SABRE

NOZZLE

Supersonic Air-Breathing Redesigned Engine Nozzle

Spring Final Review

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Air Force Research Lab

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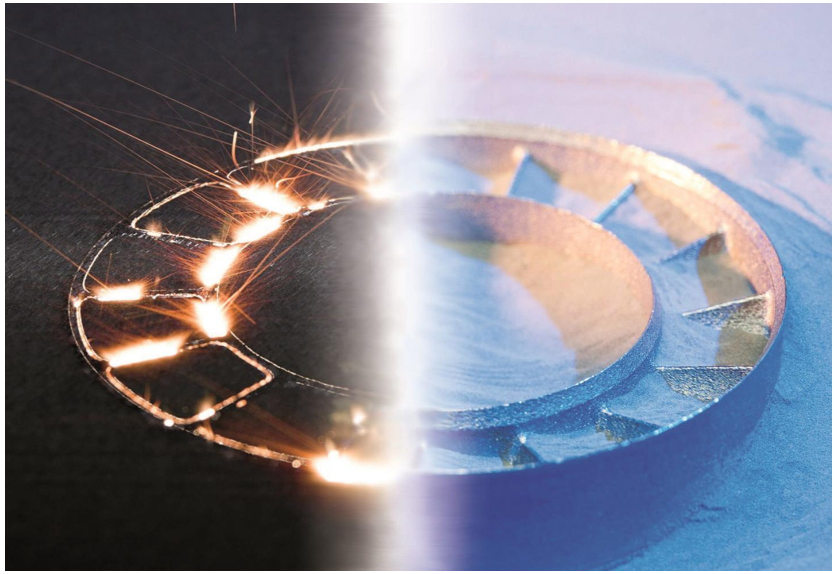
Presentation Outline

- **Project Overview**
  - Description/Background/Requirements
- **SABRE Nozzle**
  - Design and Testing
- **Cold Flow Test Bed**
  - Design and Testing
- **Systems Engineering**
- **Project Management**

Project Overview

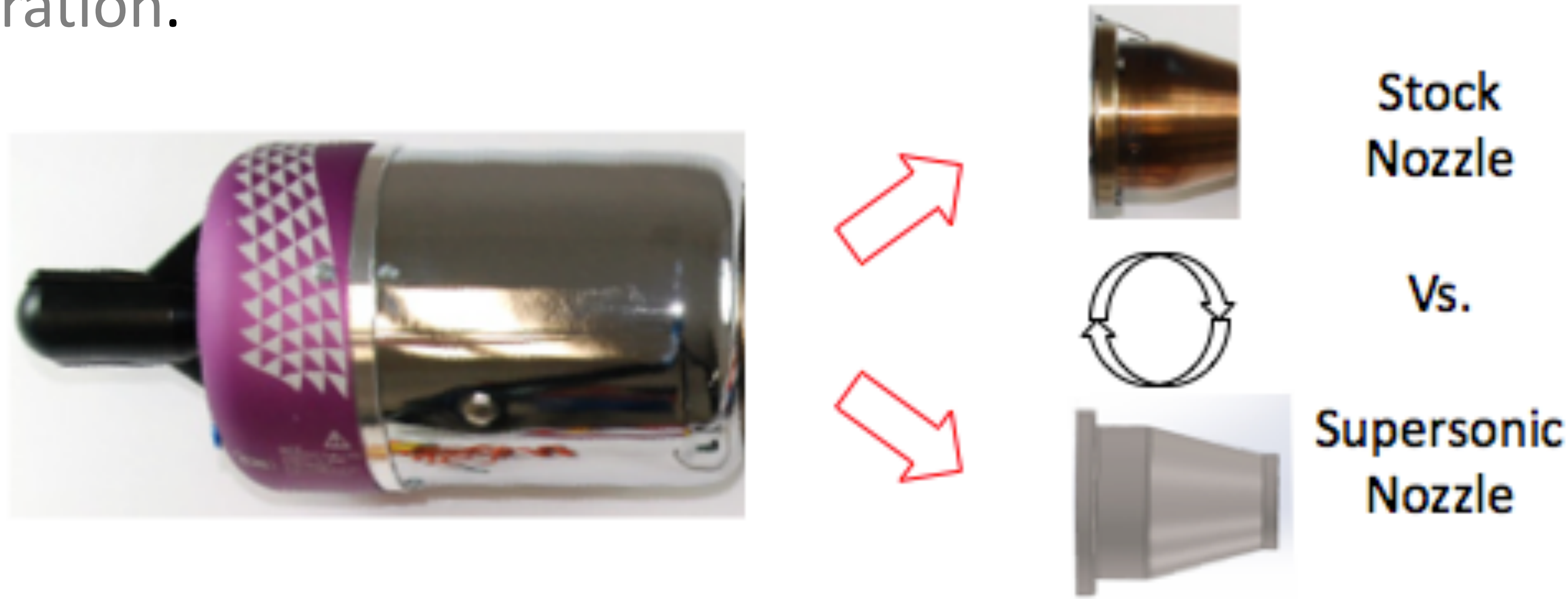
Field of Application

- Additive manufacturing provides a more efficient means of producing components of intricate designs
- Jets are expensive to completely redesign needed for multiple applications



Project Description

Model, manufacture, and **verify** an **additive manufactured nozzle** capable of accelerating flow to **supersonic exhaust** produced by a **P90-RXi JetCat** engine while maintaining the **T/W ratio** from its stock configuration.



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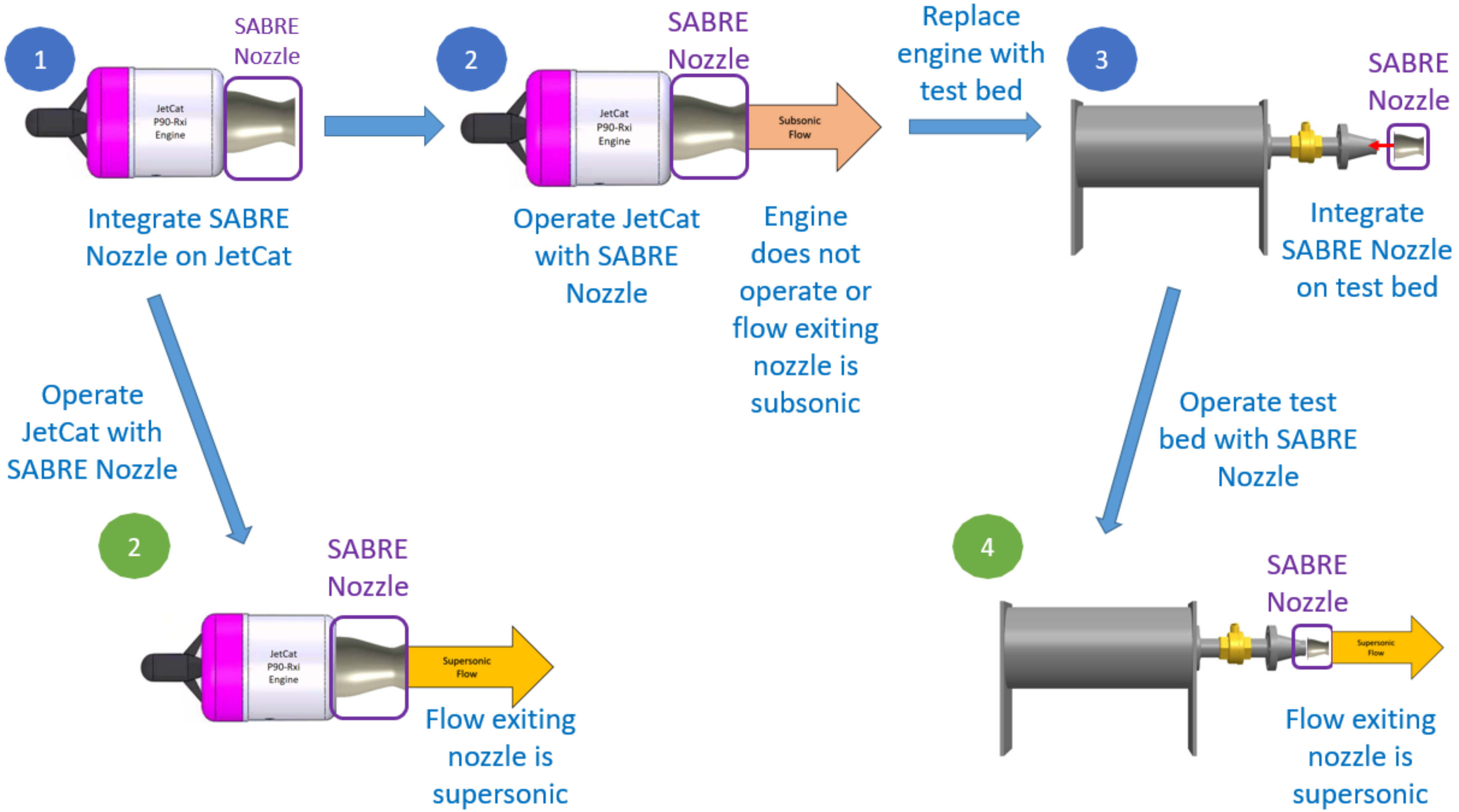


1
SABRE Nozzle
JetCat P90-Rxi Engine
Integrate SABRE Nozzle on JetCat
2
SABRE Nozzle
JetCat P90-Rxi Engine
Subsonic Flow
Operate JetCat with SABRE Nozzle
Engine does not operate or flow exiting nozzle is subsonic
Replace engine with test bed
3
SABRE Nozzle
Integrate SABRE Nozzle on test bed
Operate JetCat with SABRE Nozzle
2
SABRE Nozzle
JetCat P90-Rxi Engine
Supersonic Flow
Flow exiting nozzle is supersonic
Operate test bed with SABRE Nozzle
4
SABRE Nozzle
Supersonic Flow
Flow exiting nozzle is supersonic

Levels of Success

	Model/Simulation	Design/Manufacturing	Testing
Level 1	•**Model stock engine exhaust** with given parameters (T, V, P, $\dot{m}$) •Model **air in nozzle** (SABRE and plastic) changing from **subsonic flow to supersonic** flow •**No decrease of T/W** (SABRE Nozzle)	•Manufacture convergent-divergent nozzle that **attaches to JetCat engine** •Material **survives the exhaust environment** for at least **30 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature), **within 15%** of the needed conditions for a **M=1.3** test.
Level 2	•**Increase T/W** by 20% (SABRE Nozzle) •Verification that **modeled nozzle and plastic manufactured nozzles** output performance **within 5%** of one another	•Nozzle built using additive manufacturing, where material **survives testing environment** for at least **150 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature) **within 15%** of the needed conditions for a **M=1.06 test**.
Level 3	•Verification that **modeled nozzle and SABRE nozzle** have output performance **within 20%** of one another	•Nozzle built using additive manufacturing that **can be reused 3 times** and not fail in the testing environment	•Nozzle integrated and **tested with the JetCat engine** •Replicate an engine analog that simulates exhaust velocity and pressure (adjusted for temperature), **within 5%** of needed conditions for **M=1.3 and M=1.06** tests.

Legend
Total Success
Partial Success
No Success

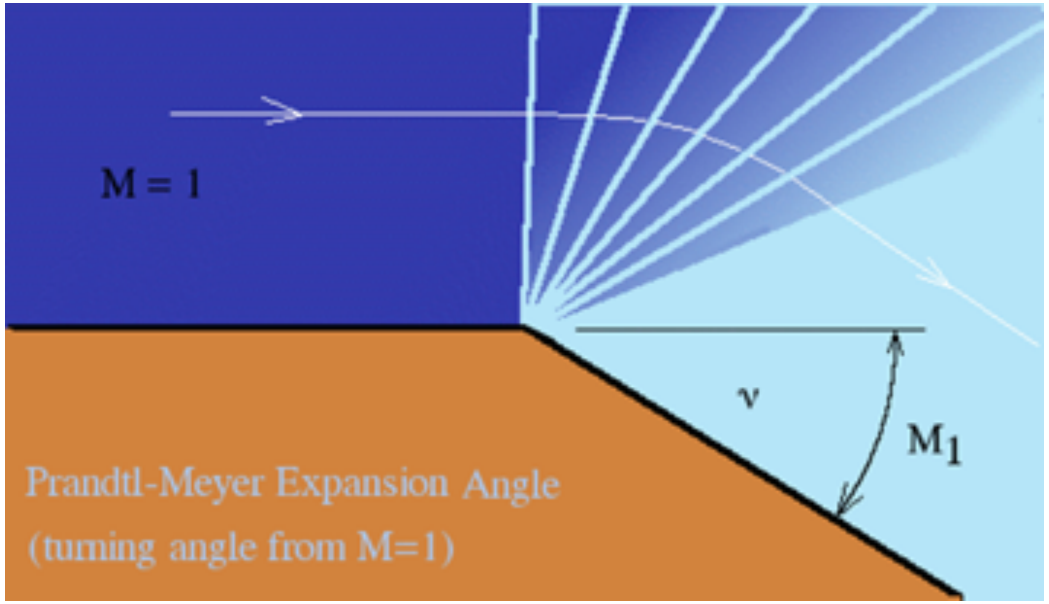
Functional Requirements

- **FR 1:** The Nozzle accelerates flow from subsonic to supersonic conditions.
- **FR 2:** The Nozzle shall maintain/increase the Thrust-to-Weight Ratio.
- **FR 3:** The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.
- **FR 4:** The Nozzle shall be able to withstand engine operation for at least 30 seconds.
- **FR 5:** The Nozzle's performance shall be verified and validated through the use of an alternate cold-flow test bed.

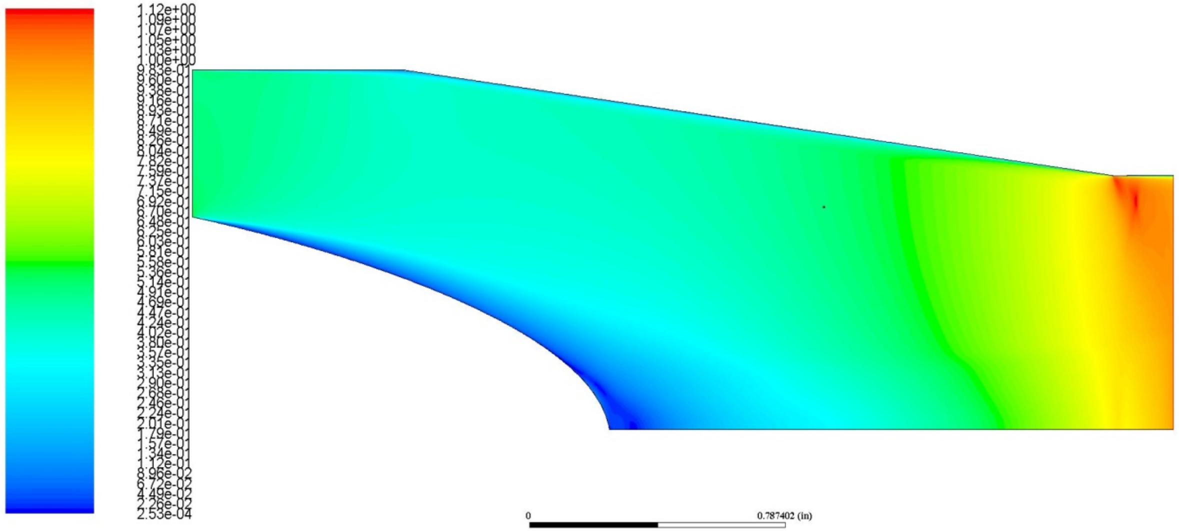
SABRE Nozzle

Supersonic Design

- Pressure ratio required: **1.89** (total/static at the exit)
- Exit Mach: **1.06**
- Entrance Mach: 1
- Prandtl-Meyer Expansion Fan Angle: **0.65 degrees**

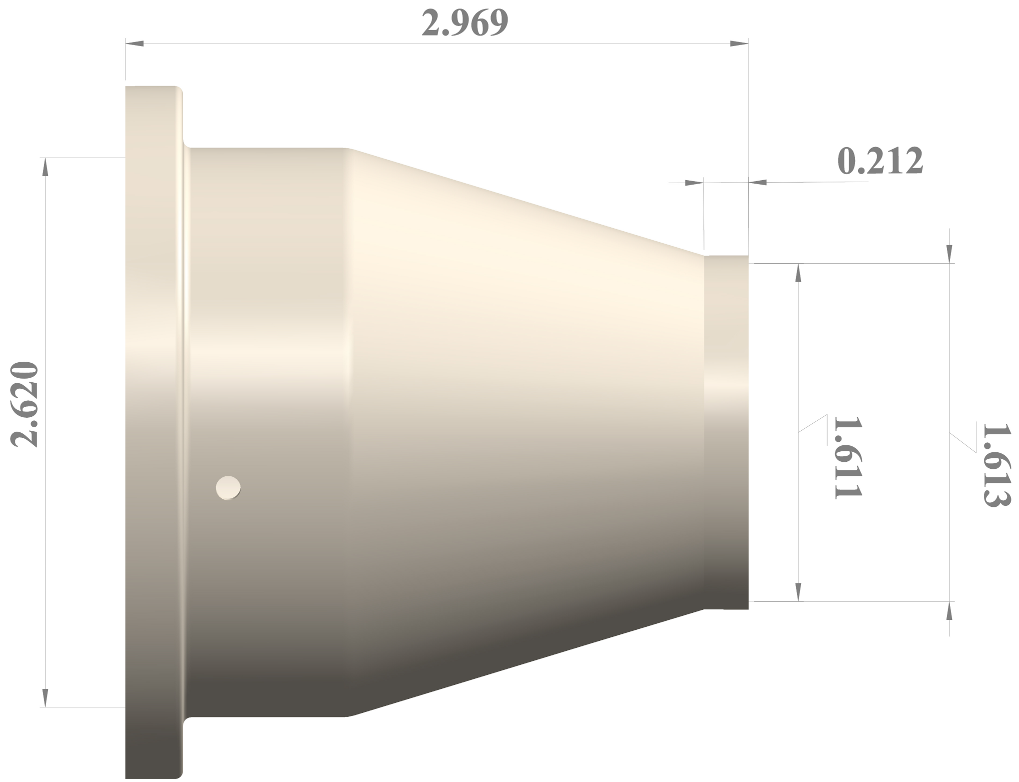


MLN contours too small for manufacturing

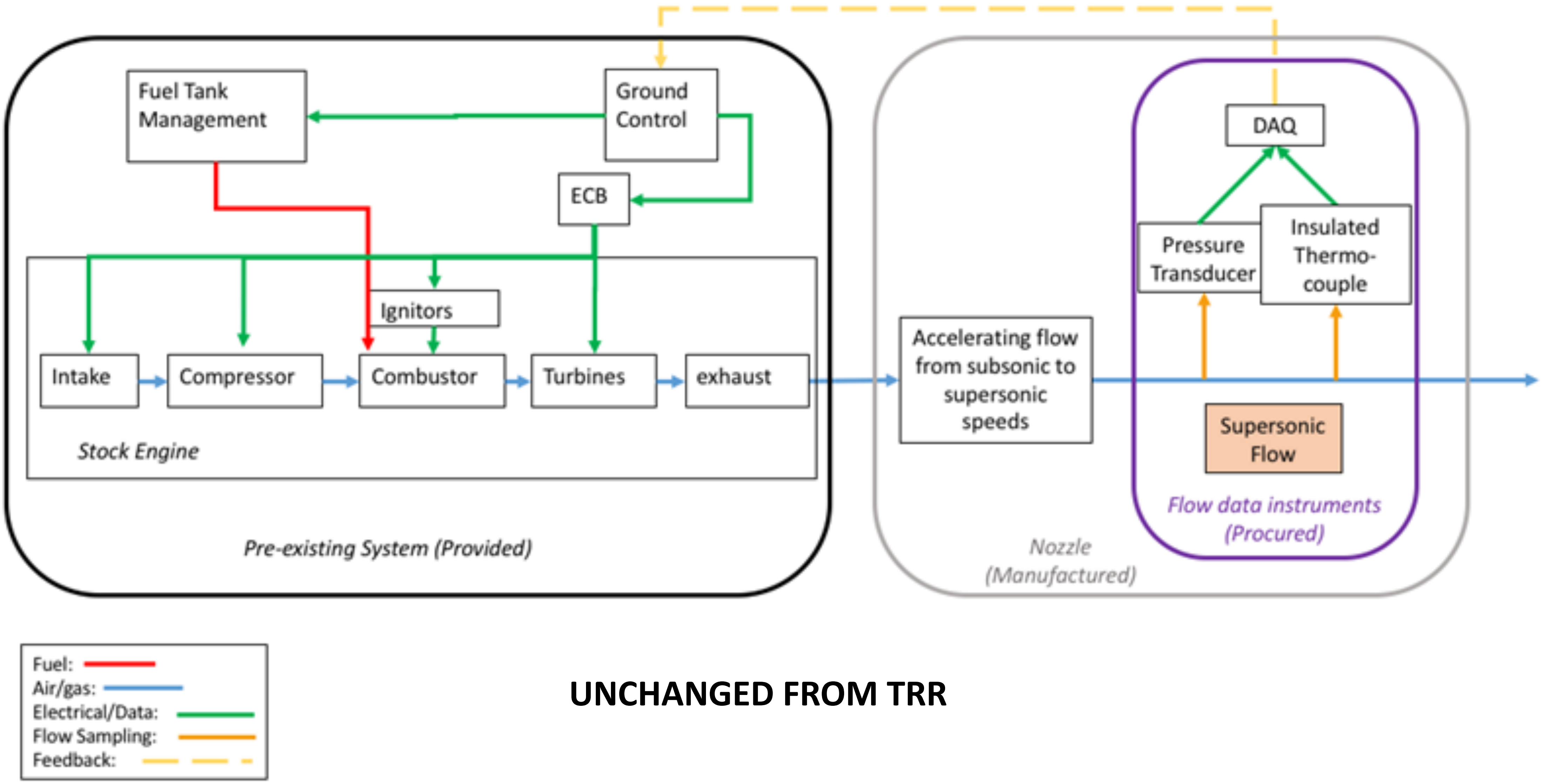


SABRE Nozzle Design

- DMLS Cobalt Chrome
- Length: 2.969"
- Inlet Diameter: 2.620"
- Throat Diameter: 1.611"
- Exit Diameter: 1.613"
- Divergent Length: 0.212"



