# PEAPOD

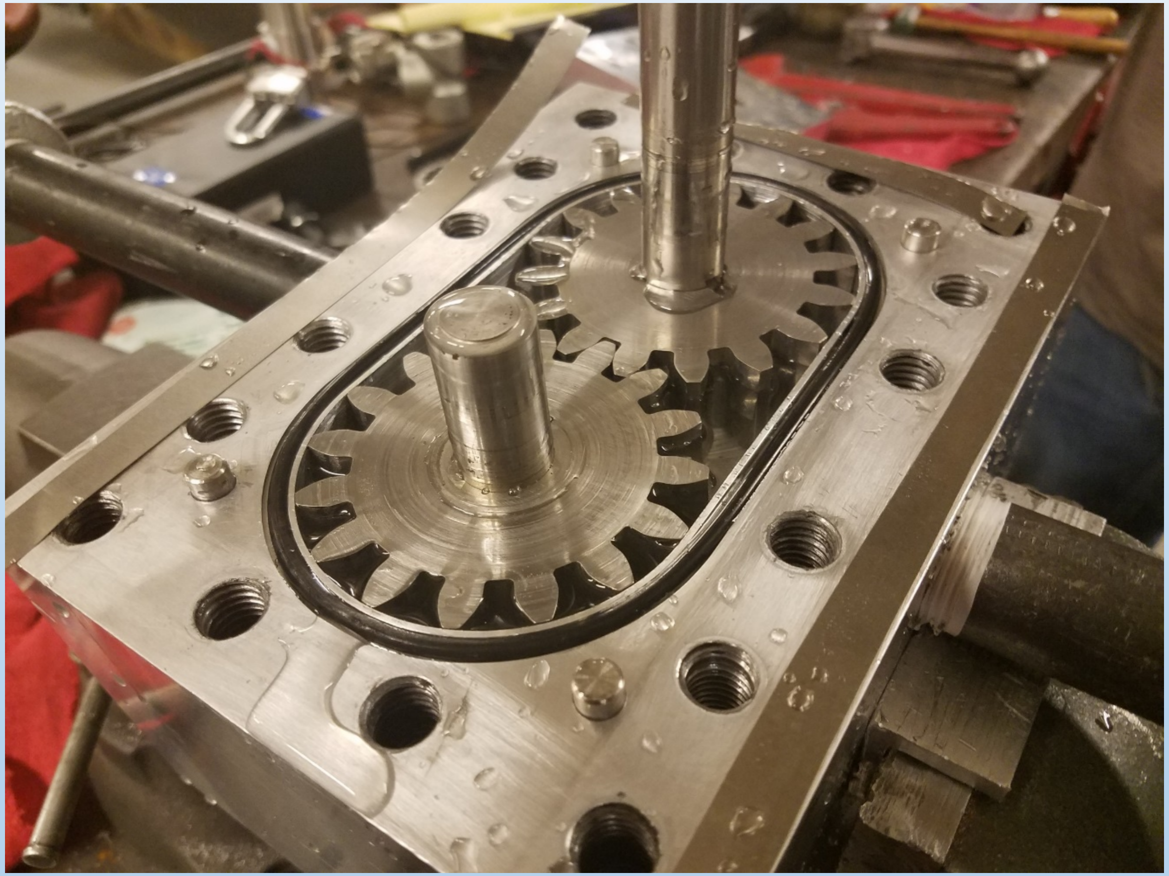
## Pneumatically Energized Auto-throttled Pump Operated for a Developmental Upperstage

## Spring Final Review

Customer: Special Aerospace Services
Chris Webber and Tim Bulk

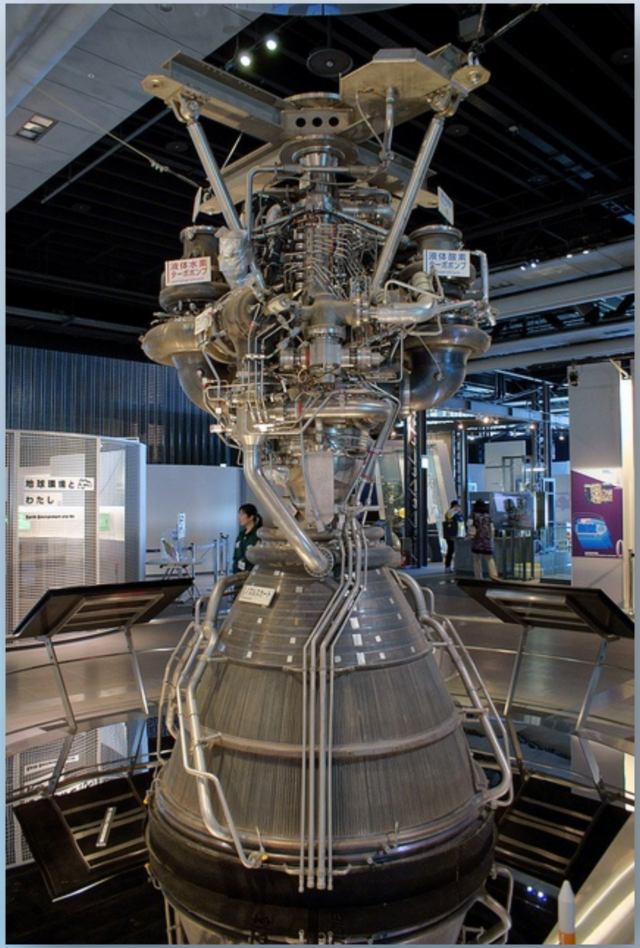
# Spring Final Review

- Project Overview
- Design Description
- Test Overview
- Test Results
- Systems Engineering
- Project Management
- Conclusions



# Project Overview

# Pumps and Their Place in Rocketry



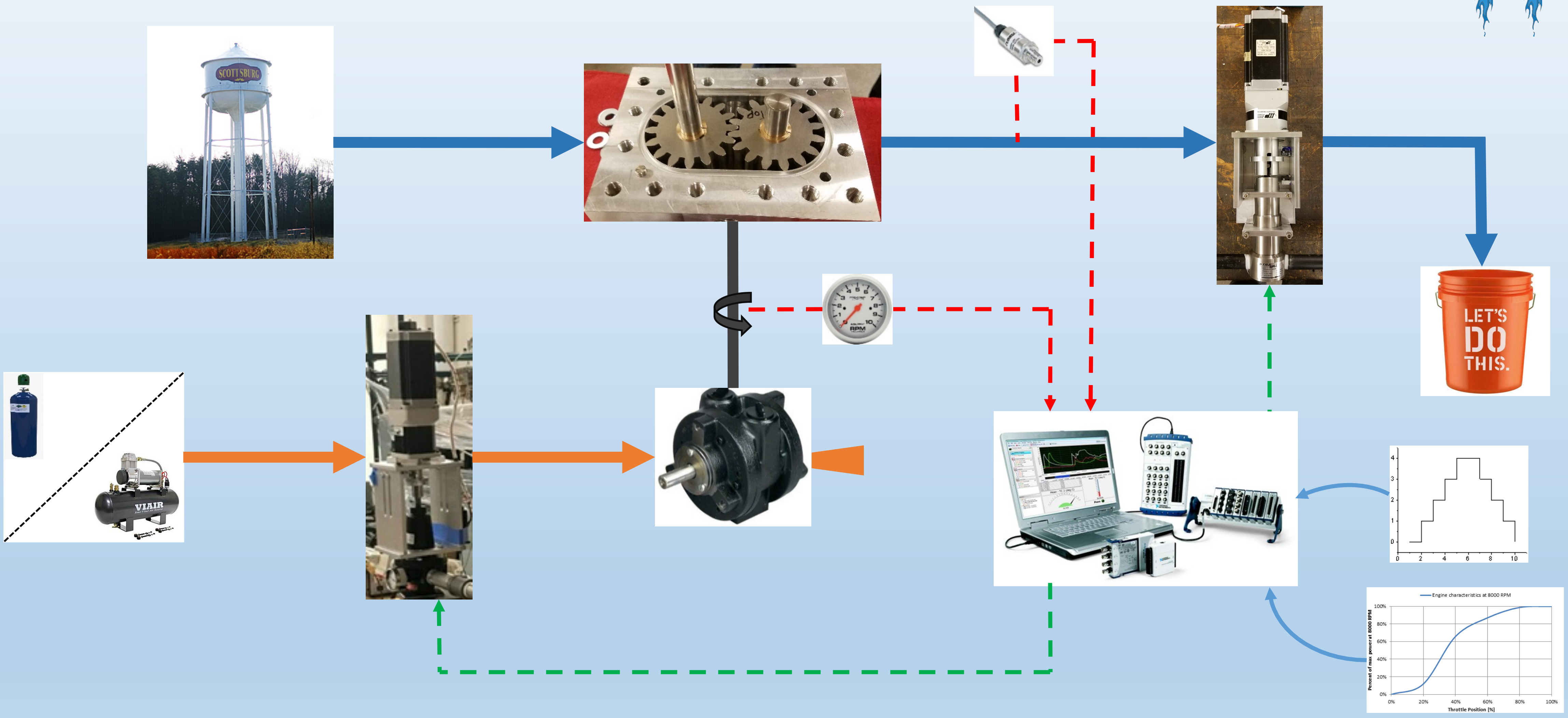
- Deliver propellants to combustor
- Low pressure fuel tanks
- Precise throttling control

# Project Motivation

- Design, manufacture, and test 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

- Would allow for greater control of combustion of rocket fuels

# CONOPS


SCOTTSBURG
RPM
VIAIR
LET'S DO THIS.
Engine characteristics at 8000 RPM
Throttle Position [%]

# Levels of Success

| Level | Performance Success |
|---|---|
| 1 | • 750 ± 15 psi outlet pressure<br>• Structural FOS 2.5<br>• 120 seconds of operation<br>• 75% efficiency of pump at full throttle |
| 2 | • 10-100% throttleability<br>• 0-100% throttle in 2 seconds<br>• All level 1 requirements |
| 3 | • 0-100% throttle in 1 second<br>• All level 1 and 2 requirements<br>• Hypergolic Compatible |

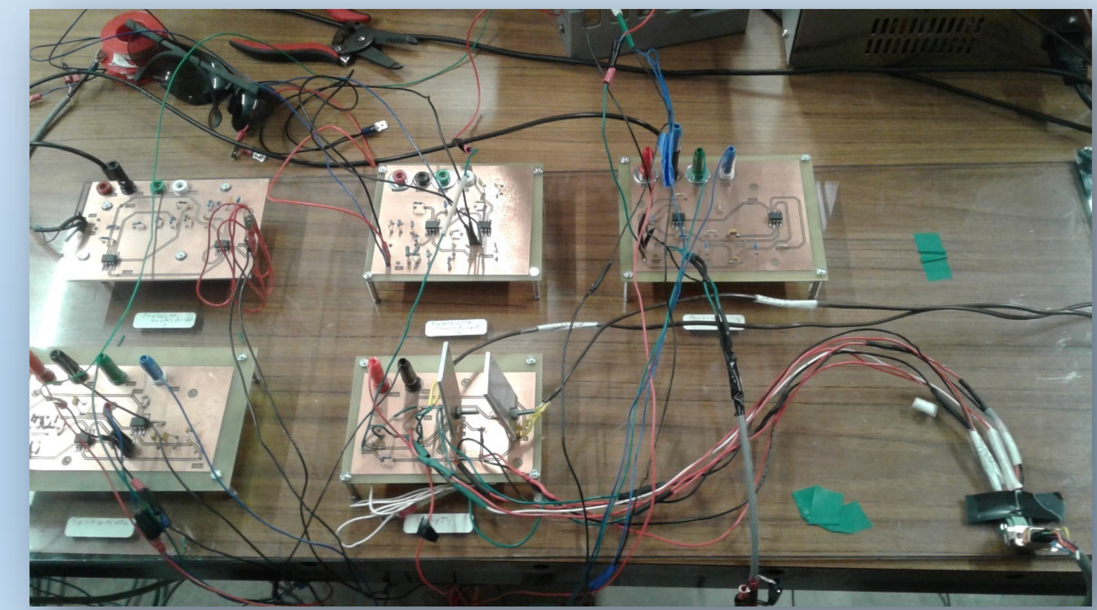
# Functional Requirements

| FR | Description |
|---|---|
| FR 1. | The pump shall be pneumatically driven using compressed helium |
| FR 2. | The pump shall be throttleable from 10% to 100% of full throttle. |
| FR 3. | The pump shall maintain an outlet pressure of 750 psi with fluctuations of less than ± 15 psi at full throttle. |
| FR 4. | The pump shall be capable of running a pre-defined throttle profile |
| FR 5. | The pump shall be capable of being restarted. |
| FR 6. | The pump shall be designed to be compatible with hypergolic propellants. |
| FR 7. | The pump shall maintain a structural factor of safety of 2.5. |
| FR 8. | The pump shall be at least 75% efficient at full throttle. |

