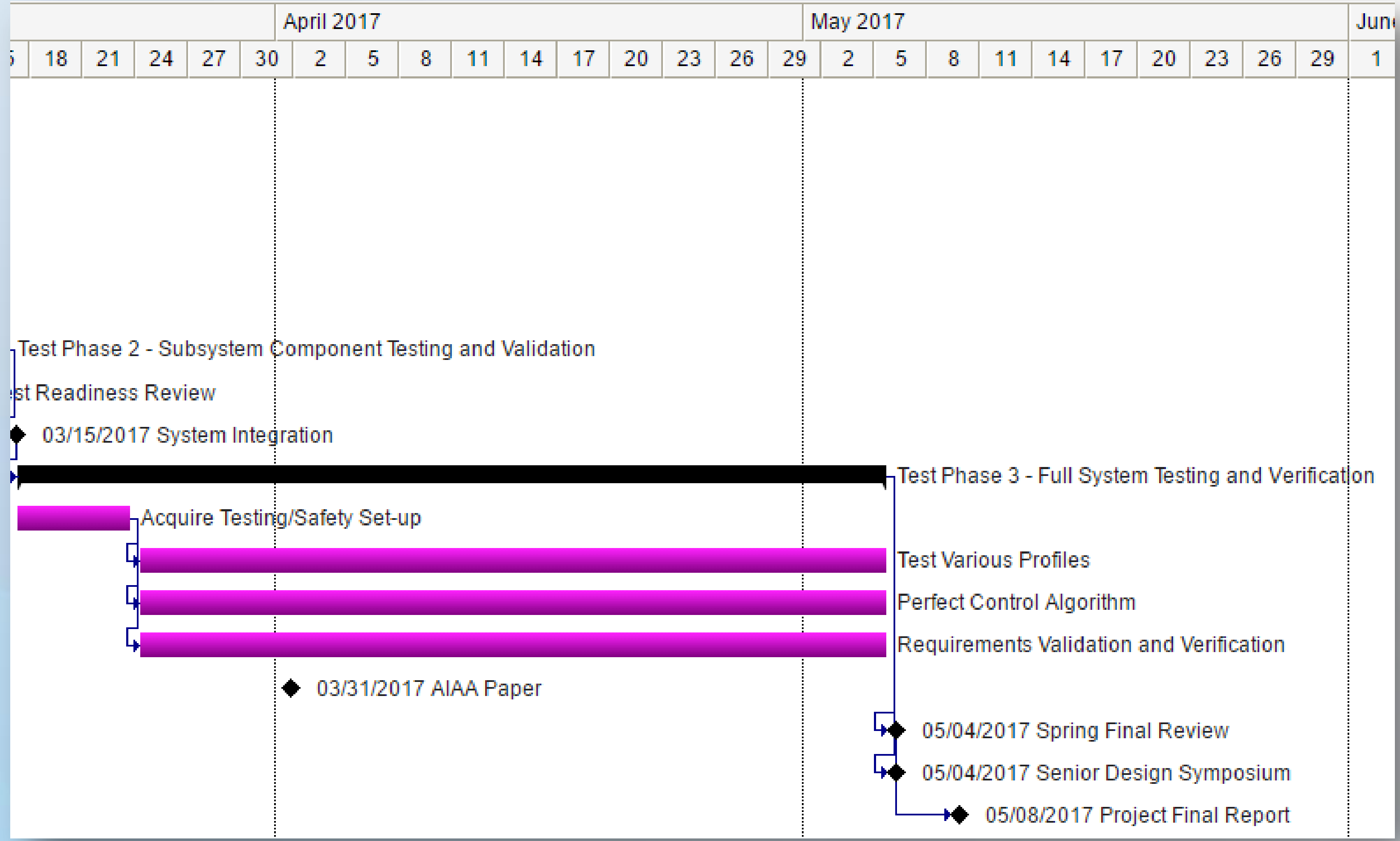


Test Phase 2 – Subsystem Testing

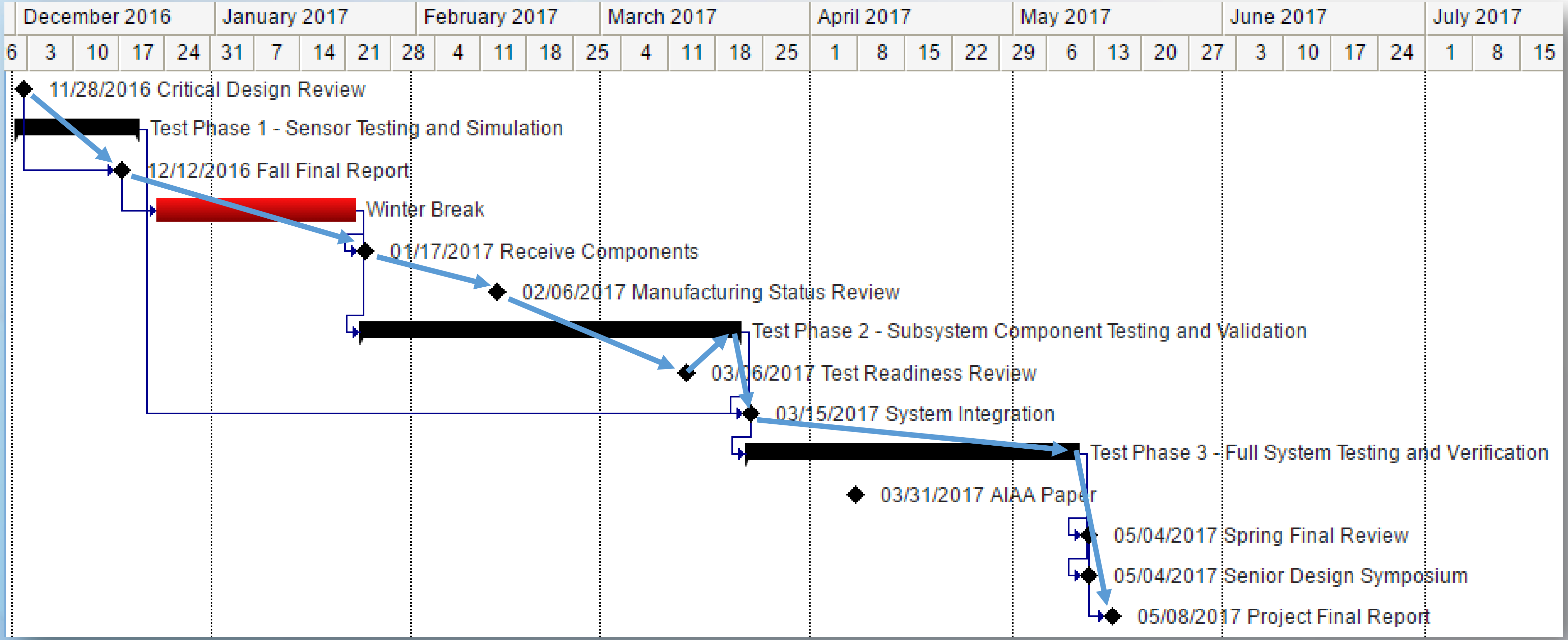


Project Description | The Design | Verification & Validation | Moving Forward

Test Phase 3 – Full System Testing



Critical Path



Finances

$5,000: SAS (Secured)

$3,000: EHP (Secured)

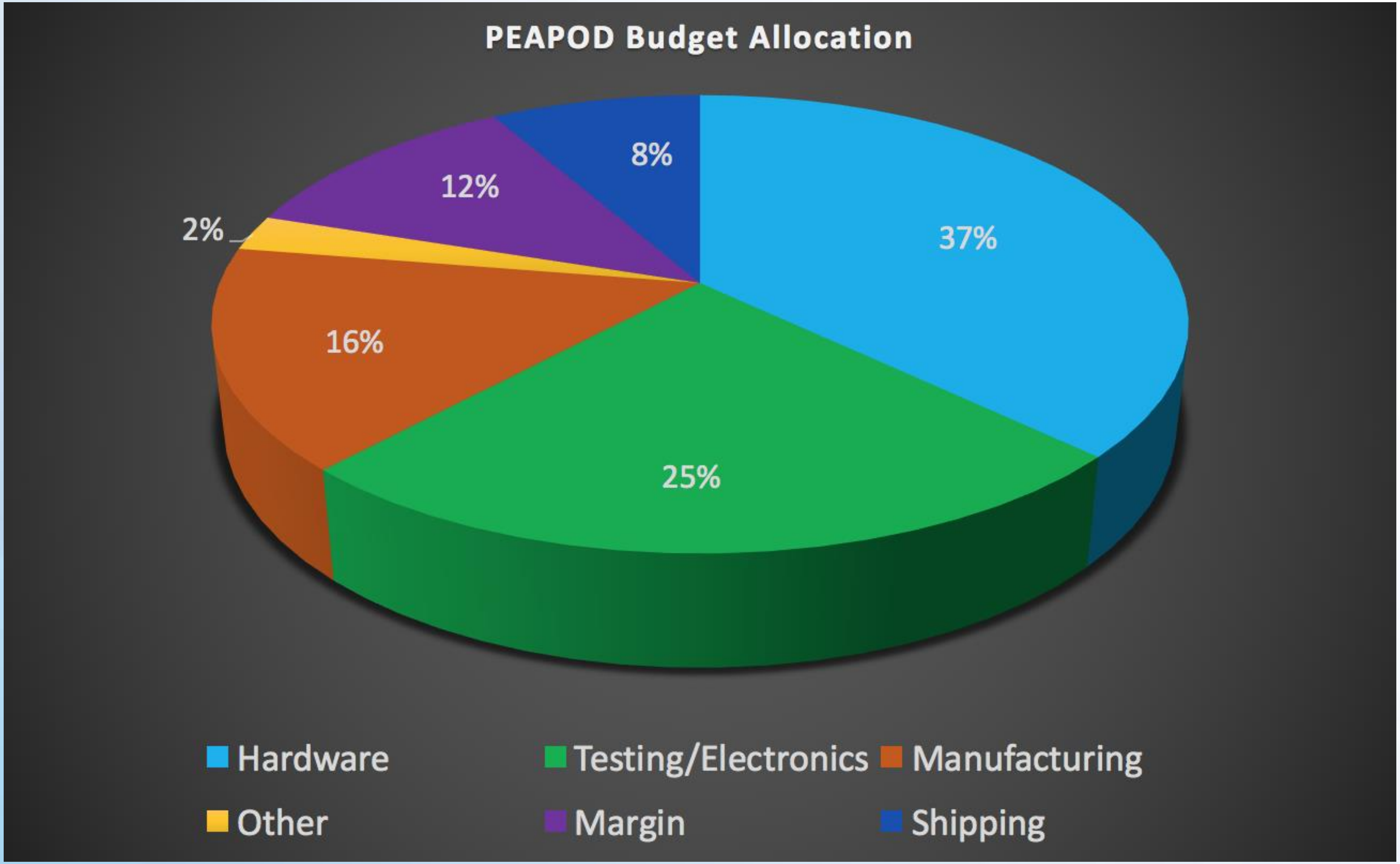
$3,000: Fund transfer (via EEF, unverified)

$11,000: Total possible

Part	Jnit (Part Numb	Price	Quantity	Subtotal	Shipping	Discount	Total
Wire		$ -	20	$ -	0	0%	$ -
Microcontroller		$ -	1	$ -	0	0%	$ -
Gear Block	1319T4	$ 89.02	4	$ 356.08	$ 13.35	0%	$ 369.43
Panel	1319T4	$ 89.02	1	$ 89.02	$ 13.35	0%	$ 102.37
Housing	8983K198	$ 57.41	1	$ 57.41	$ 8.61	0%	$ 66.02
Nuts and Bolts	As Needed	$ 35.00	1	$ 35.00	0	0%	$ 35.00
EDMing		$ 750.00	1	$ 750.00	0	0%	$ 750.00
Machining Metals	As Needed	$ -	0	$ -	0	0%	$ -
Pressure Transducers	PX309-5KG5V	$ -	4	$ -	0	0%	$ -
Pressure Transducers	YX-98071-23	$ 312.00	1	$ 312.00	$ 46.80	0%	$ 358.80
Pressure Regulator	21U842	$ 221.25	1	$ 221.25	$ 33.19	0%	$ 254.44
Pressure Regulator 2	VIC0781-0528	$ 280.00	1	$ 280.00	$ 42.00	0%	$ 322.00
Line Hookups	3/8" Lines	$ -	2	$ -	0	0%	$ -
Drive System	VA10 J	$ 1,095.00	1	$ 1,095.00	$ 164.25	0%	$ 1,259.25
Drive System Filter	3248T11	$ 78.10	1	$ 78.10	$ 11.72	0%	$ 89.82
Drive System Lube	8520T19	$ 82.59	1	$ 82.59	$ 12.39	0%	$ 94.98
Drive System Oil	1298K72	$ 24.59	1	$ 24.59	$ 3.69	0%	$ 28.28
Regulator		$ -	1	$ -	0	0%	$ -
Teflon Seal	5154T31	$ 103.76	1	$ 103.76	$ 15.56	0%	$ 119.32
Ball Bearings	6909UU	$ 19.49	1	$ 19.49	$ 2.92	0%	$ 22.41
Water Drum	56W55R	$ 41.33	1	$ 41.33	$ 6.20	0%	$ 47.53
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	$ 230.38	$ 34.56	0%	$ 264.94
Tooling for gears		$ 500.00	1	$ 500.00	0	0%	$ 500.00
Solenoid Valve	SV170	$ 367.00	1	$ 367.00	$ 55.05	0%	$ 422.05
Tachometer	RL50-850	$ 469.00	1	$ 469.00	$ 70.35	0%	$ 539.35
Binding Reports	NA	$ 100.00	2	$ 200.00	0	0%	$ 200.00
Microsoft Office	NA	$ -	1	$ -	0	0%	$ -
NI LabView	NA	$ -	1	$ -	0	0%	$ -
Matlab/Simulink	NA	$ -	1	$ -	0	0%	$ -
Solidworks 2016	NA	$ -	1	$ -	0	0%	$ -
Gantter	NA	$ -	1	$ -	0	0%	$ -
Shaft Coupler	6507K64	$ 25.15	2	$ 50.30	$ 3.77	0%	$ 54.07
Shaft Hub	6507K73	$ 23.19	1	$ 23.19	$ 3.48	0%	$ 26.67
DC Motor	PK256-02A	$ 78.00	2	$ 156.00	$ 11.70	0%	$ 167.70
Helium Piping	62145552	$ 17.09	1	$ 17.09	$ 2.56	0%	$ 19.65
Downstream Helium	438288	$ 16.52	1	$ 16.52	0	0%	$ 16.52
Pressure Regulator	214716	$ 73.97	1	$ 73.97	0	0%	$ 73.97
Tee's	181943	$ 4.83	5	$ 24.15	0	0%	$ 24.15
Helium Relief Valve	15x915	$ 50.50	1	$ 50.50	$ 7.58	0%	$ 58.08
Water Relief Valve	RL50-850	$ 69.00	1	$ 69.00	$ 10.35	0%	$ 79.35
Piezzo Transducer	113B24	$ 590.00	1	$ 590.00	$ 88.50	0%	$ 678.50
Piping	301337	$ 20.28	1	$ 20.28	0	0%	$ 20.28

Legend
Hardware
Manufacturing
Other/Software
Testing/electronics

Subtotal	$ 7,064.93	
Tax	0	
Total	$ 7,064.93	
Margin	$ 935.07	13.2%
Total w/ Margin	$ 8,000.00	


PEAPOD Budget Allocation
8%
12%
2%
37%
16%
25%
Hardware
Testing/Electronics
Manufacturing
Other
Margin
Shipping

Questions?

Table of Contents

Presentation

Back-Up Table of Contents

Back-Up Slides

References

- [1] “Material Compatibility with Liquid Rocket Propellants” Boeing, D2-113073-1.
- [2] “Rubber Chemical Resistance Chart”. MYKIN Inc. http://mykin.com/rubber-chemical-resistance-chart-6
- [3] https://s-media-cache-ak0.pinimg.com/736x/17/14/d1/1714d1aa8306c95d2c4a7b86561bb800.jpg
- [4] Kundu Pijush, K., Ira M. Cohen, P. S. Ayyaswamy, and Howard H. Hu. *Fluid Mechanics*. Burlington, MA: Academic, 2010. Print.
- [5] “Chapter 14: General Spur Gear Theory; Spur Gears”, Fundamentals of Machine Elements, 3rd ed. https://www3.nd.edu/~manufact/FME_pdf_files/FME3_Ch14.pdf
- [6] “Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth”, American National Standard ANSI-AGMA 2001-D04 http://wp.kntu.ac.ir/asgari/AGMA%202001-D04.pdf
- [7] “A Study of Friction Loss For Spur Gear Teeth”, Tso, Lu-nien, Monterey, California: US Naval Postgraduate School http://calhoun.nps.edu/bitstream/handle/10945/13158/studyoffrictionl00tsol.pdf?sequence=1
- [8] “Roark’s Formulas for Stress and Strain, ed. 7”, Pages 502 and 508 http://materiales.azc.uam.mx/gjl/Clases/MA10_I/Roark's%20formulas%20for%20stress%20and%20strain.pdf
- [9] “Lecture 7: Torsion of Circular Cross Section”, Felippa, Carlos, http://www.colorado.edu/engineering/CAS/courses.d/Structures.d/IAST.Lect07.d/IAST.Lect07.pdf
- [10] “Cast Iron Properties”, Dempsey, Jack, http://www.anvilfire.com/article.php?bodyName=/FAQs/cast_iron.htm
- [11] “Useful Tables: Thread Calcs”, RoyMech, http://www.roymech.co.uk/Useful_Tables/Screws/Thread_Calcs.html
- [12] “Useful Tables: Gear Efficiencies”, RoyMech, http://www.roymech.co.uk/Useful_Tables/Drive/Gear_Efficiency.html

- *See Budget for datasheet references for drive system, electronics, etc

Backup Slides

Design Requirements	Description	Validation/Verification
FR1	Pneumatically Driven	
DR1.1	He at 2200 psi	Final Testing
FR2	Throttleable	
DR2.1	*0.14-1.4 L/s volumetric flow rate	CFD Model and Final Testing
DR2.2	750 psi max outlet pressure	CFD Model and Final Testing
DR2.3	Maximum 15 psi oscillations	CFD Model and Final Testing
DR2.4	O/F = 2	CFD Model and Final Testing
FR3	Outlet Pressure of 750 PSI	
DR3.1		Pressure transducer
FR4	Run throttle profile	
DR4.1	Slew rate< 2 s	Final Testing
DR4.2	120 seconds	Final Testing
DR4.3	Start w/ 0 kg/s	Final Testing
FR5	Pump is restart-able	
DR5.1		Testing

*Corresponds to 2 kg/s mass flow rate of NTO and 1 kg/s mass flow rate of UDMH

Design Requirements	Description	Validation/Verification
FR6	Material compatibility	
DR6.1	UDMH and NTO	Adherence to Material info
FR7	FOS = 2.5	FEM and structural Analysis
DR3.1	UDMH and NTO	Adherence to Material info
FR8	75% Efficiency at full throttle	
DR4.1		

Functional and Design Requirements

- FR 1 – The pump shall be pneumatically driven using compressed helium.
  - DR 1.1 – The drive system of the pump shall be powered using room temperature, compressed helium at a pressure between 2000 psi and 6000 psi.
- FR 2 – The fuel streams shall be individually, digitally controlled and throttled from 10% to 100% of full throttle
  - DR 2.1 – A digital throttle shall be implemented to individually control the mass flow rate of the propellants. The total mass flow rates of the propellants must vary from 3.0 kg/s to 0.3 kg/s.
  - DR 2.2 – The target/nominal O/F ratio shall be 2.
- FR 3 – The pump shall deliver a 750 ± 15 psi outlet pressure
  - DR 3.1 – At full throttle, the pump shall be designed to maintain an outlet pressure 750 psi. The outlet pressure of the pump shall oscillate with an amplitude of less than 15 psi at all throttle settings.

Functional and Design Requirements

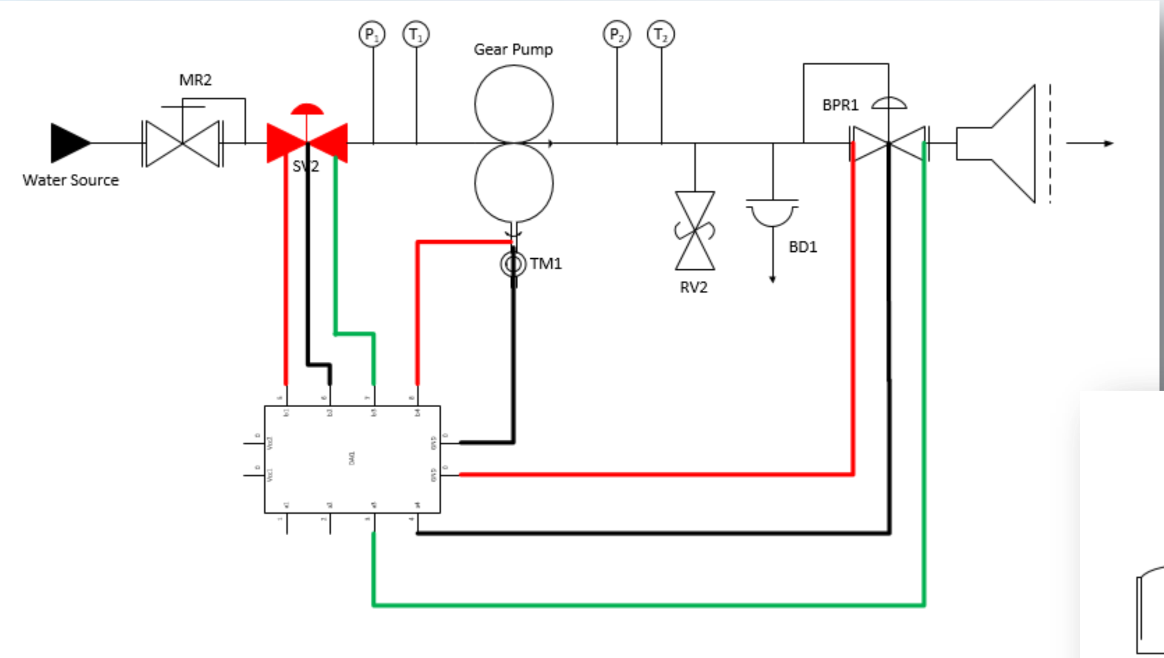
- FR 4 – The pump shall be able to run a provided throttle profile for the full duration of an upper stage burn
  - DR 4.1 – The pump must be designed such that it can be run for the full duration of a 500 second burn.
- FR 5 – The pump system shall have the ability to be restarted
  - DR 5.1 – The outlet pressure and mass flow rate of the pump shall reach the desired setting within 1 second of pump start-up. If this cannot be achieved, the client has specified that a start-up transient of 2 seconds would be acceptable, although less desirable.
  - DR 5.2 – The pump must be designed such that it can be started from 0 mass flow rate.