Functional Block Diagram



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Engine CPE's

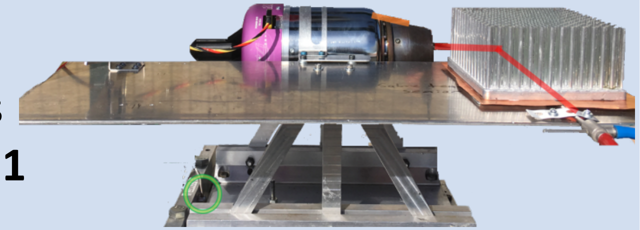
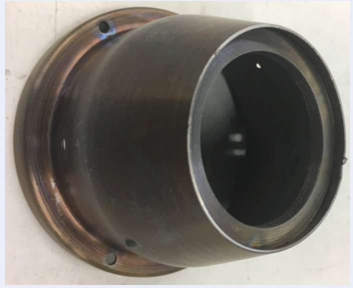
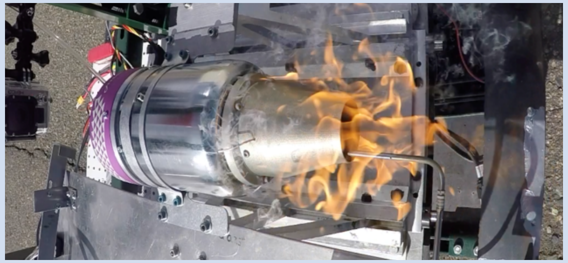
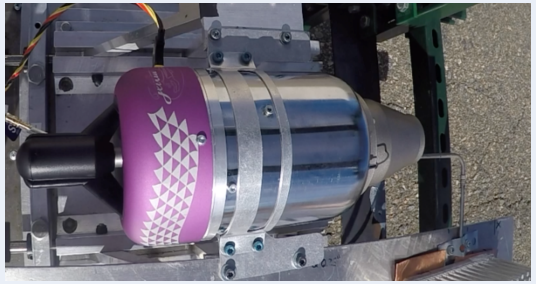
CPE 1: Engine Operation

Stock Test & Modified Test

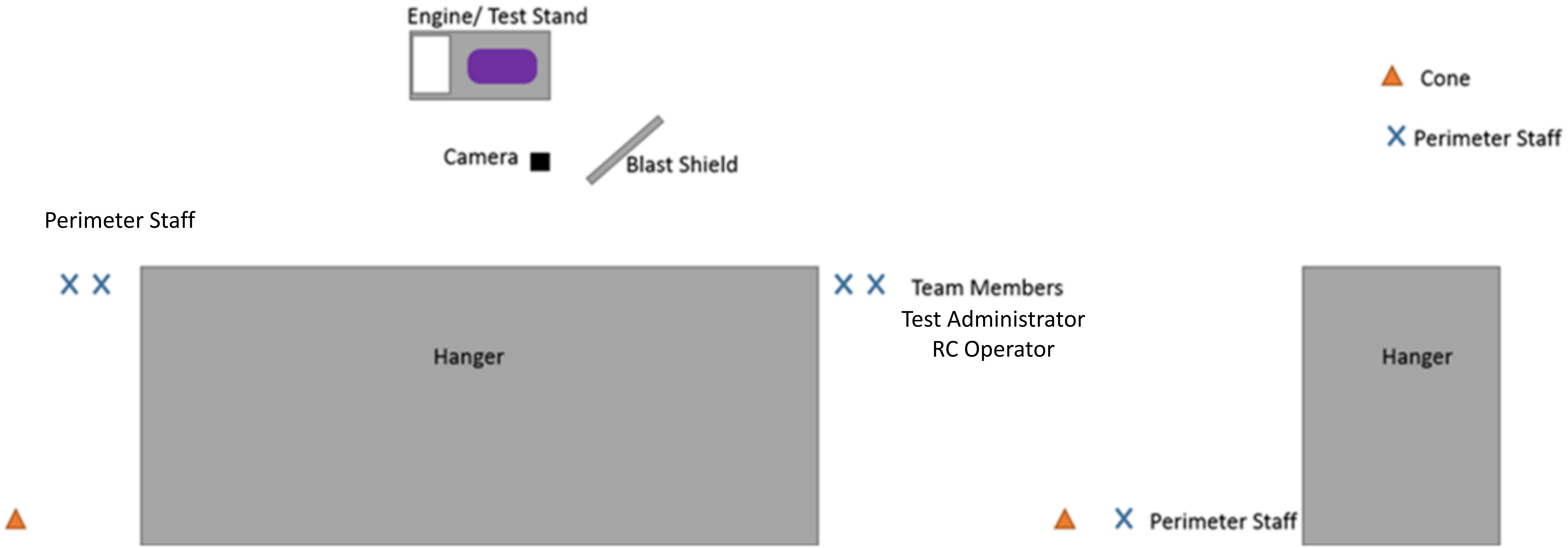
Modified Nozzle Verification

Additive Manufacturing Validation & Survivability

Engine Testing Overview

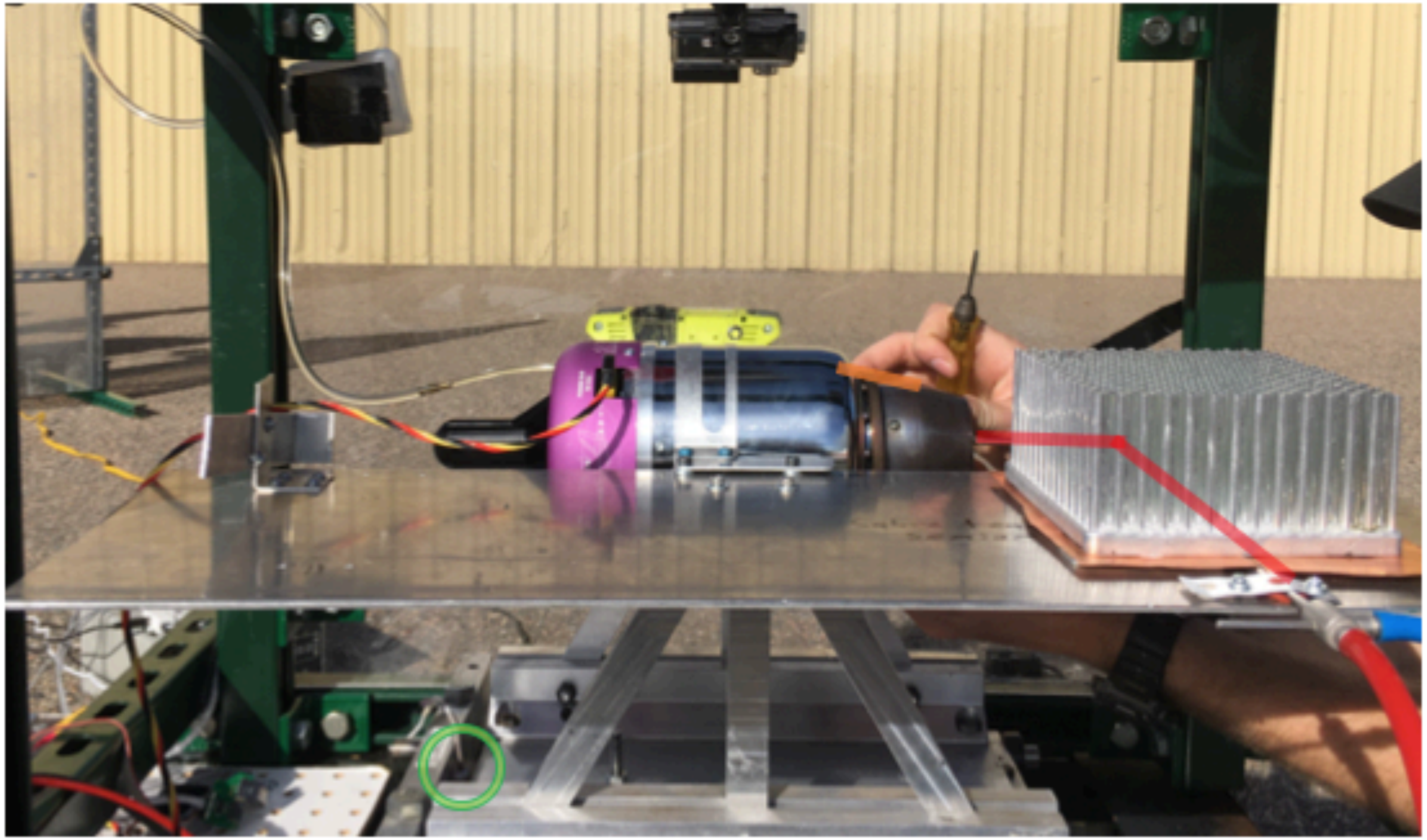
Test 1 (Nov 1st)	• Stock Engine Characteristics • Baseline & **FR 1** 	• Boulder Airport (Matt Rhode) • Stock Engine • Pitot Probes • Load Cell
Test 2 (Nov 8th)	• Stock Engine Characteristics • Chocked Nozzle Test • Baseline & **FR 1** 	• Boulder Airport (Bobby Hodgkinson) • Welded Nozzle w/ Chocked Insert • Pitot Probes • Load Cell
Test 3 (Feb 21st)	• Supersonic Nozzle Test • Survivability • **FR 1-4** 	• Boulder Airport • Additive Manufactured Nozzle • Pitot Probe • Load Cell
Test 4 (Apr 17th)	• Supersonic Nozzle Test • TSFC • **FR 1** & **FR 2** 	• Boulder Airport • Additive Manufactured Nozzle • Pitot Probes • Load Cell • Computer setup to read off TSFC

Engine Testing Setup



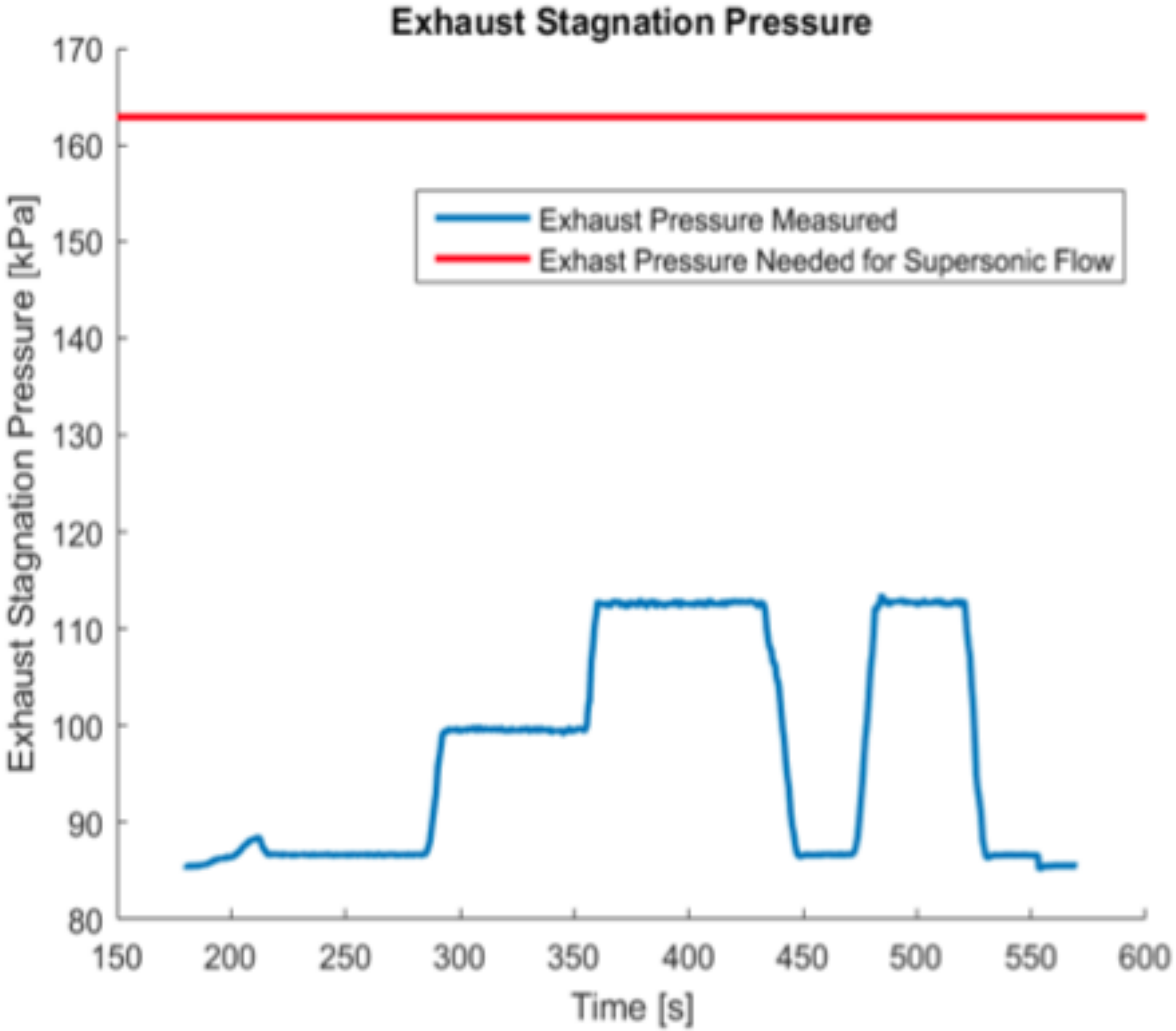
Engine Testing Setup

- Stock Thermocouple
  - Temperature
- Exhaust Pitot Probe
  - Total Pressure
  - Static Pressure
- Force Load Cell
  - Thrust
- Engine Software
  - RPM
  - Fuel Flow Rate



Engine Testing Results (Stock)

- Stagnation pressure needed at exit = **167 kPa**
- Max stagnation pressure achieved ~ **112 kPa**
- We predict the P90-RXi engine will **NOT** be capable of producing supersonic exhaust using the SABRE Nozzle



Engine Testing Results (Thrust)

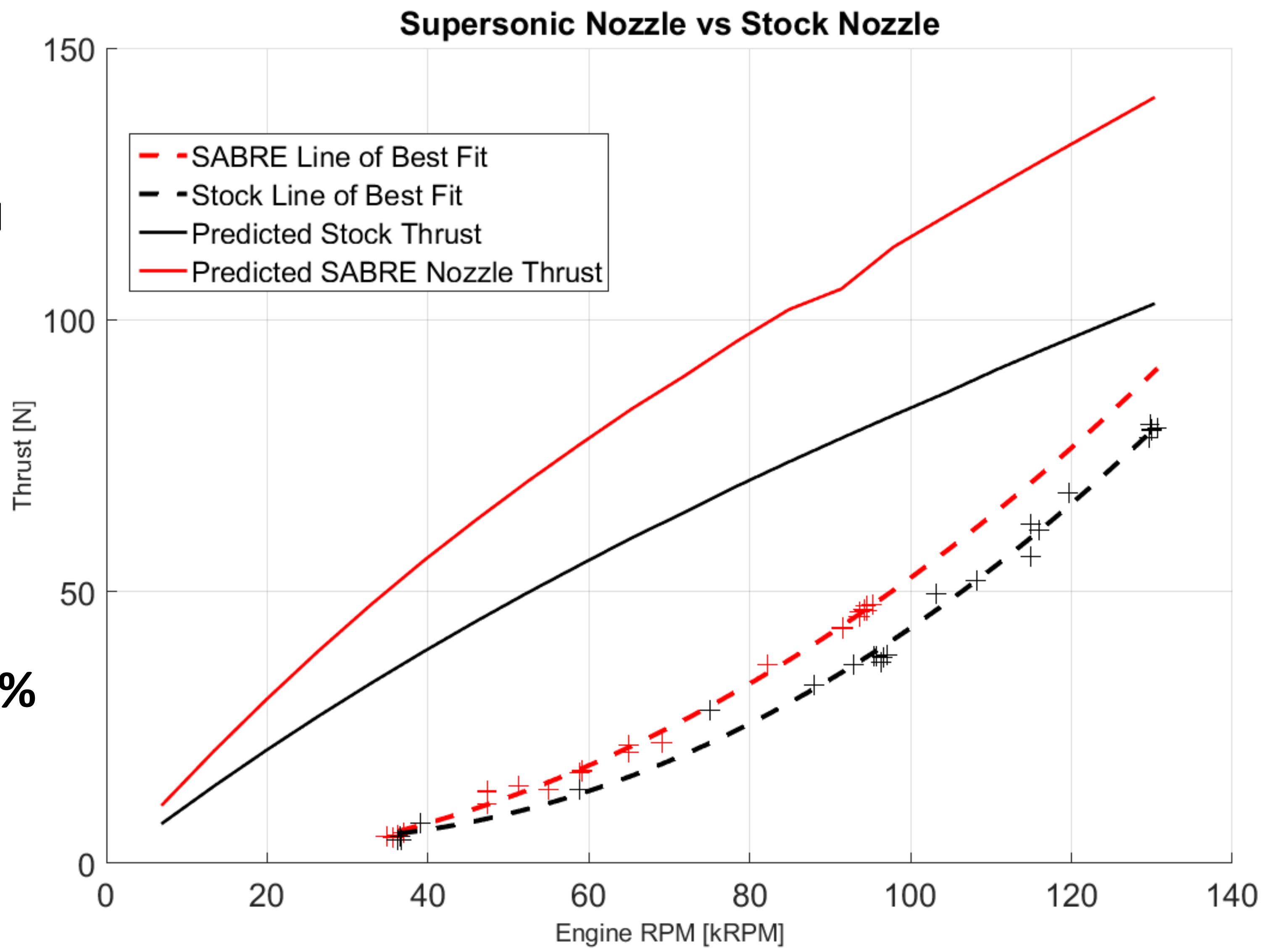
- Load Cell Error: **~0.5 N**

- Predicted Max Stock Thrust: **102.9 N**
- Predicted Max Supersonic Thrust: **140.9 N**