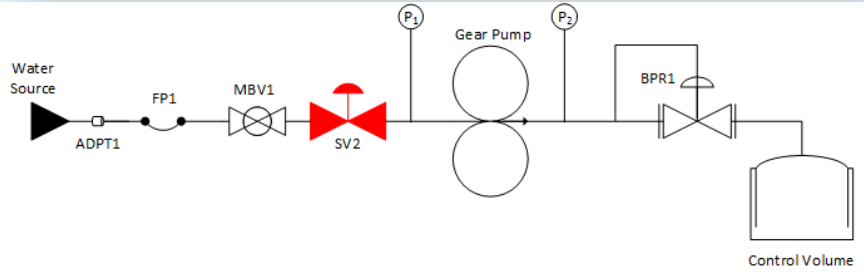
# Design Description

# Major Subsystems

- Water Subsystem
- Pneumatic Subsystem
- Pump Subsystem
- Control Subsystem



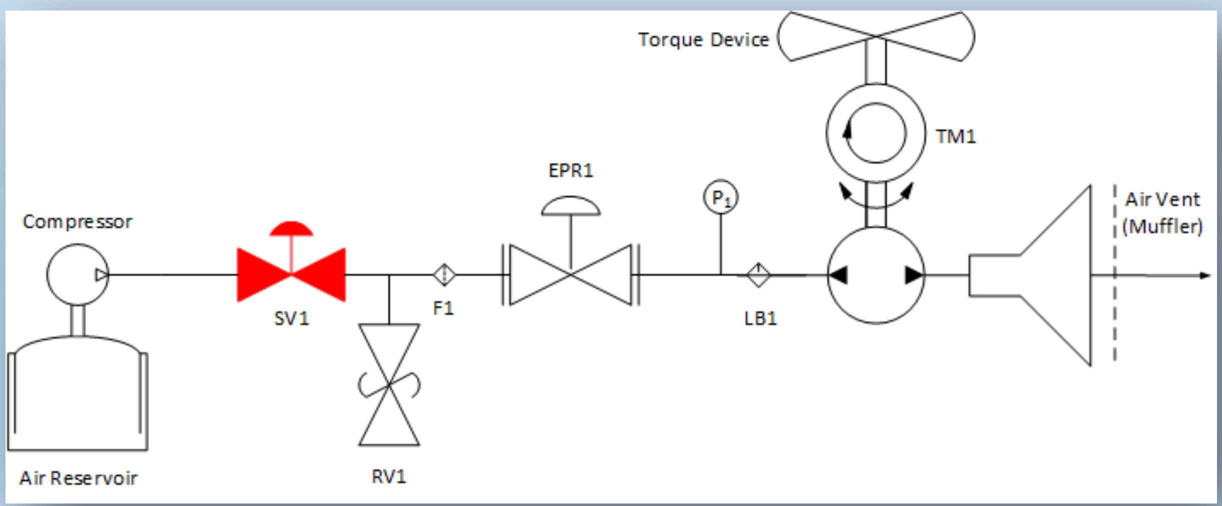
# Water Subsystem




- Steady water supply – prevent cavitation
- Measure outlet pressure (and flow rates)
- Provide backpressure (test pressure capabilities)

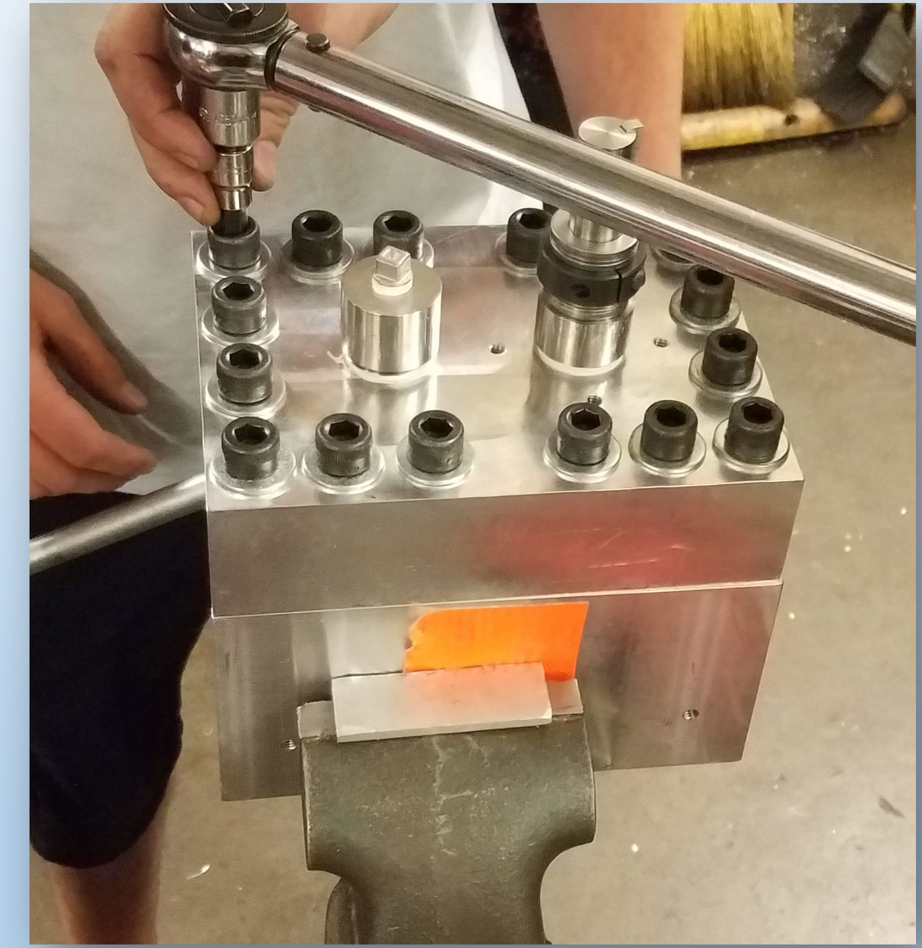
# Pneumatic Subsystem

- Power pump (rotate gears)
- Hardware side of control system



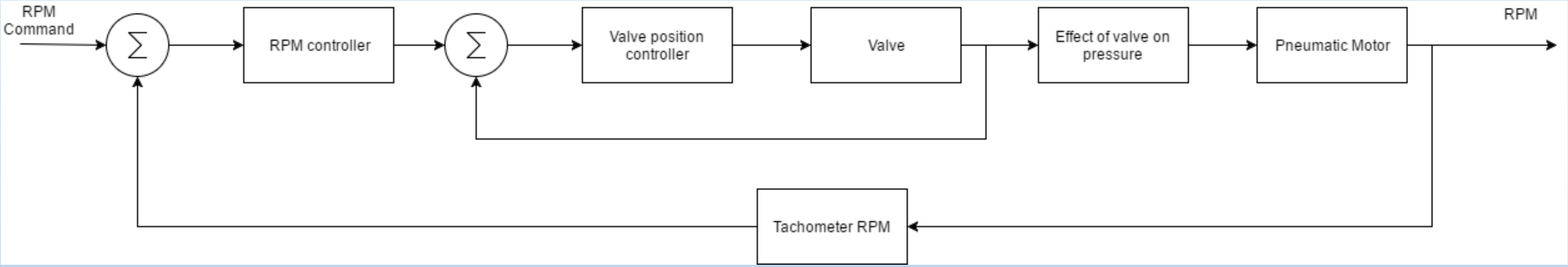
# Pump Subsystem

- Move water at constant volume/rotation
- Fulfill efficiency requirements
- Provide pressure capability
- Gear pump – 2 intermeshing gears push water through pump



# Control Subsystem

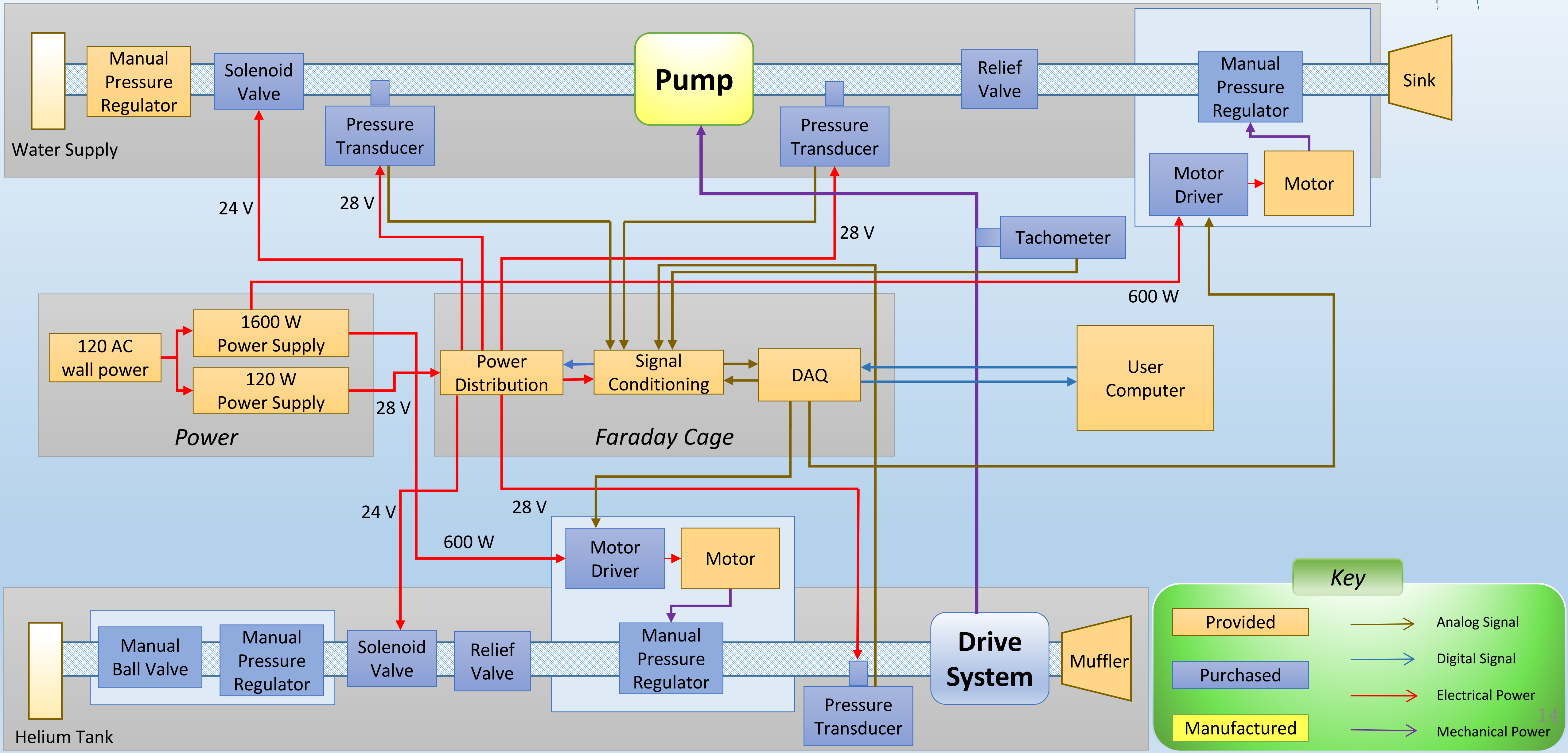
- Attempted closed loop control on RPM of the motor using feedback from a tachometer to actuate an assembled automatic pressure regulator



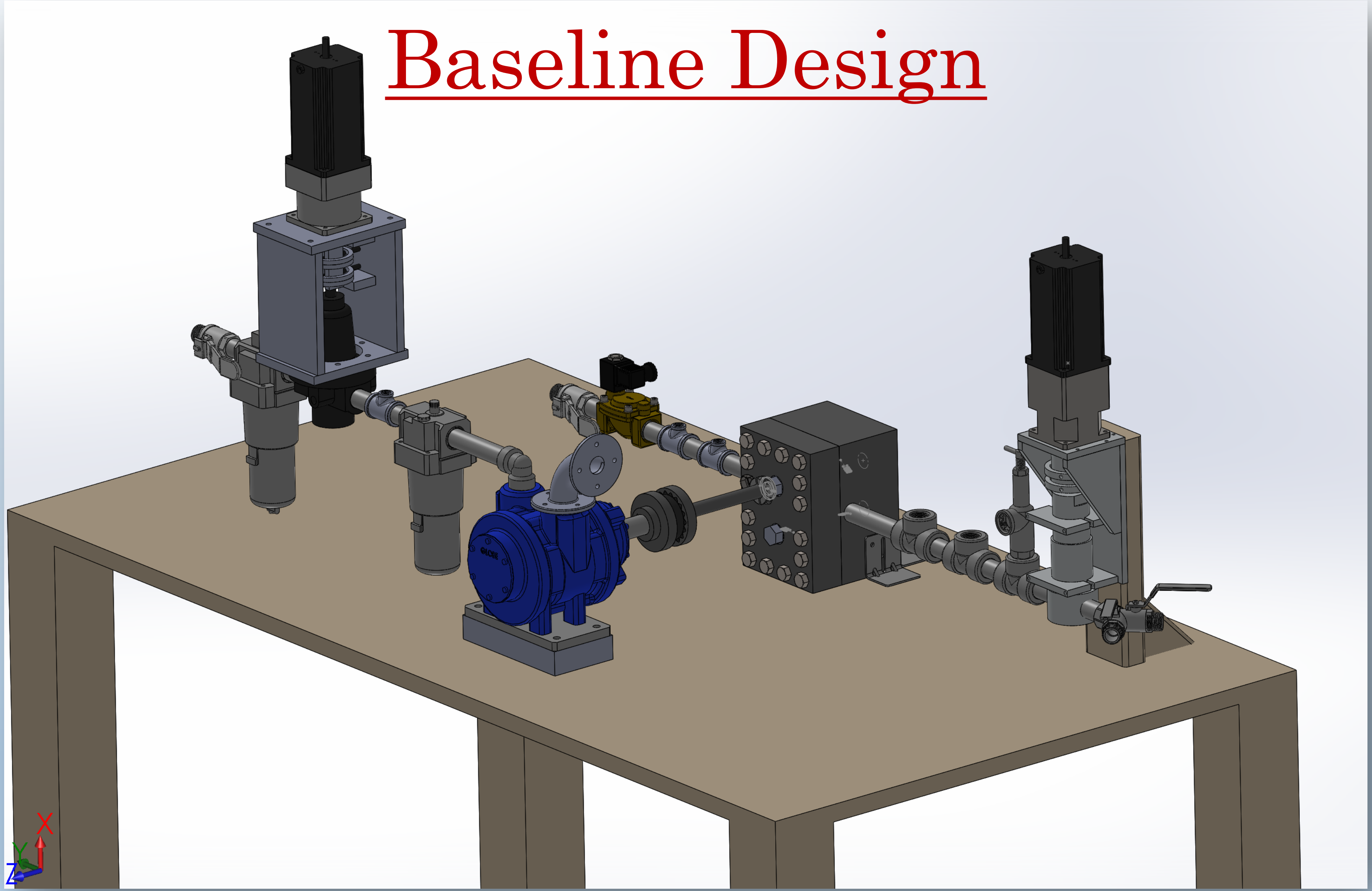

Key Parameters

- Samples rate per channel: 200 S/s/ch
- Samples per channel: 50 S/ch
- Buffer Size: 1 kS