Functional and Design Requirements

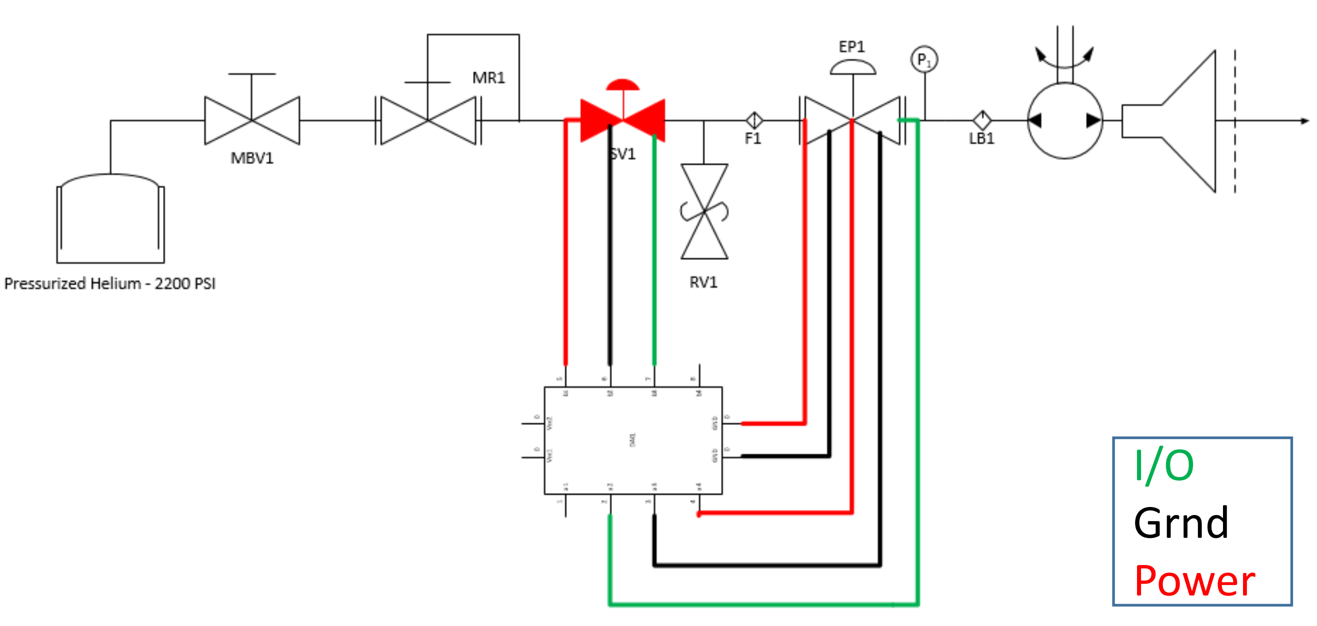
- FR 6 – The pump system shall be constructed from materials that are compatible with the client-specified hypergolic propellants
  - DR 6.1 – The pump system shall be manufactured using materials that are compatible with dinitrogen tetroxide (NTO) and unsymmetrical dimethyldydrazine (UDMH).
- FR 7 – The pump system shall designed and manufactured such that a structural factor of safety of 2.5 is maintained on all components
  - DR 7.1 – All components of the pump and pump housing shall be designed to withstand the high pressures with a structural factor of safety of 2.5 on material yield or failure.
  - DR 7.2 – All components of the pump that will experience high compressive, tensile, torque or other mechanical loads will be designed to withstand those loads with a factor of safety of 2.5 on material yield or failure.
  - DR 7.3 – All other components that will experience high stress or strain due to operation of the pump must be designed to withstand those high stresses and strains with a structural factor of safety of 2.5 on material yield or failure.
- FR 8 – The pump shall meet 75% efficiency at maximum power/capacity

Testing

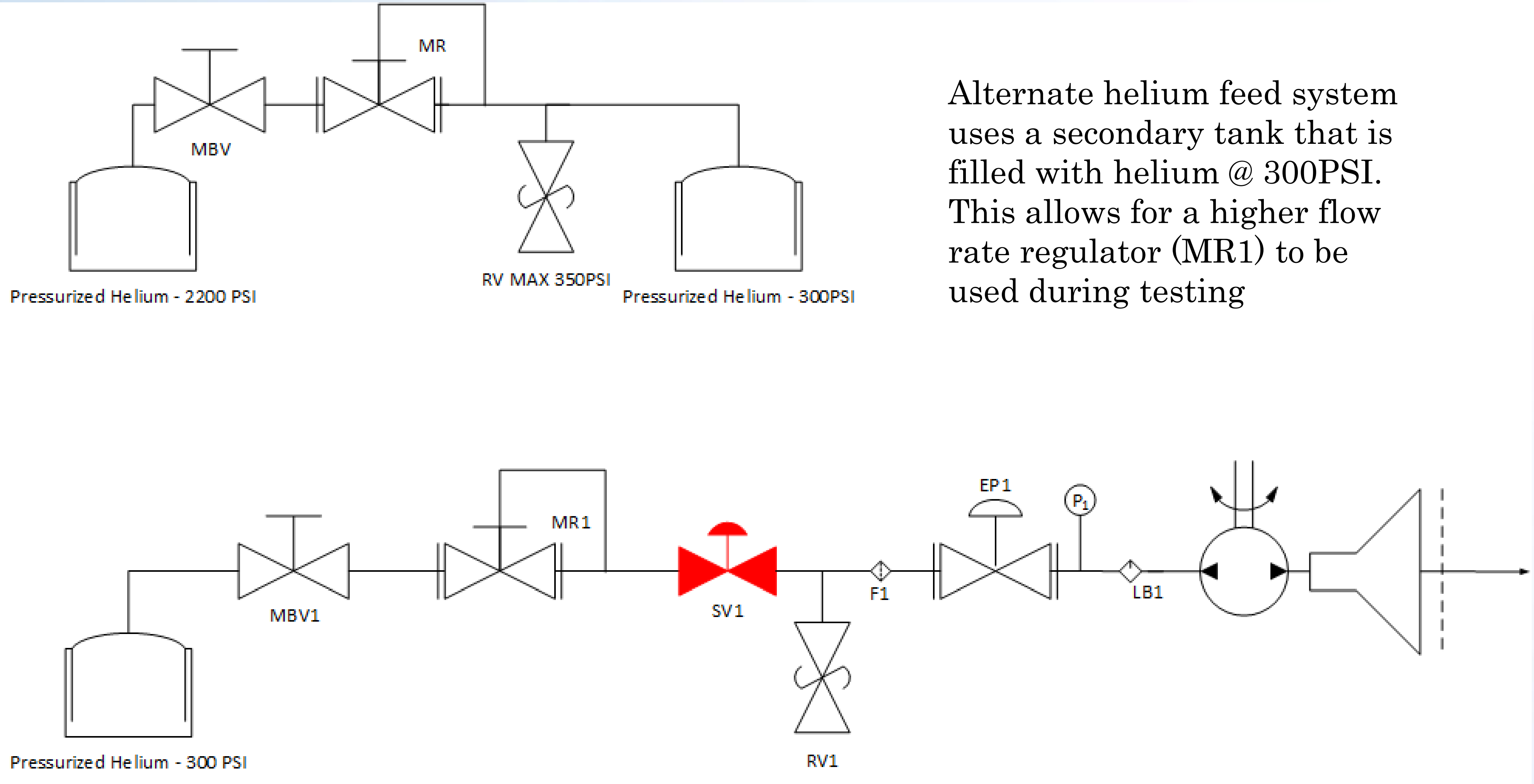
Electronic Fluid Schematic



Nomenclature
SV = Solenoid Valve EP = Electronic Pressure Regulator BPR = Back Pressure Regulator



Alternate Helium Feed system



Alternate helium feed system uses a secondary tank that is filled with helium @ 300PSI. This allows for a higher flow rate regulator (MR1) to be used during testing

Phase 1 – Sensor Testing and Simulation

Electronic pressure regulator design

- Designing motor-regulator mechanical interface
- Designing pressure regulation through control of motor voltage

Sensor Testing

- Circuit Design: Power requirements, reading outputs
- Calibration: sampling rate, noise compensation, error rejection

Simulink Modeling

- Model Drive and Pump system
- Design control law for throttling pump flow rate
- Design realistic throttle profiles

LabView Design

- System circuit design
- Implementation of safety monitoring software

Key Results to obtained

- Completion of pressure regulating system, obtaining resulting accuracy, slew rate, power requirements
- Pressure Transducer performance
- Tachometer mounting and performance
- First iteration of electronics circuit design
- First iteration of system control law
- Estimate of system slew rate (startup and shutdown)
- Generation of various throttle profiles
- First iteration of DAQ design for both data acquisition and system control
- First iteration of system user interface
- Design of system monitoring software
- Confirming testing location

Phase 2 Functional Reqs. met – None

Phase 2 – Subsystem Testing

Drive System Testing

- Motor: RPM/Torque Test
- Motor: Helium Run Test
- Manual Regulator: Pressure Fluctuations
- Electronic Regulator: Calibration to hit maximum accuracy.
- Tachometer: Calibration to hit maximum accuracy
- Power-Off testing: Verifying that solenoid valve correctly closes in case of power loss.
- Throttling Test 1: Throttling from 10-100% using the electronic pressure regulator, confirming control with pressure transducer.
- Throttling Test 2: Fully assembling drive system components. Running through throttle profiles.

Pump System Testing

- Manual Regulator: Pressure Fluctuations
- Power-Off testing: Verifying that solenoid valve correctly closes in case of power loss.
- Electronic Back Pressure Regulator: Calibration to hit maximum accuracy

Key Results to be obtained

- Numerous iterations of throttling control software, monitoring software and electronic regulator software
- Assessment of unforeseen issues, correction of affected components
- Validation of component capabilities, allowing for full system assembly to occur

Phase 2 Functional Reqs. met – FR6, FR7

Phase 3 – Full System Testing

Full scale testing to be conducted

- Drive Shaft Alignment
- Mass flow rate testing
- Throttle profile testing
- System startup and shutdown testing
- Emergency shutdown testing
- Restartability testing

Key Results to be obtained

- Determination of any misalignment of motor/pump driveshaft
- Pump performance: mass flow rate, back pressure, efficiency
- Observation of system under numerous throttle profiles
- Iteration on shutdown procedures to optimize restartability
- Iteration on control law to account for unaccounted system properties

Final Testing

Full scale testing to be conducted

- Throttle profile testing: (10 - 100% Throttle), slew rate testing.
- Quantifying magnitude of outlet pressure fluctuations
- Throttle profile testing (ran through various profiles)
- System startup and shutdown testing, with emergency shutdown and restart-ability

Key Results to be obtained

- Pump performance: mass flow rate, back pressure, efficiency
- Observation of system under numerous throttle profiles
- Iteration on shutdown procedures to optimize re-startability
- Iteration on control law to account for unaccounted system properties

Standard Testing Procedure - Example

Throttle Calibration Test

1. Pump is started up and commanded to throttle setting
2. The pump is run at throttle setting
3. Flow enters control volume for 10 secs
4. Flow is diverted back to regular vent
5. Pump is shutdown
6. Control volume is measured and recorded
7. Test is re-iterated as needed for other throttle settings

Critical Test Elements

- Pump-Drive system
- Control Volume
- Flow Bypass system
- 3 Team membersmonitoring test

Key Results to be obtained

- Validation of throttle model design
- Refinement of throttle model design
- Meeting of critical project element

Safety Set-Up

Worst Case Failures

1. Drive system flywheel – 225 J
2. Drive system casing – 16 J
3. Pump gears – 36 J

Cinder Block Housing Strength

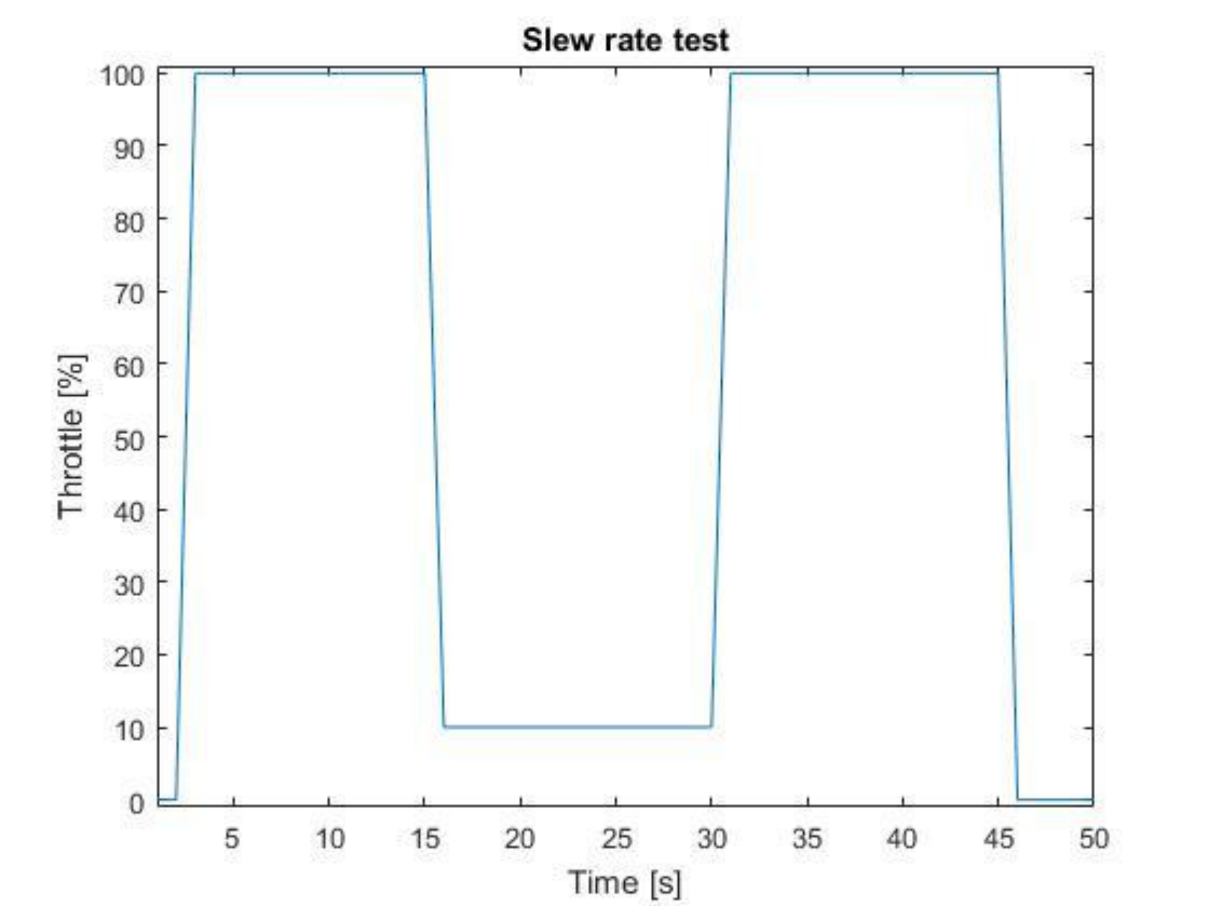
- Chipping - 300 J
- Cracking - 600 J
- Penetration - 800 J
- Failure - 1000 J
- Complete destruction - >1300 J

NPT Threading

- All piping and valving has NPT threading
- Tubing is ¾"with fittings
- Budgeted for necessary fittings to connect tubing and valving

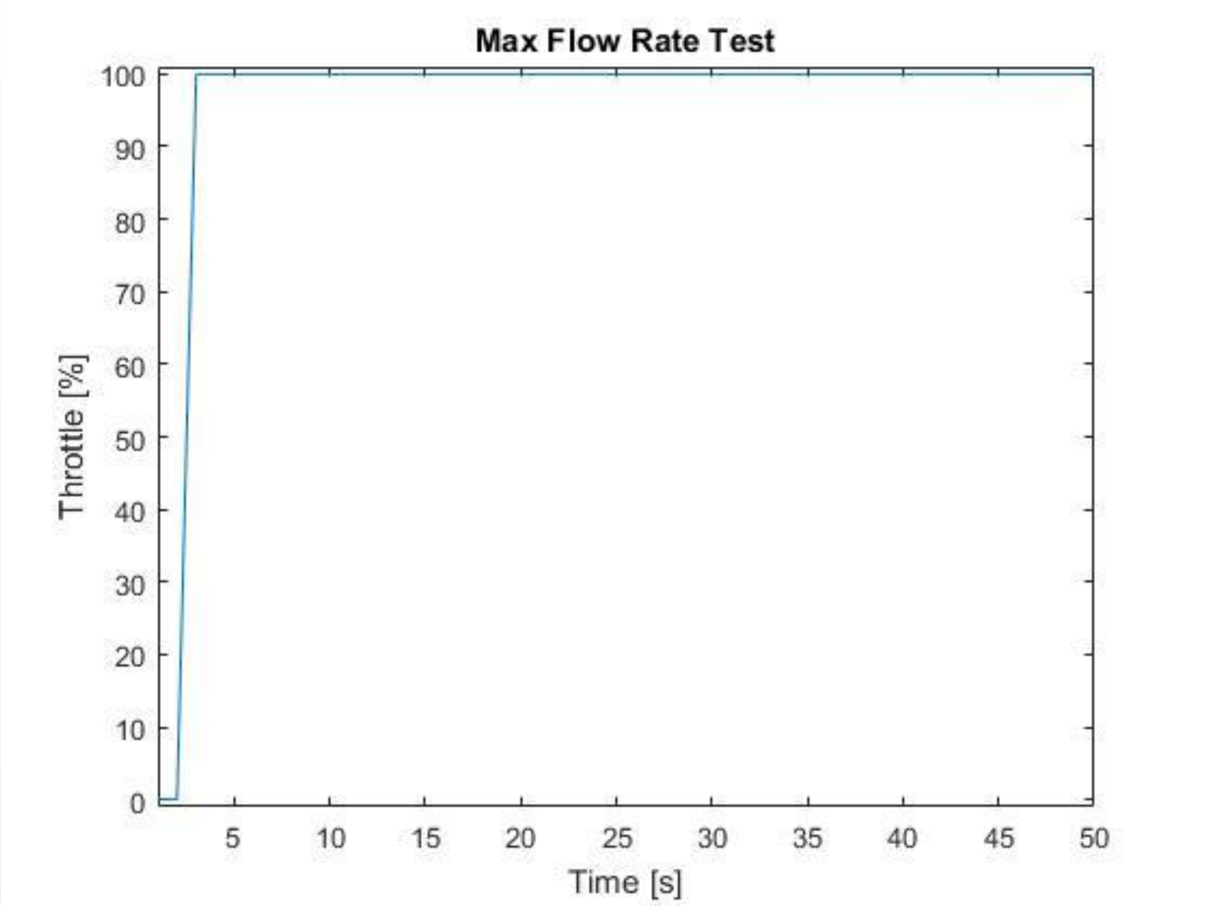
Example Throttle Profile

- Slew rate test example
  - Off, max, min, max, off
  - Verifies
    - Control accuracy
    - Control slew
    - Pneumatic slew



Example Throttle Profile

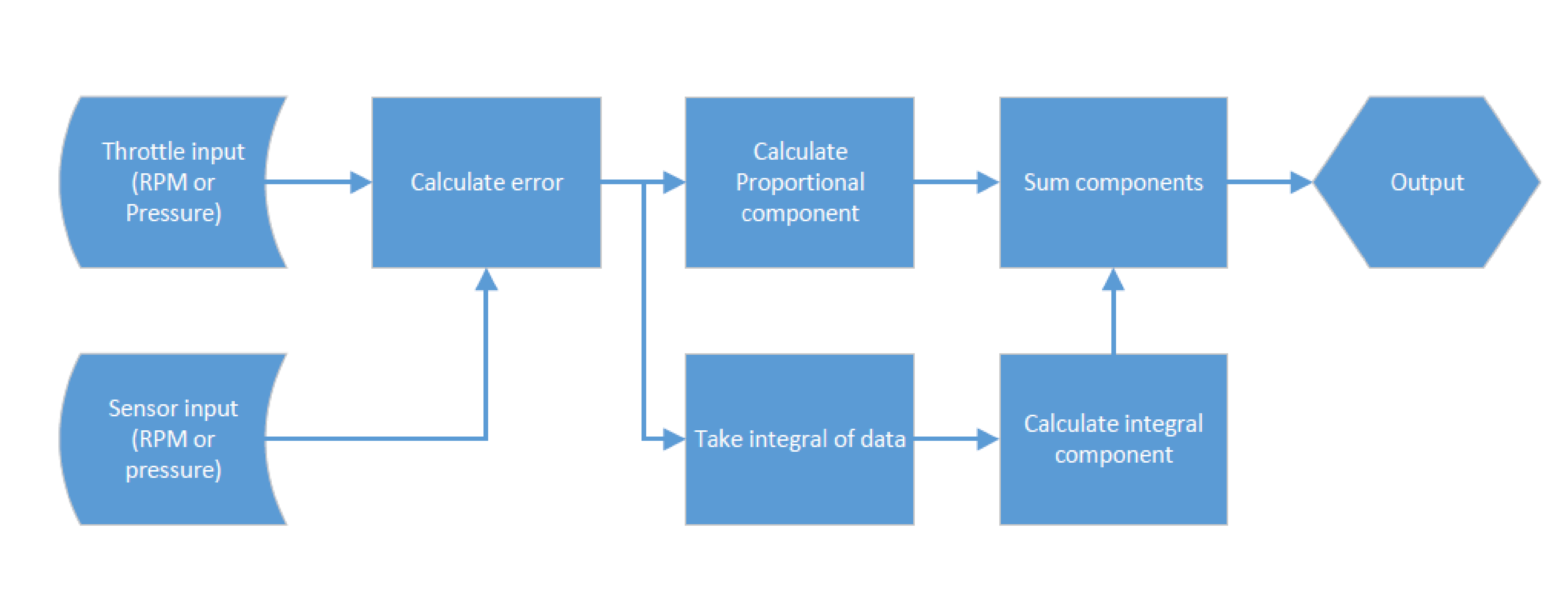
- Max flow test
  - Measure max flow rate
  - Measure max efficiency
  - Verify control stability
  - Calibrate sensors