- Actual Max Stock Thrust: **80.8 N**
- Actual Max Supersonic Thrust: **47.7 N**

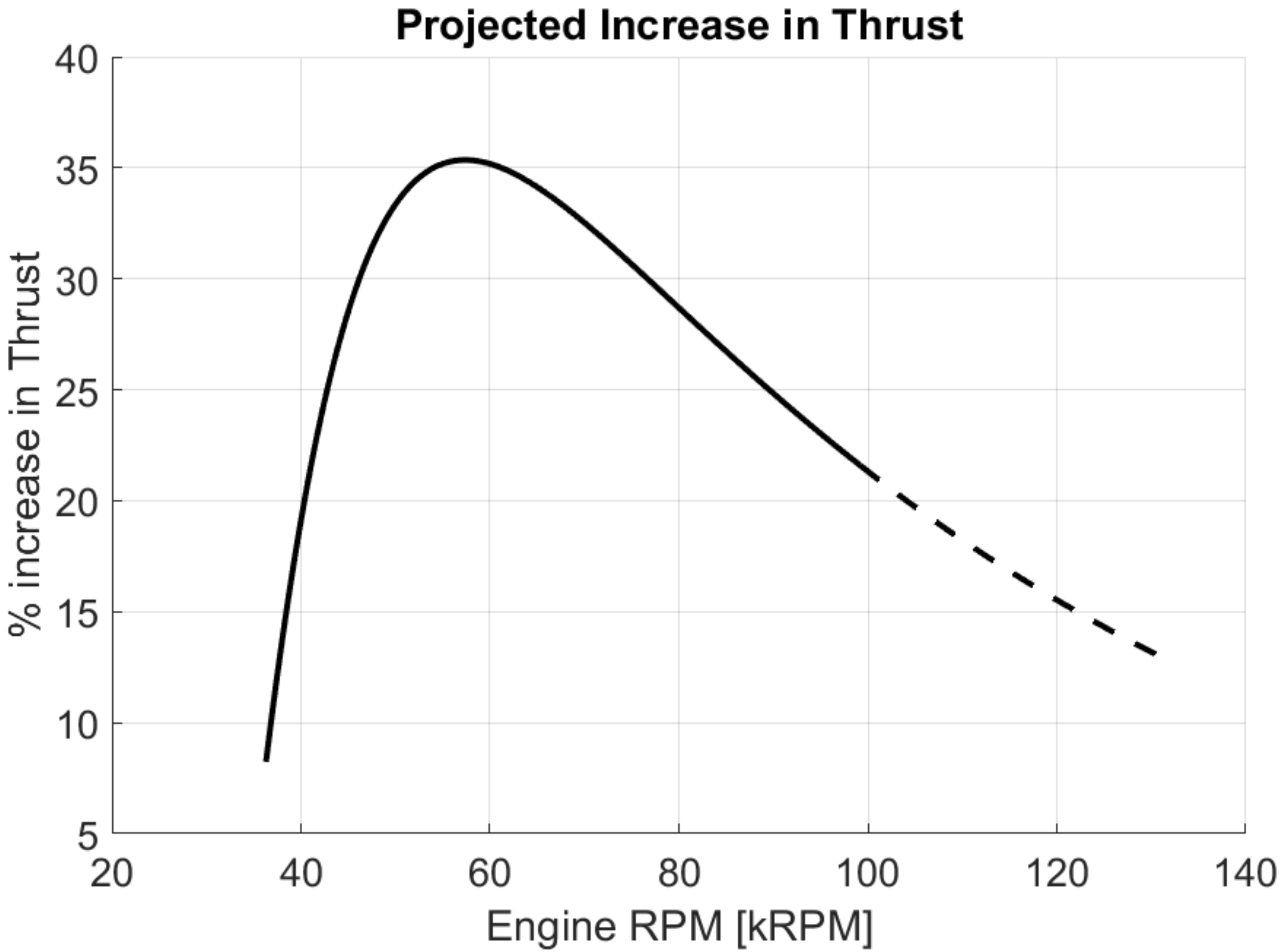
- **At 93 kRPM**:
  - Stock Nozzle Thrust: **37.7 N**
  - SABRE Nozzle Thrust: **45.8 N**

- **Thrust Increase of 8.12 N, or 21%**



Engine Testing Results (Thrust)

- Maximum of **35.3% Increase** at **42% Throttle**
- **21 % Increase** at Max Test RPM (**68% Throttle**)



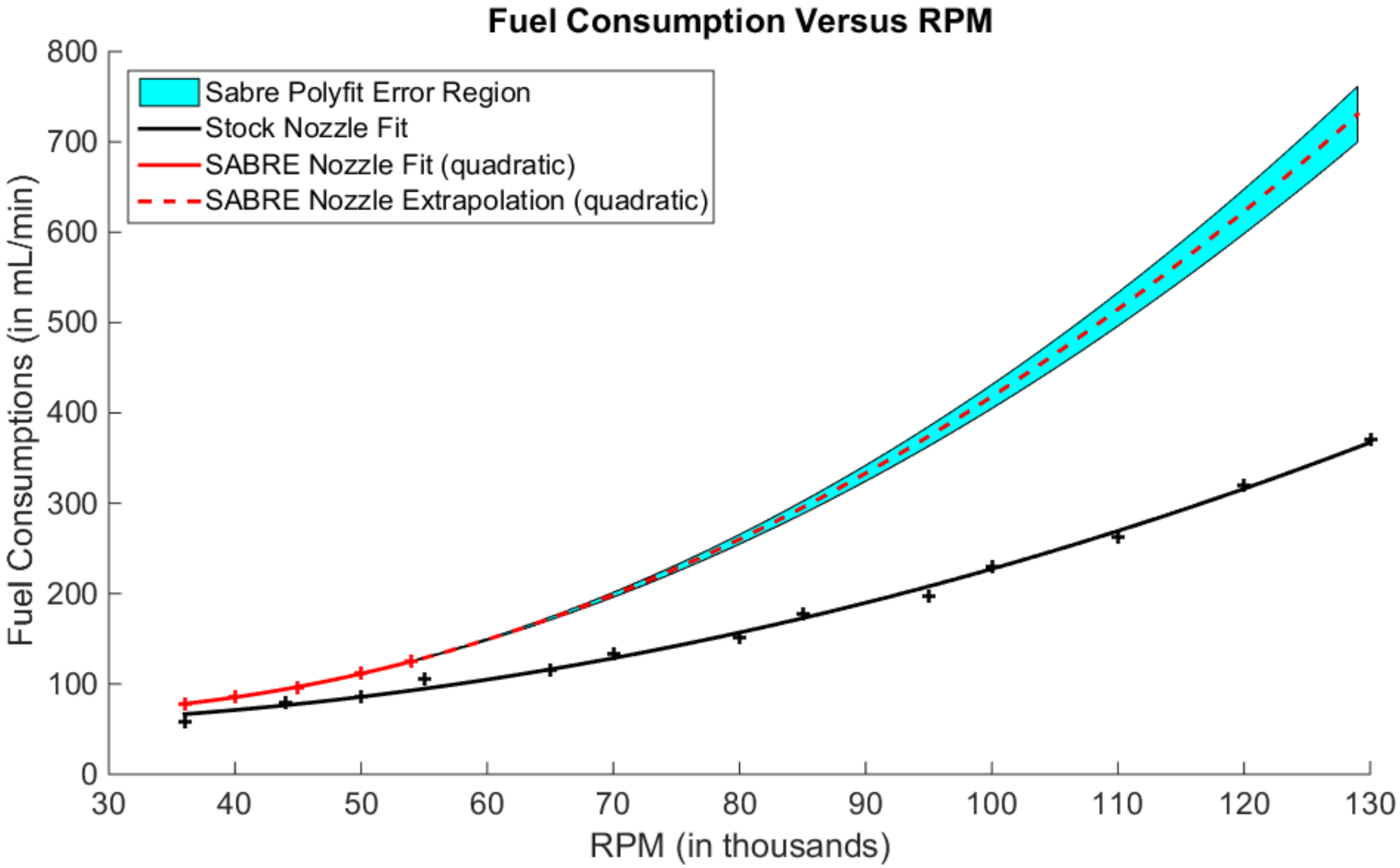
Engine Testing Results (Fuel Consumption)

Minimum SABRE Error:
0.3782 N

Maximum SABRE Error:
34.6108 N

Minimum Stock Error:
8.7354 N

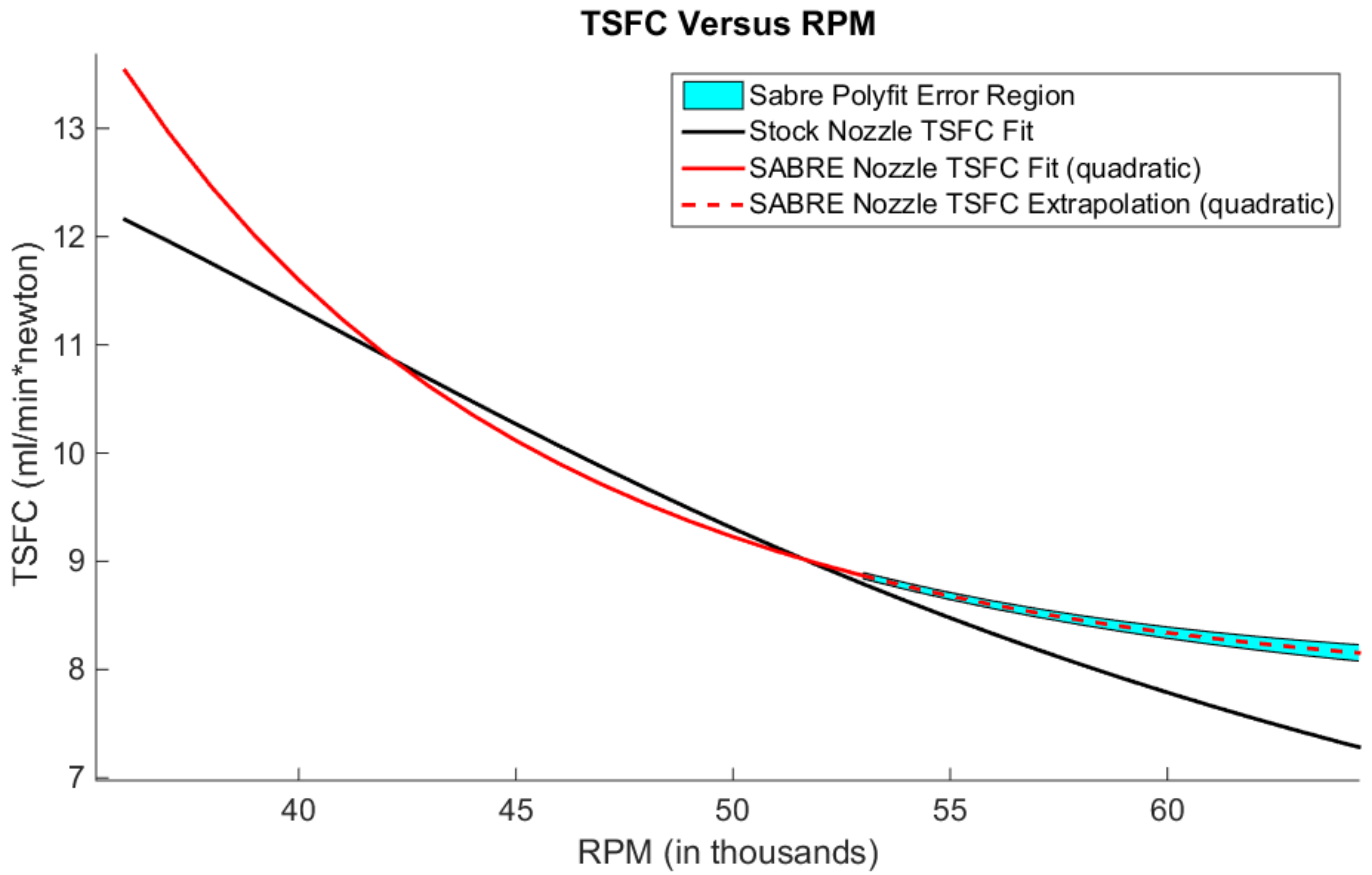
Maximum Stock Error:
7.3581 N



Engine Testing Results (TSFC)

Minimum SABRE Error:
0.3539 mL/(min*N)

Maximum SABRE Error:
0.0295 mL/(min*N)



Functional Requirements Met

- ✗ **FR 1:** The Nozzle accelerates flow from subsonic to supersonic conditions.
- ✓ **FR 2:** The Nozzle shall maintain/increase the Thrust-to-Weight Ratio.
- ✓ **FR 3:** The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.
- ✓ **FR 4:** The Nozzle shall be able to withstand engine operation for at least 30 seconds.

Engine Testing Success

	Model/Simulation	Design/Manufacturing	Testing
Level 1	•**Model stock engine exhaust** with given parameters (T, V, P, $\dot{m}$) •Model **air in nozzle** (SABRE and plastic) changing from **subsonic flow to supersonic** flow •**No decrease of T/W** (SABRE Nozzle)	•Manufacture convergent-divergent nozzle that **attaches to JetCat engine** •Material **survives the exhaust environment** for at least **30 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature), **within 15%** of the needed conditions for a **M=1.3** test.
Level 2	•**Increase T/W** by 20% (SABRE Nozzle) 100% •Verification that **modeled nozzle and plastic manufactured nozzles** output performance **within 5%** of one another	•Nozzle built using additive manufacturing, where material **survives testing environment** for at least **150 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature) **within 15%** of the needed conditions for a **M=1.06 test.**
Level 3	•Verification that **modeled nozzle and SABRE nozzle** have output performance **within 20%** of one another 0%	•Nozzle built using additive manufacturing that **can be reused 3 times** and not fail in the testing environment 100%	•Nozzle integrated and **tested with the JetCat engine** 100% •Replicate an engine analog that simulates exhaust velocity and pressure (adjusted for temperature), **within 5%** of needed conditions for **M=1.3** and **M=1.06** tests.

Legend
Total Success
Partial Success
No Success

Cold Flow Test Bed

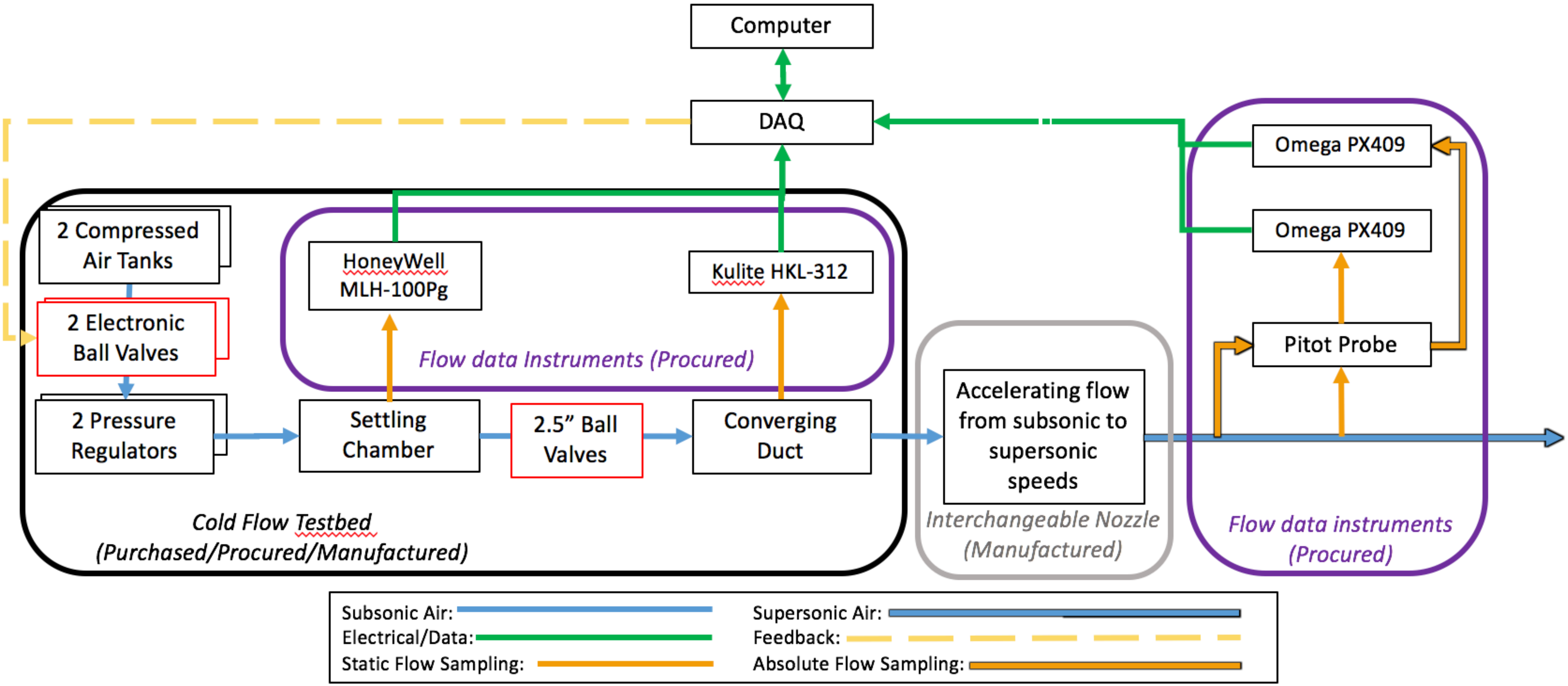
Cold Flow Test Bed Design

- Objectives:
  - Engine Conditions:
    - Mass flow rate = 0.260 kg/s -> **573.8 CFM**
    - Total pressure = 167 kPa -> **24.2 psi**
  - Scaled down SABRE nozzle test:
    - Mass flow rate = 0.202 kg/s -> **456.8 CFM**
    - Total pressure = 167 kPa -> **24.2 psi**
  - M = 1.3 test:
    - Mass flow rate = 0.281 kg/s -> **620.2 CFM**
    - Total pressure =233 kPa -> **33.8 psi**