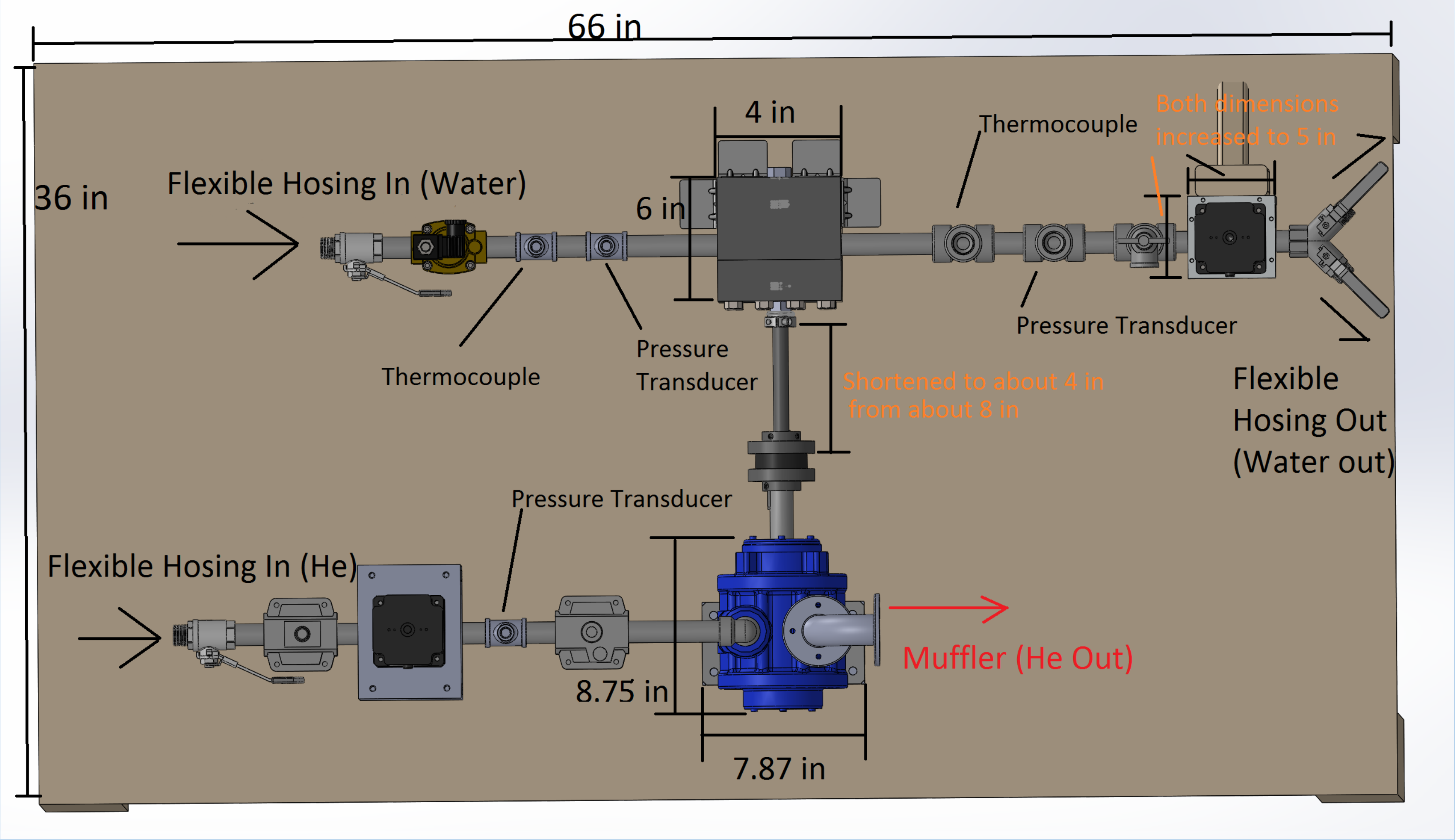
# Functional Block Diagram



# Baseline Design



# Baseline Design



# Major Design Changes

- Dynamometer in place of propeller in air motor testing
- Open loop control for most tests
- No thermocouples
- Pump – NPT shaft plug through hole, bearing placement, and seal, manufactured shafts, relief grooves added, gear/shaft axial placement

# Test Overview

# Testing Conducted

- Pump subsystem flow tests
  - Verify pump models
  - Measure flow rate and pressure achievements
- Air subsystem testing
  - Validate controllability
  - Simulate throttleability and slew rate achievements

# Pump Flow Test

| | |
|---|---|
| Description | Pump attached to manual mill<br>Inlet attached to sink<br>Fill buckets |
| Validation Goal | Efficiency Requirement<br>Design Model |
| Data Collected | Tachometer (RPM)<br>Pressure upstream<br>Pressure down stream<br>Time filling bucket<br>Mass of water in bucket |
| Variables | Ran with and without back pressure regulator<br>Varied RPM |
| Challenges | Drawing more flow than provided by sink<br>Cavitation<br>Inconsistent inlet pressure/flow |

# Air Subsystem Testing

| | |
|---|---|
| Description | Pressure regulator regulating feed pressure to motor<br>Motor RPM varying based on feed pressure<br>Back torque delivered by dynamometer |
| Validation Goal | Open loop control of motor RPM<br>Close loop control of RPM |
| Data Collected | Tachometer (RPM)<br>Pressure upstream<br>Pressure down stream<br>Time filling bucket<br>Mass of water in bucket |
| Variables | Ran with and without back pressure regulator<br>Varied RPM |
| Challenges | Drawing more flow than provided by sink<br>Cavitation<br>Inconsistent inlet pressure/flow |

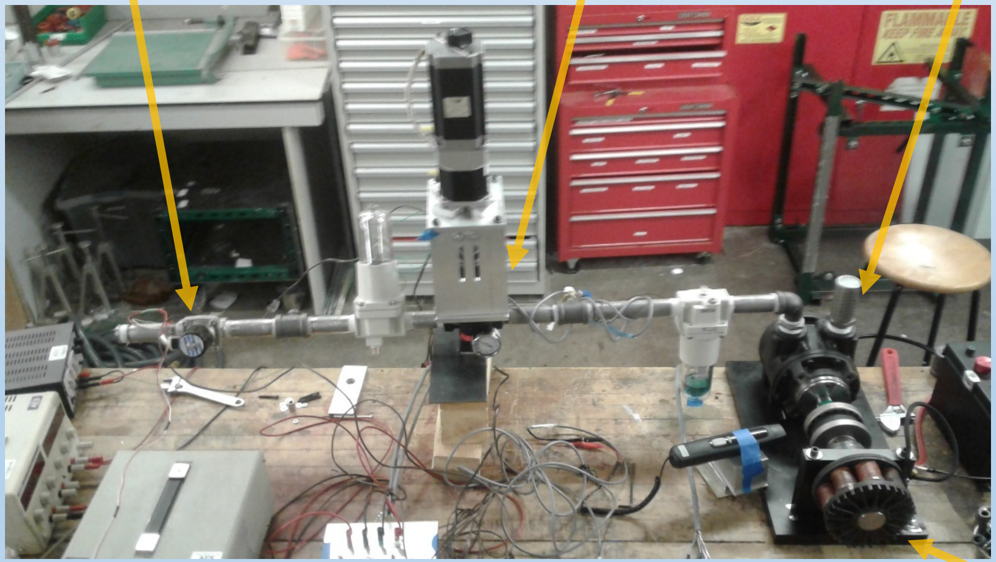
# Air Subsystem Testing

Test Rationale: Demonstrate capability to vary RPM output of motor digitally using pressure regulator.

Solenoid valve

Stepper motor and pressure regulator

Pneumatic motor



Dynamometer

Validates:

- Closed loop control using RPM feedback
- System performance at low throttle settings

Equipment Required:

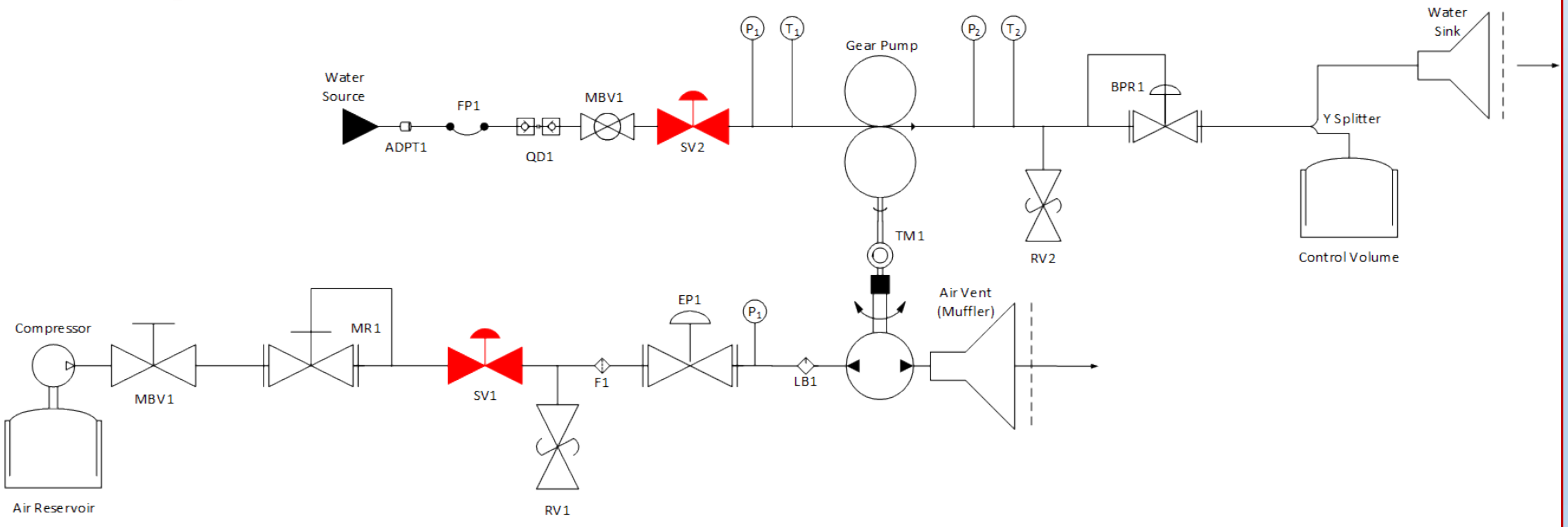
- Dynamometer
- Air subsystem
- Compressed air

# Final Testing (uncompleted)

- Test Rationale: Verify that control algorithms drive the system through a desired throttle profile. Quantify accuracy of control system and slew rates.

| | |
|---|---|
| MBV | Manual Ball Valve |
| SV | Solenoid Valve |
| RV | Relief Valve |
| P | Pressure Transducer |
| T | Thermocouple |
| MR | Manual Regulator |
| BPR | Back Pressure Regulator |
| EP | Electronic Pressure Regulator |
| F | Air Filter |
| LB | Air Lubricator |
| TM | Tachometer |

Test Setup:

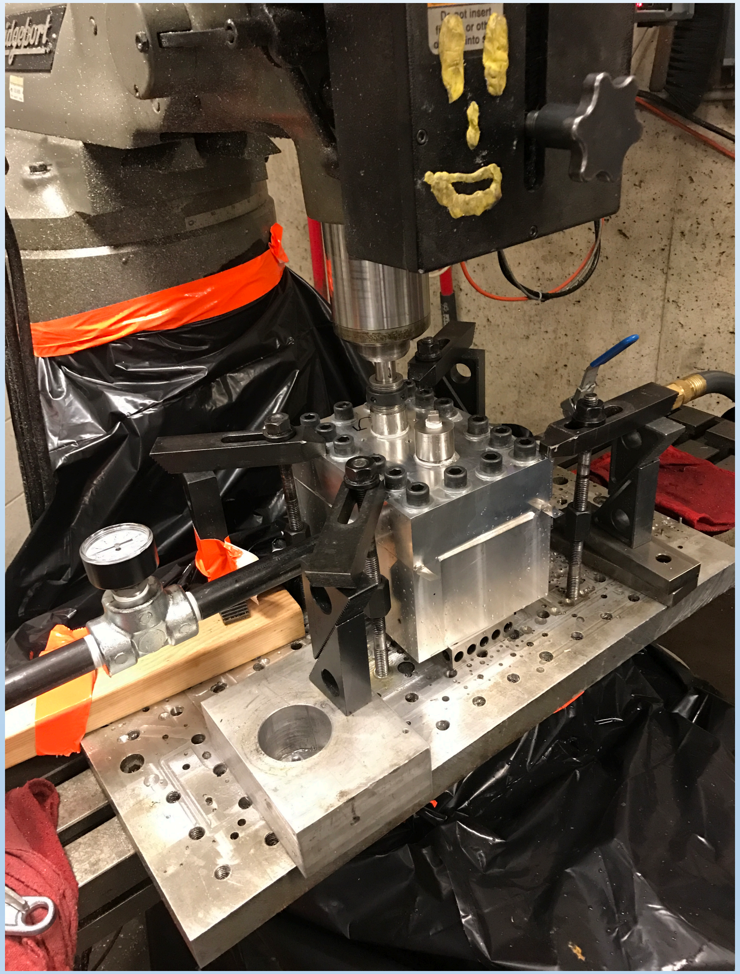


# Test Results

# Test Results – Pump

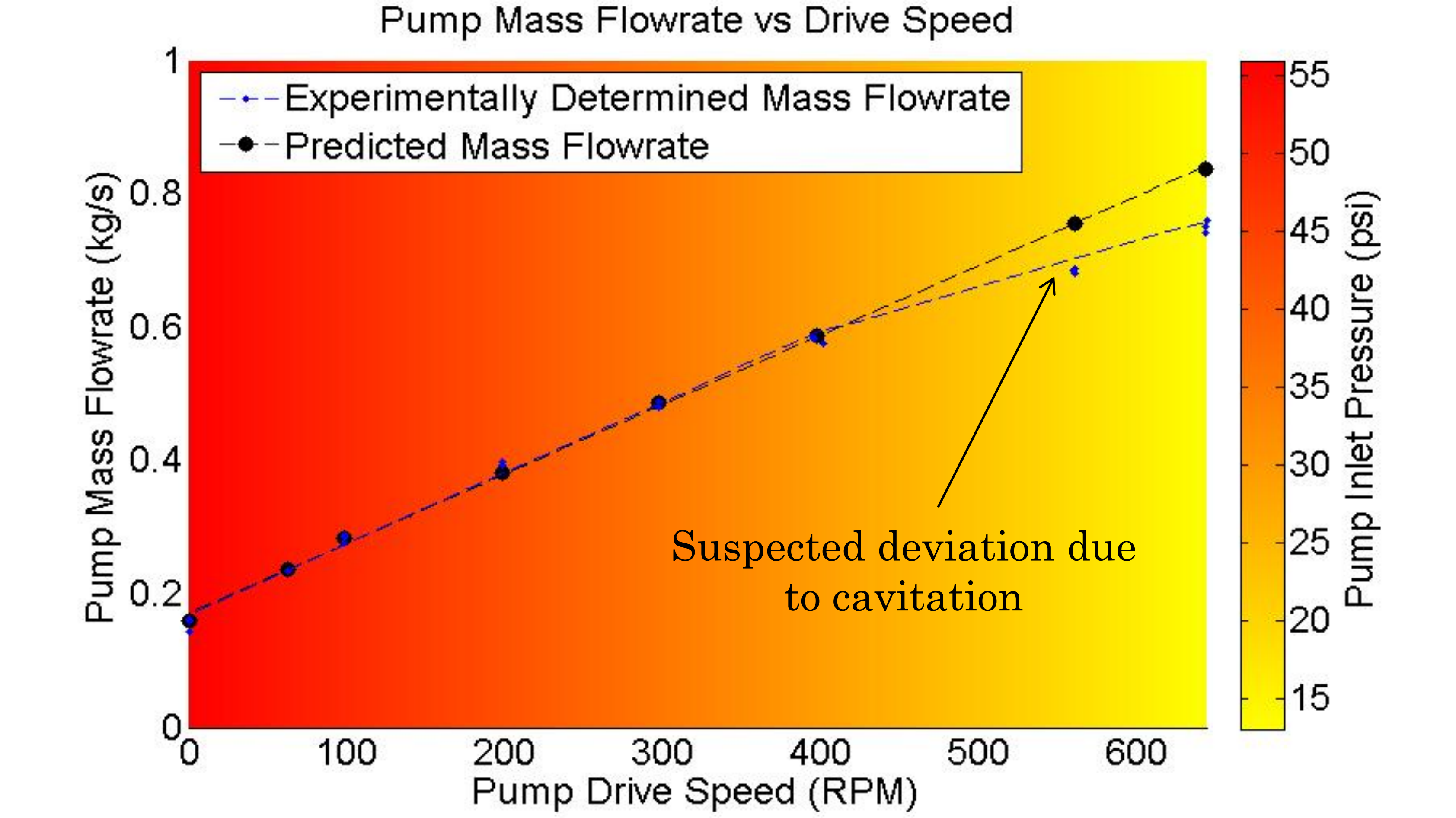
1. Flow-rate test conducted to measure the mass flowrate of the pump without controlling the outlet pressure.

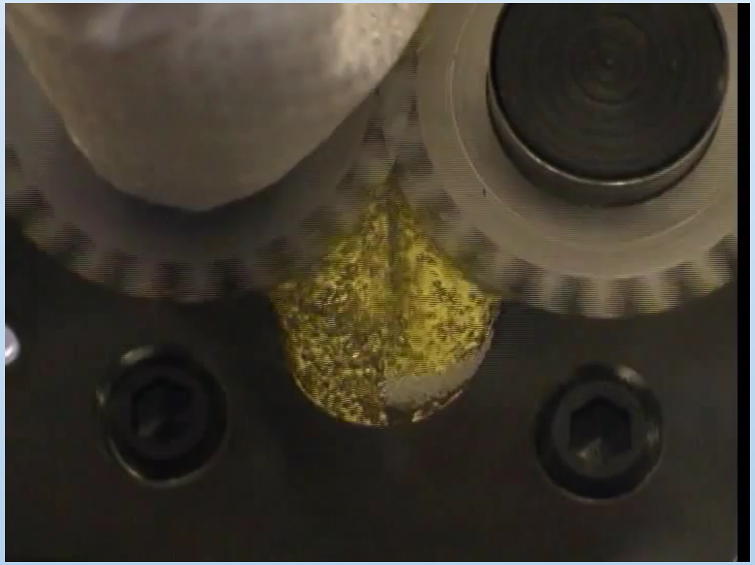
2. Back-pressure test conducted to measure the mass flowrate of the pump while controlling backpressure to simulate operational behavior.



# Model Validation – Flow Test

- Experimental data matches model to within 1% from 0 to 400 RPM
- Deviation from the model due to decrease of inlet pressure



An example of cavitation occurring in a gear pump (not ours).

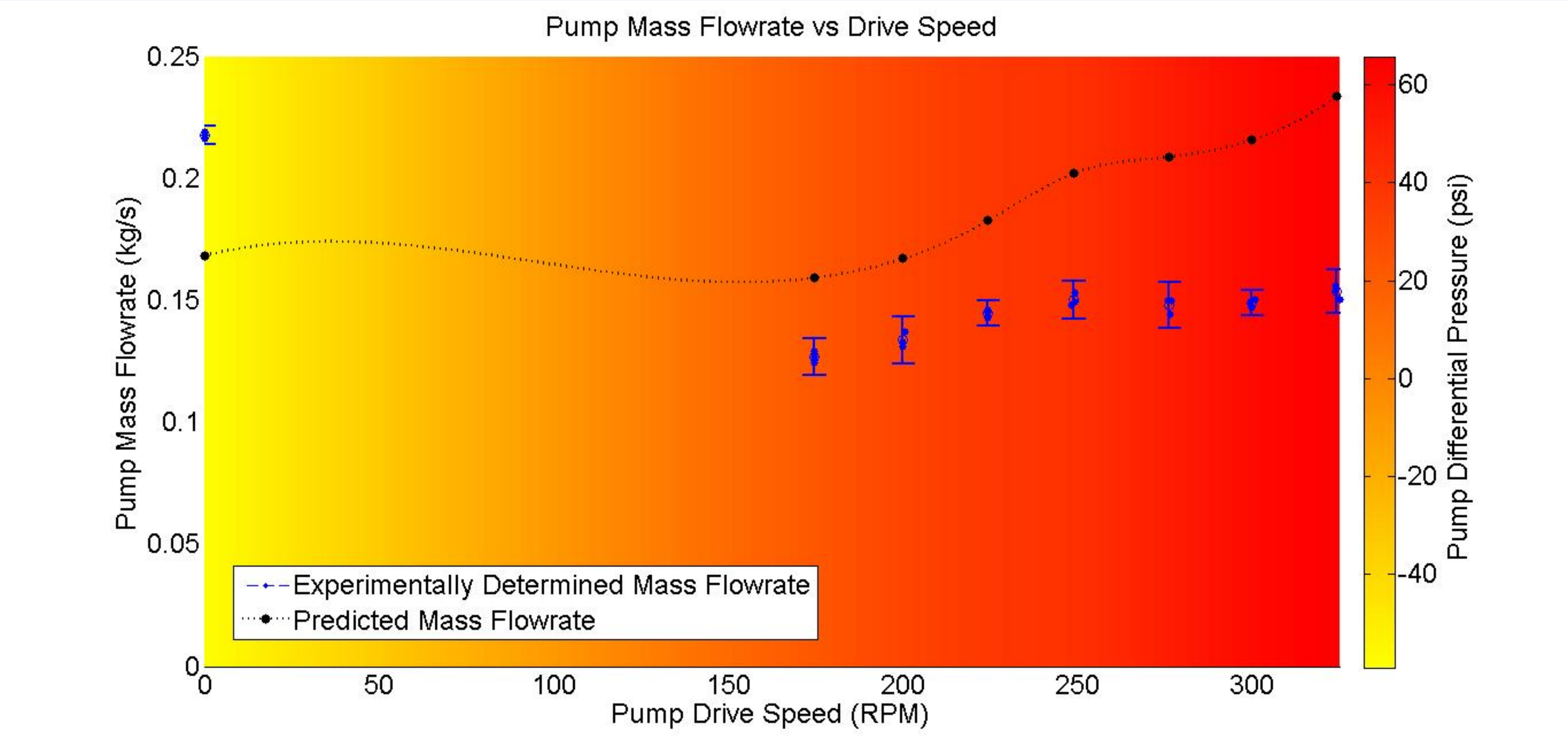
# Model Validation – Flow Test

Due to testing limitations we were not able to test through the full operational range of the pump. However, the validated model to extrapolate the behavior of the pump, the following operational parameters were predicted:

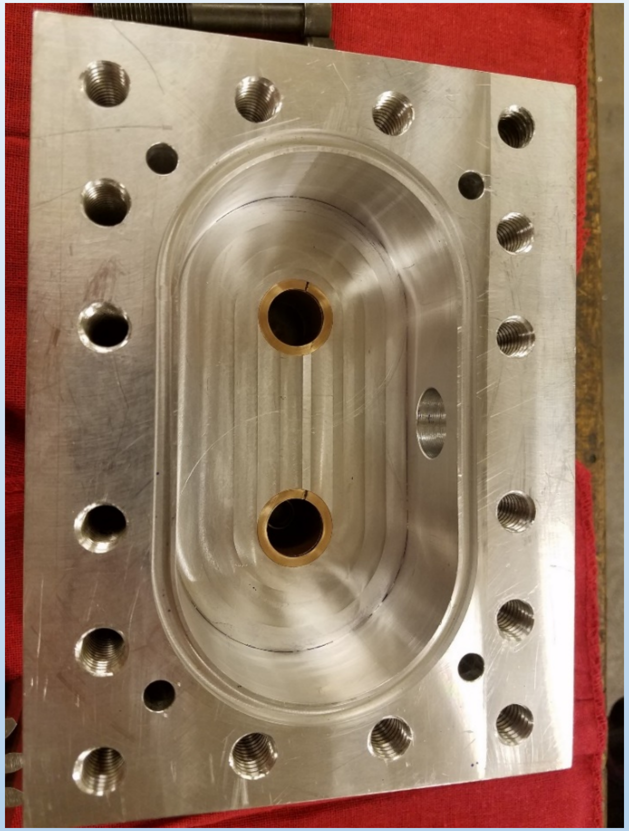
- **Required mass flowrate of 1.4 kg/s at 2610 RPM (2400 RPM max.)**
- **Required outlet pressure of 750 psi at 2610 RPM (2400 RPM max.)**
- **Full-throttle volumetric efficiency of 41.3% (75% required)**
- **Fully re-startable and self-priming**
- **Capable of the throttling mass flowrate from 10% to 100% with a drive system that can hit 2600 RPM**

# Model Validation – Back-Pressure Test

- Model deviated from experimental data
- Best explanation is an increase in pump clearances due to wear