Software

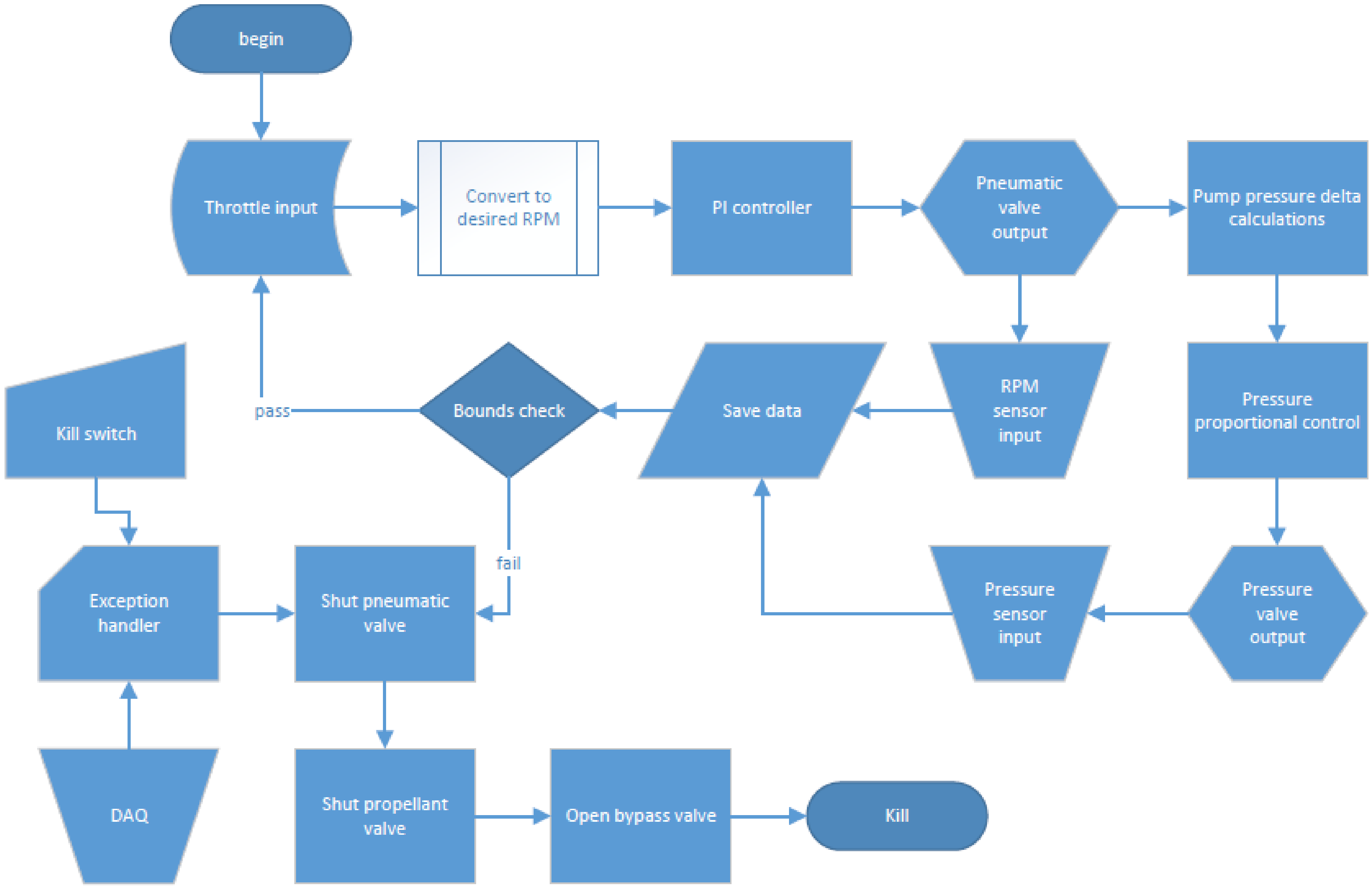
PI controller code flow

- Calculate error – feedback loop component
- Calculate integral – sensor data history
- Calculate P and I components
- Use data in memory



Software Specifics

- Throttle
  - Manual and automatic input options
- Data collection
  - Write to file while running
  - Display outputs to user
- Safety
  - Bounds check on data feed
  - Exception handling
    - Kill switch
    - DAQ error signal

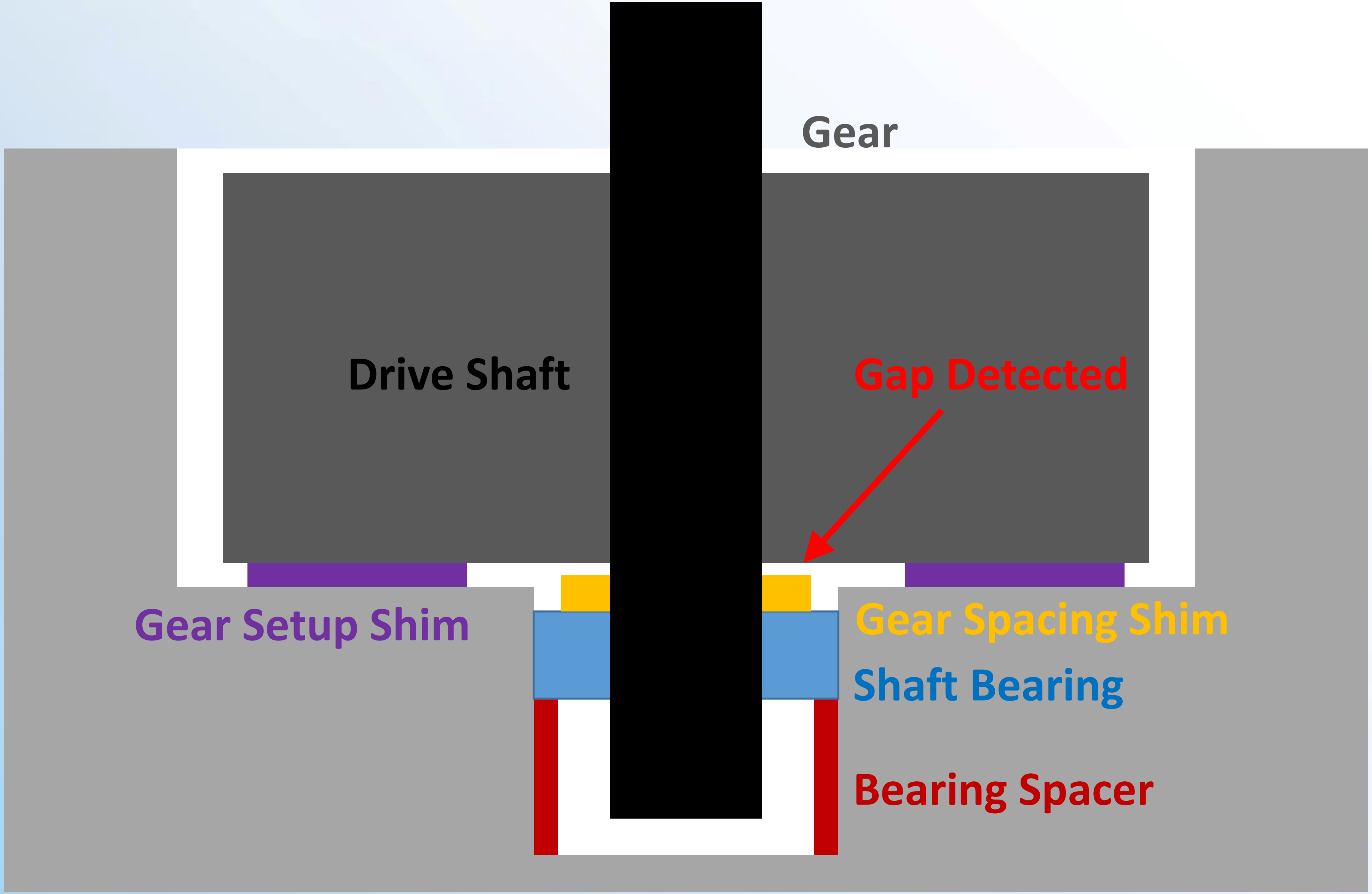

begin
Throttle input
Convert to desired RPM
PI controller
Pneumatic valve output
Pump pressure delta calculations
Kill switch
pass
Bounds check
Save data
RPM sensor input
Pressure proportional control
fail
Exception handler
Shut pneumatic valve
Pressure sensor input
Pressure valve output
DAQ
Shut propellant valve
Open bypass valve
Kill

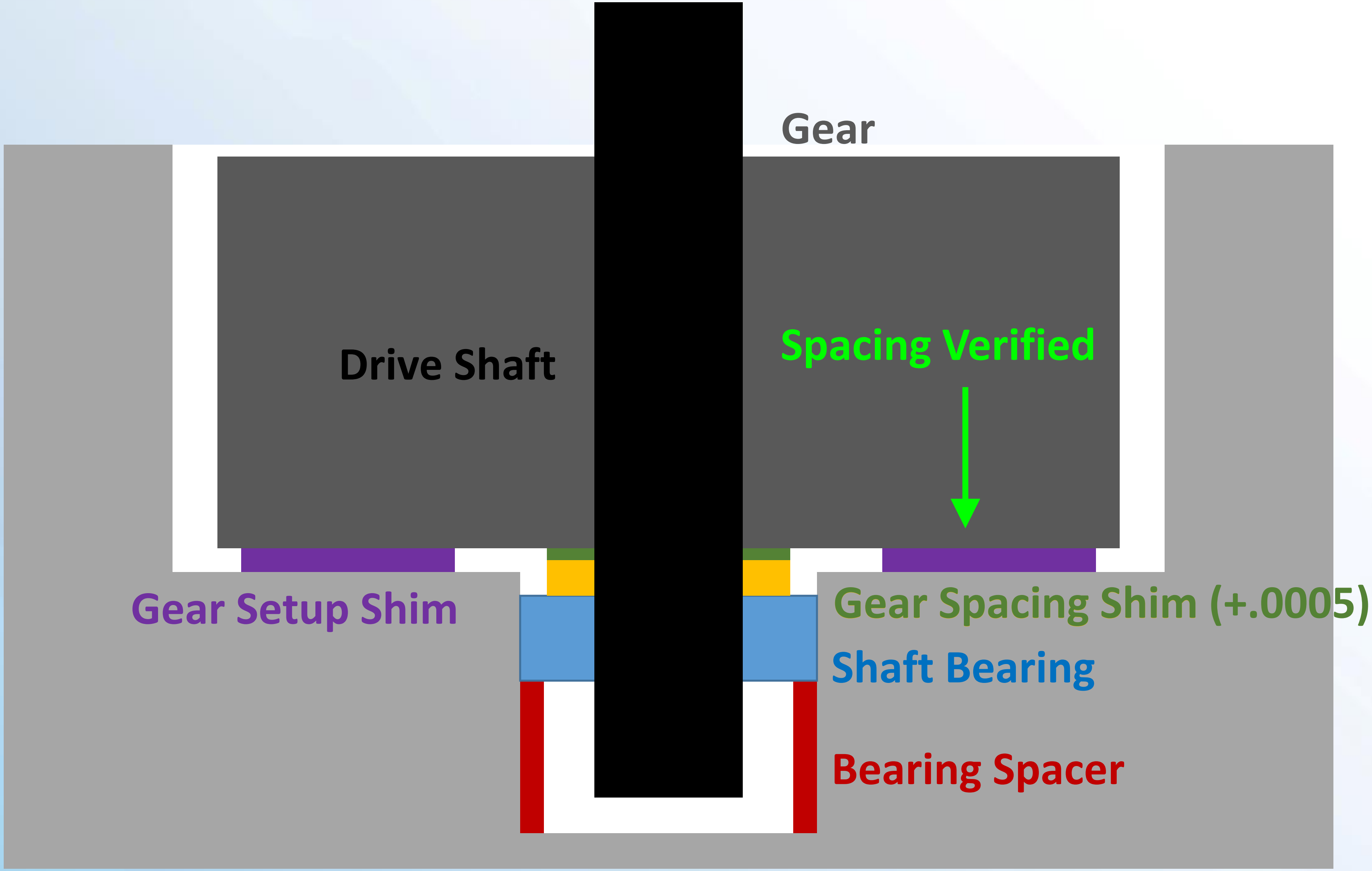
CAD Design – COTS Parts

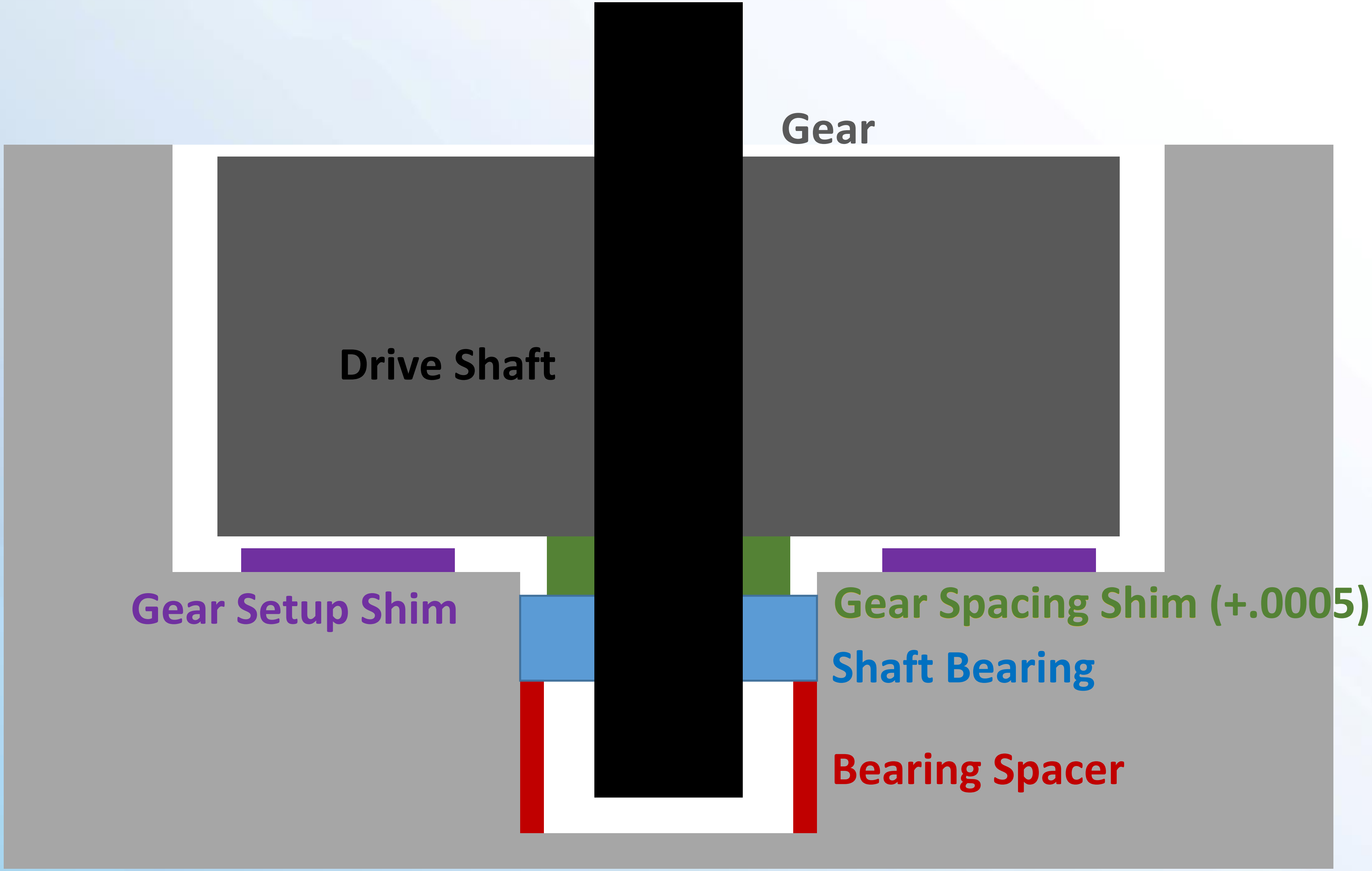
- Shaft Shims
- O-Ring Seal for face plate
- Shaft Seal
- Drive Shaft
- Placement Shaft
- Motor
- Coupler
- L-Brackets for Mounting
- Bearings
- Bolts

CAD Design – Gear Seating and Alignment

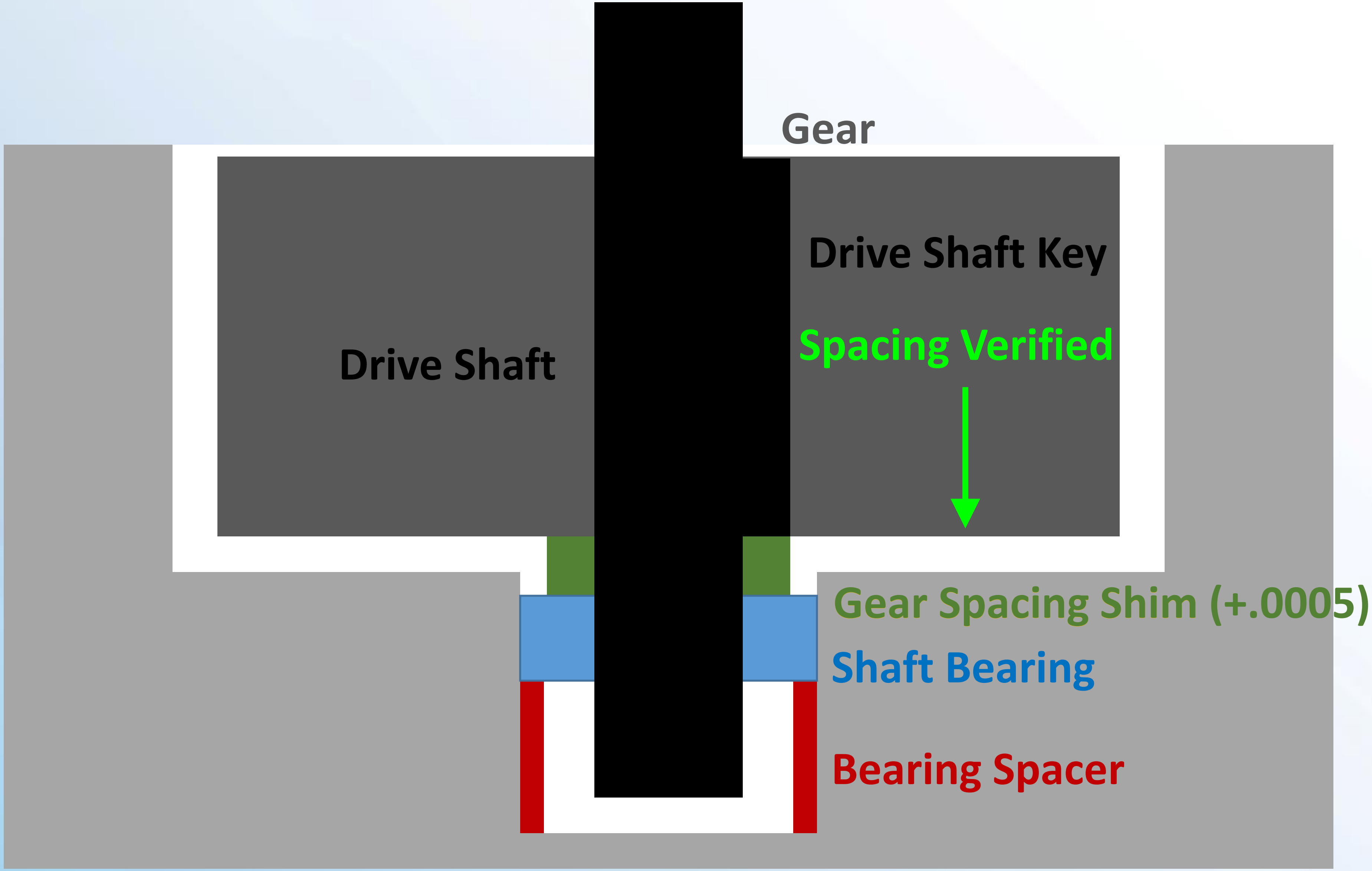
Pump Assembly


Gear
Drive Shaft
Gap Detected
Gear Setup Shim
Gear Spacing Shim
Shaft Bearing
Bearing Spacer


Gear
Drive Shaft
Spacing Verified
Gear Setup Shim
Gear Spacing Shim (+.0005)
Shaft Bearing
Bearing Spacer

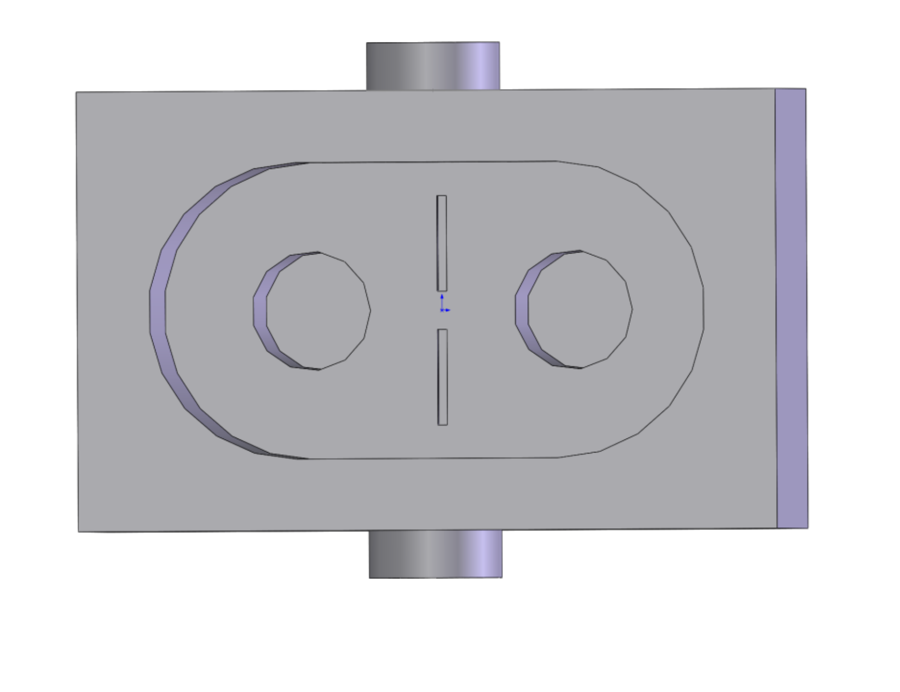


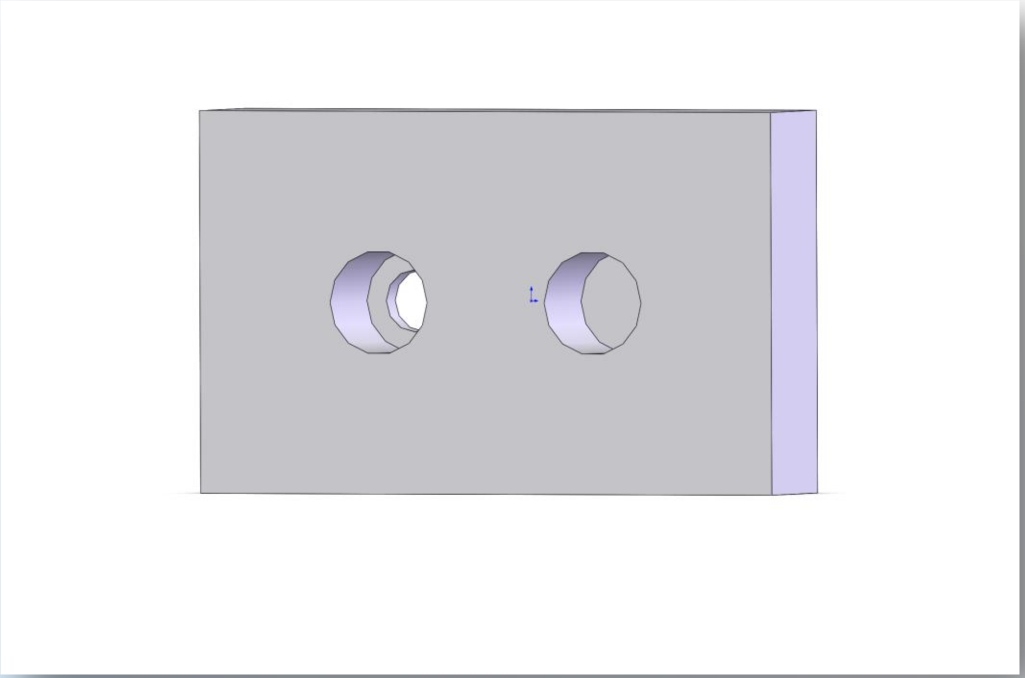
Gear
Drive Shaft
Gear Setup Shim
Gear Spacing Shim (+.0005)
Shaft Bearing
Bearing Spacer


Gear
Drive Shaft Key
Spacing Verified
Drive Shaft
Gear Spacing Shim (+.0005)
Shaft Bearing
Bearing Spacer