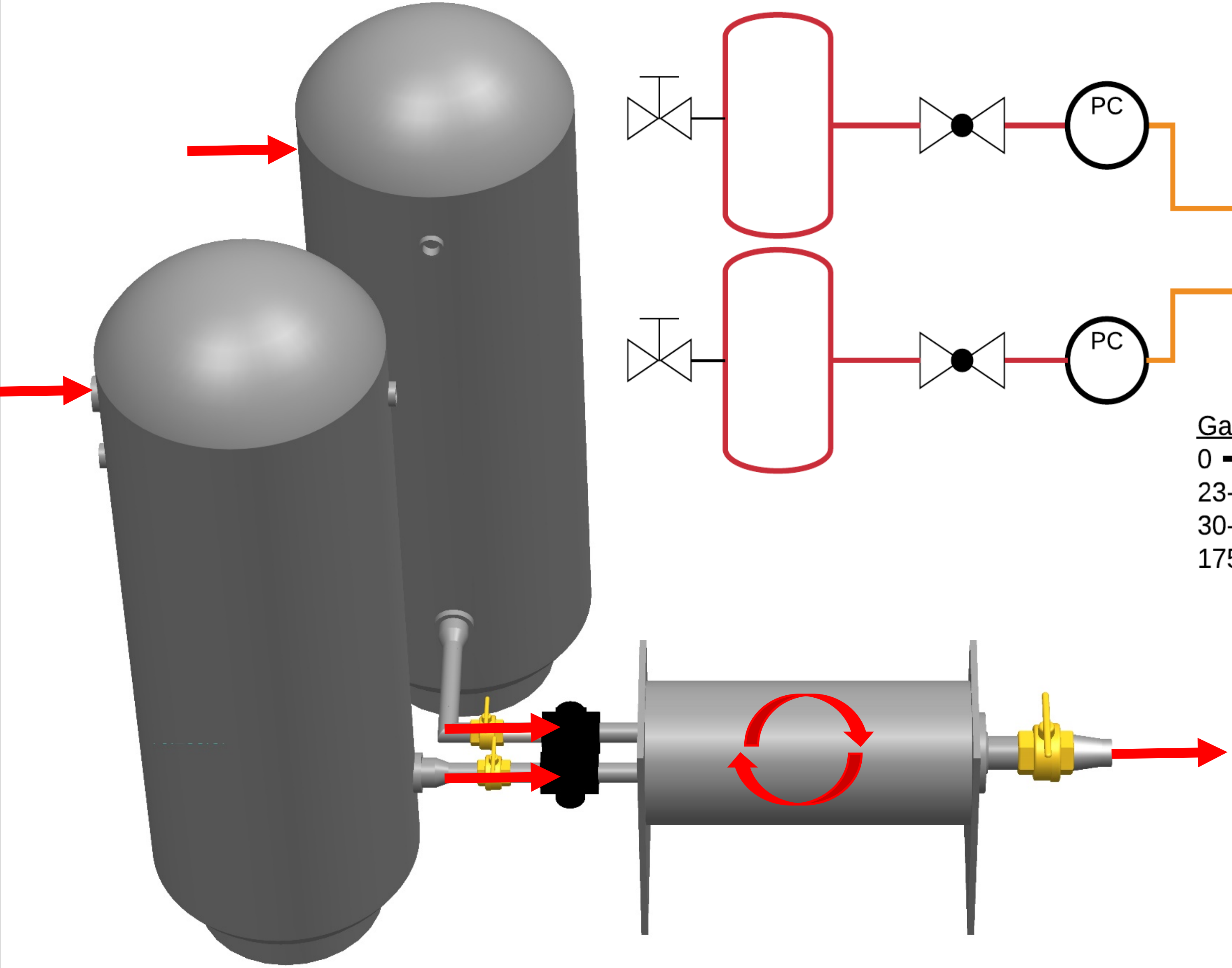
Flow Conditions to Match

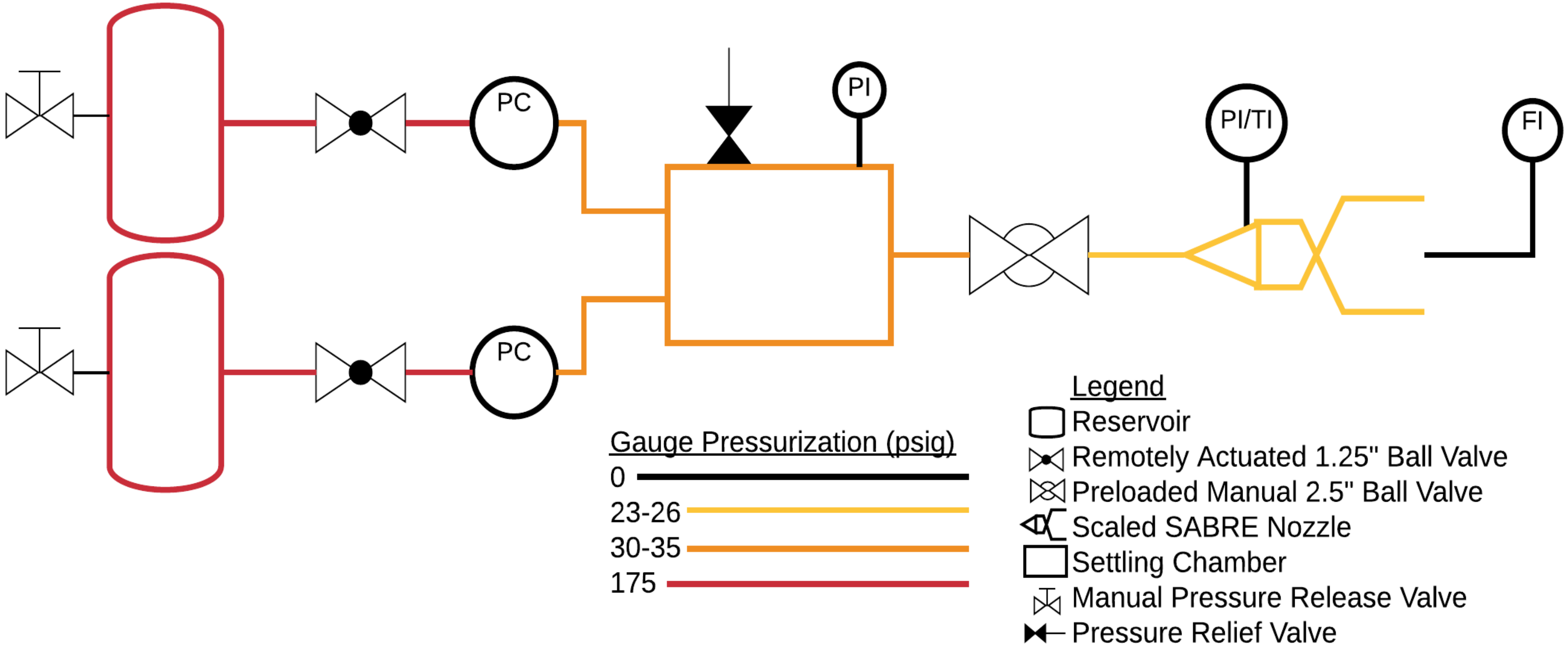
Conditions for the Design

Functional Block Diagram



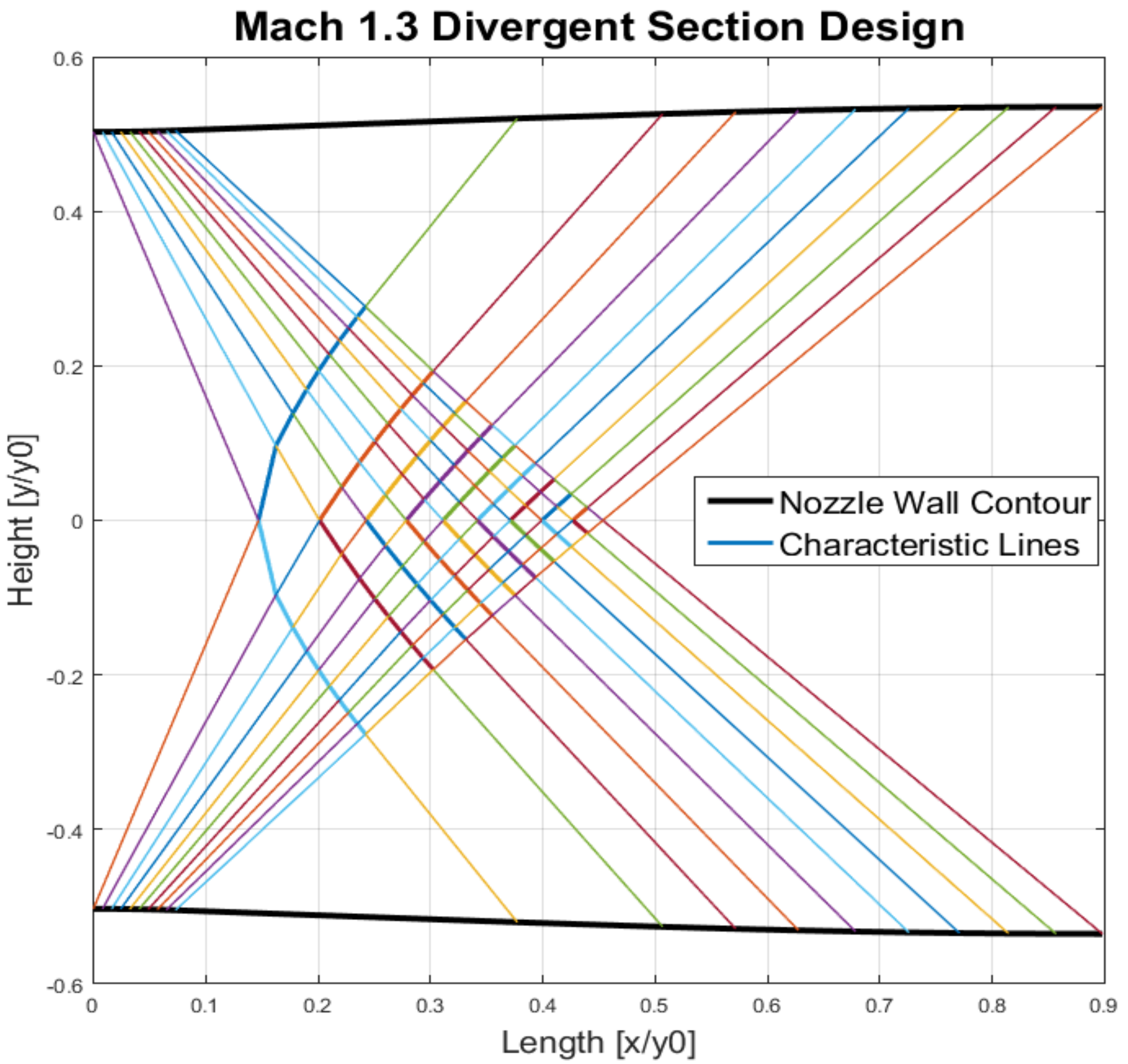
Cold Flow Test Bed Design



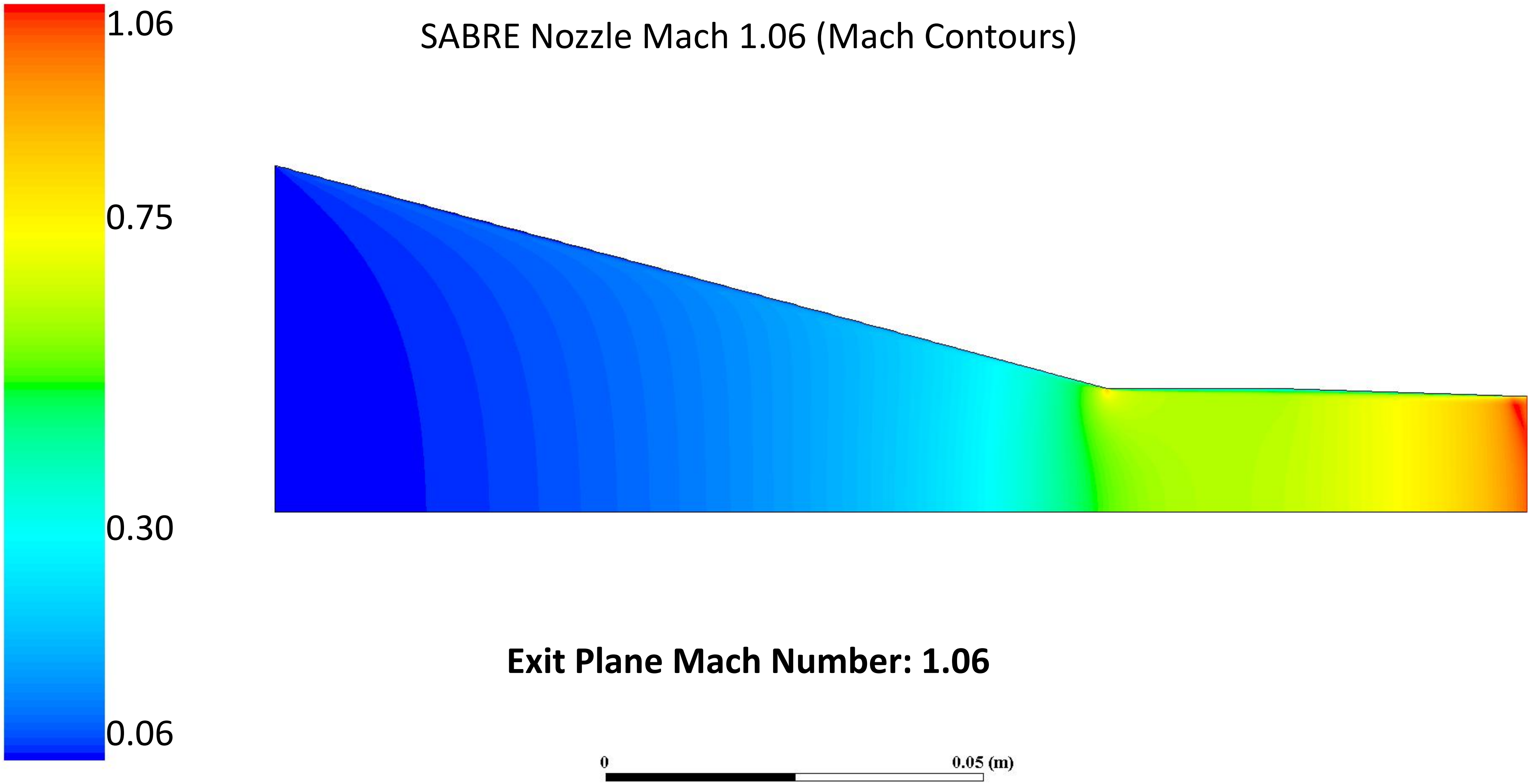


Supersonic Design

- 2D MLN Code
- For Mach numbers ~1, 2D is a good approximation
- Better performance with a true axisymmetric or 3D code
- MLN for Mach 1.3, Prandtl-Meyer Angle for Mach 1.06

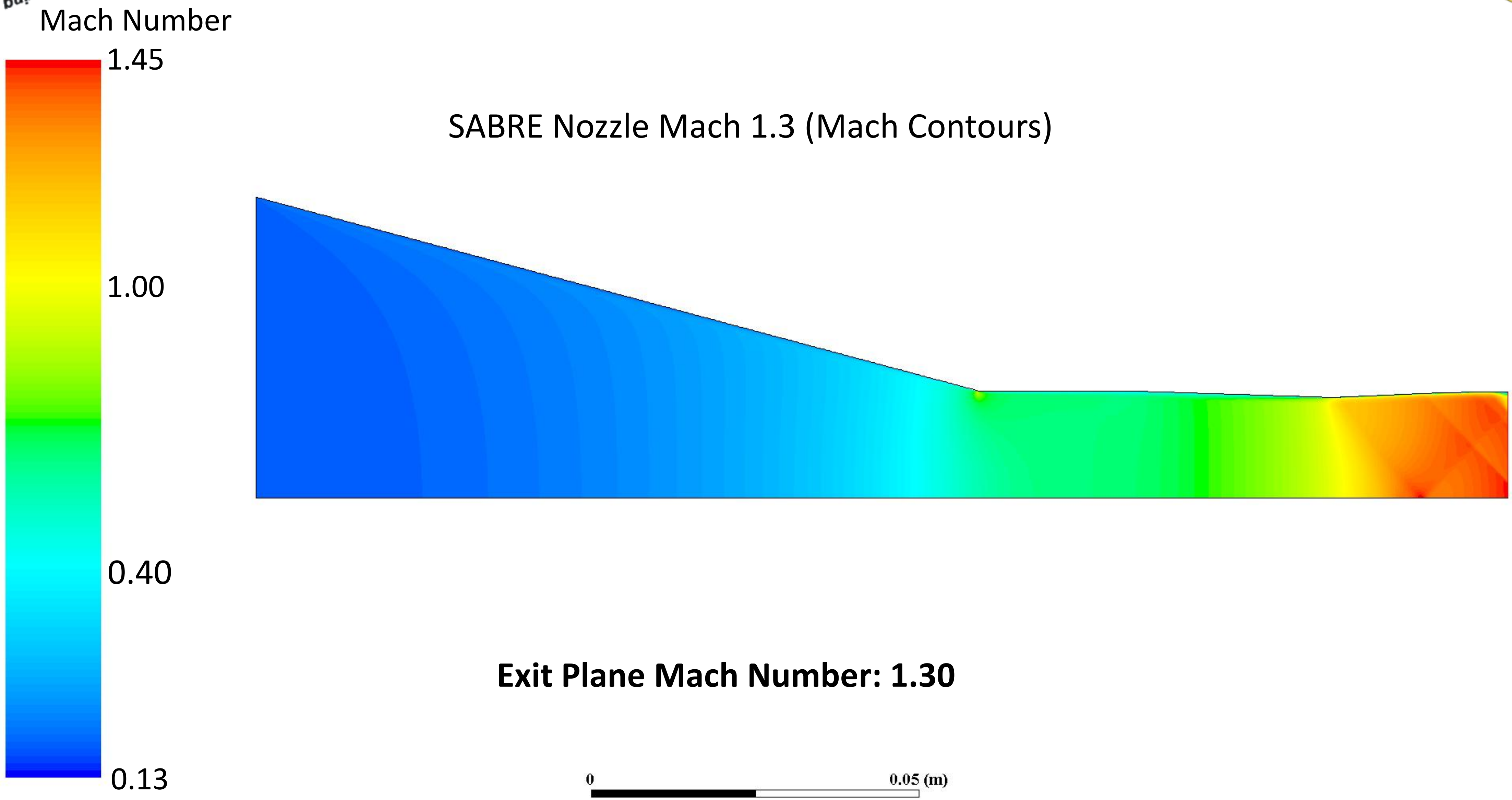


Supersonic Design



Exit Plane Mach Number: 1.06

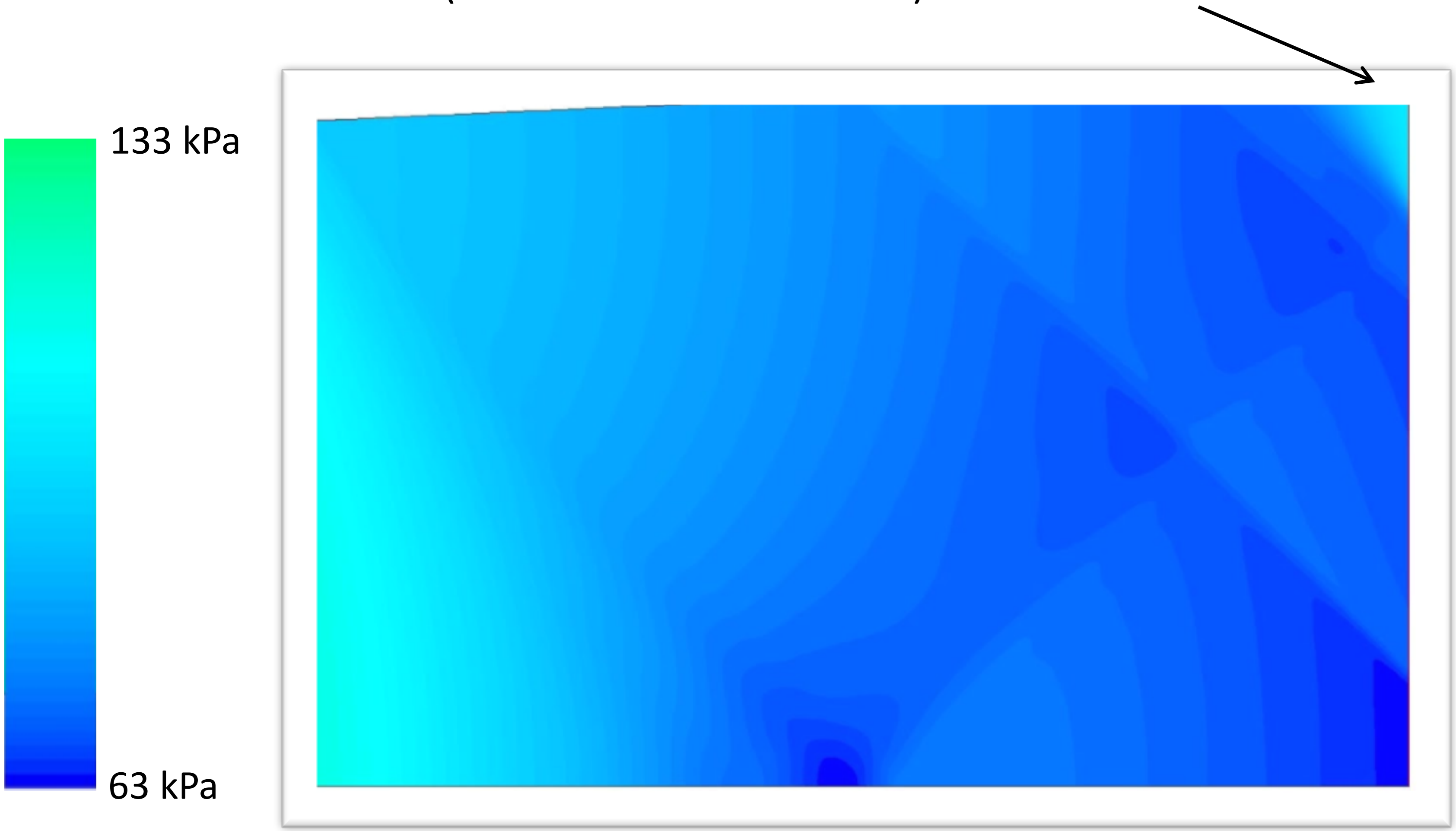
Supersonic Design



Supersonic Design

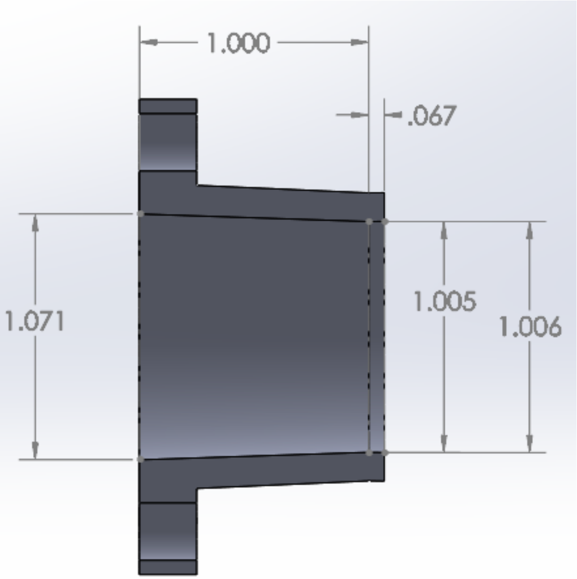
- Pressure Contours suggest **Overexpanded Nozzle**
- Likely due to **2D MLN** code, **versus 3D MLN** code
- **Test results** suggest expansion was nearly **ideal**
- **Differences** in model versus test results are likely due to **slight over-pressurization** in **settling chamber**

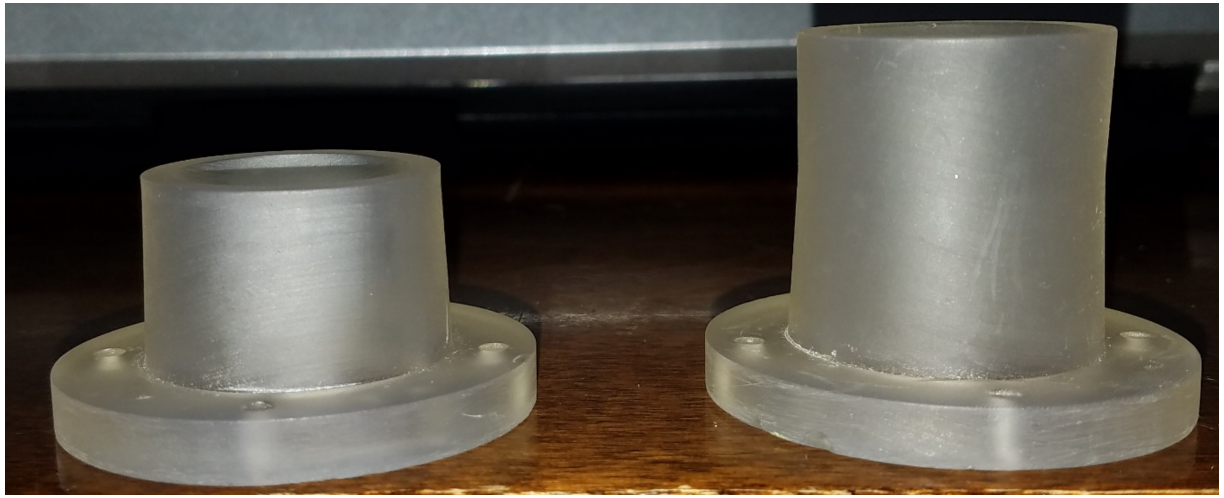
SABRE Nozzle Mach 1.3 (Static Pressure Contours)