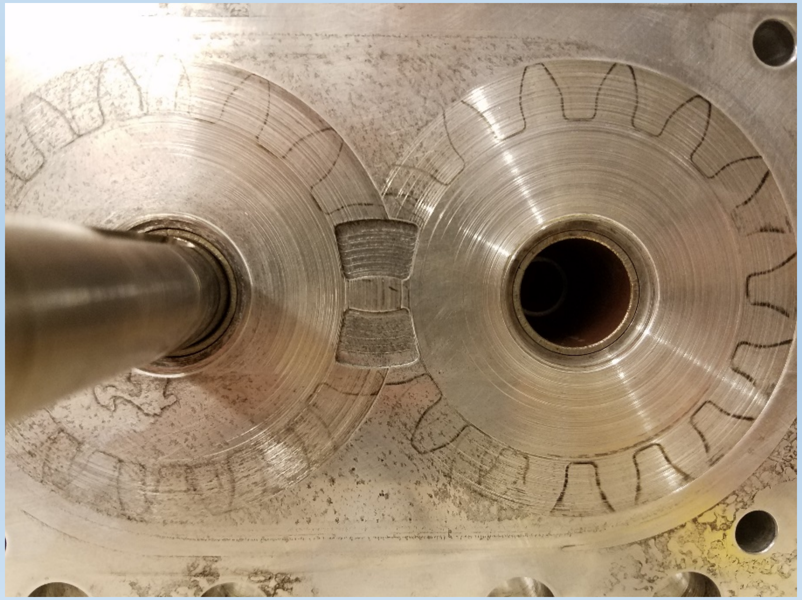
# Model Validation – Back-Pressure Test



Pre-assembly

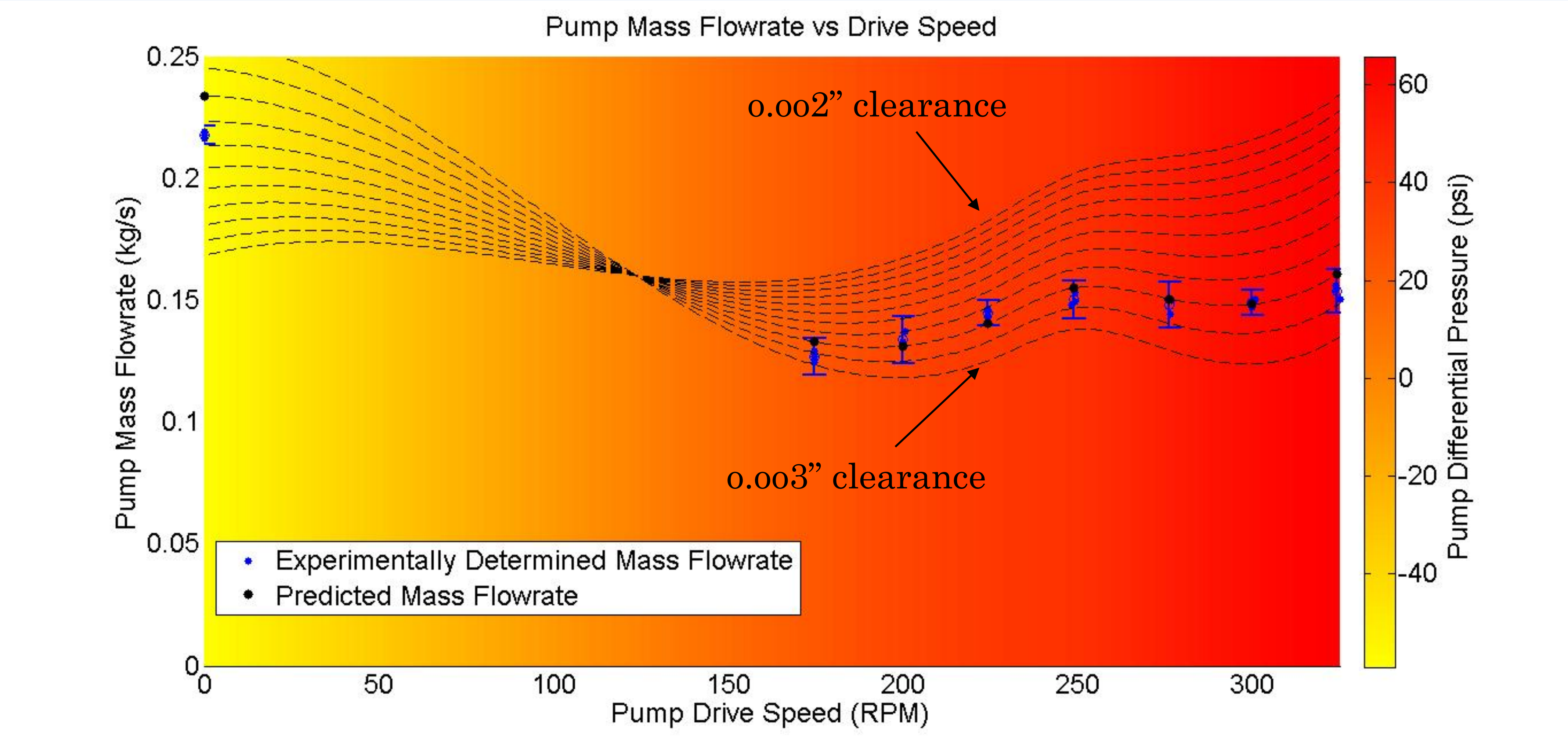
Post-assembly, pre-test

After flowrate test



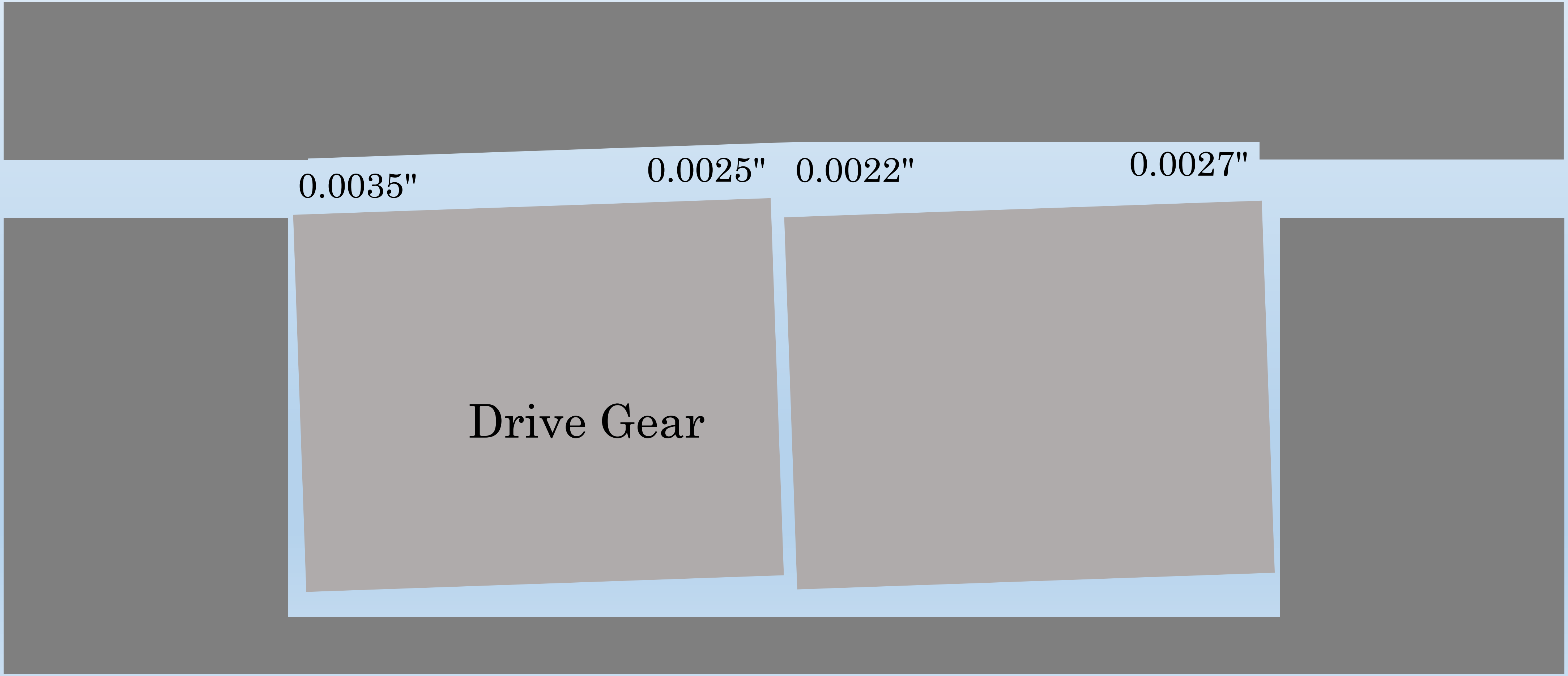
# Model Validation – Back-Pressure Test

- Model is extremely sensitive to changes in the clearance on the top and bottom of the gears.



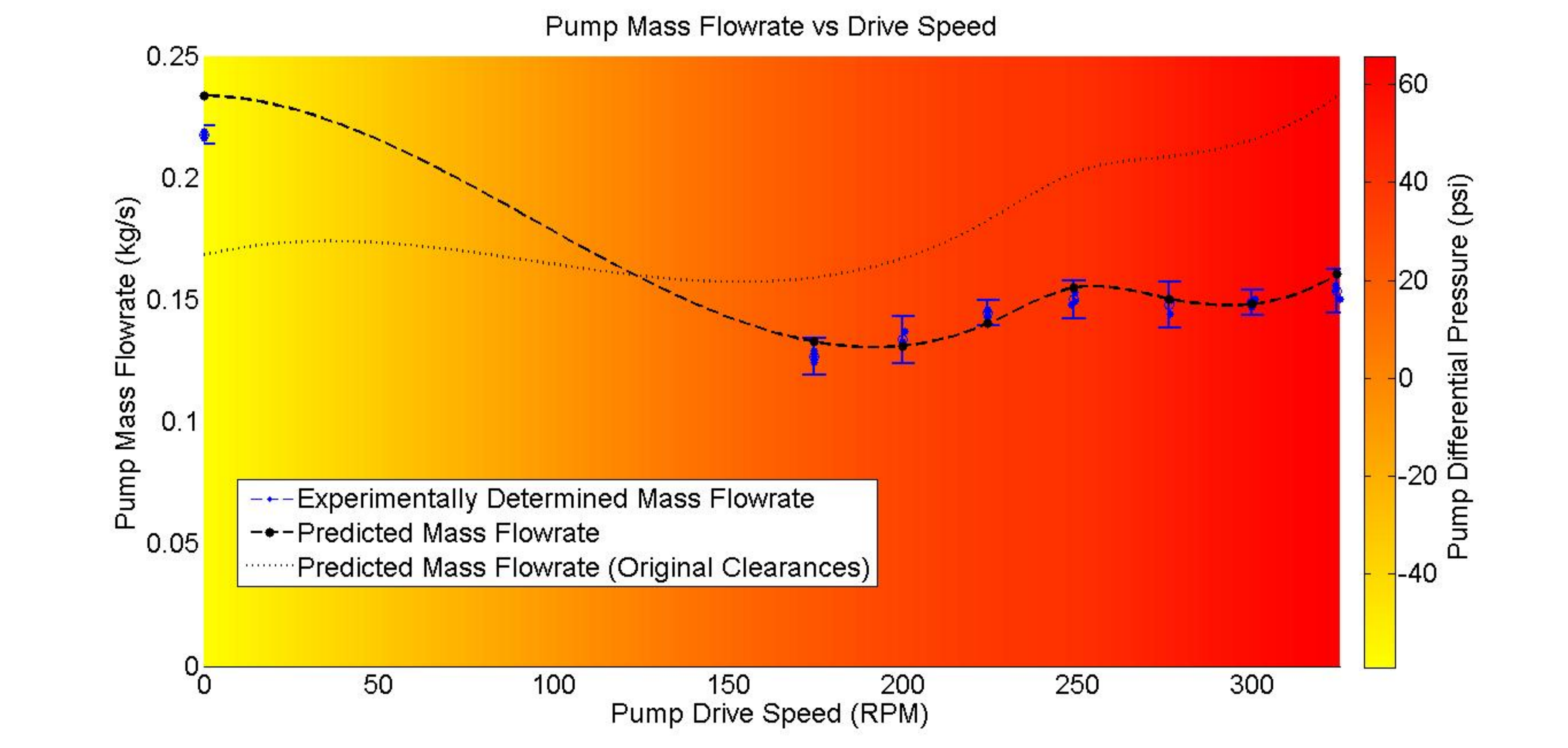
# Pump Housing Wear

- Based on measurements of clearances on top and bottom of gears after testing



# Model Validation – Back-Pressure Test

- Increasing clearance over gear tops from 0.002” to average clearance of 0.0028” yields:



# Test Results – Pump Testing

After incorporating the final pump clearances (with wear) the pump operational parameters are *predicted* to be:

- Required mass flowrate of 1.4 kg/s at 3300 RPM (2400 RPM max.)
- Required outlet pressure of 750 psi at 3300 RPM (2400 RPM max.)
- Full-throttle volumetric efficiency of 31.0% (75% required)
- Fully re-startable and self-priming
- Capable of the throttling mass flowrate from 10% to 100% with a drive system that can hit 3300 RPM