CAD Design – Housing and Panel

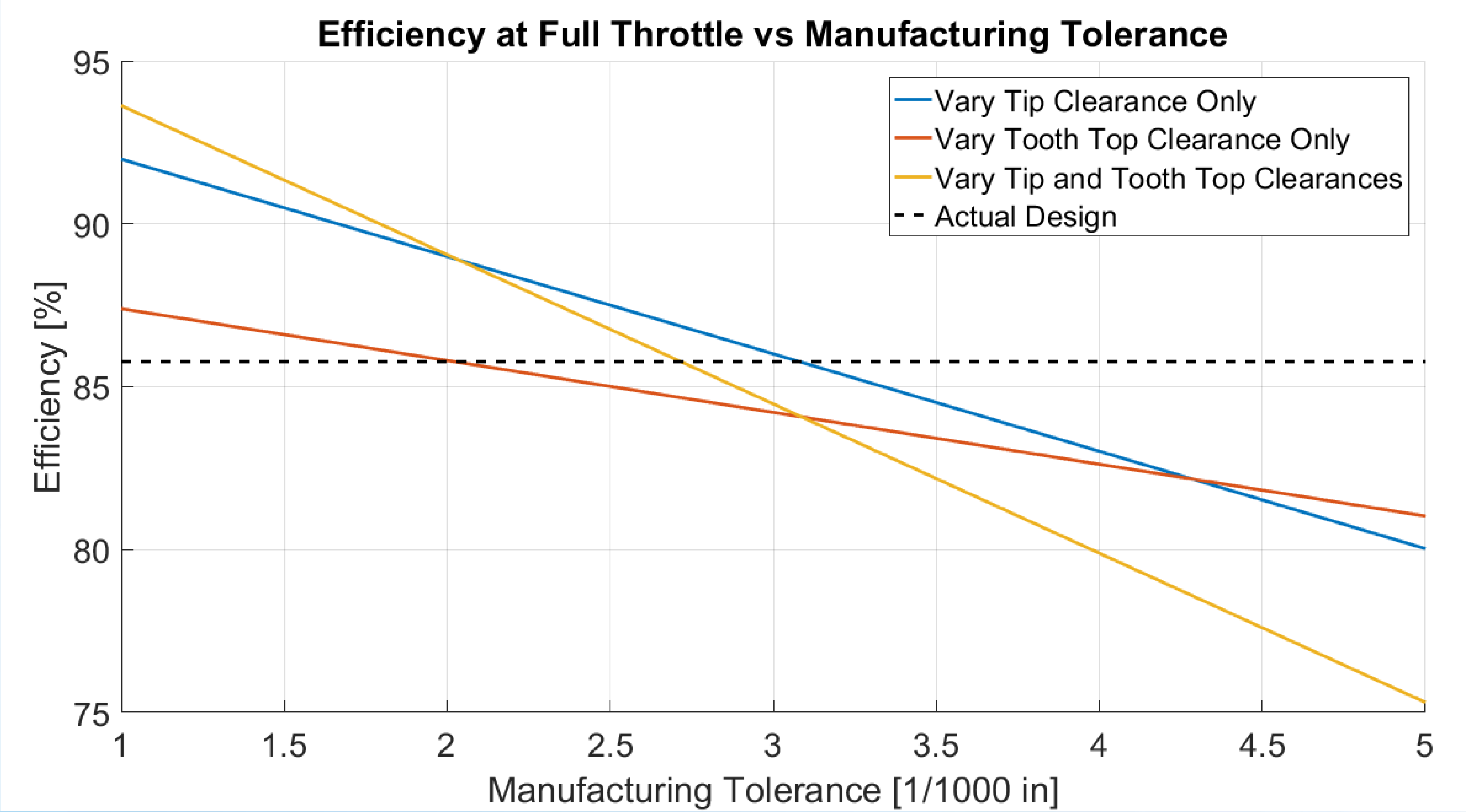
Machined either at SAS's shop or the Aerospace Machine shop on campus out of Stainless Steel 304



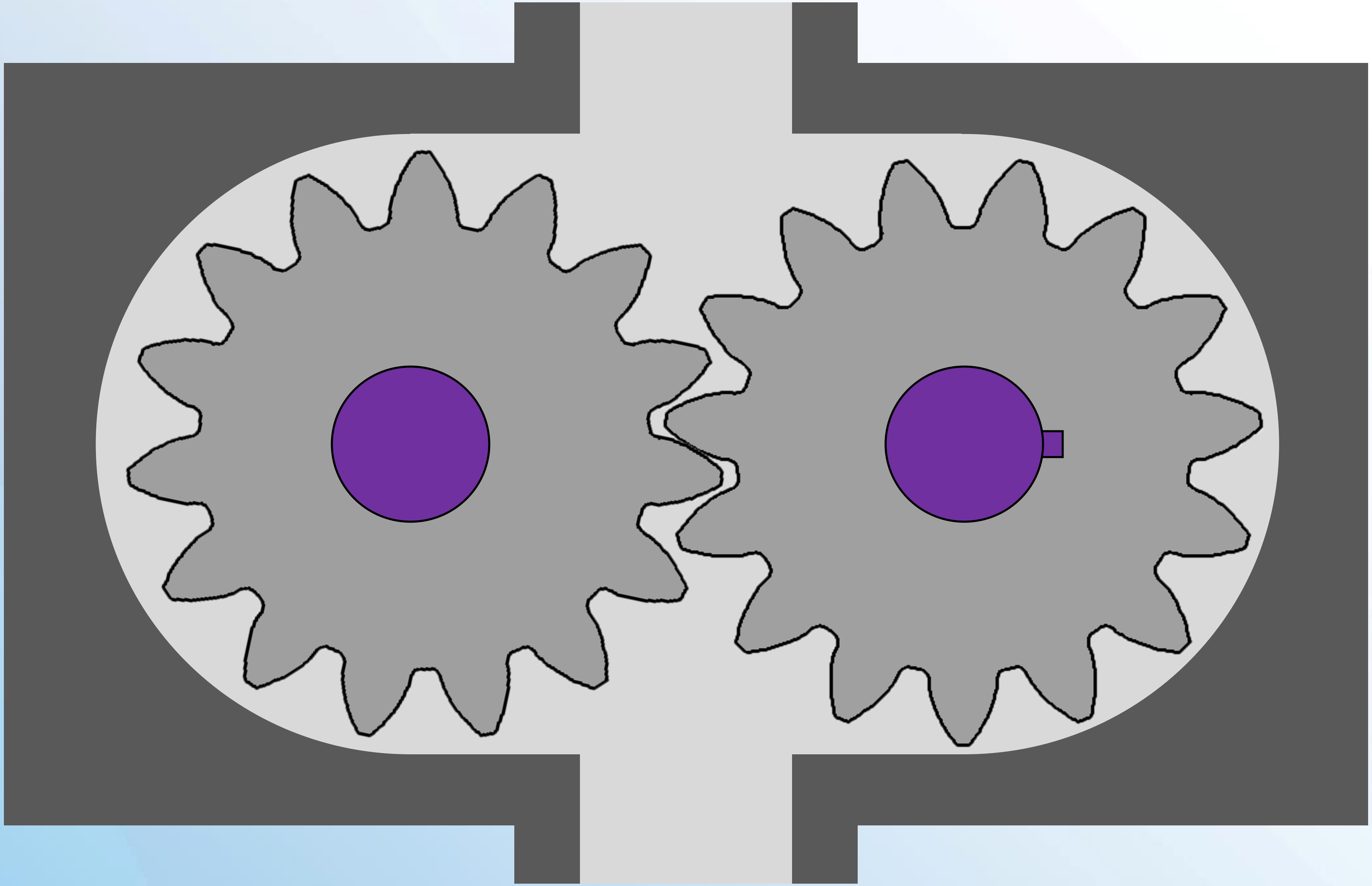


Tolerance Stackup

Tolerance Sensitivity Analysis



Tolerance Stackup: Gears and Housing

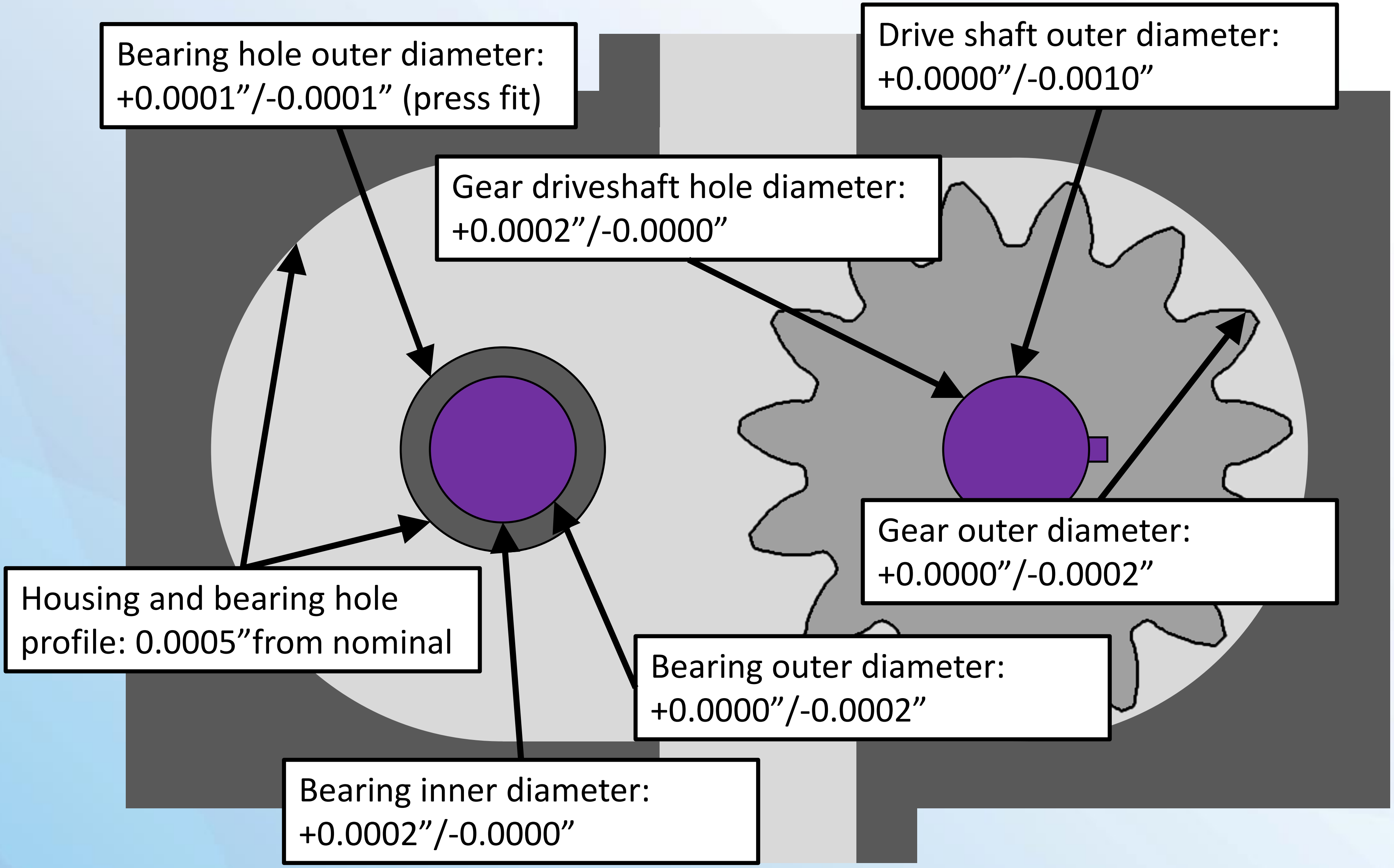


Tolerance Stackup: Error Sources

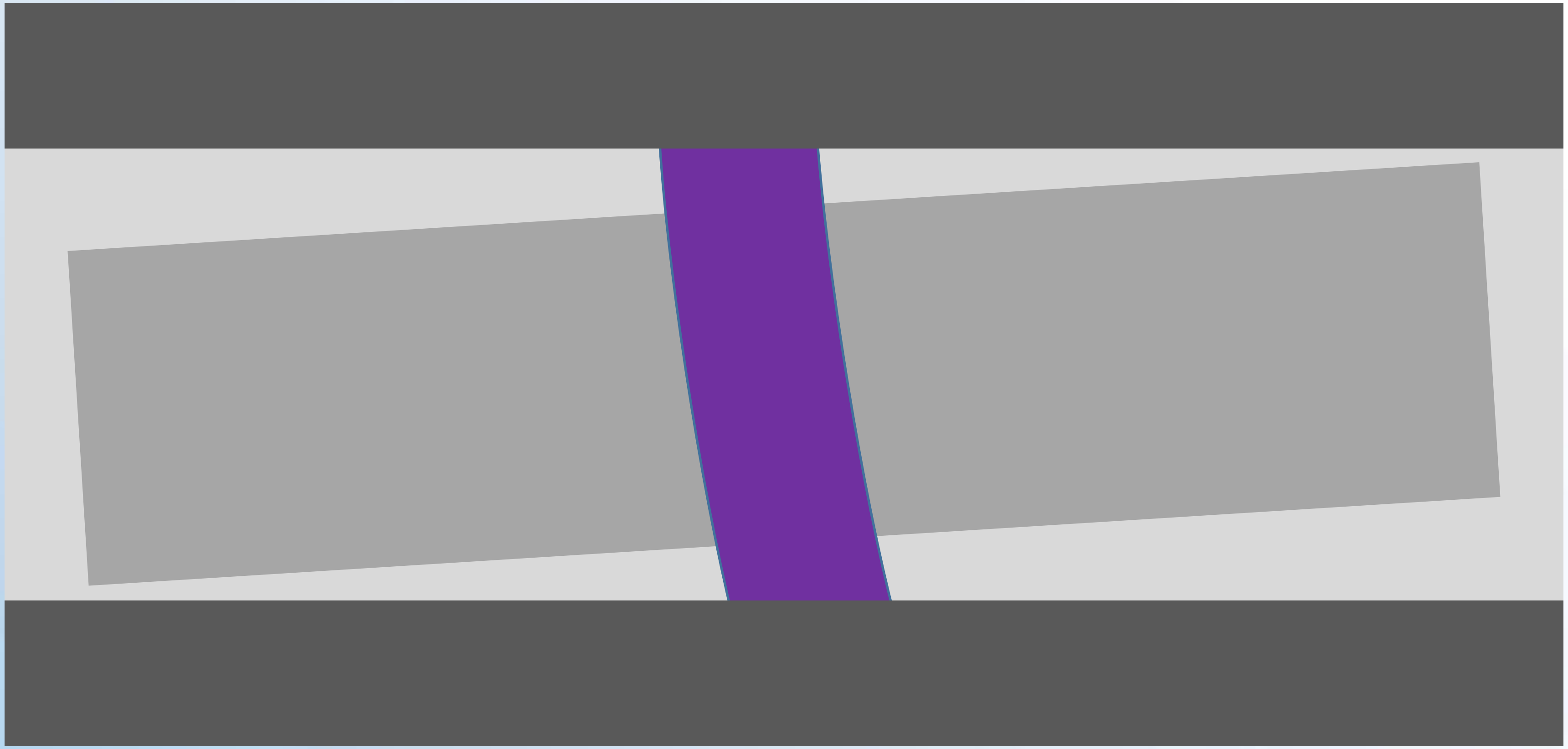
- Driveshaft outer diameter tolerance
  - +0.0000”/-0.0005”
- Bearing outer diameter tolerance
  - +0.0000”/-0.0002”
- Bearing inner diameter tolerance
  - +0.0002”/-0.0000”
- Bearing hole inner diameter tolerance
  - +0.0001”/-0.0001” (chamfered press fit)
- Housing/bearing hole profile tolerance
  - Profile misplaced up to 0.0005” from nominal profile
- Gear outer diameter tolerance
  - -0.0000”/-0.0002”
- Gear driveshaft hole inner diameter tolerance
  - +0.0002”/-0.0000”

- **Maximum clearance deviation**
  - **+0.0009”/-0.0015” (linear sum)**
- **Maximum allowable clearance deviation**
  - **+0.0015”/-0.0015 (feasible!)**
- **Minimum clearance is 0.0006” (limited by gear/housing interference)**
- **Maximum clearance is 0.0030” (limited by efficiency requirements)**

Tolerance Stackup: Gears and Housing



Tolerance Stackup: Gears and Housing



- Maximum allowable misalignment results in a 0.002” deviation at a diameter of 0.0015”
  - Results in a maximum allowable angular misalignment of 0.11°
- Straightness tolerance is 0.0030” per ft which results in 0.00025” per in
  - Results in a maximum possible misalignment of 0.014°
- Maximum bearing hole misalignment is 0.0010”
  - Results in a maximum possible misalignment of 0.038°
- Maximum gear misalignment is 0.052°

Mechanical Analysis

Mechanical Analysis: Drive Shaft

- Driveshaft properties:
  - Material: 304 Stainless
  - Diameter: 3/4”
  - Length: 12”
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Straightness tolerance of 0.003”
  - Misalignment factor of 4.0
  - Analyzed as a circular cross section with torque loading and bending due to misalignment
  - Fatigue analysis completed assuming 100 hrs of run time
- Margins
  - Displacement: 0.7 degrees of twist (twist stores 0.4% of the amount of energy that the spinning components store)
  - Material Failure: 0.45 (Max. VM Stress: 62.4 Mpa, Yield Stress: 207 Mpa)
  - Fatigue: 0.12 (Max VM Stress: 62.4 Mpa, Max Allowable Stress: 155 Mpa (for 100 hrs run time)

Mechanical Analysis: Keyway

- Key properties:
  - Material: 303 Stainless
  - Driveshaft diameter: 3/4”
  - Keyway length: 2 in
  - Keyway width: 3/16”
  - Keyway depth: 3/32”
  - Key height: 1/4”
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Keyway analyzed in pure shear (assumes close fit of gear to drive shaft)
- Margins
  - Displacement: N/A
  - Material Failure: 0.45 (Max. VM Stress: 63.0 Mpa, Yield Stress: 207 Mpa)
  - Fatigue: 0.12 (Max VM Stress: 63.0 Mpa, Max Allowable Stress: 175 Mpa (for infinite run time)

Mechanical Analysis: Keyway

- Keyway (driveshaft) properties:
  - Material: 304 Stainless
  - Driveshaft diameter: 3/4”
  - Keyway length: 2 in
  - Keyway width: 3/16”
  - Keyway depth: 3/32”
  - Key height: 1/4”
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Key analyzed in pure shear (assumes close fit of gear to drive shaft)
- Margins
  - Displacement: N/A
  - Material Failure: 0.52 (Max. VM Stress: 56.7 Mpa, Yield Stress: 215 Mpa)
  - Fatigue: 0.12 (Max VM Stress: 56.7 Mpa, Max Allowable Stress: 175 Mpa (for infinite run time)

Mechanical Analysis: Gear Teeth

- Gear properties:
  - Material: 17-4 PH, H1150
  - Gear Pitch Diameter: 2.755”
  - Face Width: 1.500”
  - Pressure Angle: 20°
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Analyzed both contact and bending stresses on teeth
  - Fatigue analysis completed assuming 100 hrs of run time
- Margins
  - Displacement: N/A
  - Material Failure: 0.56 (Max. Contact Stress: 290 Mpa, Yield Stress: 1140 Mpa)
  - Fatigue: 0.06 (Max VM Stress: 290 Mpa, Max Allowable Stress: 762 Mpa (for 100 hrs run time)

Gear Teeth Analysis: Cont'd

- Contact stress drives margins
  - margin on contact is 0.58
  - margin on bending is 48.0

- Allowable contact stress is:

$$\sigma_{allow,c} = \left(\frac{S_c}{n_s}\right)\left(\frac{Z_n\, C_H}{K_t\, K_r}\right)$$

  - S_c = yield strength of gear material
  - $n_s = 1$
  - Z_n = contact cycle factor = 0.98 for 100 hrs run time (slide 31)
  - C_H = Hardness ratio = 1 if both gears are the same material (ANSI/AGMA 2001- D04)
  - K_t = Temperature factor = 1 for T<250F (slide 30)
  - K_r = 1 for probability of survival of 99.99% (standard) (slide 30)

*Unless noted, all "slide##" denotations refer to the slide in presentation: https://www3.nd.edu/~manufact/FME_pdf_files/FME3_Ch14.pdf at which the equation or value can be found

Gear Teeth Analysis: Cont'd

- Maximum contact stress is:

$$\sigma_{maximum,c} = C_p * \sqrt{W_t\, K_o\, K_v\, K_s\, K_m\, C_f \left(\frac{1}{D\ F\ I}\right)}$$

  - D = pitch diameter
  - F = face width
  - ω = angular velocity of gears
  - Phi = pressure angle of gears
  - E = modulus of elasticity of gear material
  - v = poisson's ratio of gear material
  - $V_t = \omega$*D/2 (slide 42)
  - T_{max} = maximum gear torque = maximum driveshaft torque divided by 2
  - C_p = sqrt(E/(2*pi*(1-v^2)) = elastic coefficient
  - W_t = T/(D/2) = tangential load
  - K_o = 1.2 = overload factor (slide 37)

*Unless noted, all "slide##" denotations refer to the slide in presentation: https://www3.nd.edu/~manufact/FME_pdf_files/FME3_Ch14.pdf at which the equation or value can be found

Gear Teeth Analysis: Cont'd

- K_v = $((A+(C*sqrt(v_t))/A)^B$ = dynamic factor (A,B,C values from source below) (slide 42)
  - A = 50+(56*(1-B))
  - B = 0.25(12-Q_v)^0.667
    - Q_v = 10 (quality rating)
  - C = 14.14 (from source below)
- K_s = 1 = size factor (slide 37)
- $K_m = 1+(C_{mc}*((C_{pf}*C_{pm})+(C_{ma}*C_e)))$ (slide 38)
  - $C_{mc} = 1$
  - $C_{pf} = 0$
  - $C_{pm} = 1$ (no drive shaft flexure)
  - $C_{ma} = A+(B*F)+(C*F^2)$ (A,B, C from slide 40 of source below)
    - A = 0.127
    - B = 6.22E-4
    - C = -1.69E-7
  - $C_e = 1$
- C_f = pitting resistance factor (slide 31)
- I = ((sin(phi)*cos(phi))/4) = geometry pitting resistance factor (ANSI/AGMA 2001- D04)

*Unless noted, all "slide##" denotations refer to the slide in presentation: https://www3.nd.edu/~manufact/FME_pdf_files/FME3_Ch14.pdf at which the equation or value can be found

Mechanical Analysis: Housing End Plates

- Endplate properties:
  - Material: 304 Stainless
  - Minimum thickness: 5/8”
  - Maximum allowable displacement: 0.0001”
- Analysis assumptions and values:
  - Uses max pressure of 750 psi across full surface of endplate
  - Pressure spike factor of 1.2
  - Analyzed as rectangular area that circumscribes the oval shaped area it will cover (conservative)
  - Analyzed as a plate with fixed edges (valid because no separation on endplate bolts)
- Margins
  - Displacement: 0.00005”
  - Material Failure: 0.43 (Max. Bending Stress: 60.0 Mpa, Yield Stress: 215 Mpa)
  - Fatigue: N/A

Mechanical Analysis: Housing Walls

- Housing wall properties:
  - Material: 304 Stainless
  - Minimum thickness: 1/2”
  - Maximum allowable displacement: 0.0001”
- Analysis assumptions and values:
  - Uses max pressure of 750 psi inside of gear cavity
  - Pressure spike factor of 1.2
  - Analyzed using hoop stress and strain equations
- Margins
  - Displacement: 0.00004” (driving margin)
  - Material Failure: 4.03 (Max. Hoop Stress: 17.1 Mpa, Yield Stress: 215 Mpa)
  - Fatigue: N/A