Cold Flow Test Bed Design

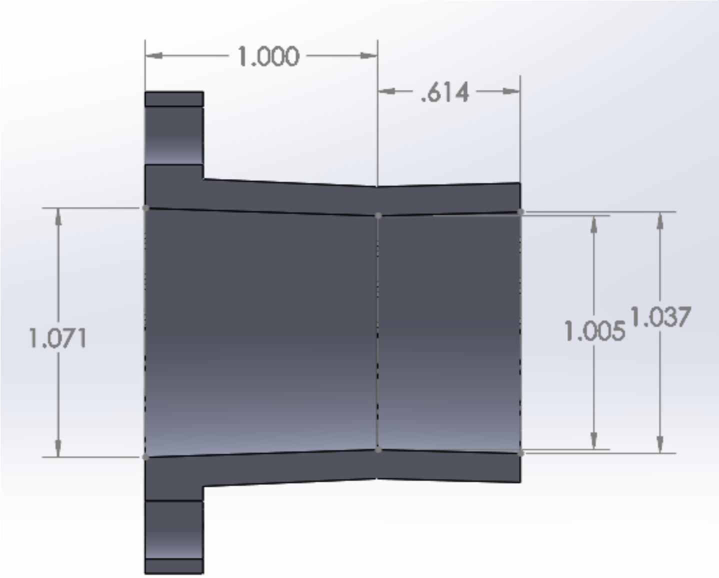
Mach 1.06 Nozzle
Length: 1.067”
Inlet Diameter: 1.071”
Throat Diameter: 1.005”
Exit Diameter: 1.006”
Divergent Length: 0.067”





Form Labs 2 printer
Clear FLGPCL02

Mach 1.30 Nozzle
Length: 1.614”
Inlet Diameter: 1.071”
Throat Diameter: 1.005”
Exit Diameter: 1.037”
Divergent Length: 0.614”



Test Bed CPE's

CPE 2: Test Bed Operation

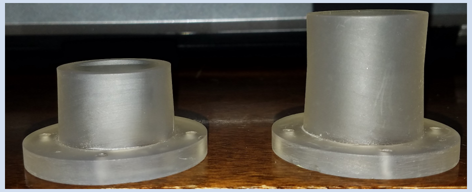
Test Bed Verification

Nozzle Design Verification

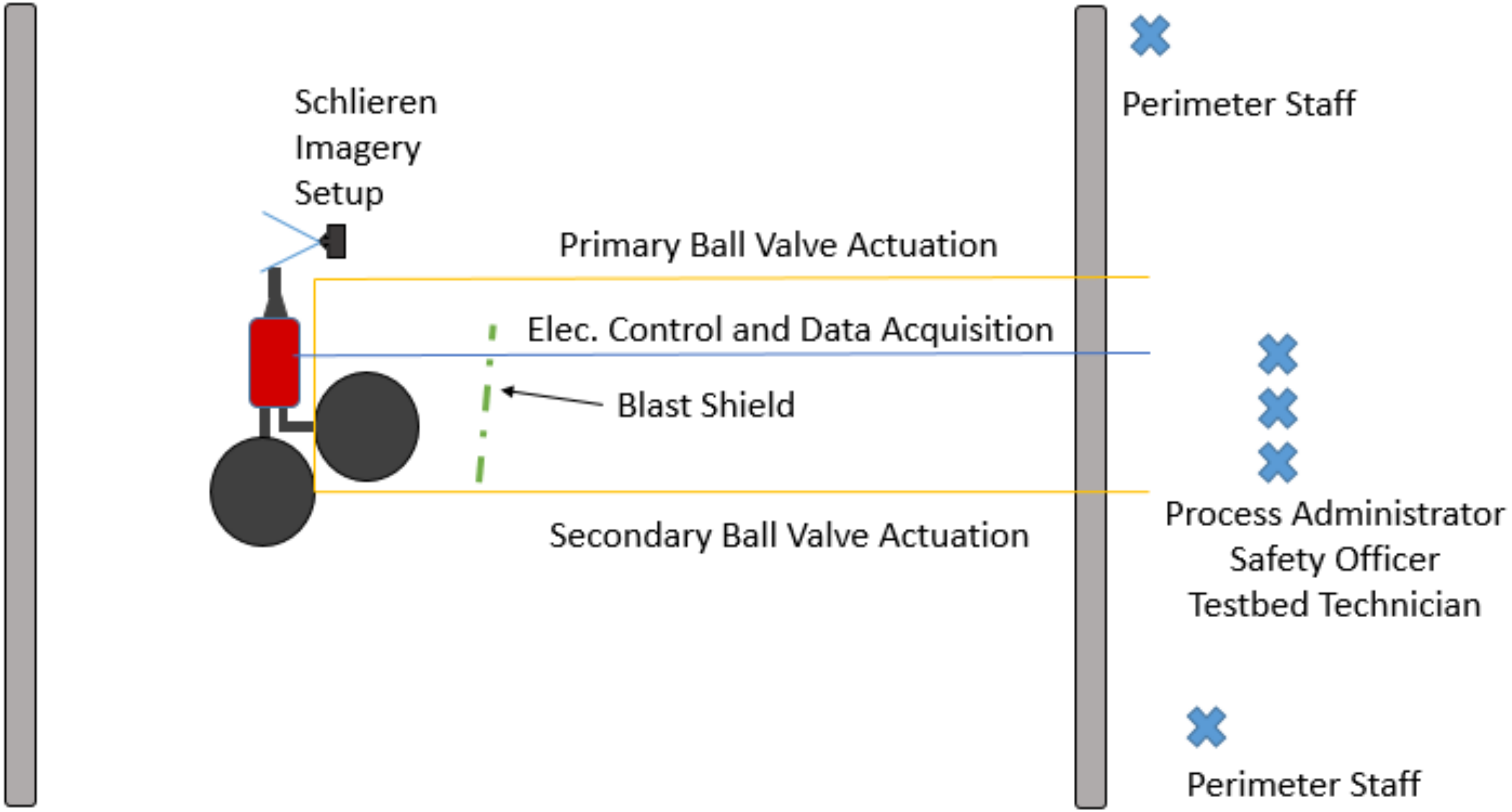
Testing Safety & Protocol

Supersonic Validation

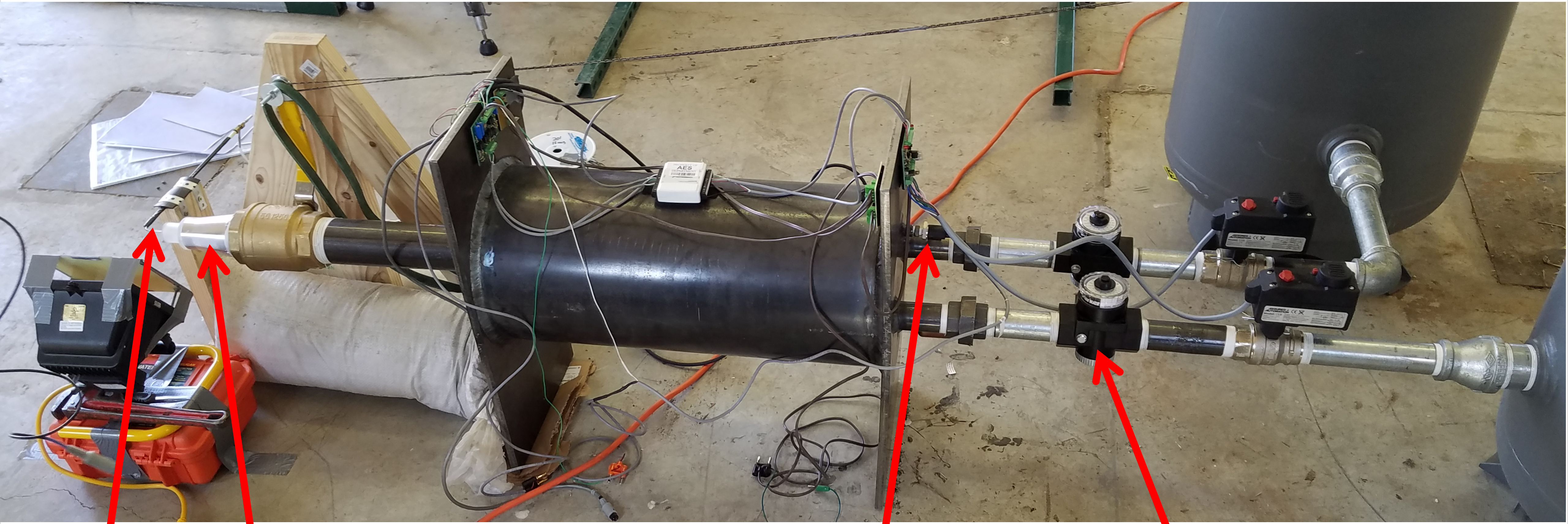
Test Bed Testing Overview

Test 1 (Apr 11th)	• System Integration • Leaks • Ball Valve Checks • M = 1.3 Tests • **FR 1** 	• Platteville (Matt Rhode) • Complete System • 2 Compressed Air Tanks • Scaled Nozzles • Pitot Probe
Test 2 (Apr 14th)	• M = 1.3 Test • Schileren Visualization • **FR 1** 	• Platteville (Matt Rhode) • Complete System • 8 Compressed Air Tanks • Scaled Nozzles • Pitot Probe
Test 3 (Apr 16th)	• M = 1.3 Test • M = 1.06 Test • Schileren Visualization • **FR 1 & FR 5** 	• Platteville • Complete System • 6 Compressed Air Tanks • Scaled Nozzles • Pitot Probe

Cold Flow Test Bed Setup



Cold Flow Test Bed Setup



Pitot Probe: Total & Static Pressure

Kulite: Temperature & Static Pressure

HoneyWell: Total Pressure

Parker 53R High Flow Pressure Regulator

Test Bed Testing Calculations

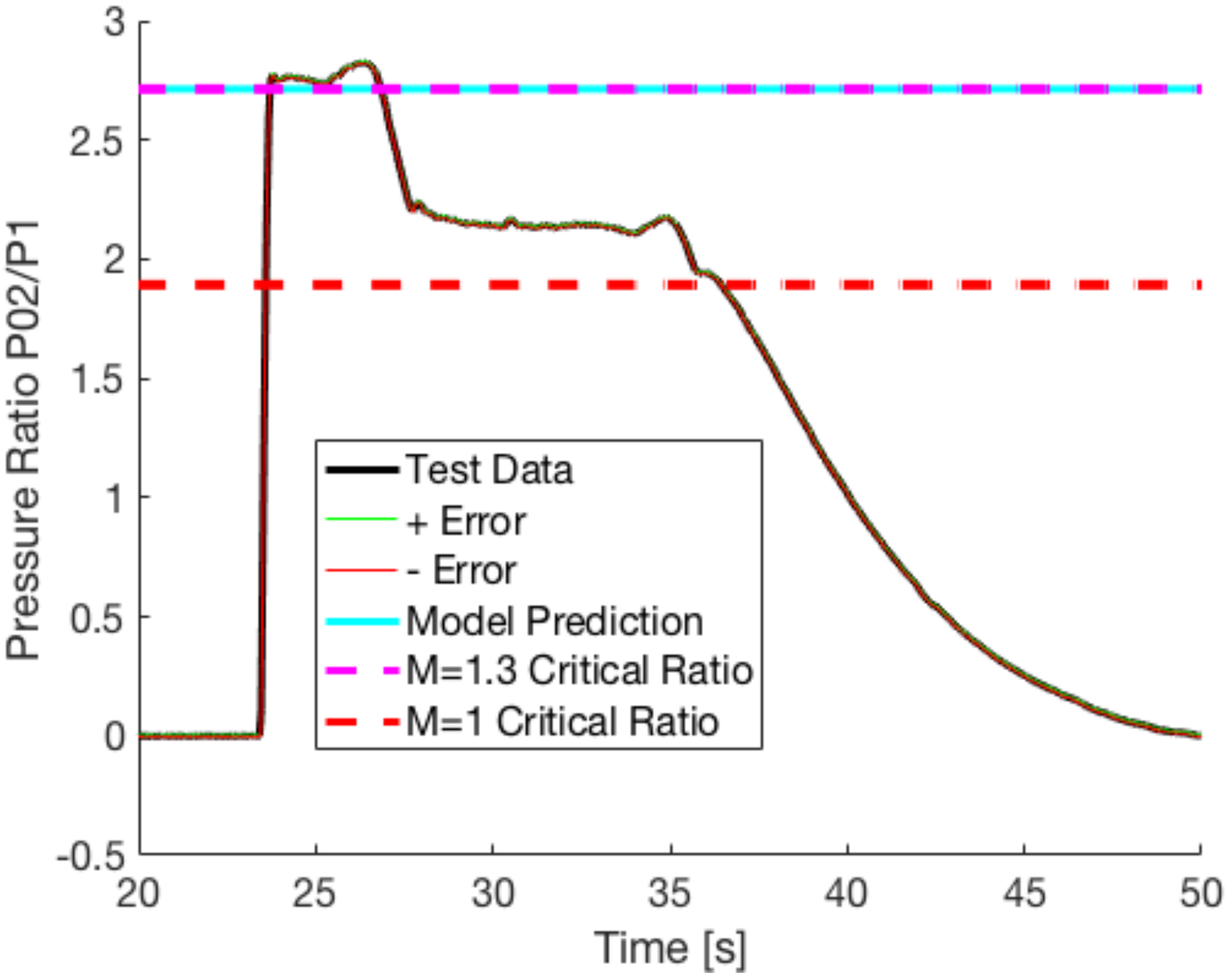
- Rayleigh Pitot Tube Formula:
  1. Holds for supersonic flow, M>1
  2. Accounts for normal shock formed in front of the pitot tube

$$\frac{p_{o_2}}{p_1} = \frac{p_{o_2}}{p_2}\frac{p_2}{p_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma-1)}\right)^{\gamma/(\gamma-1)} \frac{1-\gamma+2\gamma M_1^2}{\gamma+1}$$

- Assuming the static pressure is equal to ambient Boulder pressure = **84 kPa**
- We are able to calculate the Mach number of the flow exiting the nozzle

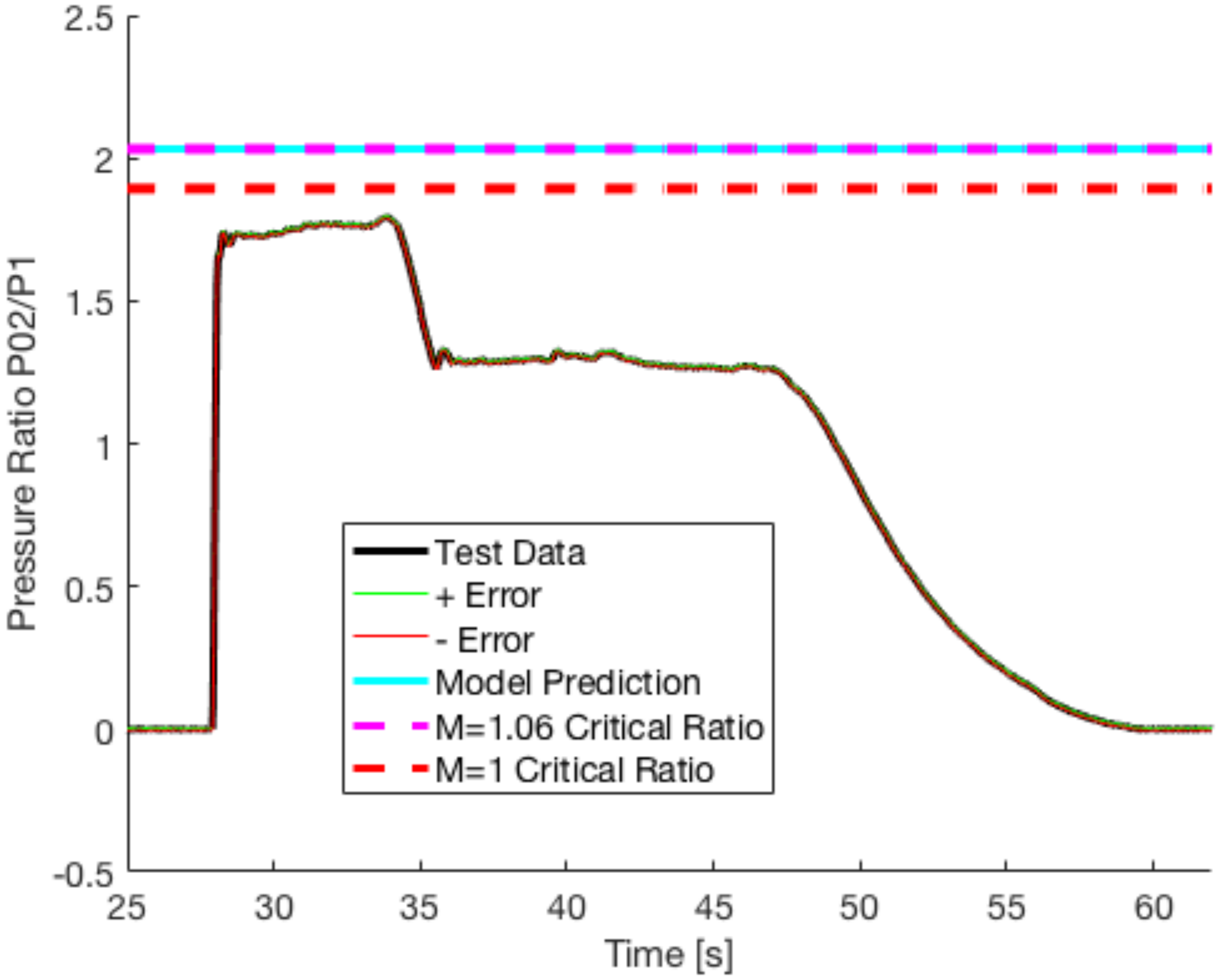
Test Bed Testing Results (Mach 1.3)

- Model predicts Mach number of **1.3** (blue line) during test
- From **24.5-26s, M = 1.3** was **achieved and maintained**
- From **24-36s, supersonic** flow was achieved
- **Pressure gradient** decreases, so **mass flow decreases**
- Resulting in Mach number decreasing to ~**1.10**
- Shock diamonds **confirm supersonic flow** in Schlieren photography



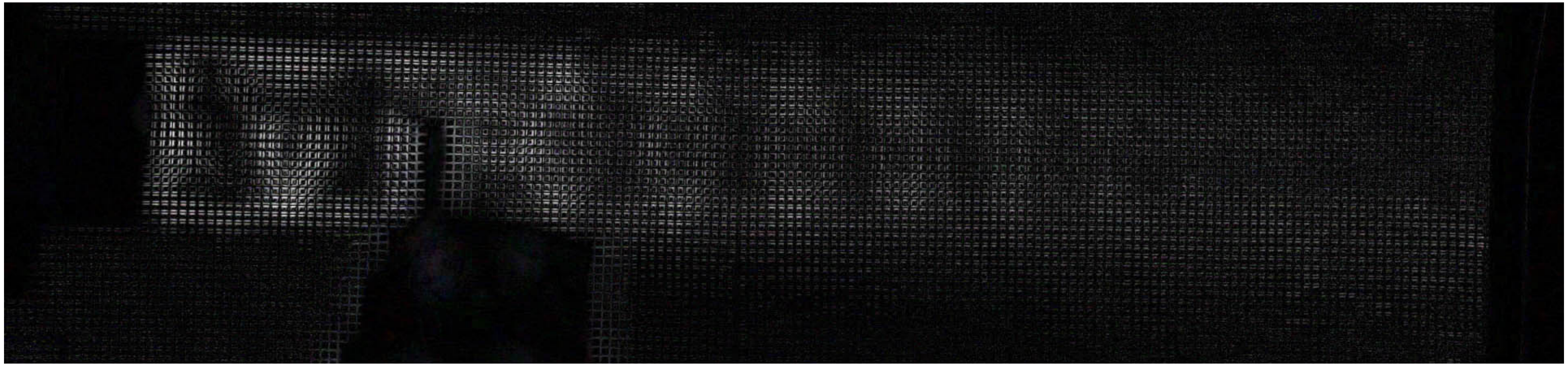
Test Bed Testing Results (Mach 1.06)

- Model predicts **consistent** Mach number of **1.06** (blue line) during test
- Pressure suggests **M < 1**
- Shock diamonds **suggest supersonic** flow in Schlieren photography
- Predicted that the pitot probe was positioned **behind** a **normal shock** at the exit, causing for proportionally **lower pressure** measurements

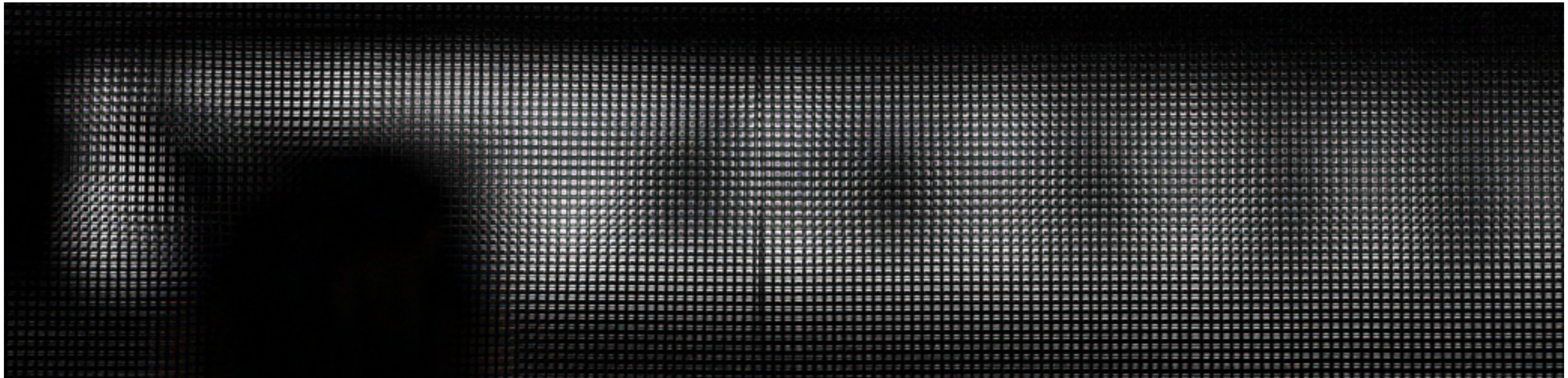


Cold Flow Schlieren Photography

Mach 1.06



Mach 1.30



Functional Requirements Met

✓ • **FR 1:** The Nozzle accelerates flow from subsonic to supersonic conditions.