# Model Validation – Flow Test

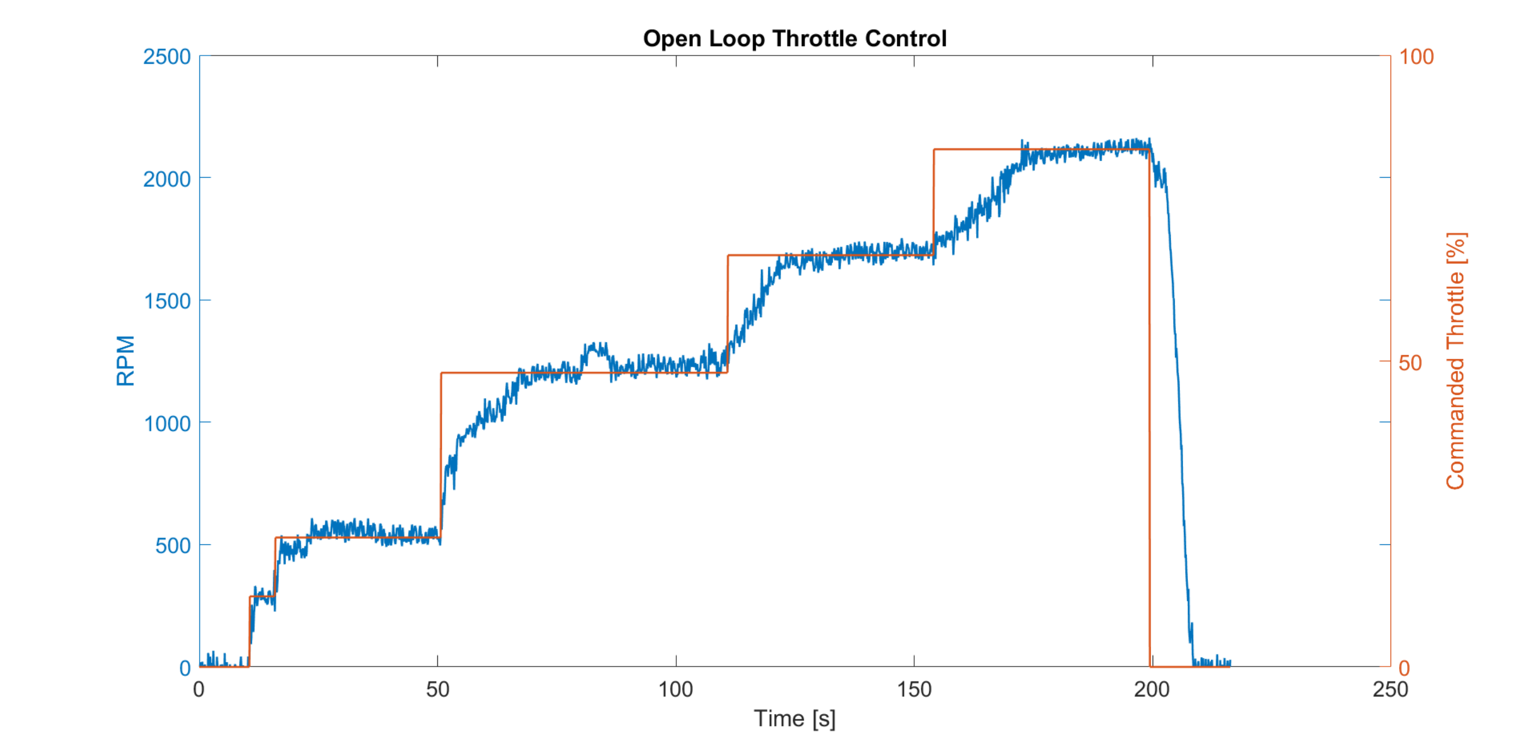
Using this testing to further validate the model:

- Required mass flowrate of 1.4 kg/s at 3300 RPM (2400 RPM max.)
- Required outlet pressure of 750 psi at 3300 RPM (2400 RPM max.)
- Full-throttle volumetric efficiency of 33.0% (75% required)
- Fully re-startable and self-priming
- Capable of the throttling mass flowrate from 10% to 100% with a drive system that can hit 3300 RPM

# Test Results - Open Loop Control

**Data collected:**
- Air motor RPM
- Pressure upstream of motor

**Test success:**
- Open loop control
- Motor performance at low throttle settings

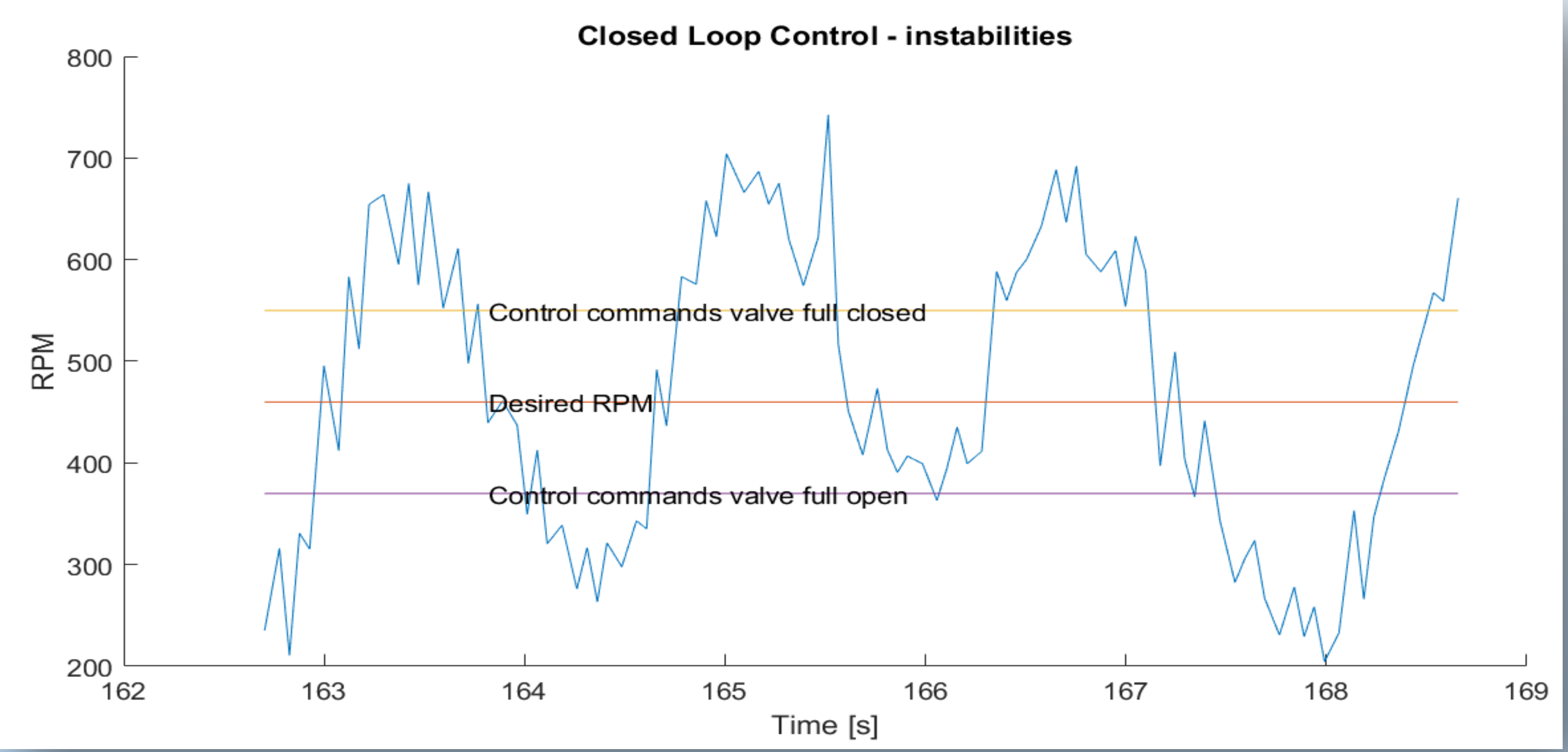



**Requirements met at test completion:**
- None

**Future tests:**
- Test more gains for stable control
- System assembly to control pump
- Test slew rate time
- Upper range of throttle settings (higher than 30%)

# Test Results - Closed Loop Control

| Control System Issue | Physical Manifestation |
|---|---|
| Electric noise during testing | Noisy data |
| Overshoot on commanded RPM | Sinusoidal RPM output |



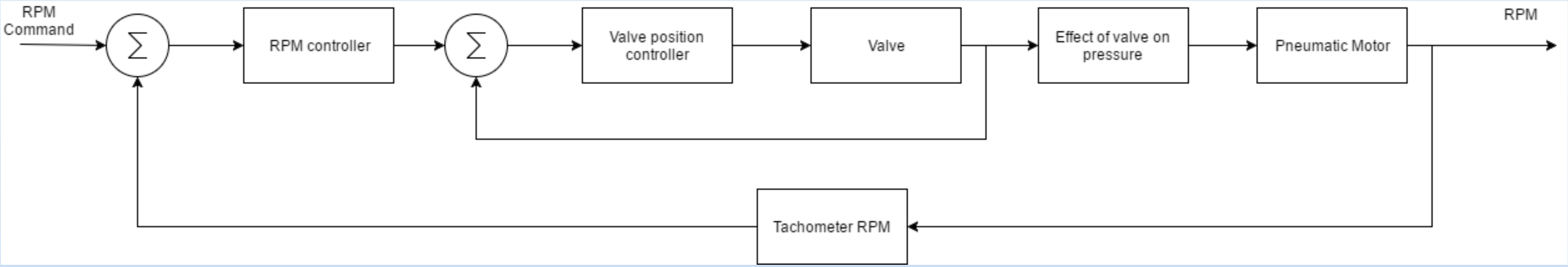
# Control System Instabilities

# Control System Instabilities

- Possible explanations
  - Incorrect PID gains– control instabilities
  - Control loop issues – Stepper motor and valve slower than RPM control loop
  - Electronic noise

- Possible Solutions
  - Determine stable control gains (10 man-hours)
  - Custom filter within software (4 man-hours)
  - Increase valve motor speeds (reduced safety limits) (2 man-hours)

# Control System Instabilities




- Possible explanations
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  - Electronic noise
- Possible Solutions
  - Determine stable control gains (10 man-hours)
  - Custom filter within software (4 man-hours)
  - Increase valve motor speeds (reduced safety limits) (2 man-hours)

# Full System Implications

Using testing results to update model parameters, the full system would operate as follows:

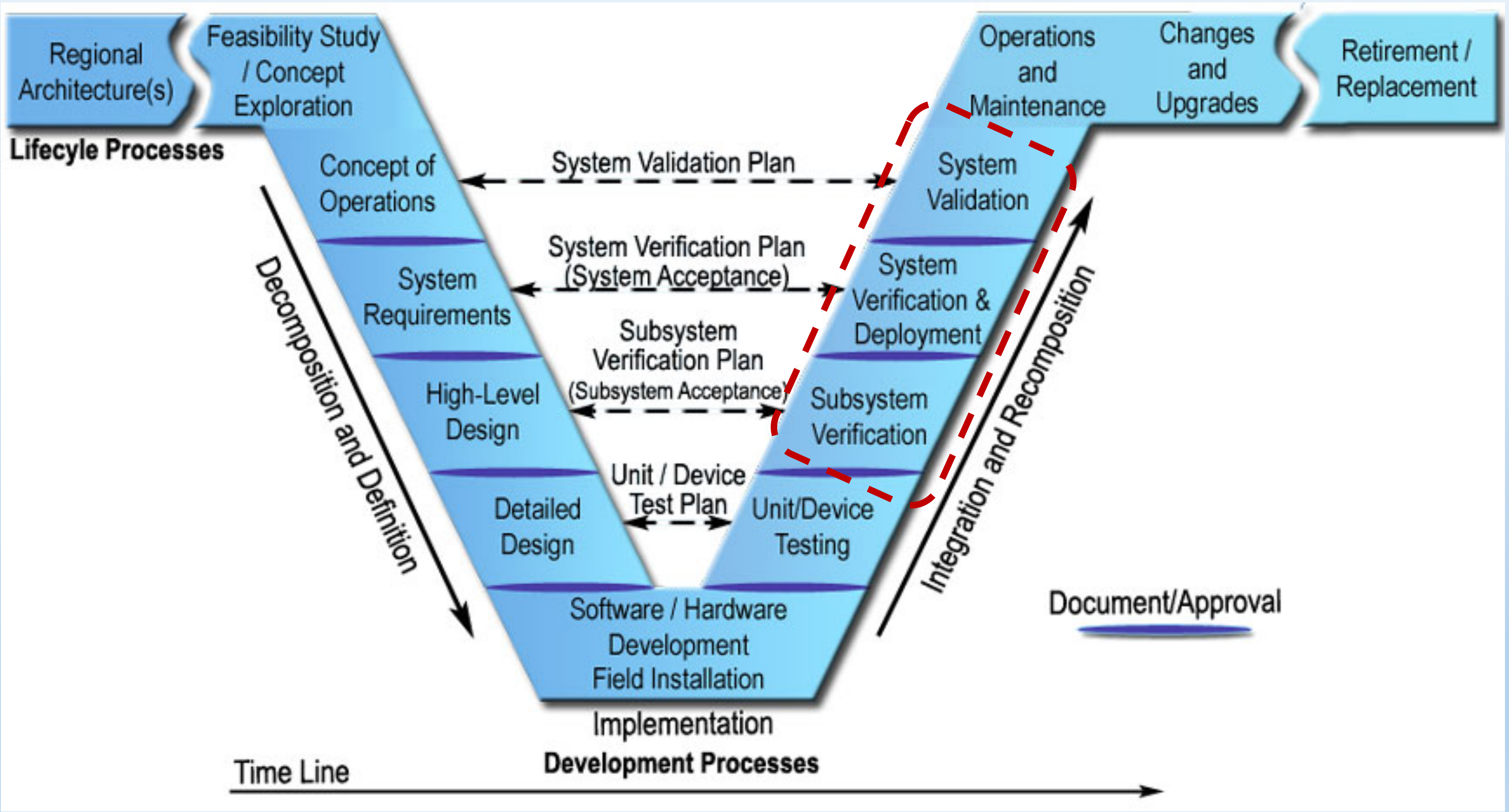
- Required mass flowrate of 1.4 kg/s at 3300 RPM (2400 RPM max.)
- Required outlet pressure of 750 psi at 3300 RPM (2400 RPM max.)
- Pressure fluctuations would exceed 15PSI at 3300 RPM
- Full-throttle volumetric efficiency of 33.0% (75% required)
- Fully re-startable and self-priming
- Capable of the throttling mass flowrate from 10% to 100% with a drive system that can hit 3300 RPM