Mechanical Analysis: Housing Walls

- Housing bolts properties:
  - Grade 8 bolts, 1/2”-13x2”
  - Minimum thread engagment: 1-1/2”
  - Tap material is 304 Stainless
  - Bolt torque: 42+/-2 ft-lbs
- Analysis assumptions and values:
  - Uses max pressure of 750 psi inside of gear cavity
  - Pressure spike factor of 1.2
  - Analyzed tensile failure of bolt, shear of threads and shear of tap
- Margins
  - Displacement: 6.02 (margin on bolt separation)
  - Material Failure: 0.04 (Max tap VM stress: 82.3 Mpa, Max. allowable stress: 215 Mpa)
  - Fatigue: N/A

Motor Mount Bolts: Housing Walls

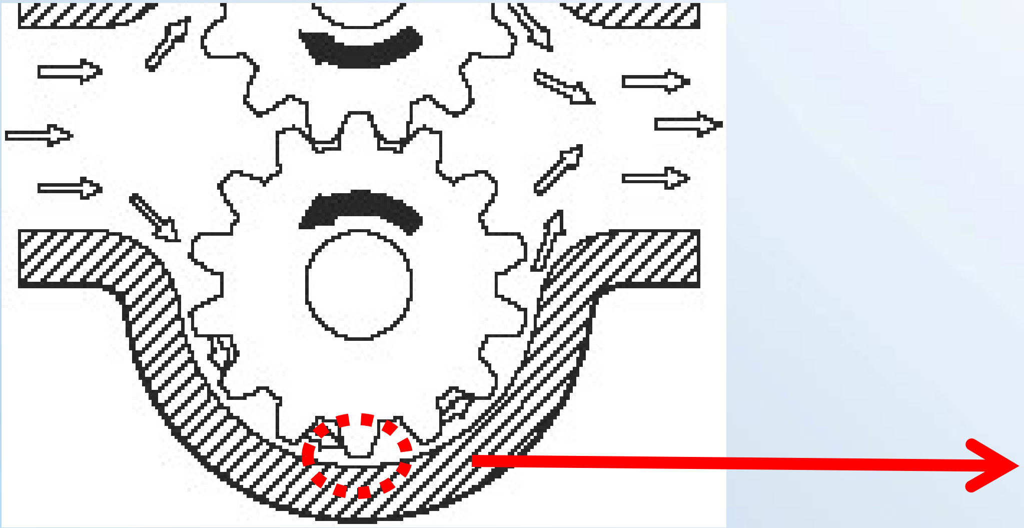
- Housing bolts properties:
  - Grade 10.9 bolts, M8-1.25x14
  - Minimum thread engagment: 12 mm
  - Tap material is Cast Iron (ASTM 20, conservative)
  - Bolt torque: 45+/-2 in-lbs
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Analyzed tensile failure of bolt, shear of threads and shear of tap
- Margins
  - Displacement: 2.47 (margin on bolt separation)
  - Material Failure: 0.02 (Max tap VM stress: 59.7 Mpa, Max. allowable stress: 152 Mpa)
  - Fatigue: N/A

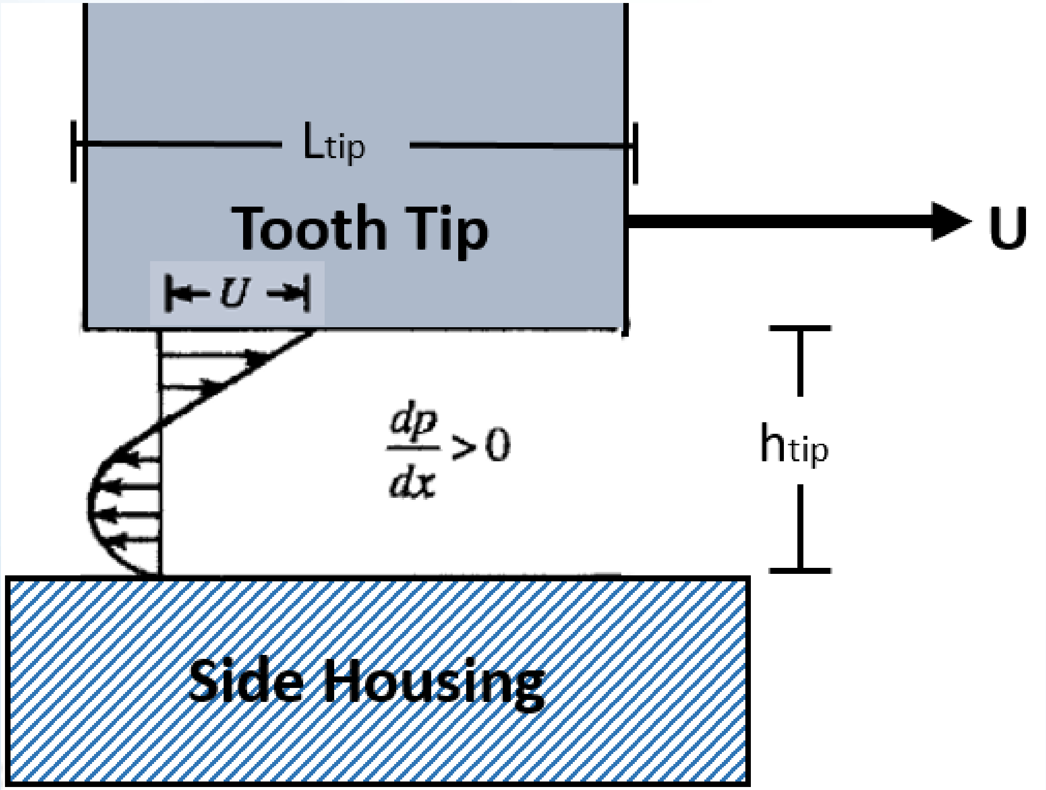
Motor Mount Bolts: Housing Walls

- Housing bolts properties:
  - Grade 10.9 bolts, M8-1.25x14
  - Minimum thread engagment: 12 mm
  - Tap material is Cast Iron (ASTM 20, conservative)
  - Bolt torque: 45+/-2 in-lbs
- Analysis assumptions and values:
  - Uses max torque of 37.15 Nm (100% throttle NTO)
  - Shock load factor of 1.2
  - Analyzed tensile failure of bolt, shear of threads and shear of tap
- Margins
  - Displacement: 2.47 (margin on bolt separation)
  - Material Failure: 0.02 (Max tap VM stress: 59.7 Mpa, Max. allowable stress: 152 Mpa)
  - Fatigue: N/A

Fluid Model

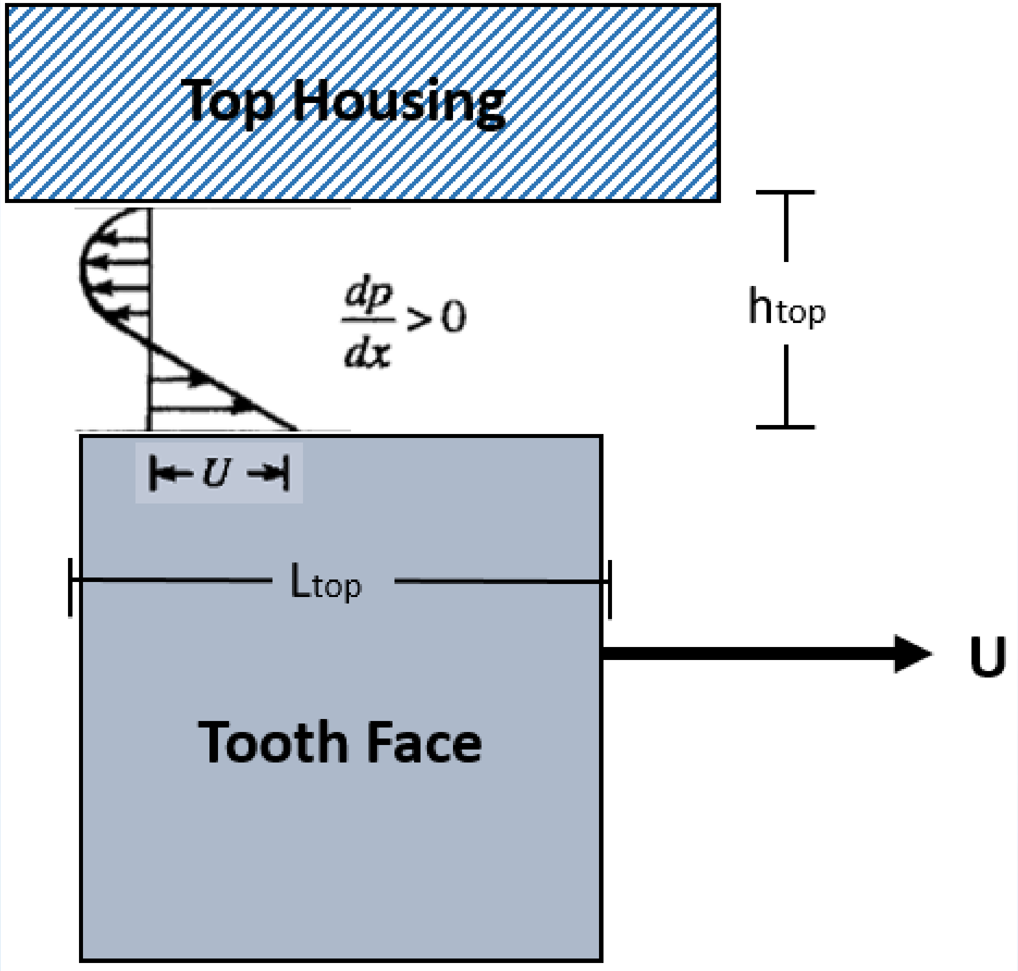
Slip-back path 1: Between teeth tips and outer housing





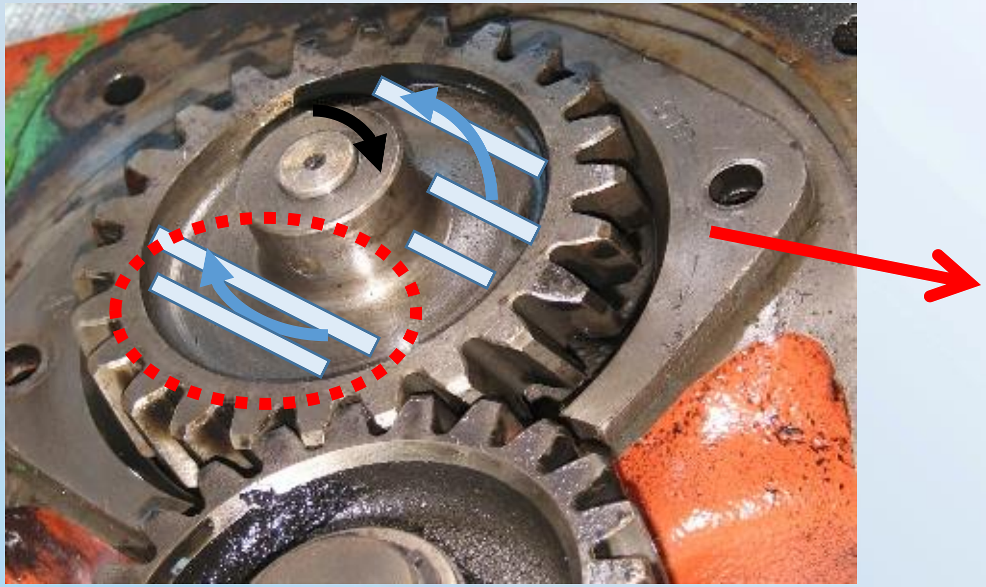
$$\dot{m}_{slip_1} = \frac{\rho h_{tip}^3 w \Delta P_1}{12 \mu L_{tip}}$$

Slip-back path 2: Between teeth tops and upper housing



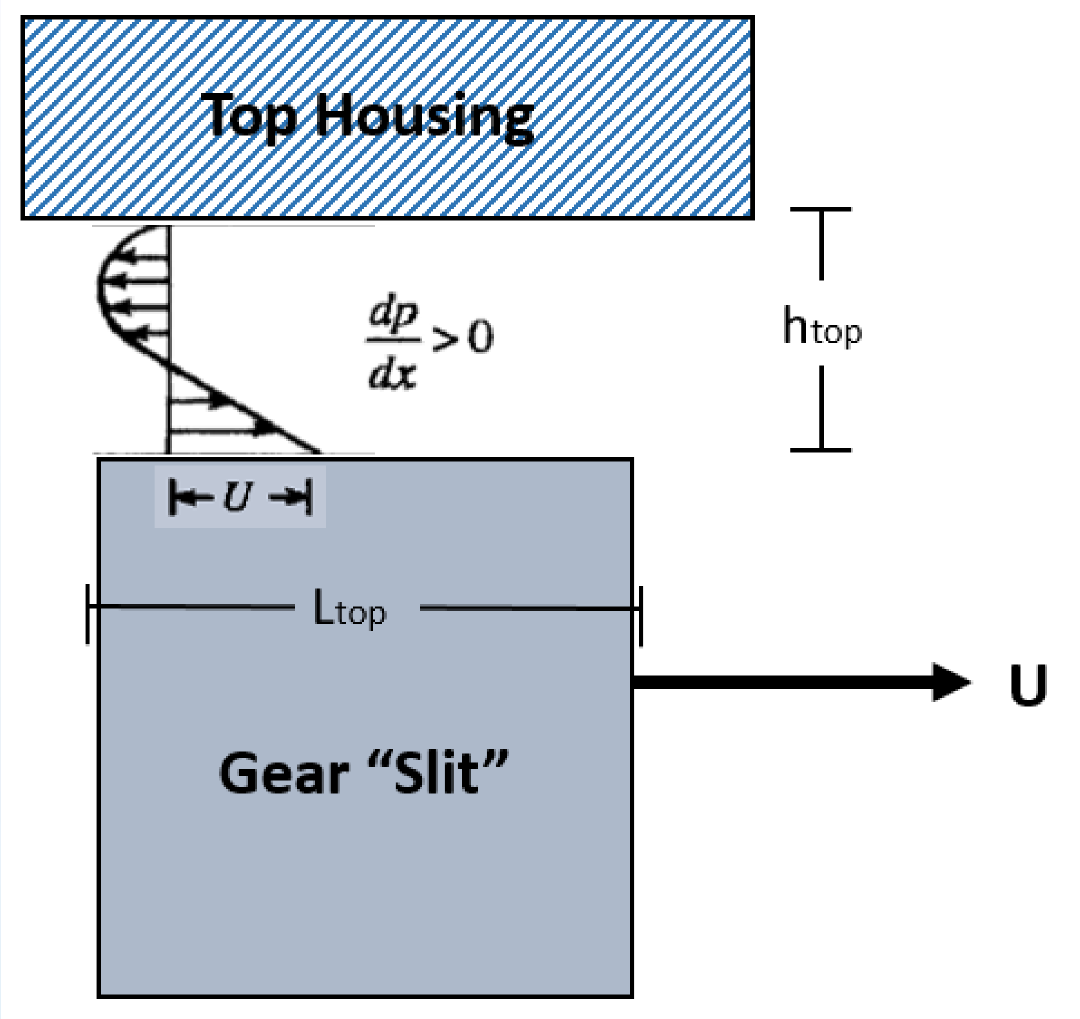
$$\dot{m}_{slip_2} = \frac{3\rho h_{top}^3 D}{16 n \mu} \frac{\Delta P_2}{L_{top}}$$

Slip-back path 3: Between gear top and upper housing

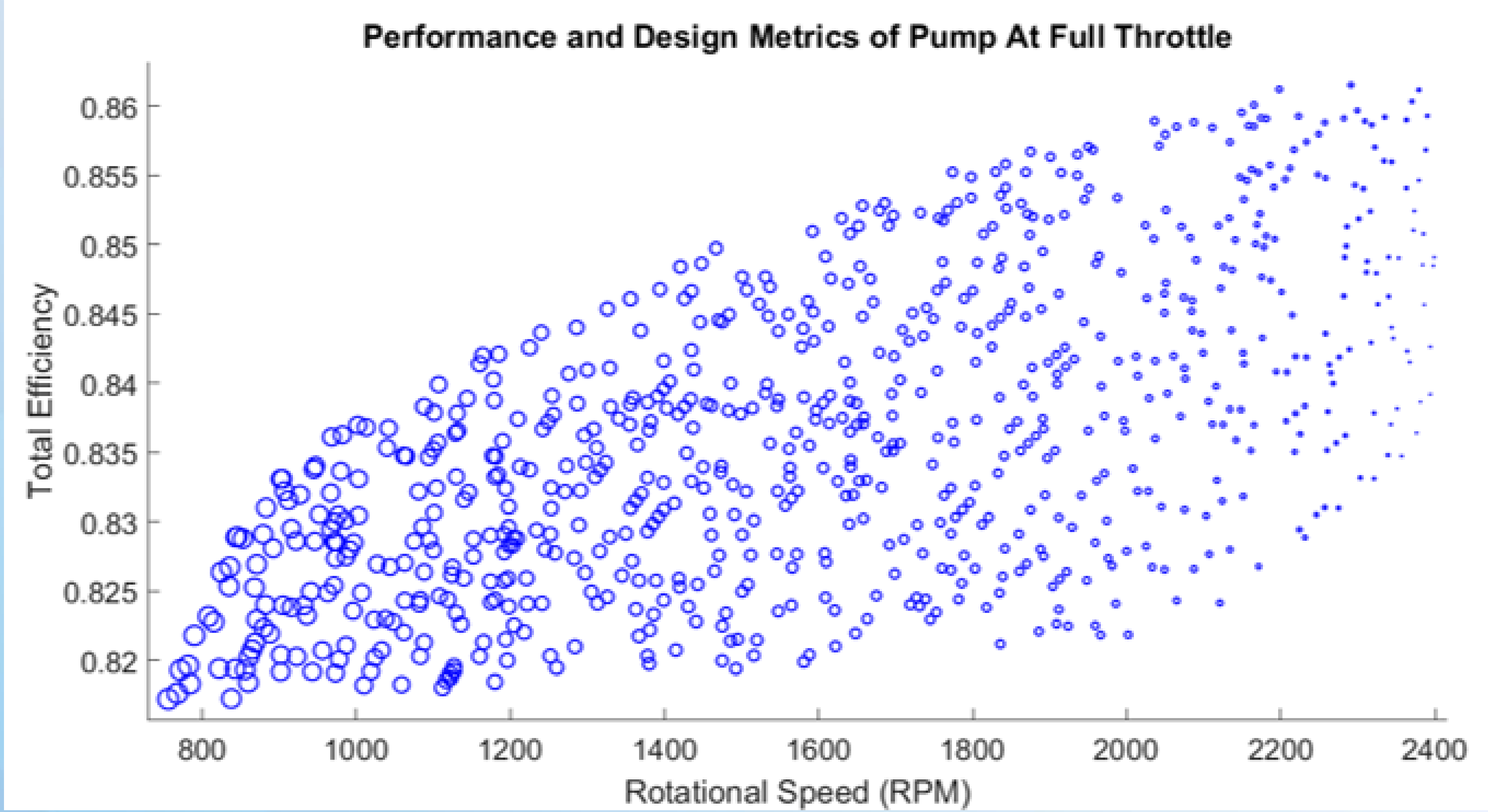


Flow not in x direction "cancels"

$$\dot{m}_{slip_3} = \frac{\pi \rho h_{top}^3 \Delta P_3}{32\mu}$$



Design Space



Thermal Model

Forced Convection

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \qquad \text{(W)}$$

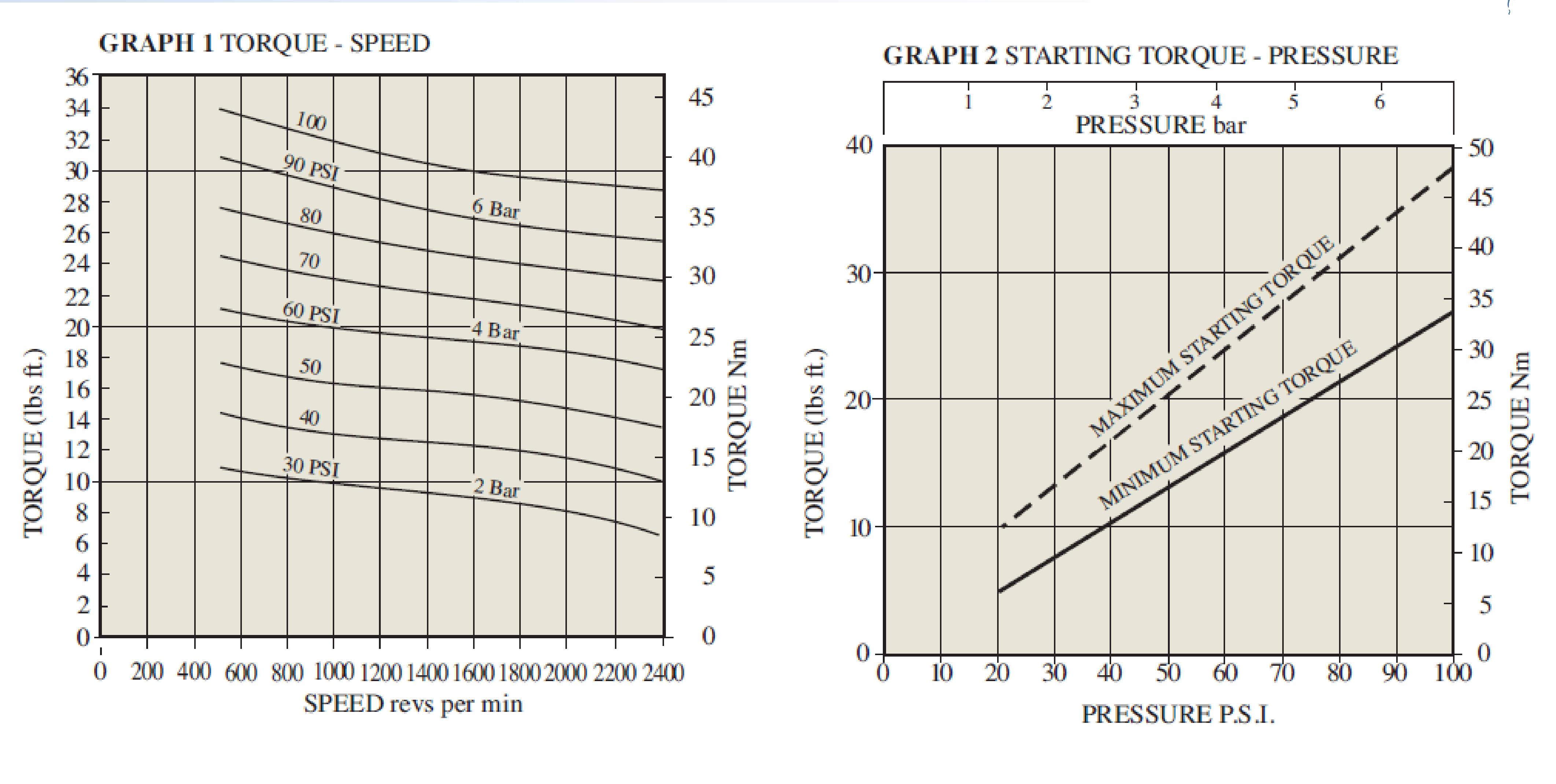
where

h = convection heat transfer coefficient, $W/m^2 \cdot °C$
A_s = heat transfer surface area, m^2
T_s = temperature of the surface, °C
T_∞ = temperature of the fluid sufficiently far from the surface, °C