✓ • **FR 5:** The Nozzle's performance shall be verified and validated through the use of an alternate cold-flow test bed.

Cold Flow Testing Success

	Model/Simulation	Design/Manufacturing	Testing
Level 1	•**Model stock engine exhaust** with given parameters (T, V, P, $\dot{m}$) •Model **air in nozzle** (SABRE and plastic) changing from **subsonic flow to supersonic** flow •**No decrease of T/W** (SABRE Nozzle)	•Manufacture convergent-divergent nozzle that **attaches to JetCat engine** •Material **survives the exhaust environment** for at least **30 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature), **within 15%** of the needed conditions for a **M=1.3** test.
Level 2	•**Increase T/W** by 20% (SABRE Nozzle) 100% •Verification that **modeled nozzle and plastic manufactured nozzles** output performance **within 5%** of one another 75%	•Nozzle built using additive manufacturing, where material **survives testing environment** for at least **150 seconds**	•Replicate an engine analog that **simulates exhaust velocity and pressure** (adjusted for temperature) **within 15%** of the needed conditions for a **M=1.06 test.** 100%
Level 3	•Verification that **modeled nozzle and SABRE nozzle** have output performance **within 20%** of one another 0%	•Nozzle built using additive manufacturing that **can be reused 3 times** and not fail in the testing environment 100%	•Nozzle integrated and **tested with the JetCat engine** 100% •Replicate an engine analog that simulates exhaust velocity and pressure (adjusted for temperature), **within 5%** of needed conditions for **M=1.3 and M=1.06** tests. 75%

M=1.3 Nozzle: **~2.5%**
Scaled down SABRE Nozzle: **~10.3%**

Legend
Total Success
Partial Success
No Success

Systems Engineering

Systems Engineering Approach

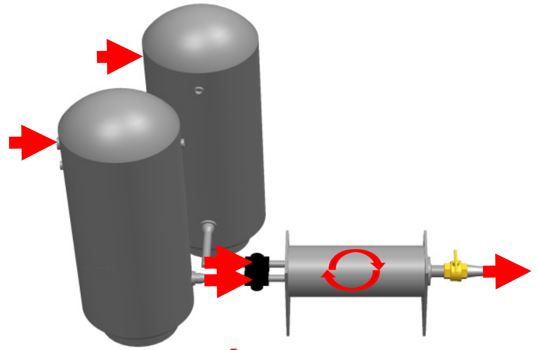
- **Top Down Design Solution:**
  - Customer Design Requirements & Prior Knowledge of the P90-Rxi Engine
    - Functional Requirements & Levels of Success
  - Design Concept Selection
    - Nozzle Contour & Test Bed Method Trade Studies
  - Risk Analysis
    - FMEA matrix approach -> Modified Engine & Cold Flow Test Bed Testing
  - Subsystem Design
    - COTS parts selection, CAD models, Additive Manufacturing

Requirements

↓

Engine Flow Conditions

↓



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- **Bottom Up Integration & Testing:**
  - Lab Testing of Electronics & Moving Mechanical Parts
  - Full System Testing
  - Modified Engine Testing

Key Trades

Nozzle Contours:

	Weighting	de Laval	Variable Geometry	Annular	Expansion-Deflection	Minimum Length
Weight	0.4	4	1	2	2	4
Cost	0.3	4	1	2	3	5
Complexity	0.25	5	1	3	2	4
Altitude Envelope	0.05	1	5	1	4	1
Total	5	4.1	1.2	2.2	2.4	4.15

- **MLN** required the least amount of material to 3D print
  - Lower **cost**
  - Lower **weight**

Test Bed Method:

	Weighting	JetCat Engine	Cold Flow	Hot Flow
Cost	0.15	4	4	2
Flow Accuracy	0.4	5	3	4
Feasibility	0.35	1	4	2
Repeatability	0.1	2	5	3
Total	5	3.15	3.7	2.9

- **Cold Flow** was chosen due to its feasibility
  - JetCat Engine was deemed unlikely to perform with the SABRE Nozzle

Systems Challenges/Lessons Learned

- **Engine System Alteration**
  - The engine could not achieve full performance with the SABRE Nozzle
  - Manufacturer tolerances are often not reliable

- **Cold Flow Test Bed Integration**
  - Appreciation for the energy in large volumes of compressed air
  - Necessity for a thorough safety plan
  - Integrating electronics to validate test bed performance

Project Management

Management Structure

Customer
Capt. Chase Guarnaccio

SABRE-Nozzle

Advisor
Brian Argrow

Test Lead
Corrina Briggs

Project Manager
Andrew Sanchez

System Engineer
Grant Vincent

Safety Lead
Alex Muller

Financial Lead
Nate Voth

Manufacturing Lead
Jack Oblack

Software Lead
Jared Cuteri

Aerodynamics Lead
Tucker Emmett

Electronics Lead
Andrew Quinn

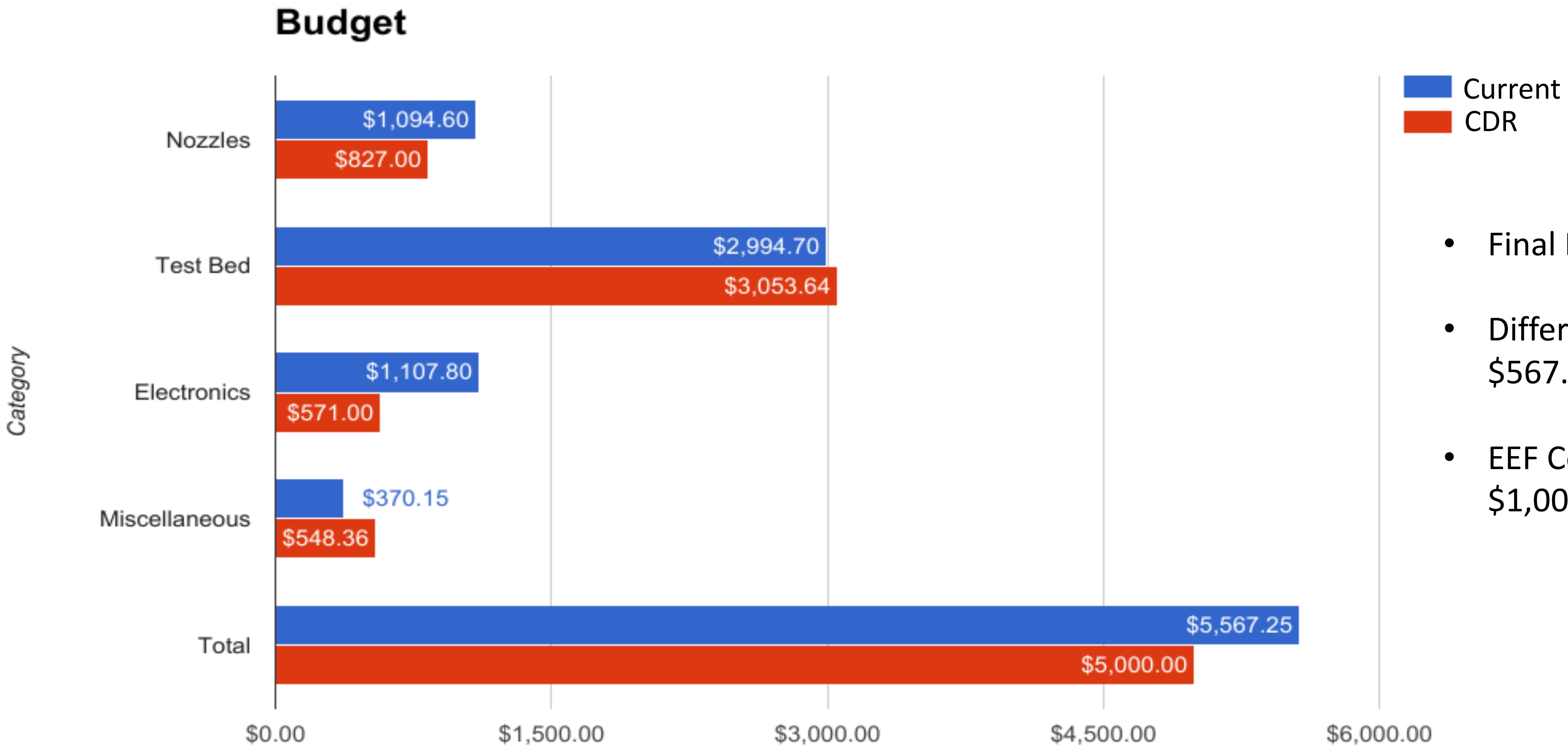
Management - Approach

- **Weekly Meetings**
  - Prepared list of goals and tasks
  - Deadlines for upcoming milestones
  - Summarize priorities for the next week
- **Team Communication**
  - Utilized GroupMe messenger
  - Team availabilities
- **Utilized TeamGantt as Schedule Tracker**
  - Reference for progress throughout the year
  - Aided in meetings for team priorities
  - Great resource for determining time remaining

Management - Lessons

- **Weekly Meetings**
  - Physical list of tasks most effective
  - Continuous feedback best for project progress
  - Assign all team members a task(s) for week
- **TeamGantt Chart**
  - Hard to edit with several users
  - Sections hard to detail without cluttering page

Budget



- Final Budget: $5,567.25
- Difference from CDR: $567.25
- EEF Contributions: $1,000

Total Project Cost

- Assuming:
  - $65,000 yearly annual Salary
  - 2,080 hrs/year (40 hrs/week)
  - 200% Overhead Rate

Total Hours	3920.5 hours
Total Direct Labor Cost	$122,515.63
Overhead Rate	200%
Overhead Cost	$245,031.26
Material Cost	$6,000
Total Industry Cost	**$382,546.89**

Acknowledgements

Air Force Research Laboratory

CU Boulder AES Department

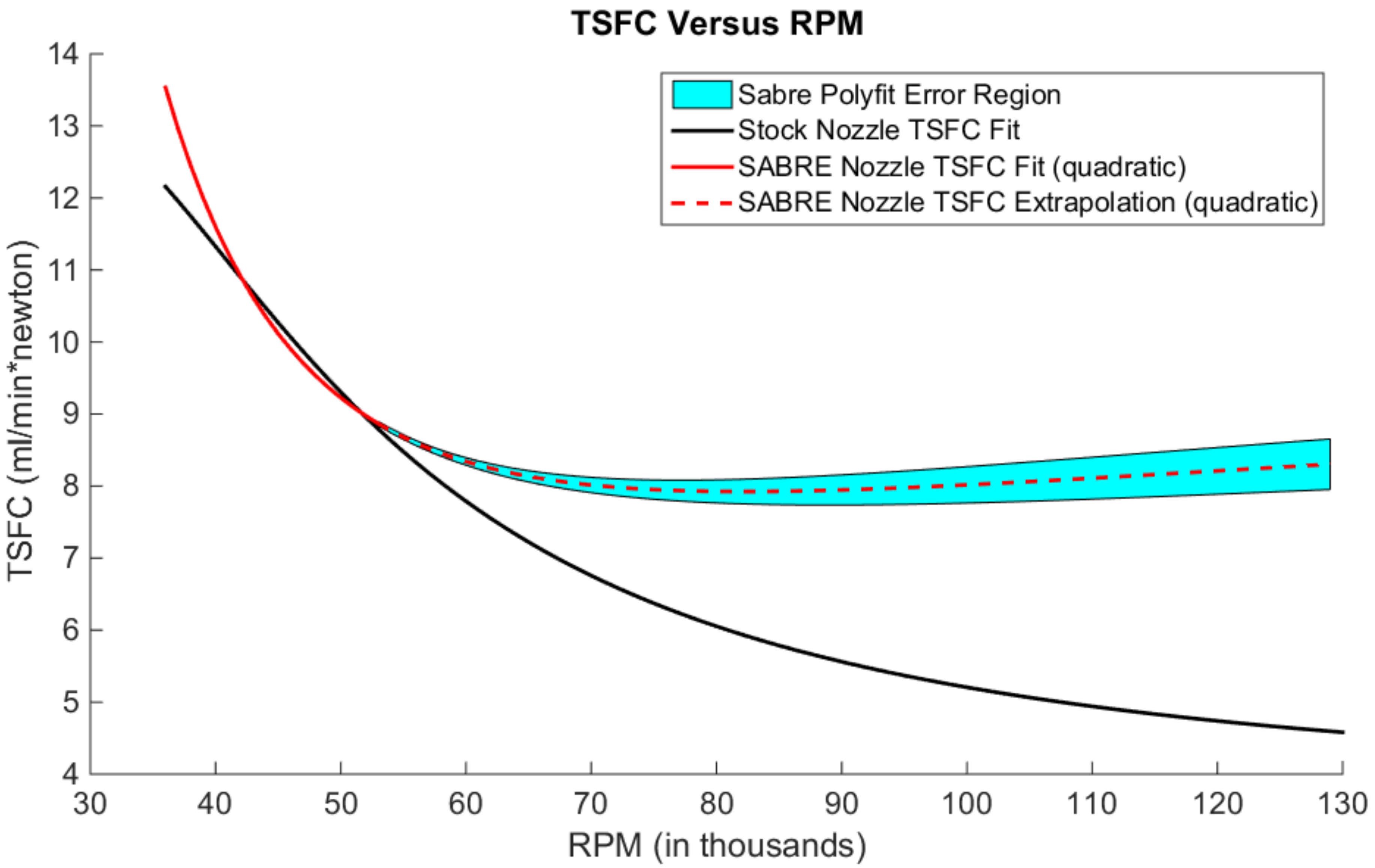
Dr. Nabity

Dr. Argrow

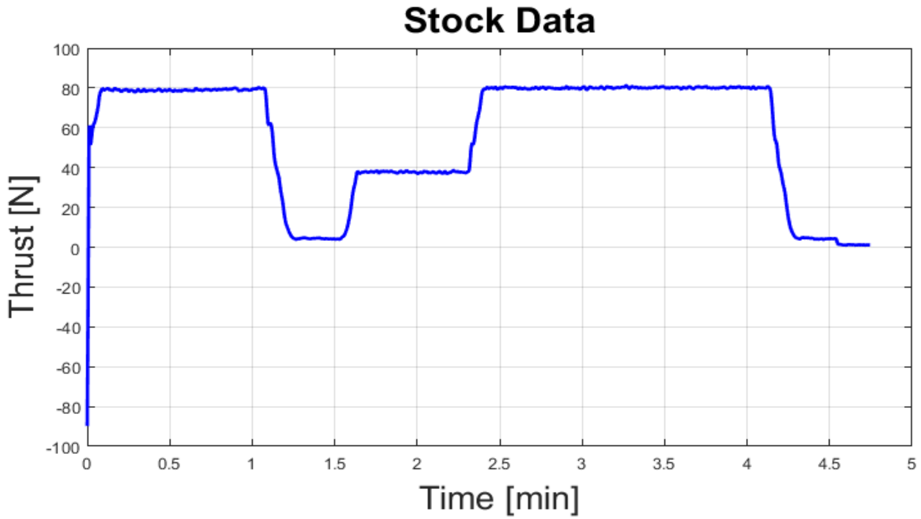
Questions?

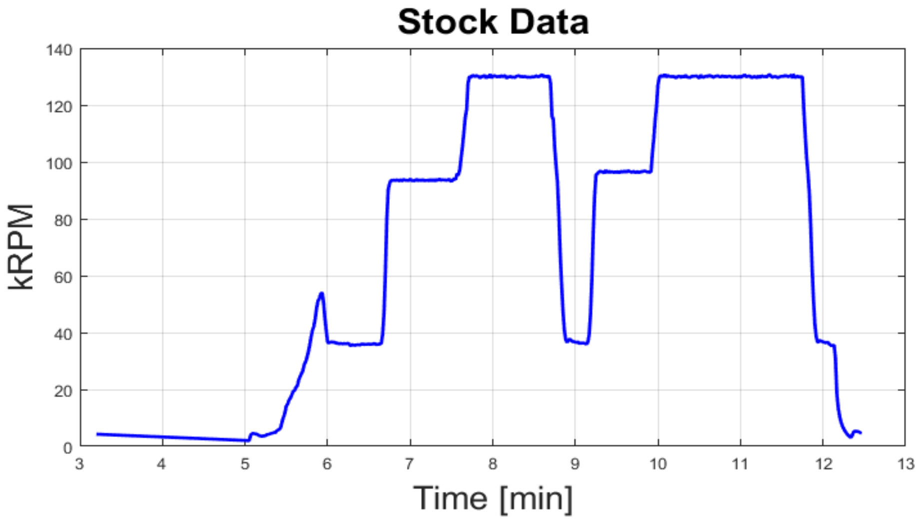
Appendix

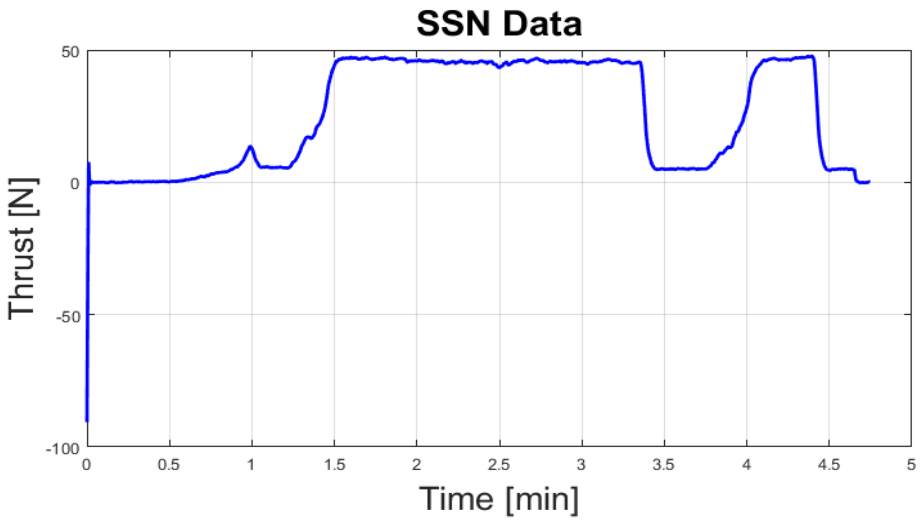
Engine Testing Results (TSFC)