# Status of Functional Requirements

| FR | Description | Result/Predicted Result |
|---|---|---|
| FR 1. | The pump shall be pneumatically driven using compressed helium | Failure, pneumatically driven was a success, helium was untested. |
| FR 2. | The pump shall be throttleable from 10% to 100% of full throttle. | Untested/Failure, could not meet mass flow rates with air motor/mill, but could throttle 0%-100% of air motor's capabilities. |
| FR 3. | The pump shall maintain an outlet pressure of 750 psi with fluctuations of less than ± 15 psi at full throttle. | Untested, full system integration needed, but with validated model the drive speed needed is 2610 RPM (max. drive speed = 2400 RPM). |
| FR 4. | The pump shall be capable of running a pre-defined throttle profile | Untested/Failure, no closed loop control demonstrated. |
| FR 5. | The pump shall be capable of being restarted. | Met, restarted multiple times during testing. |
| FR 6. | The pump shall be designed to be compatible with hypergolic propellants. | Failed, due to budgetary constraints. |
| FR 7. | The pump shall maintain a structural factor of safety of 2.5. | Met, designed accordingly. |
| FR 8. | The pump shall be at least 75% efficient at full throttle. | Failed, predicted efficiency ~ 43%. |

# System Engineering

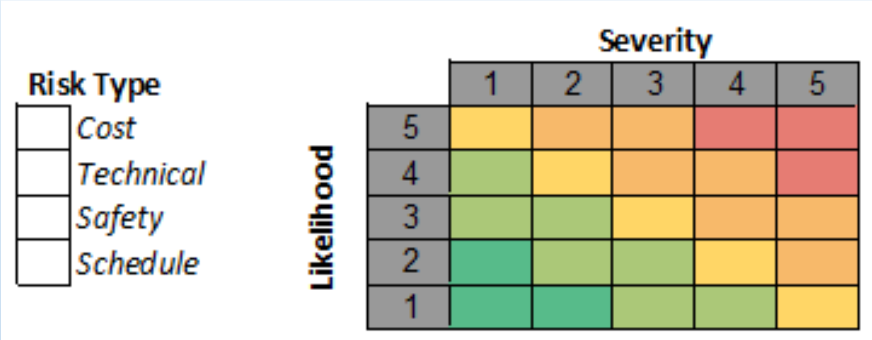
# Where we are:



Regional Architecture(s)
Feasibility Study / Concept Exploration
Lifecycle Processes
Concept of Operations
System Requirements
High-Level Design
Detailed Design
Software / Hardware Development Field Installation
Implementation
Development Processes
Unit/Device Testing
Subsystem Verification
System Verification & Deployment
System Validation
Operations and Maintenance
Changes and Upgrades
Retirement / Replacement
System Validation Plan
System Verification Plan (System Acceptance)
Subsystem Verification Plan (Subsystem Acceptance)
Unit / Device Test Plan
Decomposition and Definition
Integration and Recomposition
Document/Approval
Time Line

# The Risks

- Risks from CDR that persisted
  - Tolerance Stack-Up
  - Driveshaft Leakage




- Unforeseen risks that were not mitigated appropriately:
  - Control of the air motor (was not foreseen)
  - Testing Schedule
  - Manufacturing Schedule -

# Mitigating Risks

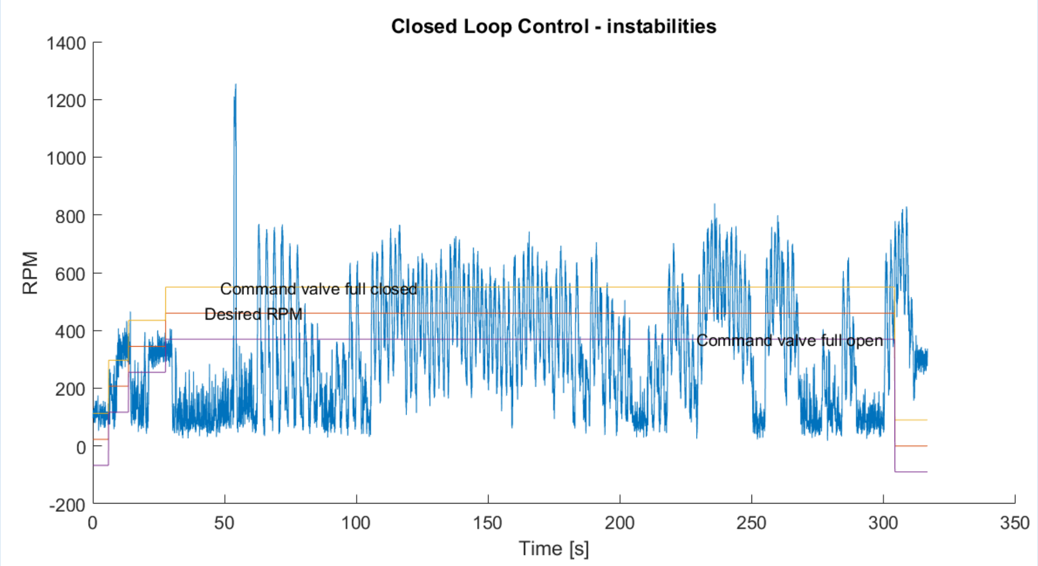
**Risks from CDR that persisted:**

- Tolerance Stack-Up
  - Mitigated very well given machining limitations
  - Could mitigate by planning to build two pumps and use lessons-learned
- Driveshaft Leakage
  - Expected to have low likelihood and high risk
  - Seal always leaked at start of tests, before seal seated
  - Could mitigate by pressurizing pump cavity to seat the seal before testing

# Mitigating Risks – cont'd

**Unforeseen risks that were not mitigated appropriately:**

- Closed-loop control of the air motor (was not foreseen)
  - Control proved challenging due to non-ideal hardware
  - Large amounts of noise in tachometer signal
  - Slow control actuator (stepper motor and manual regulator)



# Mitigating Risks – cont'd

**Unforeseen risks that were not mitigated appropriately:**

- Manufacturing Schedule
  - First began to fall behind schedule due to availability of stainless steel (took 10 days to ship)
  - Manufacturing error caused the first housing to be scrapped (lost 10-12 days of shop time)
  - Manufacturing schedule slip allowed other subsystems leads to fall behind without feeling critical-path schedule pressure

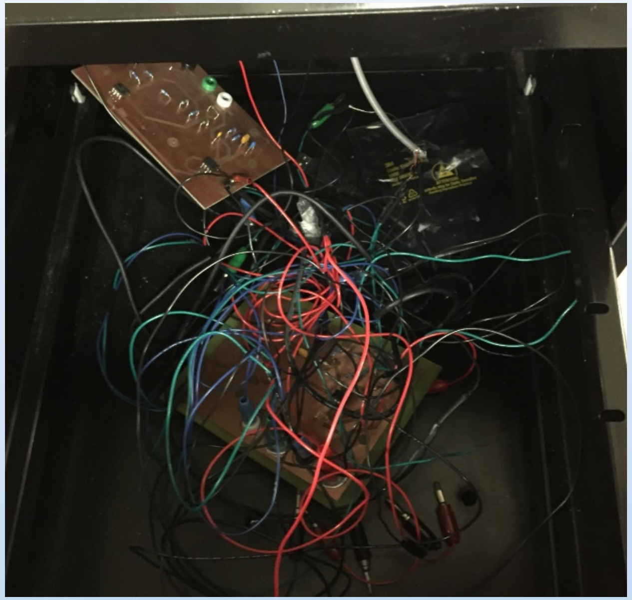
# Mitigating Risks – cont'd

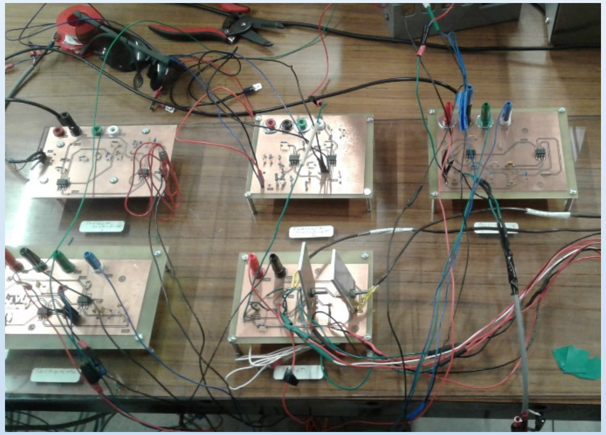
**Unforeseen risks that were not mitigated appropriately:**

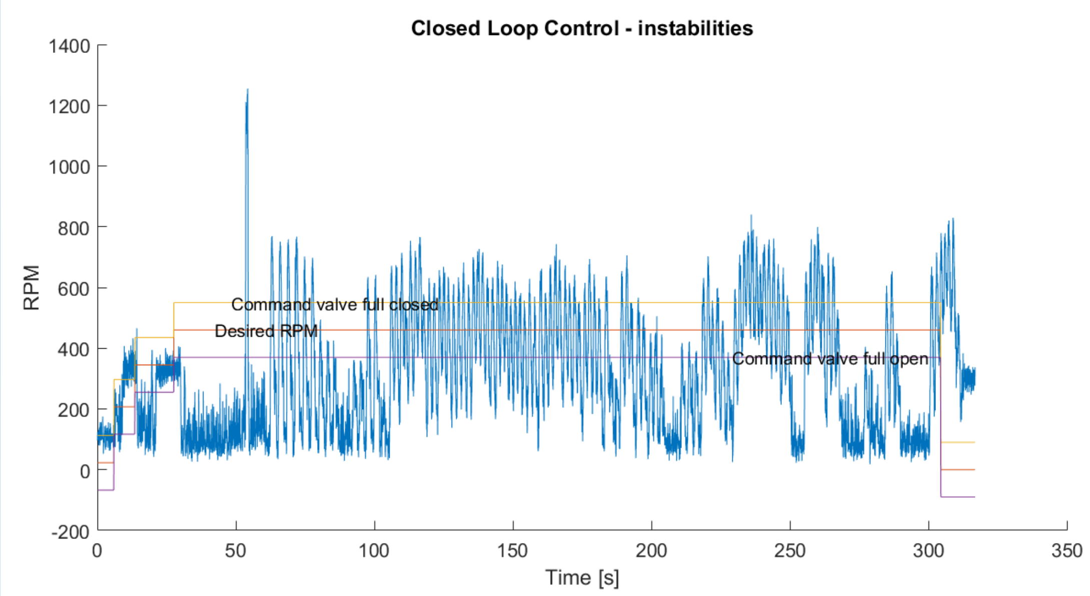
- Testing Schedule
  - Subsystem testing was not completed on schedule due to:
    - Lack of critical-path schedule pressure
    - Time requirement from manufacturing
  - Could have gotten creative to validate and tune the closed-loop control model even though we didn't have a working drive system

# Lessons Learned

- Hold subsystem leads accountable for completing work, problem solving efficiently, and maintaining a high-quality of work
- Require that subsystem leads get creative and test/validate their work
- Maintain a broader view on the project
- Focus more on subsystem testing and helping subsystem leads with troubleshooting
- Require a higher level of personal commitment and responsibility from all members of team





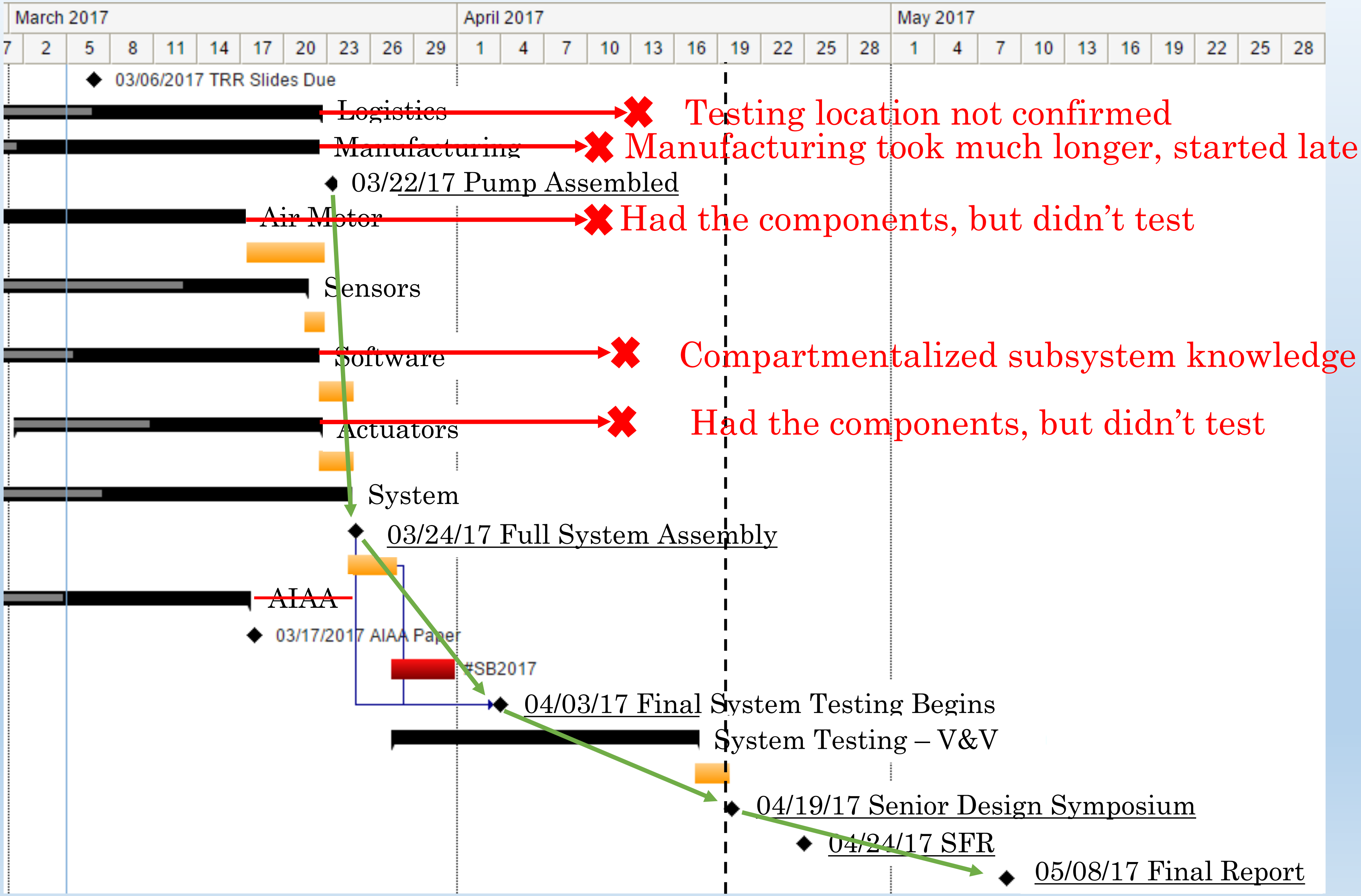


# Project Management

# Management Successes

- Pump was manufactured despite multiple design iterations and errors.
- Air motor successfully run showing possible low throttle-ability
- Under-budget
- Successful motor-to-regulator integration