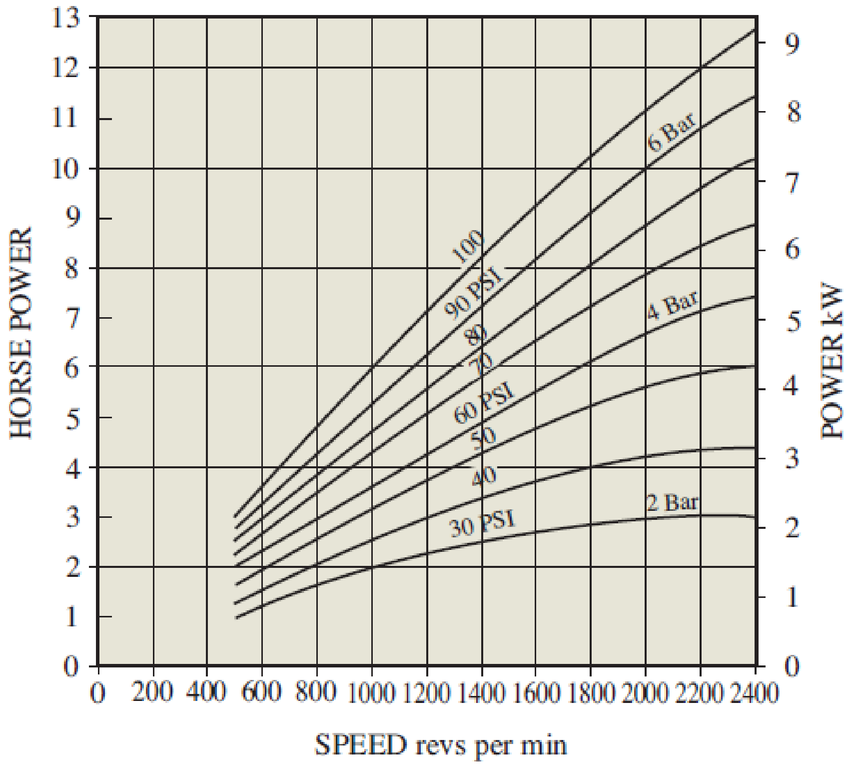
- Tooth tip temperature rises by only 2 deg C

- dL ~= 1.17e-5
- clearance = 3e-3

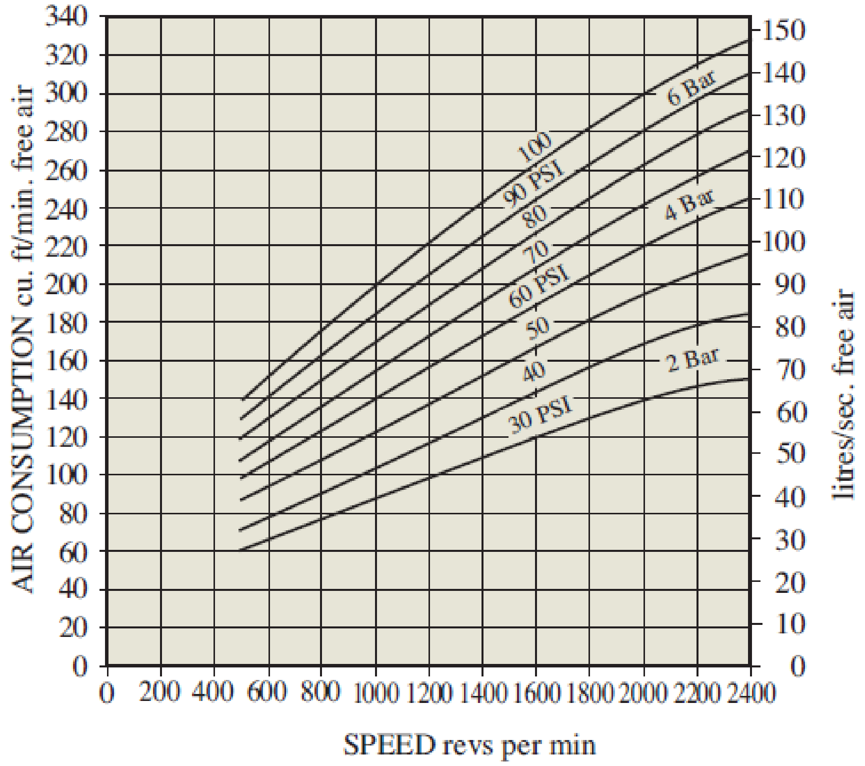
Drive System Specs



GRAPH 3 POWER - SPEED



GRAPH 4 CONSUMPTION - SPEED



Attitude:

The motor can be operated in all positions.

Airline filtration and lubrication:

Use 64 micron filtration or better. Choose a lubricator suitable for the flow required. Prior to start up, inject oil into the inlet port.

Lubricator drop rate:

8-10 drops per minute continuous operation.
14-16 drops per minute intermittent operation.

Polar Moment of Inertia:

30 lb.in2 (8.8 g.m2).

Maximum overhung force on shaft:

400 lbf (1750N) In certain circumstances this may be extended. Consult your Globe Distributor. Axial loads should be kept down to a minimum.

Maximum temperatures:

-40° to +176° Farenheit. (-20° to +80°C)

Simulation Assumptions

- Back pressure is treated as being what it ideally should be given mass flow rate
  - Simulation can account for non-ideal artificial back pressures, in the case of testing the back pressure will likely not be what it ideally should be
- Transient flow effects not considered
- Kinetic energy change not considered due to large piping which makes these effects negligible
- No control law implemented, exact knowledge of states used to command throttle values
  - Slow pressure regulator slew rate implemented (1 sec) to ensure system can work with artificial slew rate limitations. Implemented due to the idealized control giving excessively fast control.

Budget

Part	Unit (Part Numb	Price	Quantity	Subtotal	Shipping	Discount	Total		Reference
Wire		$ -	20	$ -	0	0%	$ -		Trudy's Shop. Ask before using
Microcontroller		$ -	1	$ -	0	0%	$ -		University Provided
Gear Block	1319T4	$ 89.02	4	$ 356.08	$ 13.35	0%	$ 369.43		https://www.mcmaster.com/#catalog/122/3792/=150xvbq
Panel	1319T4	$ 89.02	1	$ 89.02	$ 13.35	0%	$ 102.37		https://www.mcmaster.com/#catalog/122/3792/=150xvbq
Housing	8983K198	$ 57.41	1	$ 57.41	$ 8.61	0%	$ 66.02		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gwanw
Nuts and Bolts	As Needed	$ 35.00	1	$ 35.00	0	0%	$ 35.00		http://www.homedepot.com/p/Prime-Line-1-4-20-Carriage-Bolts-with-Nuts-GD-52103/202633663
EDMing		$ 750.00	1	$ 750.00	0	0%	$ 750.00		
Machining Metals	As Needed	$ -	0	$ -	0	0%	$ -		SAS Will Machine for us to specified tolerances. Given advanced notice
Pressure Transducers	PX309-5KG5V	$ -	4	$ -	0	0%	$ -		SAS Provided. http://www.omega.com/pptst/PX309-5V.html
Pressure Transducers	YX-98071-23	$ 312.00	1	$ 312.00	$ 46.80	0%	$ 358.80		http://www.davis.com/Product/GE_Druck_PTX5072_Pressure_Transmitter_1000_psi_Sealed_4_20m
Pressure Regulator	21U842	$ 221.25	1	$ 221.25	$ 33.19	0%	$ 254.44		https://www.grainger.com/product/PARKER-300-psi-Aluminum-Nonrising-21U842
Pressure Regulator 2	VIC0781-0528	$ 280.00	1	$ 280.00	$ 42.00	0%	$ 322.00		http://www.airgas.com/product/Gas-Equipment/Gas-Equipment-Accessories/Industrial-Gas-Regulat
Line Hookups	3/8" Lines	$ -	2	$ -	0	0%	$ -		SAS Provided. http://www.mcmaster.com/#quick-disconnect-hose-couplings/=14gt96o
Drive System	VA10 J	$ 1,095.00	1	$ 1,095.00	$ 164.25	0%	$ 1,259.25		globe
Drive System Filter	3248T11	$ 78.10	1	$ 78.10	$ 11.72	0%	$ 89.82		https://www.mcmaster.com/#catalog/122/1008/=150y0vn
Drive System Lube	8520T19	$ 82.59	1	$ 82.59	$ 12.39	0%	$ 94.98		https://www.mcmaster.com/#catalog/122/1022/=150y14e
Drive System Oil	1298K72	$ 24.59	1	$ 24.59	$ 3.69	0%	$ 28.28		https://www.mcmaster.com/#catalog/122/2195/=150y1on
Regulator		$ -	1	$ -	0	0%	$ -		SAS Provided
Teflon Seal	5154T31	$ 103.76	1	$ 103.76	$ 15.56	0%	$ 119.32		https://www.zoro.com/dayton-shaft-seal-58-in-ptfe-carbon-ceramic-3acf6/i/G0758633/?gclid=CPmp
Ball Bearings	6909UU	$ 19.49	1	$ 19.49	$ 2.92	0%	$ 22.41		http://www.mcmaster.com/#ring-seals/=14iup14
Water Drum	56W55R	$ 41.33	1	$ 41.33	$ 6.20	0%	$ 47.53		http://www.thecarycompany.com/55-gallon-tight-head-plastic-drum-56w55r?utm_source=google_s
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	$ 230.38	$ 34.56	0%	$ 264.94		http://www.skygeek.com/dupont-lubricants-grease-240ad-2-oz-tube-240ad2oz.html?utm_source=g
Tooling for gears		$ 500.00	1	$ 500.00	0	0%	$ 500.00		
Solenoid Valve	SV170	$ 367.00	1	$ 367.00	$ 55.05	0%	$ 422.05		http://www.omega.com/pptst/SV170_SERIES.html
Tachometer	RL50-850	$ 469.00	1	$ 469.00	$ 70.35	0%	$ 539.35		http://www.abqindustrial.net/store/a2108-handheld-tachometer-with-analog-output-p-513.html?gc
Binding Reports	NA	$ 100.00	2	$ 200.00	0	0%	$ 200.00		
Microsoft Office	NA	$ -	1	$ -	0	0%	$ -		University Provided
NI LabView	NA	$ -	1	$ -	0	0%	$ -		University Provided
Matlab/Simulink	NA	$ -	1	$ -	0	0%	$ -		University Provided
Solidworks 2016	NA	$ -	1	$ -	0	0%	$ -		University Provided
Gantter	NA	$ -	1	$ -	0	0%	$ -		University Provided
Shaft Coupler	6507K64	$ 25.15	2	$ 50.30	$ 3.77	0%	$ 54.07		https://www.mcmaster.com/#catalog/122/1232/=150y3jp
Shaft Hub	6507K73	$ 23.19	1	$ 23.19	$ 3.48	0%	$ 26.67		https://www.mcmaster.com/#catalog/122/1232/=150y40g
DC Motor	PK256-02A	$ 78.00	2	$ 156.00	$ 11.70	0%	$ 167.70		http://catalog.orientalmotor.com/plp/itemdetail.aspx?cid=1002&categoryname=stepping-moto
Helium Piping	62145552	$ 17.09	1	$ 17.09	$ 2.56	0%	$ 19.65		http://www.mscdirect.com/product/details/62145552?mkwid=txg6YEZy&cid=PLA-Google-PLA+-+Tes
Downstream Helium	438288	$ 16.52	1	$ 16.52	0	0%	$ 16.52		http://www.homedepot.com/p/Mueller-Streamline-1-in-x-48-in-Steel-Sch-40-Black-Pipe-585-480HC/
Pressure Regulator	214716	$ 73.97	1	$ 73.97	0	0%	$ 73.97		https://www.lowes.com/pd/Wilkins-1-in-Bronze-Female-In-Line-Pressure-Reducing-Valve/3132425
Tee's	181943	$ 4.83	5	$ 24.15	0	0%	$ 24.15		http://www.homedepot.com/p/Mueller-Global-1-in-Galvanized-Malleable-Iron-Tee-510-605HN/100
Helium Relief Valve	15x915	$ 50.50	1	$ 50.50	$ 7.58	0%	$ 58.08		https://www.grainger.com/product/CONRADER-Brass-Air-Safety-Valve-with-15X915?s_pp=false&pic
Water Relief Valve	RL50-850	$ 69.00	1	$ 69.00	$ 10.35	0%	$ 79.35		https://www.shopcross.com/product/brand-hydraulics-rl50-850-adjustable-relief-valve-12-npt0-20-g
Piezzo Transducer	113B24	$ 590.00	1	$ 590.00	$ 88.50	0%	$ 678.50		http://www.pcb.com/Products.aspx?m=113B24
Piping	301337	$ 20.28	1	$ 20.28	0	0%	$ 20.28		http://www.homedepot.com/p/1-in-x-10-ft-Galvanized-Steel-Pipe-565-1200HC/100576427

Legend
Hardware
Manufacturing
Other/Software
Testing/electronics

Subtotal	$ 7,064.93	
Tax	0	
Total	$ 7,064.93	
Margin	$ 935.07	13.2%
Total w/ Margin	$ 8,000.00	

Itemized Budget List Pt.2

Part	Unit (Part Numb	Price	Quantity	Subtotal	Shipping	Discount	Total	Reference
Wire		$ -	20	$ -	0	0%	$ -	Trudy's Shop. Ask before using
Microcontroller		$ -	1	$ -	0	0%	$ -	University Provided
Gear Block	1319T4	$ 89.02	4	$ 356.08	$ 13.35	0%	$ 369.43	https://www.mcmaster.com/#catalog/122/3792/=
Panel	1319T4	$ 89.02	1	$ 89.02	$ 13.35	0%	$ 102.37	https://www.mcmaster.com/#catalog/122/3792/=
Housing	8983K198	$ 57.41	1	$ 57.41	$ 8.61	0%	$ 66.02	http://www.mcmaster.com/#standard-stainless-st
Nuts and Bolts	As Needed	$ 35.00	1	$ 35.00	0	0%	$ 35.00	http://www.homedepot.com/p/Prime-Line-1-4-20-
EDMing		$ 750.00	1	$ 750.00	0	0%	$ 750.00	
Machining Metals	As Needed	$ -	0	$ -	0	0%	$ -	SAS Will Machine for us to specified tolerances. Giv
Pressure Transducers	PX309-5KG5V	$ -	4	$ -	0	0%	$ -	SAS Provided. http://www.omega.com/pptst/PX3(
Pressure Transducers	YX-98071-23	$ 312.00	1	$ 312.00	$ 46.80	0%	$ 358.80	http://www.davis.com/Product/GE_Druck_PTX507
Pressure Regulator	21U842	$ 221.25	1	$ 221.25	$ 33.19	0%	$ 254.44	https://www.grainger.com/product/PARKER-300-p
Pressure Regulator 2	VIC0781-0528	$ 280.00	1	$ 280.00	$ 42.00	0%	$ 322.00	http://www.airgas.com/product/Gas-Equipment/G
Line Hookups	3/8" Lines	$ -	2	$ -	0	0%	$ -	SAS Provided. http://www.mcmaster.com/#quick-
Drive System	VA10 J	$ 1,095.00	1	$ 1,095.00	$ 164.25	0%	$ 1,259.25	globe
Drive System Filter	3248T11	$ 78.10	1	$ 78.10	$ 11.72	0%	$ 89.82	https://www.mcmaster.com/#catalog/122/1008/=
Drive System Lube	8520T19	$ 82.59	1	$ 82.59	$ 12.39	0%	$ 94.98	https://www.mcmaster.com/#catalog/122/1022/=
Drive System Oil	1298K72	$ 24.59	1	$ 24.59	$ 3.69	0%	$ 28.28	https://www.mcmaster.com/#catalog/122/2195/=
Regulator		$ -	1	$ -	0	0%	$ -	SAS Provided
Teflon Seal	5154T31	$ 103.76	1	$ 103.76	$ 15.56	0%	$ 119.32	https://www.zoro.com/dayton-shaft-seal-58-in-ptf
Ball Bearings	6909UU	$ 19.49	1	$ 19.49	$ 2.92	0%	$ 22.41	http://www.mcmaster.com/#ring-seals/=14iup14
Water Drum	56W55R	$ 41.33	1	$ 41.33	$ 6.20	0%	$ 47.53	http://www.thecarycompany.com/55-gallon-tight-
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	$ 230.38	$ 34.56	0%	$ 264.94	http://www.skygeek.com/dupont-lubricants-greas
Tooling for gears		$ 500.00	1	$ 500.00	0	0%	$ 500.00	

Itemized Budget List Complete

Solenoid Valve	SV170	$ 367.00	1	$ 367.00	$ 55.05	0%	$ 422.05	http://www.omega.com/pptst/SV170_SERIES.html
Tachometer	RL50-850	$ 469.00	1	$ 469.00	$ 70.35	0%	$ 539.35	http://www.abqindustrial.net/store/a2108-handheld-tachometer-wit
Binding Reports	NA	$ 100.00	2	$ 200.00	0	0%	$ 200.00	
Microsoft Office	NA	$ -	1	$ -	0	0%	$ -	University Provided
NI LabView	NA	$ -	1	$ -	0	0%	$ -	University Provided
Matlab/Simulink	NA	$ -	1	$ -	0	0%	$ -	University Provided
Solidworks 2016	NA	$ -	1	$ -	0	0%	$ -	University Provided
Gantter	NA	$ -	1	$ -	0	0%	$ -	University Provided
Shaft Coupler	6507K64	$ 25.15	2	$ 50.30	$ 3.77	0%	$ 54.07	https://www.mcmaster.com/#catalog/122/1232/=150y3jp
Shaft Hub	6507K73	$ 23.19	1	$ 23.19	$ 3.48	0%	$ 26.67	https://www.mcmaster.com/#catalog/122/1232/=150y40g
DC Motor	PK256-02A	$ 78.00	2	$ 156.00	$ 11.70	0%	$ 167.70	http://catalog.orientalmotor.com/plp/itemdetail.aspx?cid=1002&c
Helium Piping	62145552	$ 17.09	1	$ 17.09	$ 2.56	0%	$ 19.65	http://www.mscdirect.com/product/details/62145552?mkwid=txg6Y
Downstream Helium	438288	$ 16.52	1	$ 16.52	0	0%	$ 16.52	http://www.homedepot.com/p/Mueller-Streamline-1-in-x-48-in-Stee
Pressure Regulator	214716	$ 73.97	1	$ 73.97	0	0%	$ 73.97	https://www.lowes.com/pd/Wilkins-1-in-Bronze-Female-In-Line-Pres
Tee's	181943	$ 4.83	5	$ 24.15	0	0%	$ 24.15	http://www.homedepot.com/p/Mueller-Global-1-in-Galvanized-Mall
Helium Relief Valve	15x915	$ 50.50	1	$ 50.50	$ 7.58	0%	$ 58.08	https://www.grainger.com/product/CONRADER-Brass-Air-Safety-Valv
Water Relief Valve	RL50-850	$ 69.00	1	$ 69.00	$ 10.35	0%	$ 79.35	https://www.shopcross.com/product/brand-hydraulics-rl50-850-adju
Piezzo Transducer	113B24	$ 590.00	1	$ 590.00	$ 88.50	0%	$ 678.50	http://www.pcb.com/Products.aspx?m=113B24
Piping	301337	$ 20.28	1	$ 20.28	0	0%	$ 20.28	http://www.homedepot.com/p/1-in-x-10-ft-Galvanized-Steel-Pipe-56

Risk Metrics

Likelihood	
1	Not likely
2	Low likelihood
3	Likely
4	Highly Likely
5	Near certainty

Severity - Technical	
1	Minimal or no impact
2	Minor performance shortfall, same approach retained
3	Moderate performance shortfall, but work arounds available
4	Unacceptable, but work arounds available
5	Unacceptable; no alternatives exist

Severity - Cost	
1	Minimal or no impact
2	<1% of budget to replace
3	<5% of budget to replace
4	<10% of budget to replace
5	>10% of budget to replace

Severity - Safety	
1	Minimal or no impact
2	Could result in: injury or occupational illness not resulting in a lost work day
3	Could result in: injury or occupational illness resulting in one or more lost work day(s)
4	Could result in: permanent partial disability,injuries or occupational illness
5	Could result in: death or permanent total disability

Severity - Schedule	
1	Minimal or no impact
2	Additional activities required but able to meet key deadlines (few hrs - 1d)
3	Minor schedule slip; will miss internal deadline (1d - 3d)
4	Critical path affected (+3d)
5	Cannot achieve milestone

Risk Matrices: Highest

Highest Risk							
Additive Risk Matrix		Severity					
			1	2	3	4	5
		Cost	Minimal or no impact	<1% of budget to replace	<5% of budget to replace	<10% of budget to replace	>10% of budget to replace
		Schedule	Minimal or no impact	Additional activities required but able to meet key deadlines (few hrs - 1d)	Minor schedule slip; will miss internal deadline (1d - 3d)	Critical path affected (+3d)	Cannot achieve milestone
		Technical	Minimal or no impact	Minor performance shortfall, same approach retained	Moderate performance shortfall, but work arounds available	Unacceptable, but work arounds available	Unacceptable; no alternatives exist
		Safety	Minimal or no impact	Could result in: injury or occupational illness not resulting in a lost work day	Could result in: injury or occupational illness resulting in one or more lost work day(s)	Could result in: permanent partial disability,injuries or occupational illness	Could result in: death or permanent total disability
Likelihood			1	2	3	4	5
5	Near certainty >95%	5		31			
4	Highly Likely >65%	4			30,37,38		
3	Likely >35%	3				2,4,5,9	3,22,47,53
2	Low likelihood <35%	2					20,21,35,36,45,46,52
1	Not likely <10%	1					

Risk Highest Severity

Risk (highest severity)	L	Highest S	L*S
Loss of Power to Computer	1	2	2
He Manual Ball Valve Failure	1	3	3
Housing breaking	1	4	4
Gears breaking	1	4	4
Thermal Material Failure	1	4	4
Inadequate H2O mass flow rate	1	4	4
Pressure Gauge Failure	1	4	4
Assembly Schedule	2	2	4
Computer Crashes	2	2	4
Labview Crashes	2	2	4
High pressure helium failure	1	5	5
K bottle regulator failure	1	5	5
Microcontroller failure	2	3	6
Incorrect Calibration of Pressure Transducers	2	3	6
Incorrect Calibration of Tachometer	2	3	6
Pressure Sensor 1 Failure	2	3	6
H2O Manual Pressure Regulator Failure	2	3	6
H2O Solenoid Valve Fail Open	2	3	6
He Manual Pressure Regulator Failure	2	3	6
H20 Delivery Sys Failure	2	3	6
Noise in sensors	3	2	6
Valve freezing	3	2	6
Outlet Pressure Harm	2	4	8
Not hitting tolerances on gears	2	4	8
Not hitting tolerance on housing	2	4	8
Incorrect Pressure Data Acquisition	2	4	8
Incorrect Tachometer Data Acquisition	2	4	8
Cavitation	2	4	8
Bearing failure	2	4	8
Improper lubrication	2	4	8
Pressure buildup between teeth	2	4	8
Tube Failures	2	4	8
H2O Solenoid Valve Failure	2	4	8
He Solenoid Valve Fail Open	2	4	8
He Solenoid Valve Failure	2	4	8
He Regulator failure	2	4	8
Helium line failure	2	4	8
Inadequate He mass flow rate	2	4	8
Cannot resolve pressure fluctuations	3	3	9
Housing seal failure/leakage	3	3	9
>+/-15psi pressure spikes	3	3	9
Vibration in the drive shaft	3	3	9
Pressure Sensor 2 Failure	2	5	10
Electronic Pressure Gauge Failure	2	5	10
Drive shaft breaking	2	5	10
Drive system failure	2	5	10
Exit Relief Valve Failure	2	5	10
Burst Disk Failure	2	5	10
He Relief Valve Failure	2	5	10
Vibration in the pump	5	2	10
Weight of gear pump causing injury	3	4	12
Testing Schedule	3	4	12
Manufacturing Schedule	3	4	12
Tolerance stack-up doesn't meet clearance requirements	3	4	12
Driveshaft seal failure/leakage	4	3	12
Over Pressure Drive System	4	3	12
Drive system can't operate at 10%	4	3	12
Over Budget	3	5	15
Tachometer Failure	3	5	15
Electronic Back Pressure Regulator Failure	3	5	15
He Electronic Pressure Regulator Failure	3	5	15