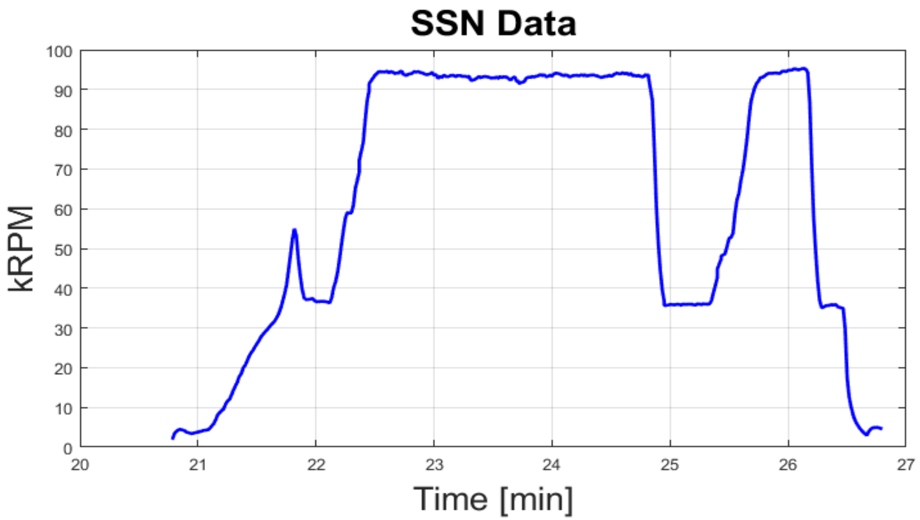


Engine Testing Data









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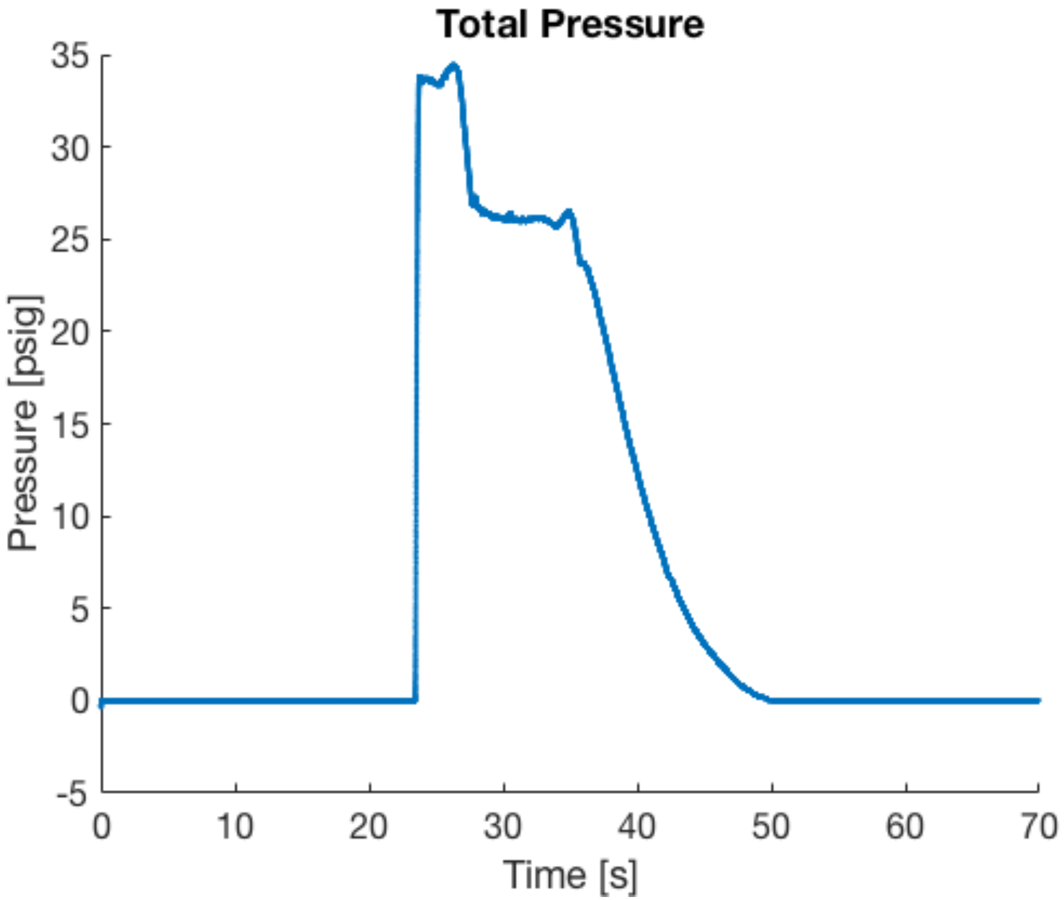
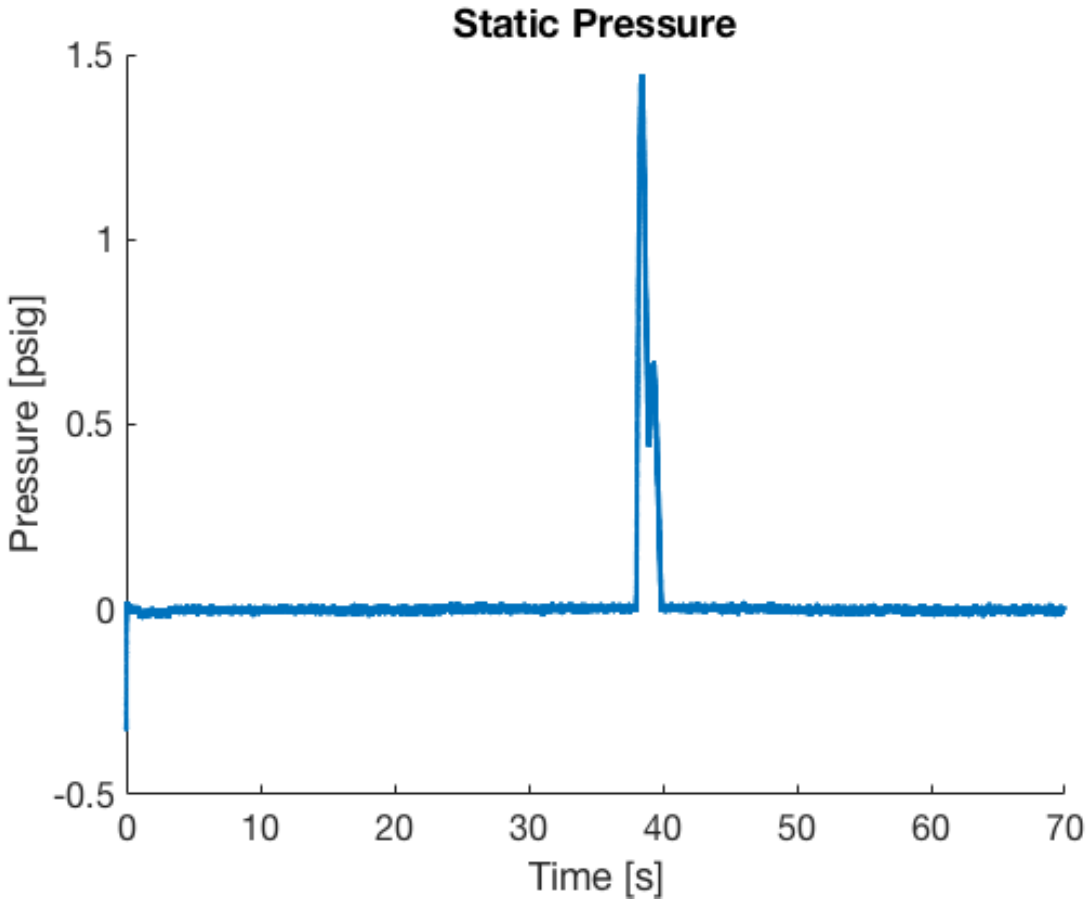
At Nozzle Exit





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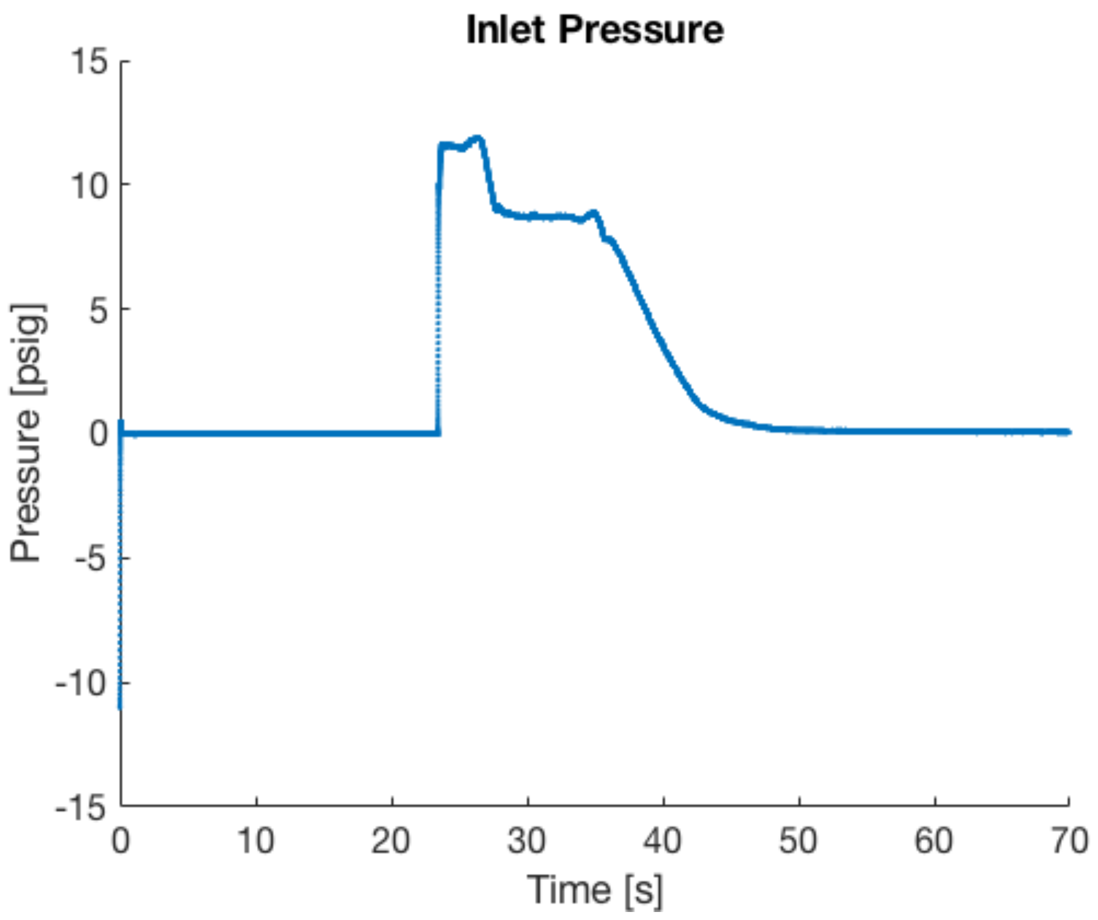

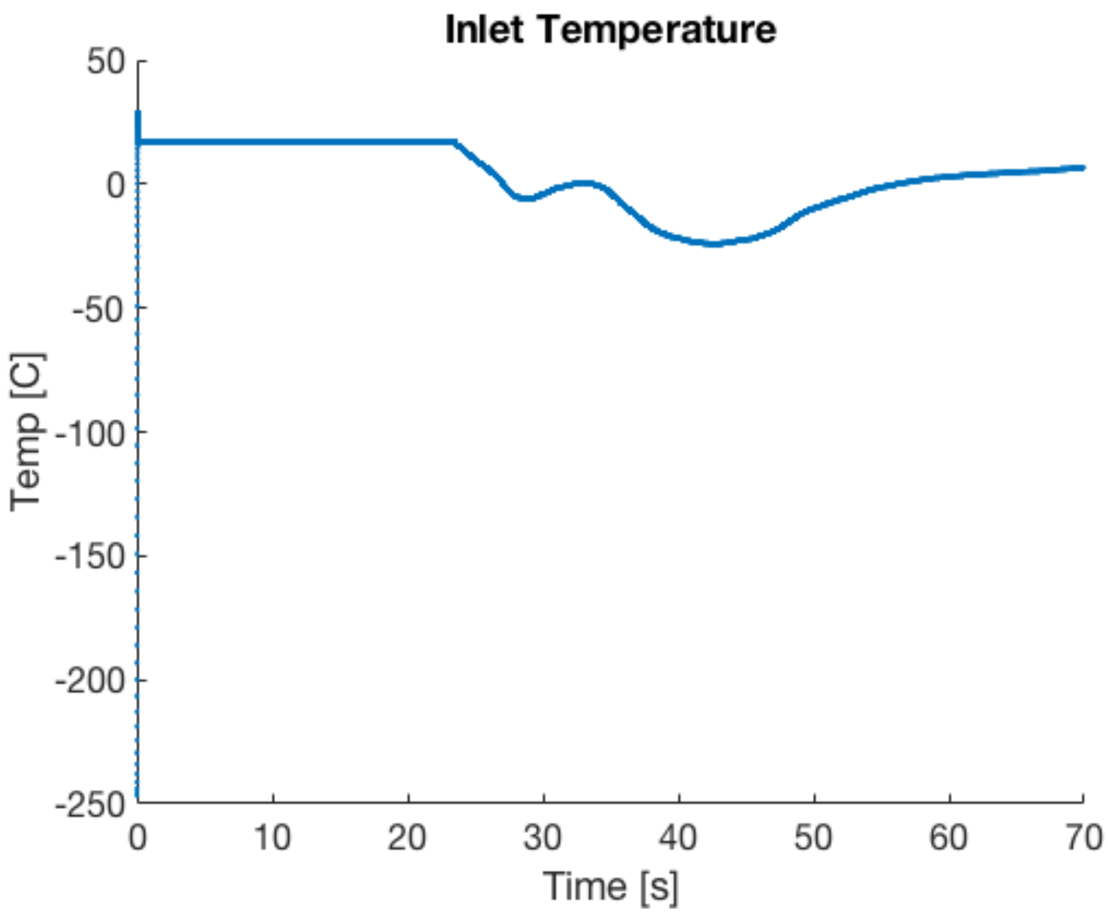

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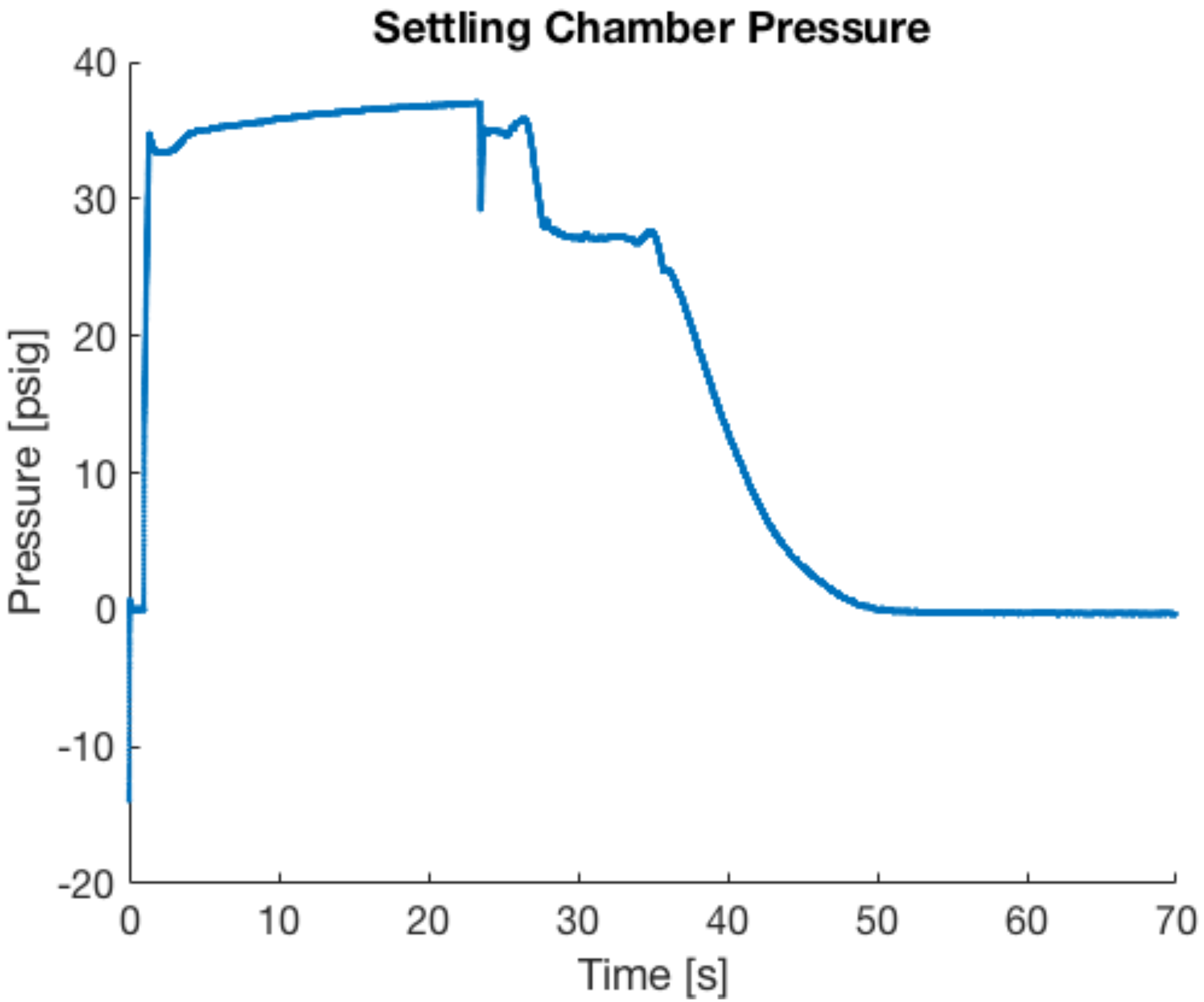