# Schedule, where we went wrong



# Project Management, Lessons Learned

1. Communication is essential
2. Go with your gut
3. Be careful showing margin in the schedule and set hard deadlines
4. Don't compartmentalize
5. Finding a way to keep people involved is challenging
6. Always overestimate how long tasks will take by 3-4 times
7. Be optimistic, but realistic
8. Don't be afraid to ask for help or other opinions
9. Hold teammates accountable for missed deadlines and excuses
10. Productive meetings, greater frequency

# Planned vs. Actual Budget

Total Funding: $8,000

## Planned Budget (From TRR)

- Predicted Cost: $6826.90
- Predicted Margin: $1,173.10

## Actual Budget

- Total Cost: $7690.65
- Total Margin: $309.35

Over planned budget by: 12.65%

# Total Project Cost

| | | |
|---|---|---|
| • Wage Expense: | $150,070.31 | (4802.25 hours at $31.25/hr) |
| • Materials Expense: | $7,690.65 | |
| • Overhead Expense: | $315,521.93 | (200% overhead) |

- Total Project Cost: **$473,282.89**

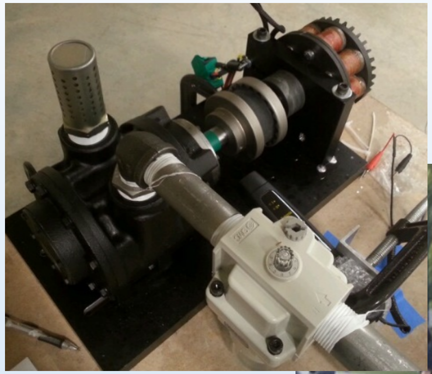
- Savings for Customer: $473,282.89 - $20,000 = **$453,282.89**

# Conclusions

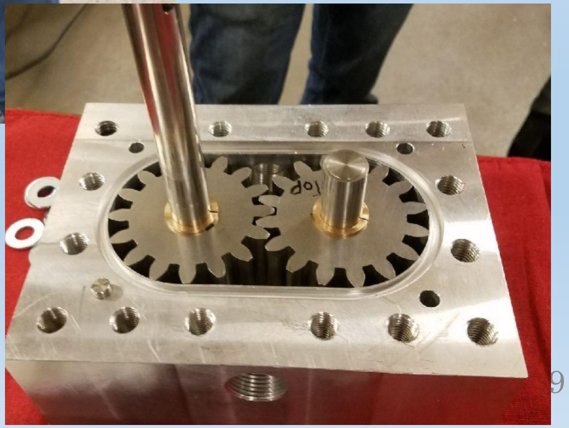
# Suggested Design Iterations

- Manufacturing Improvements:
  - Budget more manufacturing time
  - Access to more precise machining equipment
  - Iterate design with manufacturing abilities in mind
- Component Improvements
  - Purchase electronic pressure regulators
  - Purchase higher accuracy tachometer
- Software Improvements
  - Develop control law, allow for adjustments to command rates

# Questions?



# Thank You!



Tim Bulk, Chris Webber, Cameron Brown, Josh Stamps and CU Boulder Faculty,

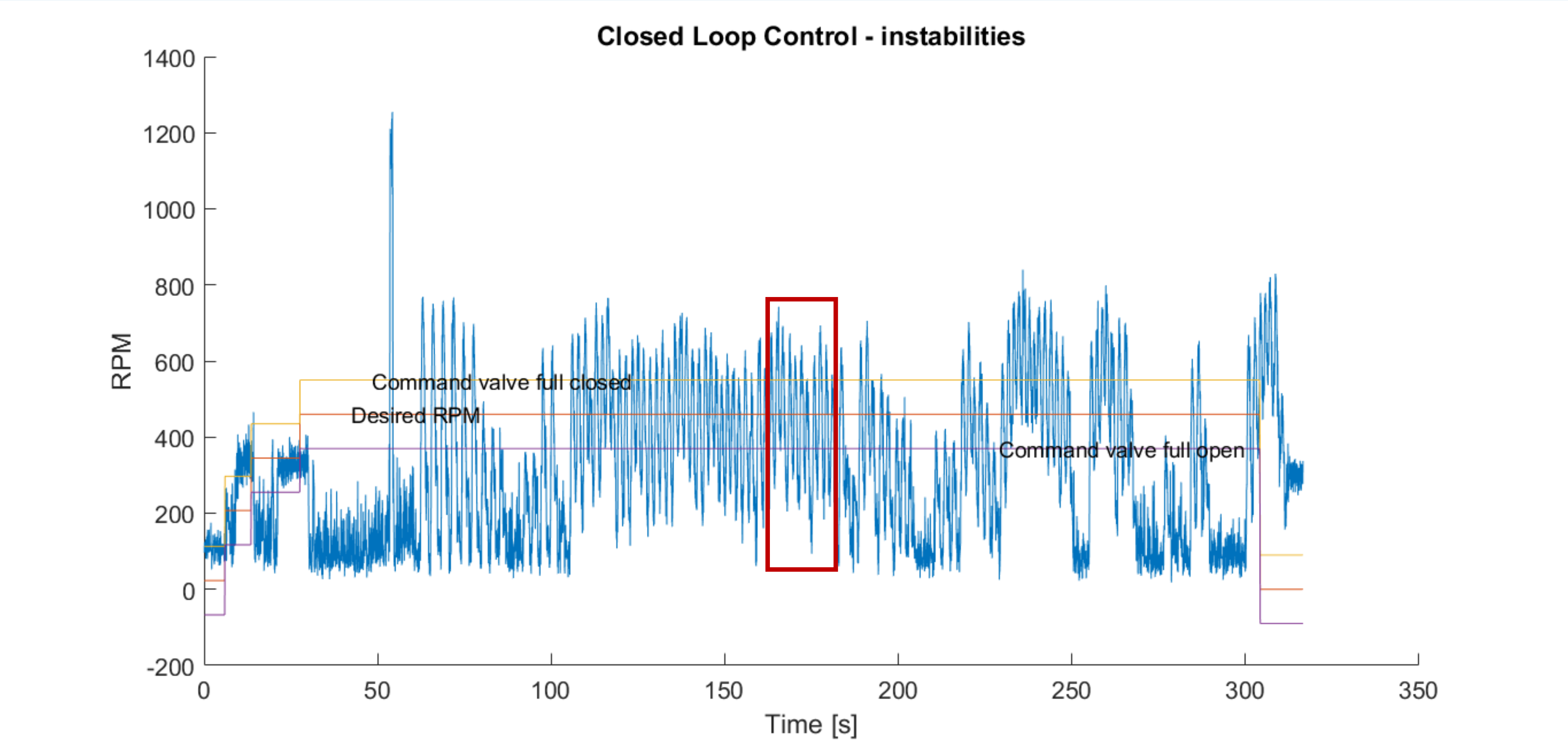
The PEAPOD team would like to thank you for all your help and guidance this semester. We couldn't have done it without you!

-The PEAPOD team

# Backup Slide

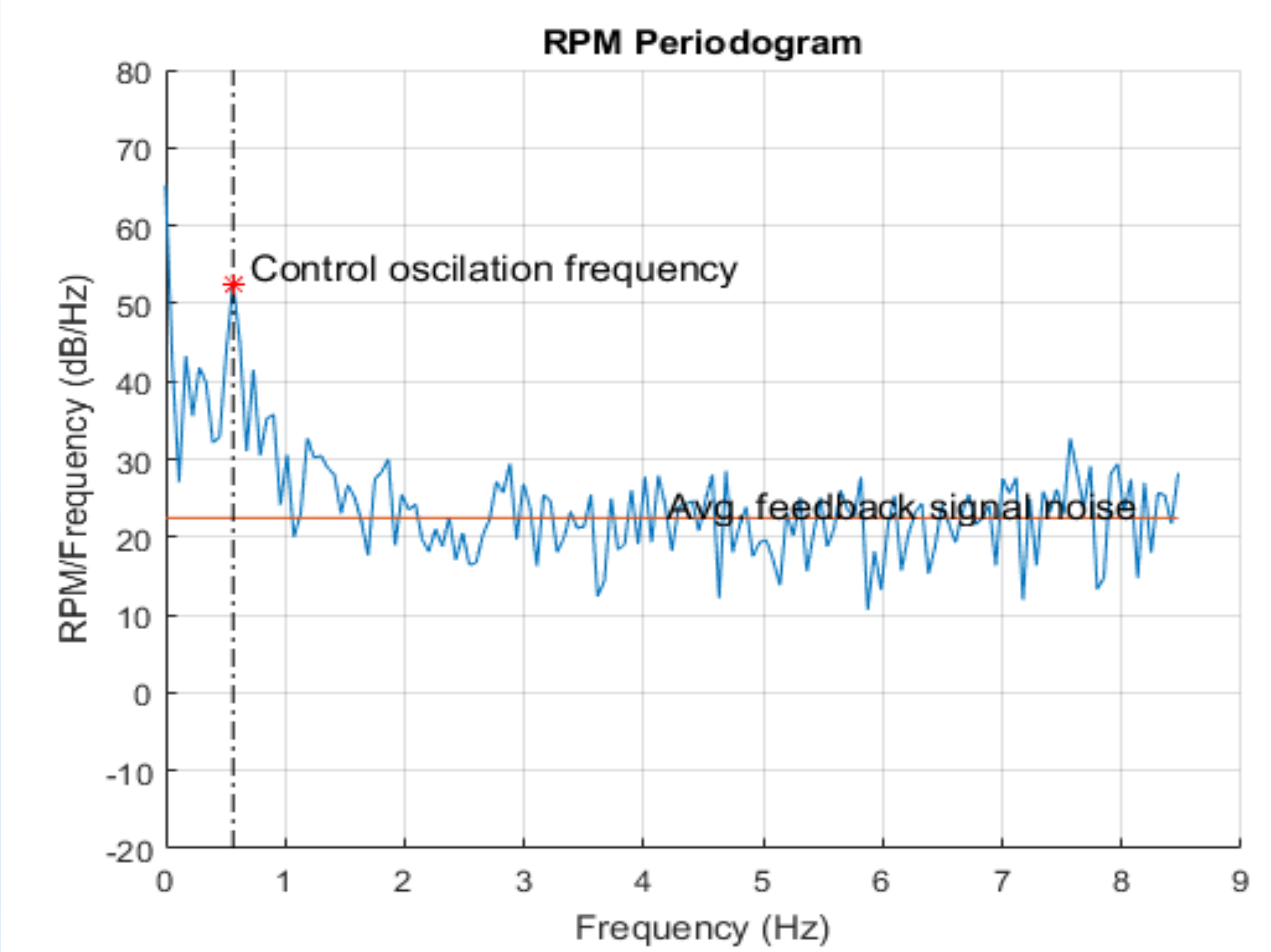
# Closed Loop Instabilities

- Closed loop control on RPM using the Tachometer



# Control System Instabilities

- Signal noise well above desired (0 dB)
- System oscilation at 0.56 Hz



# Levels of Success

| Level | Performance Success |
|---|---|
| 1 | • 750 ± 15 psi outlet pressure<br>• Structural FOS 2.5<br>• 120 seconds of operation<br>• 75% efficiency of pump at full throttle |
| 2 | • 10-100% throttleability<br>• 0-100% throttle in 2 seconds<br>• All level 1 requirements |
| 3 | • 0-100% throttle in 1 second<br>• All level 1 and 2 requirements<br>• Hypergolic Compatible |

**Key**
**Completed**
**Not met**
**Untested**

# Unmet Functional Requirements

- 75% Efficiency at full throttle
  - Based on extrapolation of experimental data at low throttle (~43%)
- Hypergolic compatibility
  - Manufacturing errors
  - Lack of time in schedule
  - Lack of budget

# Untested Levels of Success

| Functional Requirement | Why was it untested? | Predicted Result |
|---|---|---|
| 750 + 15 psi outlet pressure | Could not test at full throttle because of power and flowrate limitations. | Failure, with validated model, max drive speed is 2610 RPM (max. drive speed = 2400 RPM). |
| 120 seconds of operation at full throttle | Could not test at full throttle because of power and flowrate limitations. | Success, pump was operated for >16 min. during testing. |
| 10 – 100% throttleability | Could not test at full throttle because of power and flowrate limitations. | Failure, with validated model, max drive speed is 2610 RPM (max. drive speed = 2400 RPM). |
| 0 – 100% throttle in 2 seconds | Unable to integrate pump with drive system due to time constraints. | Failure, with validated model, max drive speed is 2610 RPM (max. drive speed = 2400 RPM). |

*However, using a drive system that could operate at >2600 RPM, we expect that we could meet all requirements listed above.