Risk Matrices: Highest List

List of Risks				
20	Pressure Sensor 2 Failure	2	5	10
21	Electronic Pressure Gauge Failure	2	5	10
35	Drive shaft breaking	2	5	10
36	Drive system failure	2	5	10
45	Exit Relief Valve Failure	2	5	10
46	Burst Disk Failure	2	5	10
52	He Relief Valve Failure	2	5	10
31	Vibration in the pump	5	2	10
2	Weight of gear pump causing injury	3	4	12
4	Testing Schedule	3	4	12
5	Manufacturing Schedule	3	4	12
9	Tolerance stack-up doesn't meet clearance requirements	3	4	12
30	Driveshaft seal failure/leakage	4	3	12
37	Over Pressure Drive System	4	3	12
38	Drive system can't operate at 10%	4	3	12
3	Over Budget	3	5	15
22	Tachometer Failure	3	5	15
47	Electronic Back Pressure Regulator Failure	3	5	15
53	He Electronic Pressure Regulator Failure	3	5	15

Risk Average Severity Pt.1

Risk (avg. severity)	L	Cost S	Technical S	Schedule S	Safety S	Avg. S	L*S
Loss of Power to Computer	1	1	2	1	2	2	2
He Manual Ball Valve Failure	1	2	2	2	3	3	3
Inadequate H2O mass flow rate	1	2	4	2	1	3	3
Pressure Gauge Failure	1	2	3	2	4	3	3
Assembly Schedule	2	1	2	2	1	2	4
Microcontroller failure	2	1	3	2	2	2	4
Computer Crashes	2	1	2	1	2	2	4
Labview Crashes	2	1	2	1	2	2	4
Incorrect Calibration of Tachometer	2	1	3	2	2	2	4
Housing breaking	1	3	4	4	2	4	4
Gears breaking	1	4	4	4	2	4	4
Thermal Material Failure	1	4	4	4	2	4	4
H2O Solenoid Valve Fail Open	2	1	3	1	2	2	4
He Solenoid Valve Fail Open	2	1	4	1	2	2	4
H20 Delivery Sys Failure	2	2	3	2	1	2	4
High pressure helium failure	1	3	4	3	5	4	4
K bottle regulator failure	1	3	4	2	5	4	4
Outlet Pressure Harm	2	4	1	3	4	3	6
Not hitting tolerances on gears	2	4	3	4	1	3	6
Not hitting tolerance on housing	2	3	3	4	1	3	6
Incorrect Pressure Data Acquisition	2	2	4	3	1	3	6
Incorrect Tachometer Data Acquisition	2	3	4	3	1	3	6
Noise in sensors	3	1	2	2	1	2	6
Incorrect Calibration of Pressure Transducers	2	1	3	3	2	3	6
Pressure Sensor 1 Failure	2	3	3	2	1	3	6
Cavitation	2	2	4	3	1	3	6
Bearing failure	2	2	4	3	1	3	6
Improper lubrication	2	2	4	2	1	3	6
Pressure buildup between teeth	2	3	3	4	2	3	6
Vibration in the drive shaft	3	1	3	1	1	2	6

Risk Average Severity Pt.2

Vibration in the drive shaft	3	1	3	1	1	2	6
Valve freezing	3	2	2	2	2	2	6
Tube Failures	2	2	2	3	4	3	6
H2O Manual Pressure Regulator Failure	2	2	3	2	3	3	6
He Manual Pressure Regulator Failure	2	2	2	2	3	3	6
Pressure Sensor 2 Failure	2	3	5	4	2	4	8
Electronic Pressure Gauge Failure	2	3	5	4	3	4	8
Drive shaft breaking	2	3	5	3	2	4	8
Drive system failure	2	5	5	5	1	4	8
Drive system can't operate at 10%	4	1	3	3	1	2	8
H2O Solenoid Valve Failure	2	4	4	4	4	4	8
Exit Relief Valve Failure	2	2	4	3	5	4	8
He Solenoid Valve Failure	2	4	4	4	4	4	8
He Relief Valve Failure	2	2	4	3	5	4	8
He Regulator failure	2	3	4	2	4	4	8
Helium line failure	2	3	4	3	3	4	8
Inadequate He mass flow rate	2	4	4	4	1	4	8
Weight of gear pump causing injury	3	1	1	3	4	3	9
Testing Schedule	3	1	3	4	1	3	9
Tolerance stack-up doesn't meet clearance requirements	3	3	4	3	2	3	9
Cannot resolve pressure fluctuations	3	3	3	3	2	3	9
Housing seal failure/leakage	3	2	3	3	1	3	9
>+/-15psi pressure spikes	3	2	3	3	1	3	9
Vibration in the pump	5	1	2	1	1	2	10
Burst Disk Failure	2	4	4	4	5	5	10
Over Budget	3	5	4	4	1	4	12
Manufacturing Schedule	3	4	4	4	1	4	12
Tachometer Failure	3	3	5	4	3	4	12
Driveshaft seal failure/leakage	4	2	3	3	1	3	12
Over Pressure Drive System	4	2	3	3	2	3	12
Electronic Back Pressure Regulator Failure	3	5	5	4	2	4	12
He Electronic Pressure Regulator Failure	3	5	5	4	2	4	12

Risk Matrices: Averages

Average Severity Matrix							
		Avgerage Severity					
			1	2	3	4	5
Likelihood			1	2	3	4	5
5	Near certainty >95%	5		31			
4	Highly Likely >65%	4			30,37		
3	Likely >35%	3				3,5,22,47,53	
2	Low likelihood <35%	2					46
1	Not likely <10%	1					

List of Risks		L	S	S	S	S	Avg S	
31	Vibration in the pump	5	1	2	1	1	2	10
46	Burst Disk Failure	2	4	4	4	5	5	10
3	Over Budget	3	5	4	4	1	4	12
5	Manufacturing Schedule	3	4	4	4	1	4	12
22	Tachometer Failure	3	3	5	4	3	4	12
30	Driveshaft seal failure/leakage	4	2	3	3	1	3	12
37	Over Pressure Drive System	4	2	3	3	2	3	12
47	Electronic Back Pressure Regulator Failure	3	5	5	4	2	4	12
53	He Electronic Pressure Regulator Failure	3	5	5	4	2	4	12

Risk Matrices: Cost

Cost Matrix							
		Severity					
			1	2	3	4	5
		Cost	Minimal or no impact	<1% of budget to replace	<5% of budget to replace	<10% of budget to replace	>10% of budget to replace
Likelihood			1	2	3	4	5
5	Near certainty >95%	5					
4	Highly Likely >65%	4					
3	Likely >35%	3				5	3,47,53
2	Low likelihood <35%	2					36
1	Not likely <10%	1					

List of Cost Risks		L	Cost S	
36	Drive system failure	2	5	10
5	Manufacturing Schedule	3	4	12
3	Over Budget	3	5	15
47	Electronic Back Pressure Regulator Failure	3	5	15
53	He Electronic Pressure Regulator Failure	3	5	15

Risk Matrices: Technical

Technical Matrix							
		Severity					
			1	2	3	4	5
		Technical	Minimal or no impact	Minor performance shortfall, same approach retained	Moderate performance shortfall, but work arounds available	Unacceptable, but work arounds available	Unacceptable; no alternatives exist
Likelihood			1	2	3	4	5
5	Near certainty >95%	5		31			
4	Highly Likely >65%	4			30,37,38		
3	Likely >35%	3				3,5,9	22,47,53
2	Low likelihood <35%	2					20,21,35,36
1	Not likely <10%	1					

List of Risks				
20	Pressure Sensor 2 Failure	2	5	10
21	Electronic Pressure Gauge Failure	2	5	10
31	Vibration in the pump	5	2	10
35	Drive shaft breaking	2	5	10
36	Drive system failure	2	5	10
3	Over Budget	3	4	12
5	Manufacturing Schedule	3	4	12
9	Tolerance stack-up doesn't meet clearance requirements	3	4	12
30	Driveshaft seal failure/leakage	4	3	12
37	Over Pressure Drive System	4	3	12
38	Drive system can't operate at 10%	4	3	12
22	Tachometer Failure	3	5	15
47	Electronic Back Pressure Regulator Failure	3	5	15
53	He Electronic Pressure Regulator Failure	3	5	15

Risk Matrices: Schedule

Schedule Matrix							
		Severity					
			1	2	3	4	5
		Schedule	Minimal or no impact	Additional activities required but able to meet key deadlines (few hrs - 1d)	Minor schedule slip; will miss internal deadline (1d - 3d)	Critical path affected (+3d)	Cannot achieve milestone
Likelihood			1	2	3	4	5
5	Near certainty >95%	5					
4	Highly Likely >65%	4			30,37,38		
3	Likely >35%	3				3,4,5,22,47,53	
2	Low likelihood <35%	2					36
1	Not likely <10%	1					

List of Risks				
36	Drive system failure	2	5	10
3	Over Budget	3	4	12
4	Testing Schedule	3	4	12
5	Manufacturing Schedule	3	4	12
22	Tachometer Failure	3	4	12
30	Driveshaft seal failure/leakage	4	3	12
37	Over Pressure Drive System	4	3	12
38	Drive system can't operate at 10%	4	3	12
47	Electronic Back Pressure Regulator Failure	3	4	12
53	He Electronic Pressure Regulator Failure	3	4	12

Risk Matrices: Safety

Safety Matrix							
		Severity					
			1	2	3	4	5
		Safety	Minimal or no impact	Could result in: injury or occupational illness not resulting in a lost work day	Could result in: injury or occupational illness resulting in one or more lost work day(s)	Could result in: permanent partial disability,injuries or occupational illness	Could result in: death or permanent total disability
Likelihood			1	2	3	4	5
5	Near certainty >95%	5					
4	Highly Likely >65%	4					
3	Likely >35%	3				2	
2	Low likelihood <35%	2					45,46,52
1	Not likely <10%	1					

List of Risks				
45	Exit Relief Valve Failure	2	5	10
46	Burst Disk Failure	2	5	10
52	He Relief Valve Failure	2	5	10
2	Weight of gear pump causing injury	3	4	12

Embedded Systems

Linearization of Drive System Model

- Linearize model for the RPM provided
- Allows to look at the control aspects of it

$$\frac{\Omega}{U(s)} = \frac{1}{sI + f_v}$$

Drive System Linearized Derivation

$$I\dot{\omega} + f_v\omega = u$$
$$\Omega(sI + f_v) = U$$

$$f_v = \frac{64}{Re}$$

$$\frac{\Omega}{U(s)} = \frac{1}{sI + f_v}$$

Control Requirements

- Stable control
- Phase margin: 70 – 80 degrees -> damping from 0.8 – 1.2
- Overshoot: < 10%
- Ramp error: 0.1 %

Electronics

Analog to Digital Conversions

- Converting from ADC to pressure
- Find the MSMT out of the ADC to get the Voltage into the ADC
- Find the pressure out of the Pressure transducer
- Find pressure by dividing it by the voltage per pressure ratio

$$V_{ADC} = V_{out,max} \frac{MSMT}{2^{16}}$$

$$V_{Press} = \frac{V_{ADC}}{G} + V_{offset}$$

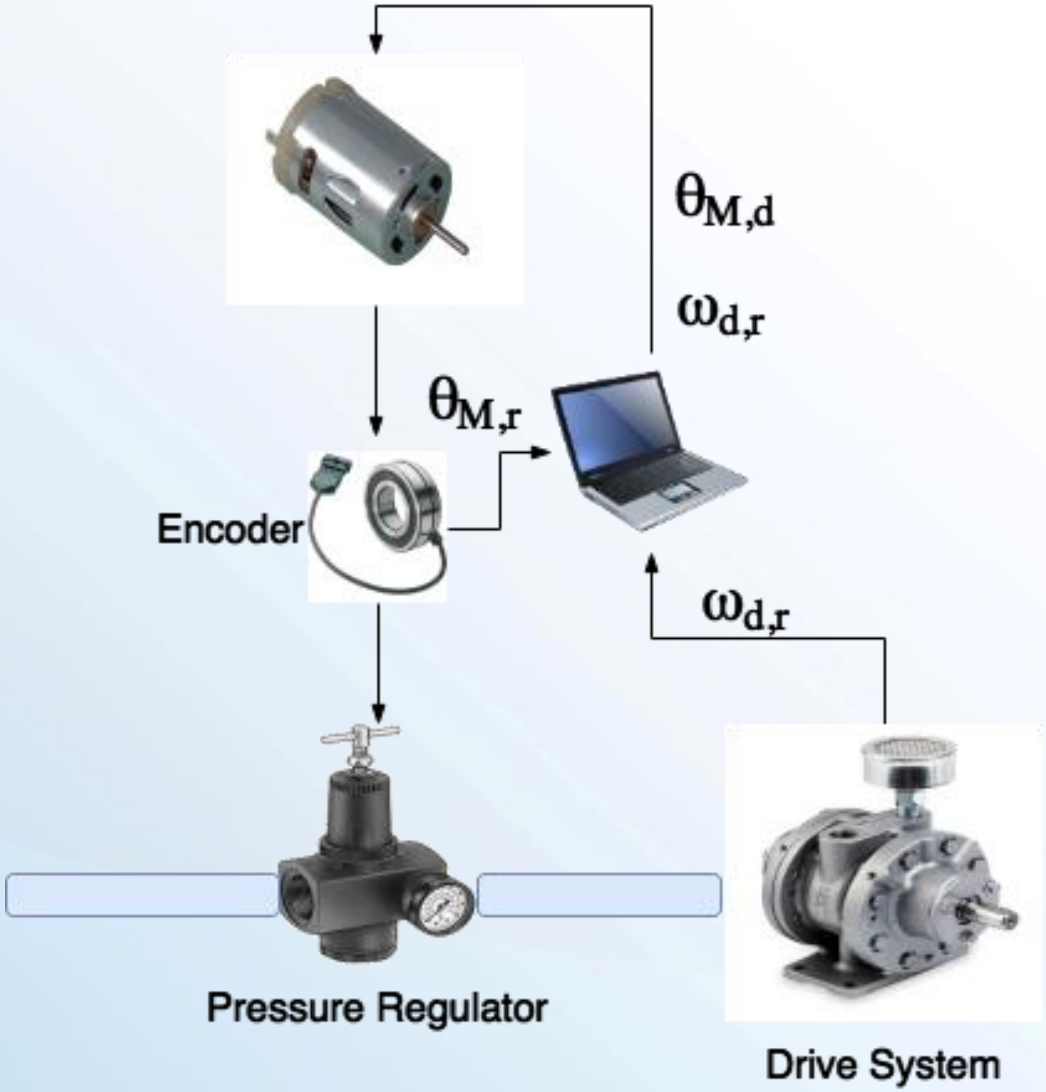
$$P = \frac{V_{Press}}{Ratio_{V2P}}$$

Automatic Pressure Regulator

- Electronic pressure regulators with high volume flow are not found, but manual do exists
- Combining a manual pressure regulator with an encoder and stepper motor
- Motor shall have a minimum angular velocity of 300 RPM
- No error, and time of settle of less than 1 second

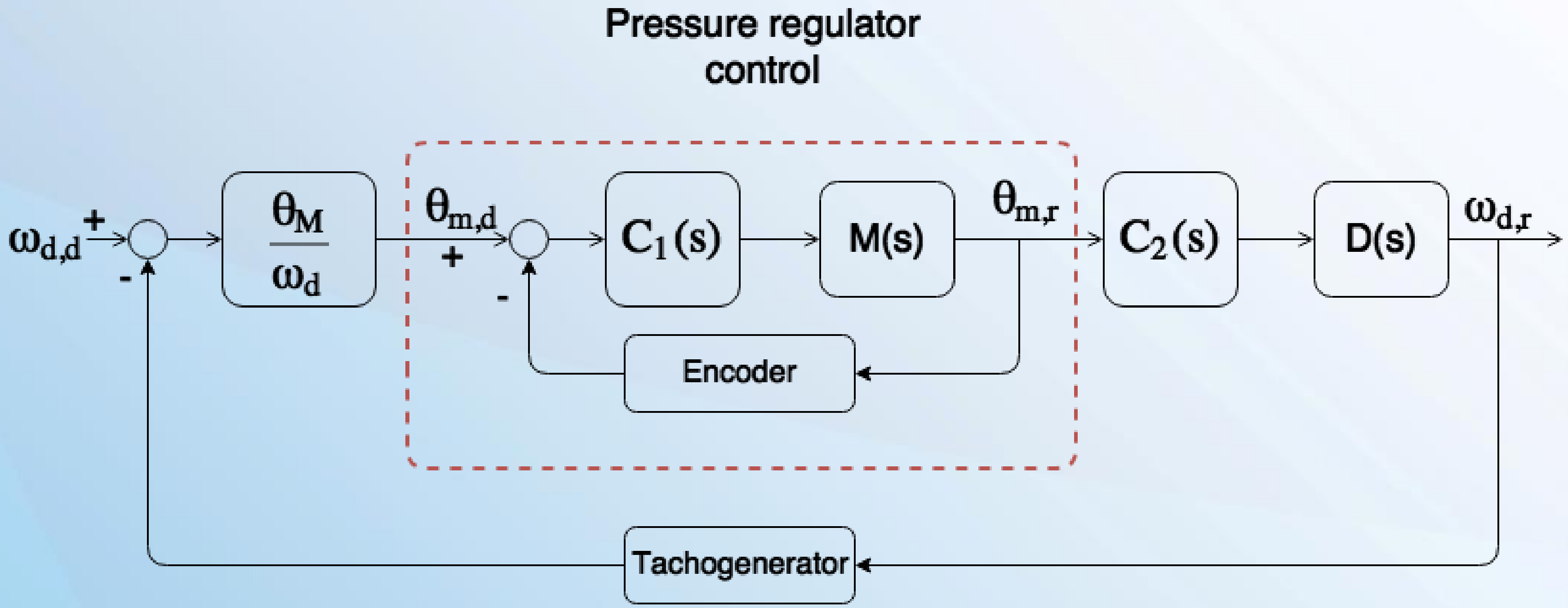
Automatic Pressure Regulator FBD

- Controlling a stepper motor based on the position
- This position will allow the output pressure



Automatic Pressure Regulator Diagram

- Control points of view for the pressure regulator
- Can be simplified by combining both plants
- Needs to be tested to find the correlation of angular position with output RPM



Automatic Pressure Regulator

- This can be simplified by combining
  - the drive system transfer function and
  - the motor transfer function

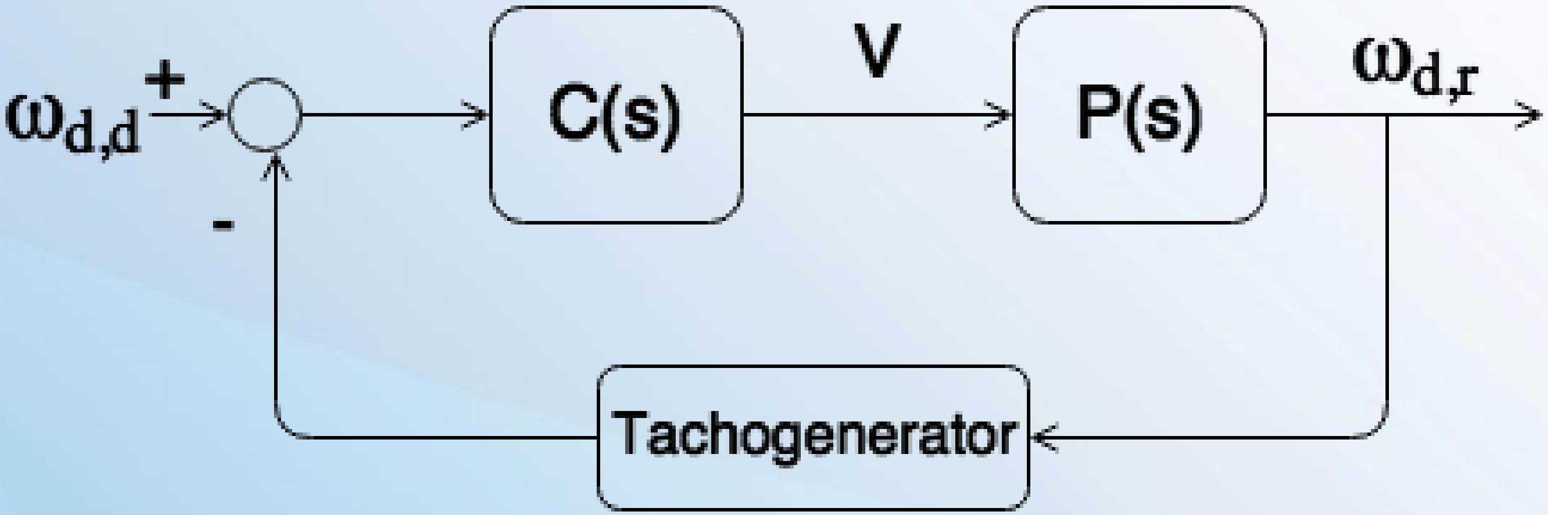
$$D(s) = \frac{\Omega_D(s)}{\Theta_{pr}(s)} = \frac{1}{Is + f_v} \quad [\frac{RPM}{rad}]$$

$$P(s) = \frac{\Omega_D(s)}{V(s)} = \frac{K}{s((Js+b)(Ls+R)+K^2)(Is+f_v)} \quad [\frac{RPM}{V}]$$