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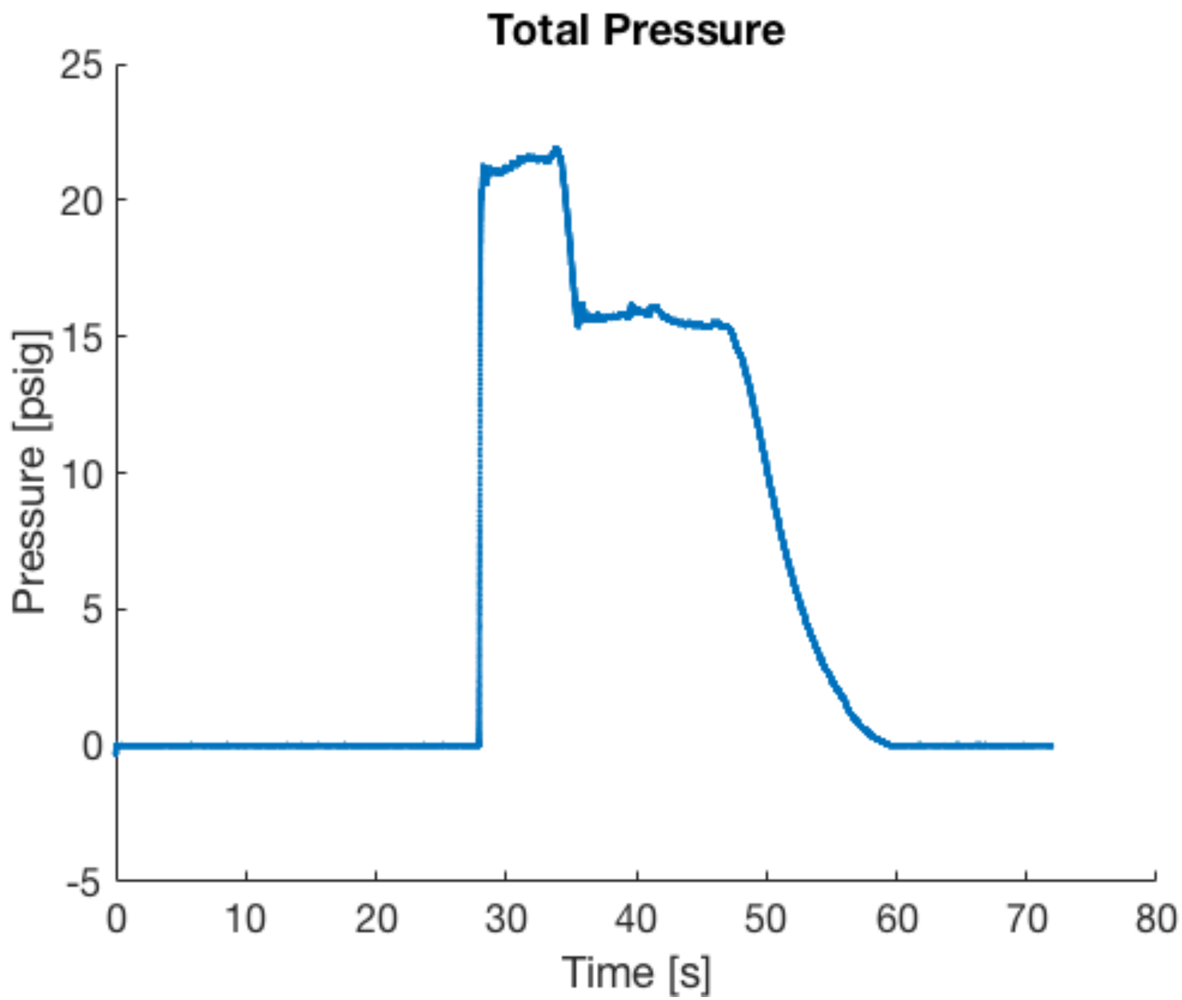
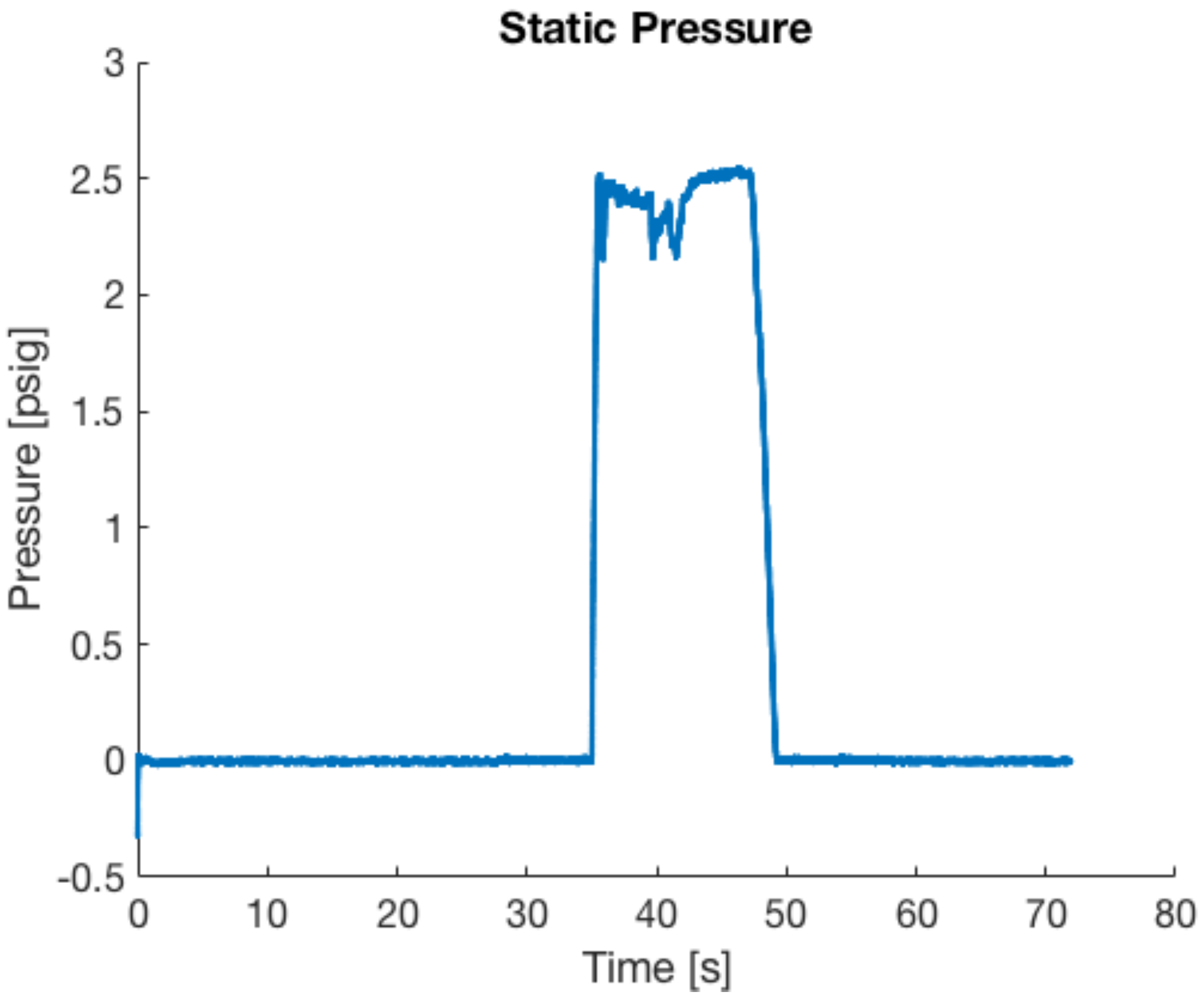
At Nozzle Exit





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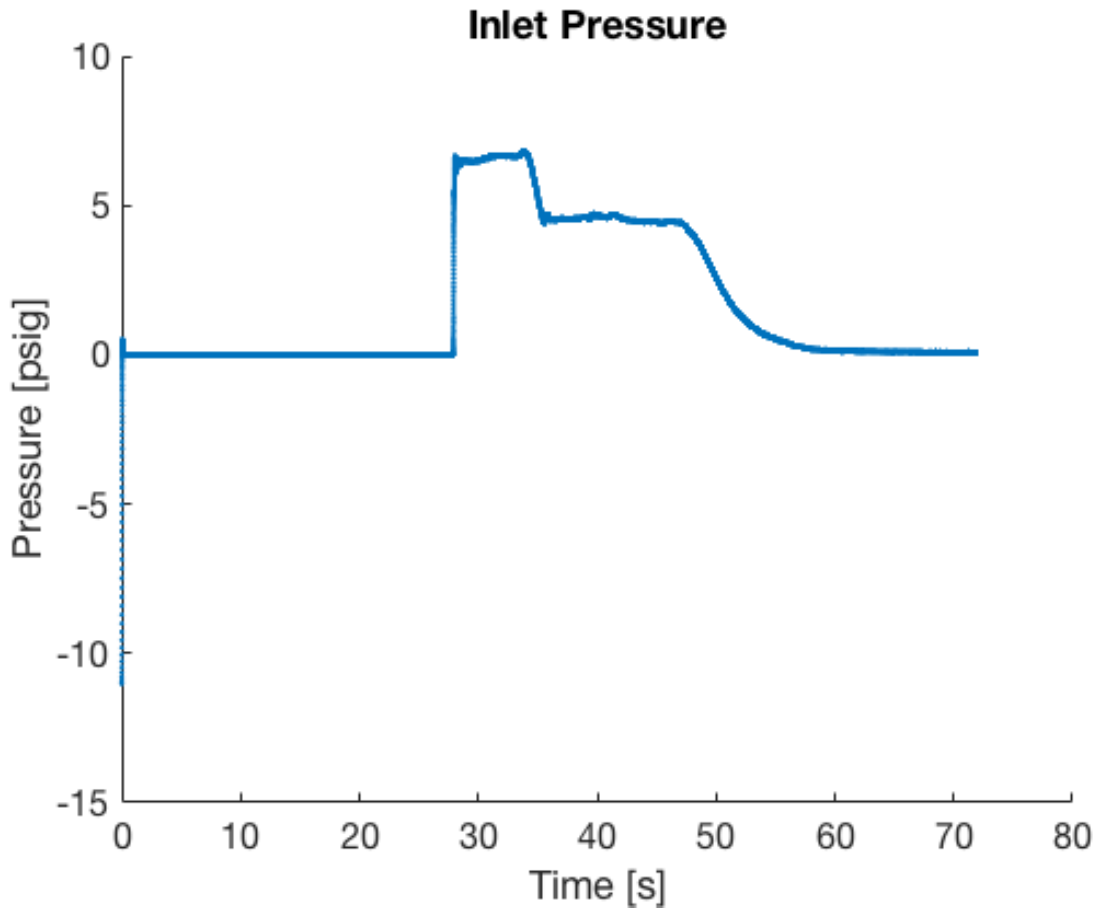

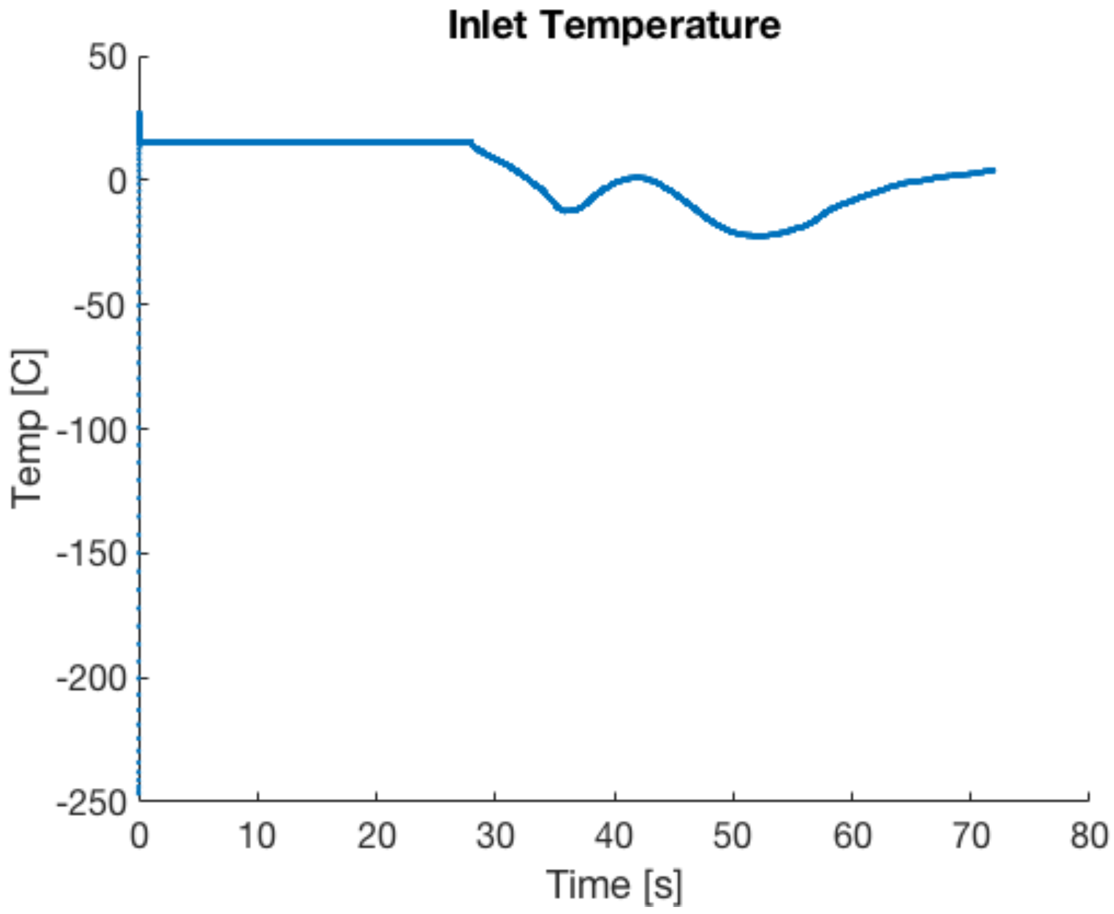

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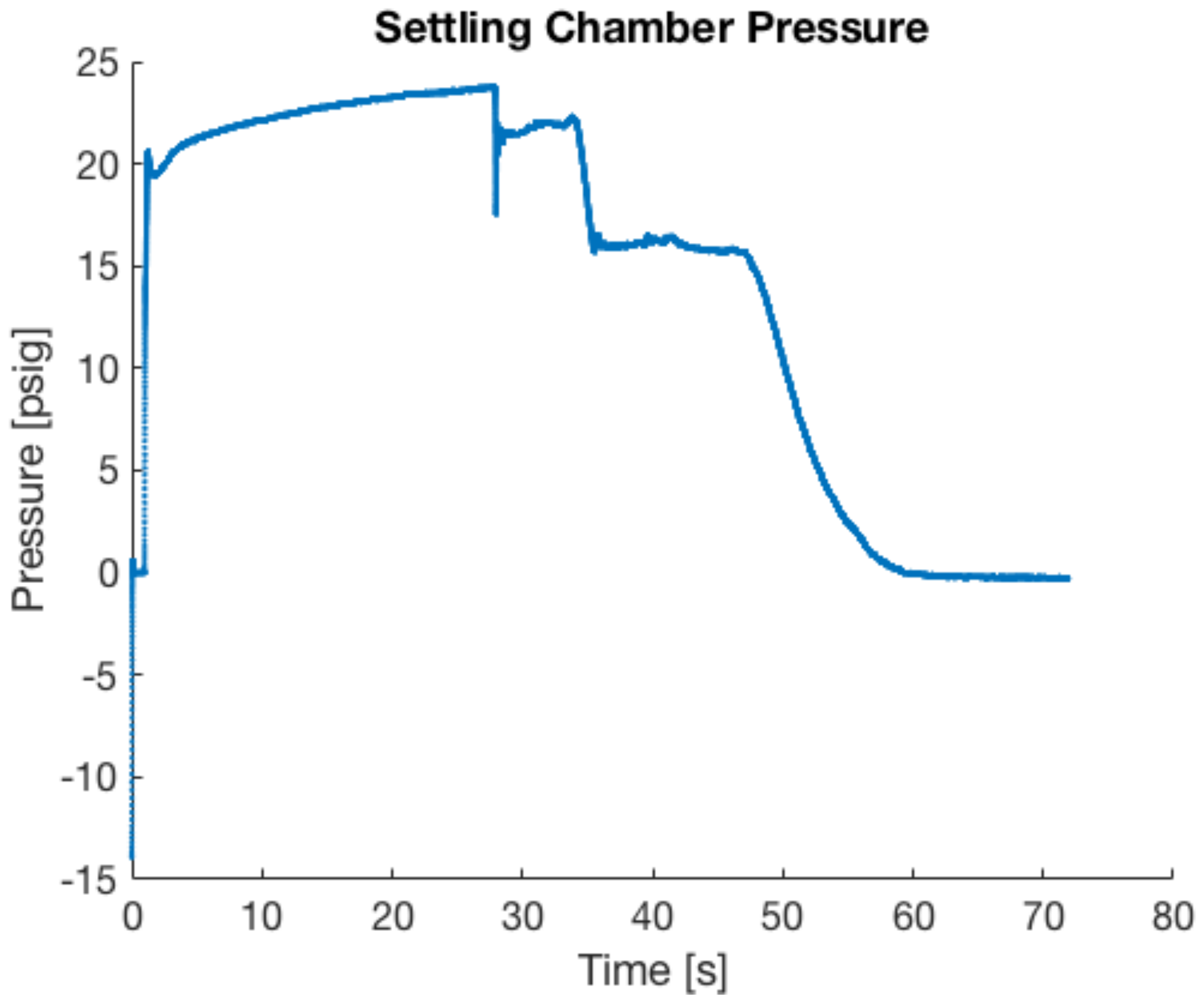
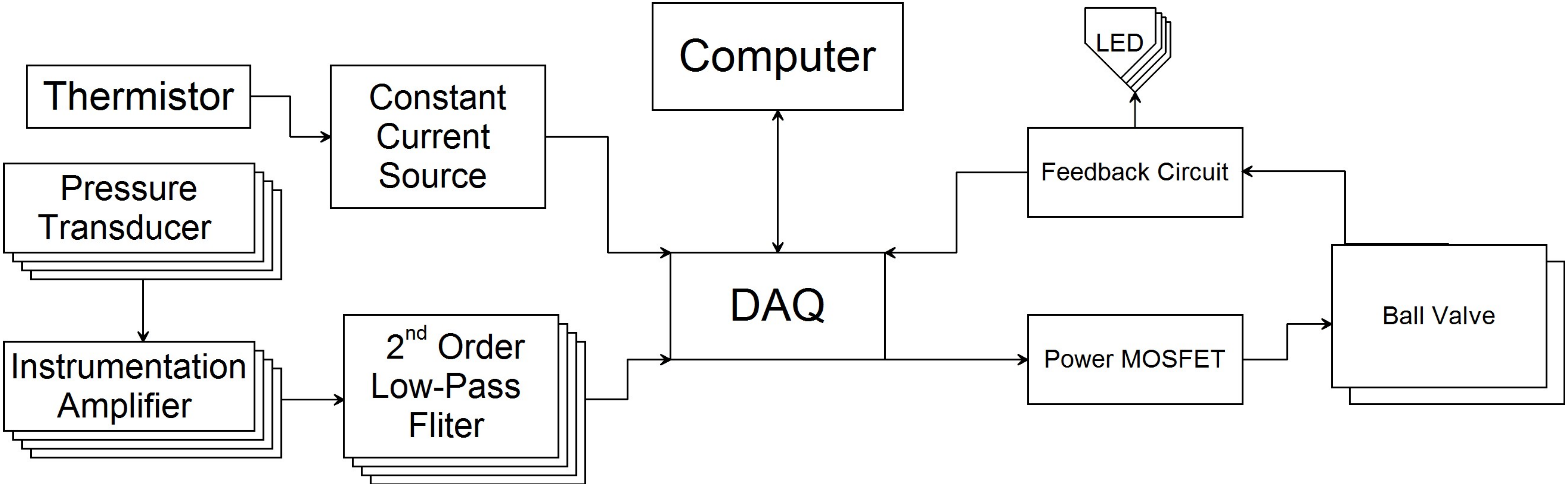
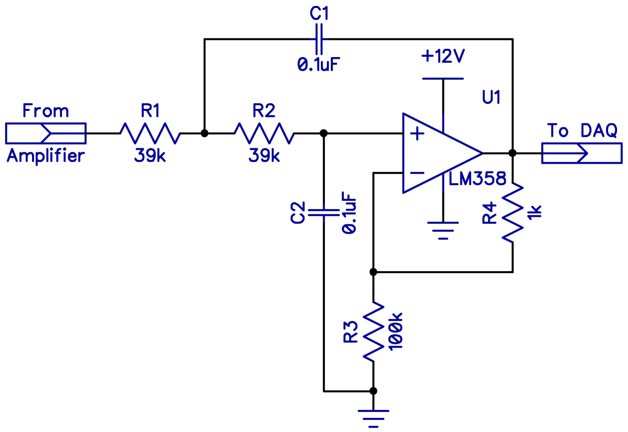


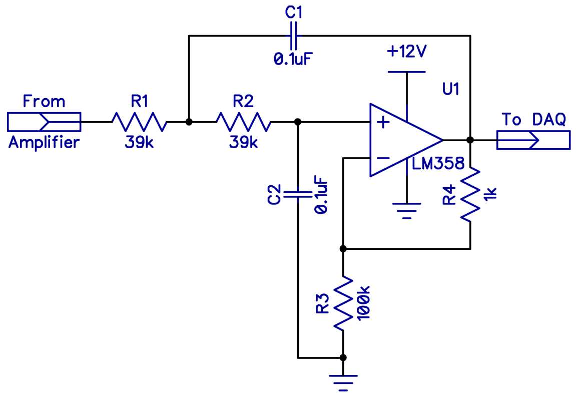
Hardware Flow Chart



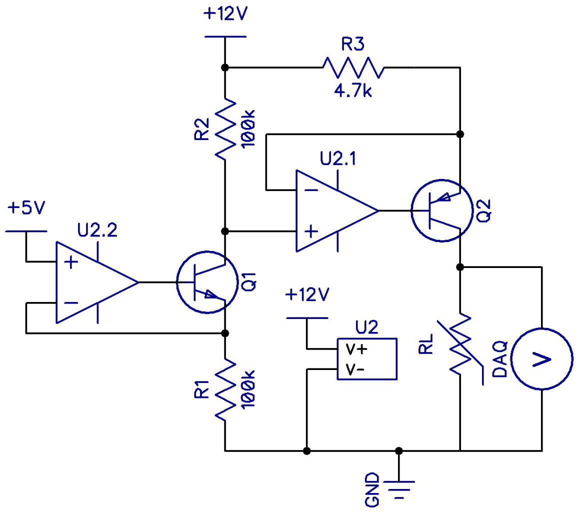
Circuit Diagrams



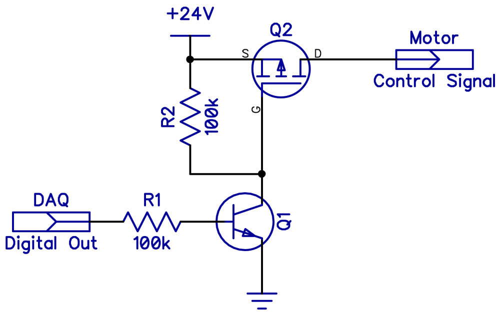
Instrumentation Amplifier



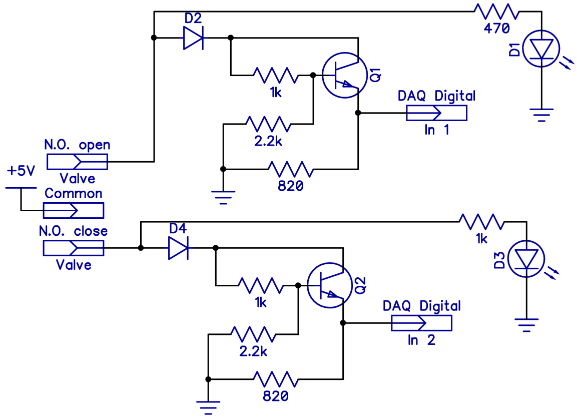
2nd Order Low Pass Filter



Thermistor Measurement



Power MOSFET



Feedback Circuit

Cold Flow Adjustment

- Stagnation temperature affects the optimal throat and exit areas of the nozzle.
- Cold flow test requires nozzle designed to operate at cold flow stagnation temperature
- Same design method can be used to design cold flow nozzle