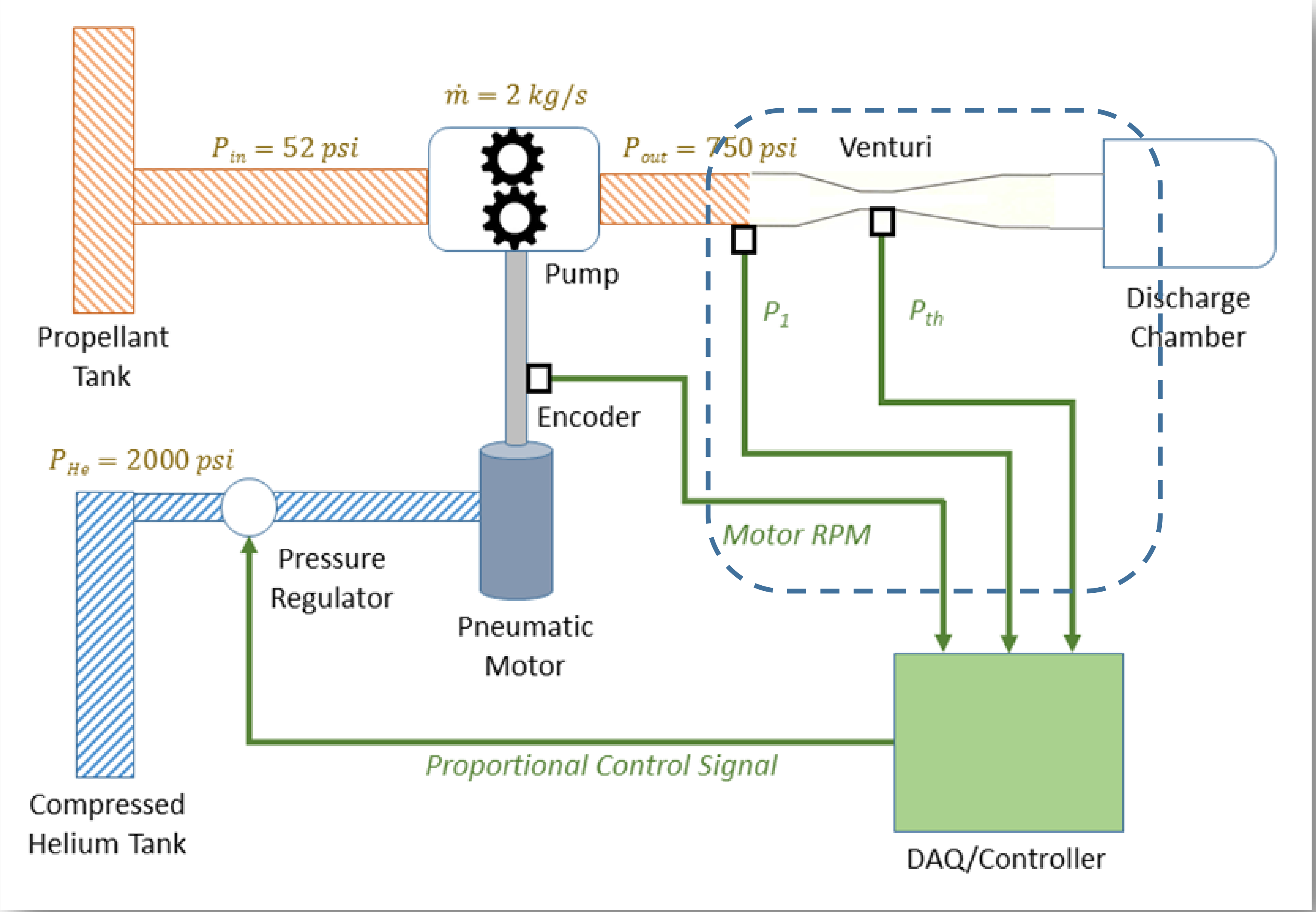
$$M(s) = \frac{\Theta_{pr}(s)}{V(s)} = \frac{K}{s((Js+b)(Ls+R)+K^2)} \quad [\frac{rad}{V}]$$

Automatic Pressure Regulator

- Simplified version of the model
- Allows to control the drive system based on the voltage input

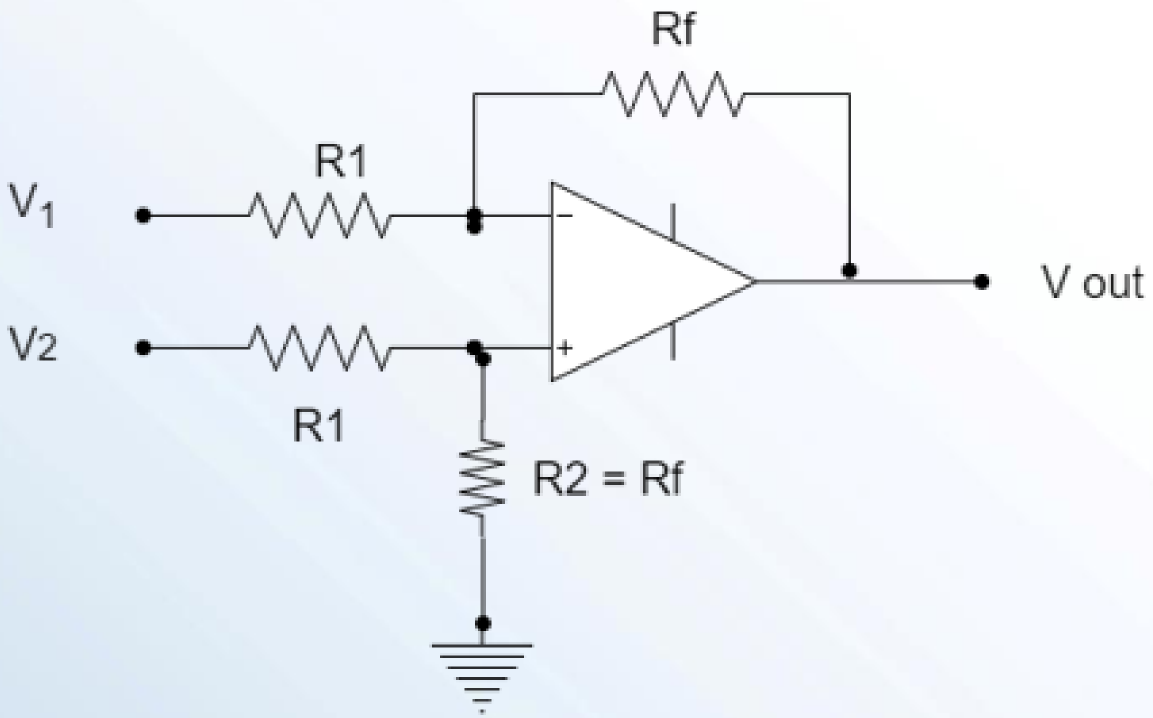


Signal Processing



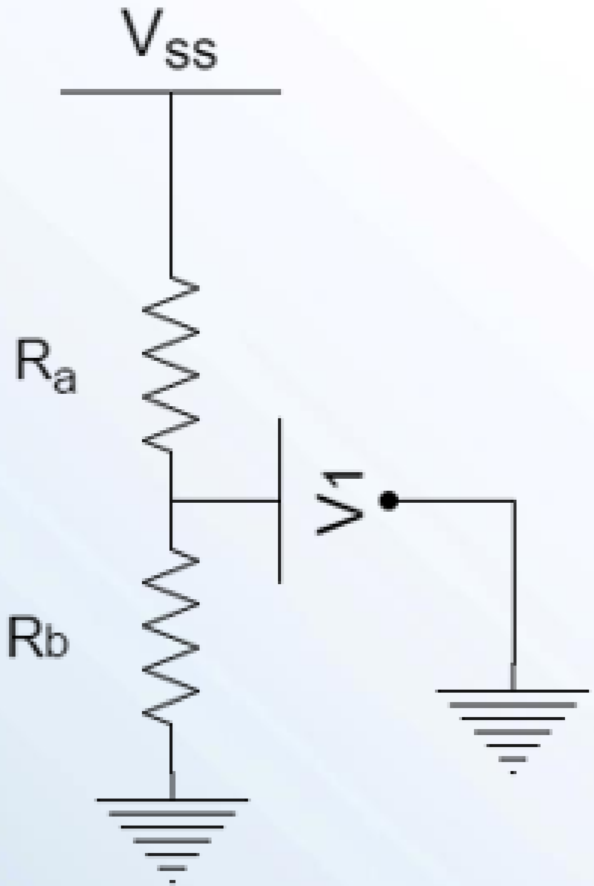
Signal Processing – Differential Amplifier

- Use for creating an offset and applying a gain to the voltage out of the pressure transducer
- This will allow us to look at a range from 600 – 800 psi a with higher accuracy.



Signal Processing – Voltage divider

- Being able to from 28 V to .6 V
- The output will be used to provide the offset needed for V1



Signal Processing – Noise Mitigation

Low pass filter Vs Sallen-key filter

Low pass filter

- Easy to make
- First order filter
- Only one pole

$$T = \frac{1}{1 + sRC}$$

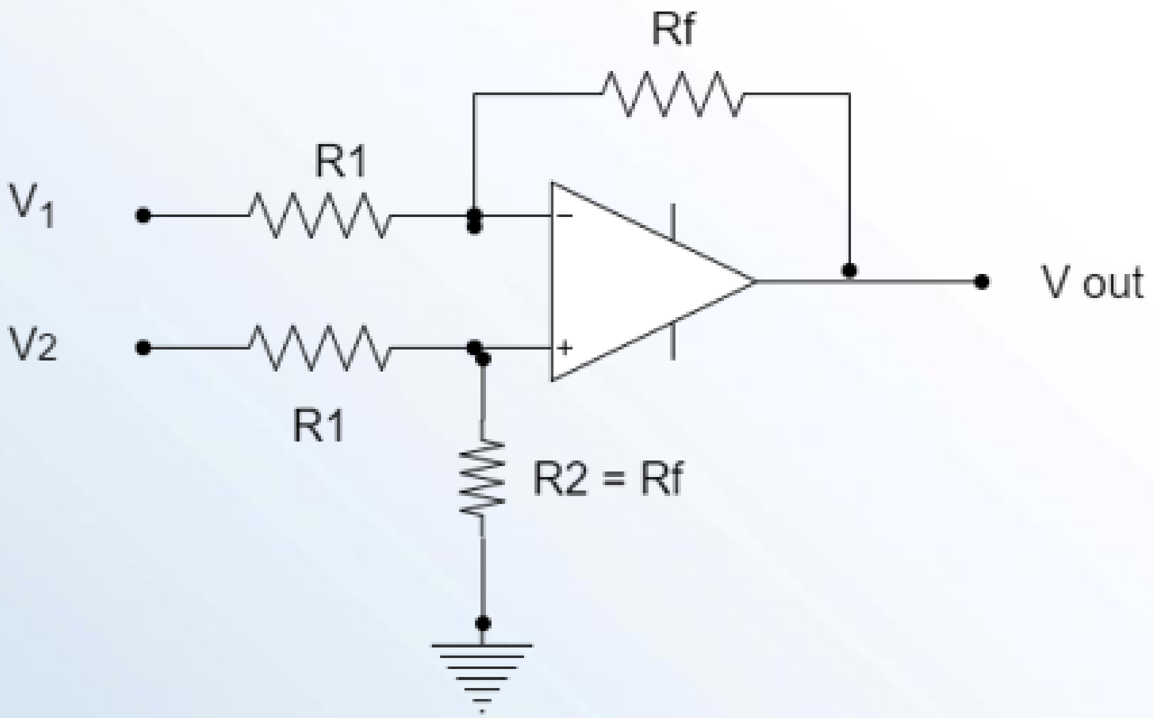
Sallen-key filter

- Harder to make
- Second order filter
- Two poles

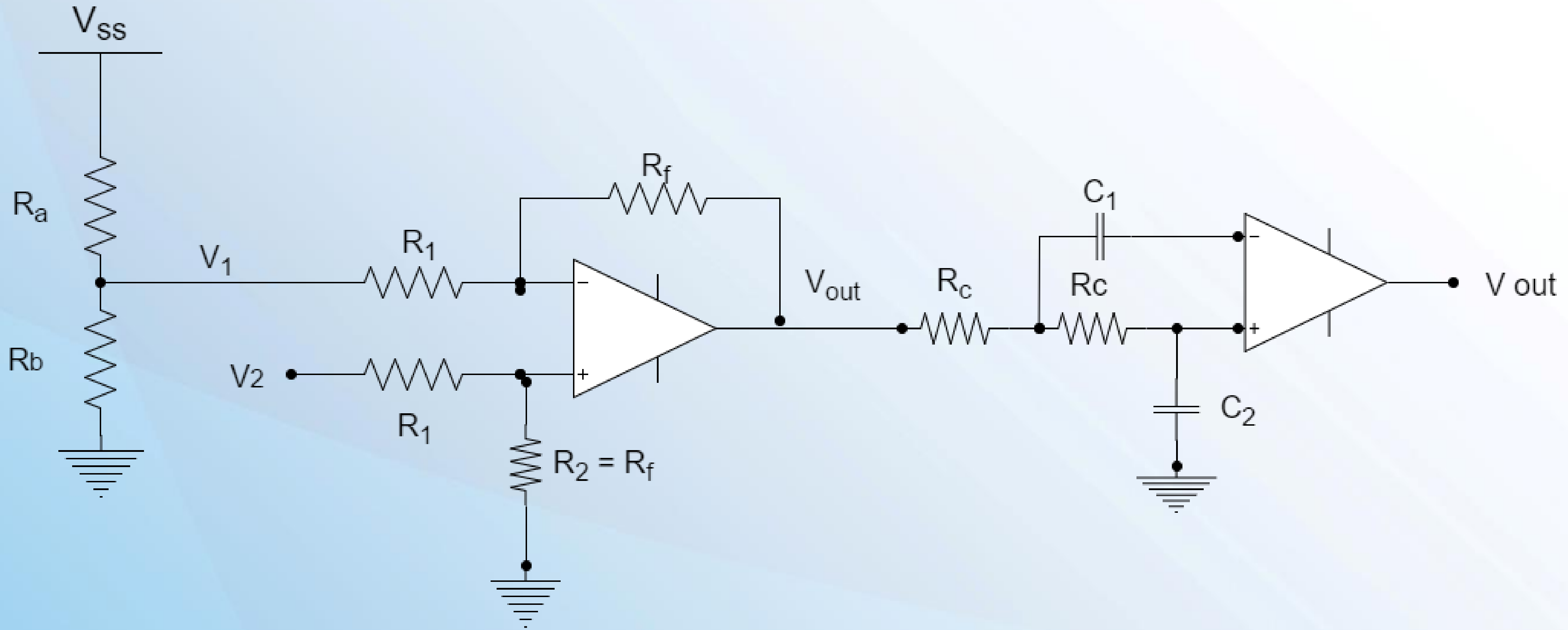
$$T = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

Signal Processing – Noise Mitigation

- Prevents to look at high frequencies that are irrelevant
- This will have a cutoff frequency at 2 kHz



Signal Processing – Electronic diagram

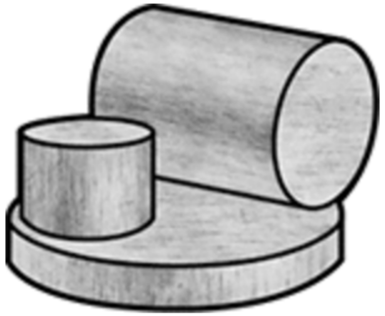


Parts List

Gear Block

High-Strength 17-4 PH Stainless Steel Rod

4-1/2" Diameter



Length, in.
- 1/2
- 1
- 2
- 3

Each

ADD TO ORDER

1319T4

Alloy	17-4 PH
Shape	Rod
Finish	Unpolished
Diameter	4 1/2"
Diameter Tolerance	+1/16"
Yield Strength	110,000 psi
Hardness	Hard (Rockwell C35)
Specifications Met	ASTM A564 and AMS 5643
Construction	Hot Rolled
Material Condition	Annealed
Material Composition	
Chromium	15-17.5%
Nickel	3-5%
Carbon	0-0.07%
Manganese	0-1%

Parts List: Pressure Transducer

Specifications	
Product Type	Pressure Transmitter
Media compatibility	Fluids compatible with 316L stainless steel and Hastelloy C287
Output	4 to 20 mA (2-wire)
Range	0 to 10,000 psi, sealed diaphragm
Process connection	1/4" NPT(F)
Electrical connections	DIN 43650 Form A demountable (mating connector supplied)
Accuracy	±0.2% full-scale (combined effects of nonlinearity, hysteresis, and repeatability)
Power	7 to 28 VDC (Note: supply voltage is 7 to 32 VDC in nonhazardous area operation)
Qty/ea	1
Manufacturer number	PTX5072-TC-A1-CA-H6-PE
Brand	GE Druck
CE Compliance	Yes

Parts List: Piezo Pressure Transducer

PERFORMANCE			
Measurement Range (for ±5V output)	1000 psi	6895 kPa	
Useful Overrange (for ± 10V output)	2000 psi	13790 kPa	[2]
Sensitivity (±10 %)	5.0 mV/psi	0.725 mV/kPa	
Maximum Pressure	10000 psi	68950 kPa	
Resolution	5 mpsi	0.035 kPa	[3]
Resonant Frequency	≥500 kHz	≥500 kHz	
Rise Time	≤1.0 μ sec	≤1.0 μ sec	
Low Frequency Response (-5 %)	0.005 Hz	0.005 Hz	
Non-Linearity	≤1.0 % FS	≤1.0 % FS	[1]

Parts List: Tachometer

Speed Ranges	
Range 1	100 - 6000 RPM
Range 2	1000 - 60,000 RPM
Resolution	+/- 1.5mV
Accuracy	+/- 0.5%
Optical Range	50 - 1000mm
Optical angle	+/- 45 deg.
Light Source	Red LED
Optical Angle	+/- 45 Degrees
Carry Case	Included
Contact Adapter	Optional
Voltage Output	-6 vdc Both Ranges
Connections	Coiled cable with 2 x 4mm plugs fitted

Parts List: Thermocouple

T	-250° to 350°C (-328° to 662°F)	Greater of 1.0°C or 0.75%	Greater of 0.5°C or 0.4%

Parts List: Pressure Regulator

TECHNICAL SPECS

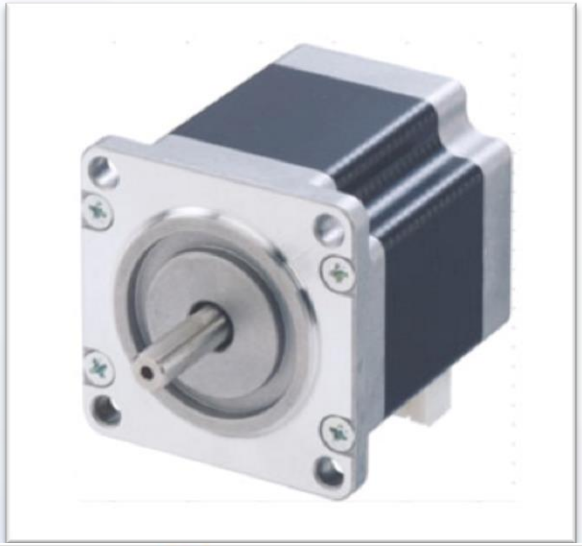
Item	General Purpose Air Regulator	Gauge Port	1/4" NPT
Pipe Size (Regulators)	1"	Series	R119
Max. Flow (Regulators)	400 cfm	Valve Design	Balanced
Max. Flow Range	Greater than 301 cfm	Overall Height (Regulators)	10.02"
Max. Inlet Pressure (Regulators)	300 psi	Overall Width (Regulators)	4.69"
Max. Temp. (Regulators)	125 Degrees F	Overall Length	4.69"
Adjustment Range (Regulators)	0 to 125 psi	Body Material	Aluminum
Overall Height Range	Greater than 8.01 in.	Includes	Regulator, (2) Gauge Plugs
Adjustment Knob	Nonrising		

Parts List: Back Pressure Regulator

MODEL	PROCESS PORT SIZE	REFERENCE PORT SIZE	BODY MATERIAL	MAX PRESSURE RATING	MIN CV	MAX CV	DIM A	DIM B
							SEE FIGURE 1	
BD12S	1.5"	1/8"	Stainless Steel 316/316L	50	0.1	14.3	9.5	3.9
BDM12S	1.5"	1/8"	Stainless Steel 316/316L	150	0.1	14.3		
BD12A	1.5"	1/8"	Anodized Aluminum		0.1	14.3	9.5	3.9
BD12P	1.5"	1/8"	PVC	50	0.1	14.3	9	4.3
BD16S	2"	1/8"	Stainless Steel 316/316L	75	0.3	30.2	11	4.1
BDM16S	2"	1/8"	Stainless Steel 316/316L	150	0.3	30.2		
BD16A	2"	1/8"	Anodized Aluminum		0.3	30.2	11	4.1
BD16P	2"	1/8"	PVC	65	0.3	30.2	11	5.1
BD24S	3"	1/4"	Stainless Steel 316/316L	50	0.6	60	15	6.1
BDM24S	3"	1/4"	Stainless Steel 316/316L	100	0.6	60		
BD24A	3"	1/4"	Anodized Aluminum		0.6	60	15	6.1
BD24P	3"	1/4"	PVC	30	0.6	60	15	8.8
BD32S	4"	1/4"	Stainless Steel 316/316L	75	1.5	160	20	8.1
BD32A	4"	1/4"	Anodized Aluminum		1.5	160	20	8.1
BD32P	4"	1/4"	PVC	30	1.5	160	20	9.6

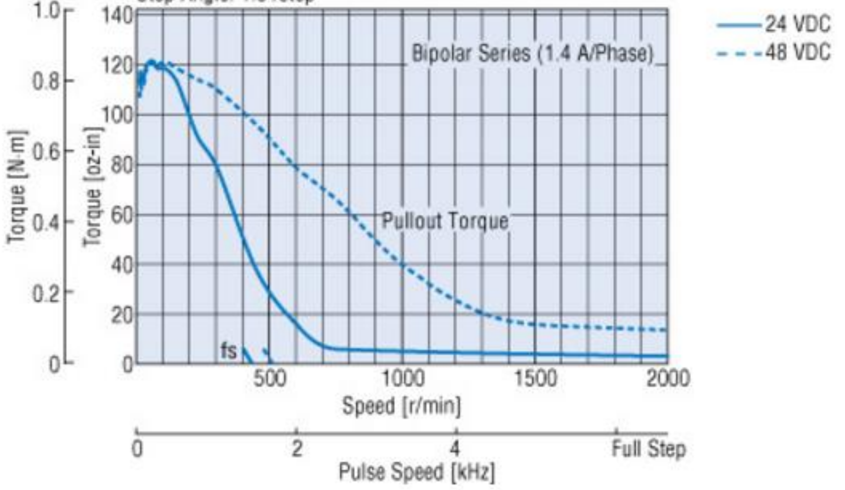
Parts List: Step motor

Holding Torque ?	Bipolar (Series) 0.84 N·m Unipolar 0.6 N·m
Shaft/Gear Type	Round Shaft (No Gearhead)
Shaft	Single
Type	Standard
Encoder	Not Equipped
Basic Step Angle	1.8°
Output Step Angle	1.8 °
Electromagnetic Brake	Not Equipped
Motor Connection Type	Flying Leads
Connection Type	Bipolar (Series) Unipolar
Current per Phase (A/phase)	1.4 [Bipolar (Series)] 2 [Unipolar]
Lead Wires	6
Voltage (VDC)	4.2 [Bipolar (Series)] 3 [Unipolar]
Resistance (Ω/phase)	3 [Bipolar (Series)] 1.5 [Unipolar]
Inductance (mH/phase)	5.6 [Bipolar (Series)] 1.4 [Unipolar]
Rotor Inertia	230×10^{-7} kg·m²
RoHS Compliant ?	Yes



PK256-02B Bipolar (Series)

Bipolar Constant Current Driver
With Damper **D6CL-6.3F**: J_L = 0.77 oz-in² (140×10^{-7} kg·m²)
Step Angle: 1.8°/step



PK256-02B Unipolar

Power Input: 24 VDC Unipolar Constant Current Driver
With Damper **D6CL-6.3F**: J_L = 0.77 oz-in² (140×10^{-7} kg·m²)
Step Angle: 1.8°/step