SABRE NOZZLE

Supersonic Air-Breathing Redesigned Engine Nozzle

Testing Readiness Review

Customer
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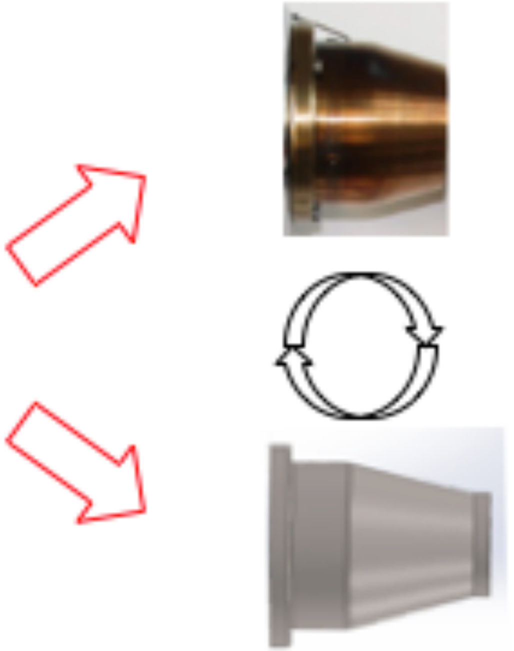
Presentation Outline

- **Project Overview**
  - Description/Objectives
  - Updated Test Bed Design
- **Schedule**
- **Testing Readiness**
  - Completed Testing
  - Upcoming Testing
- **Budget**

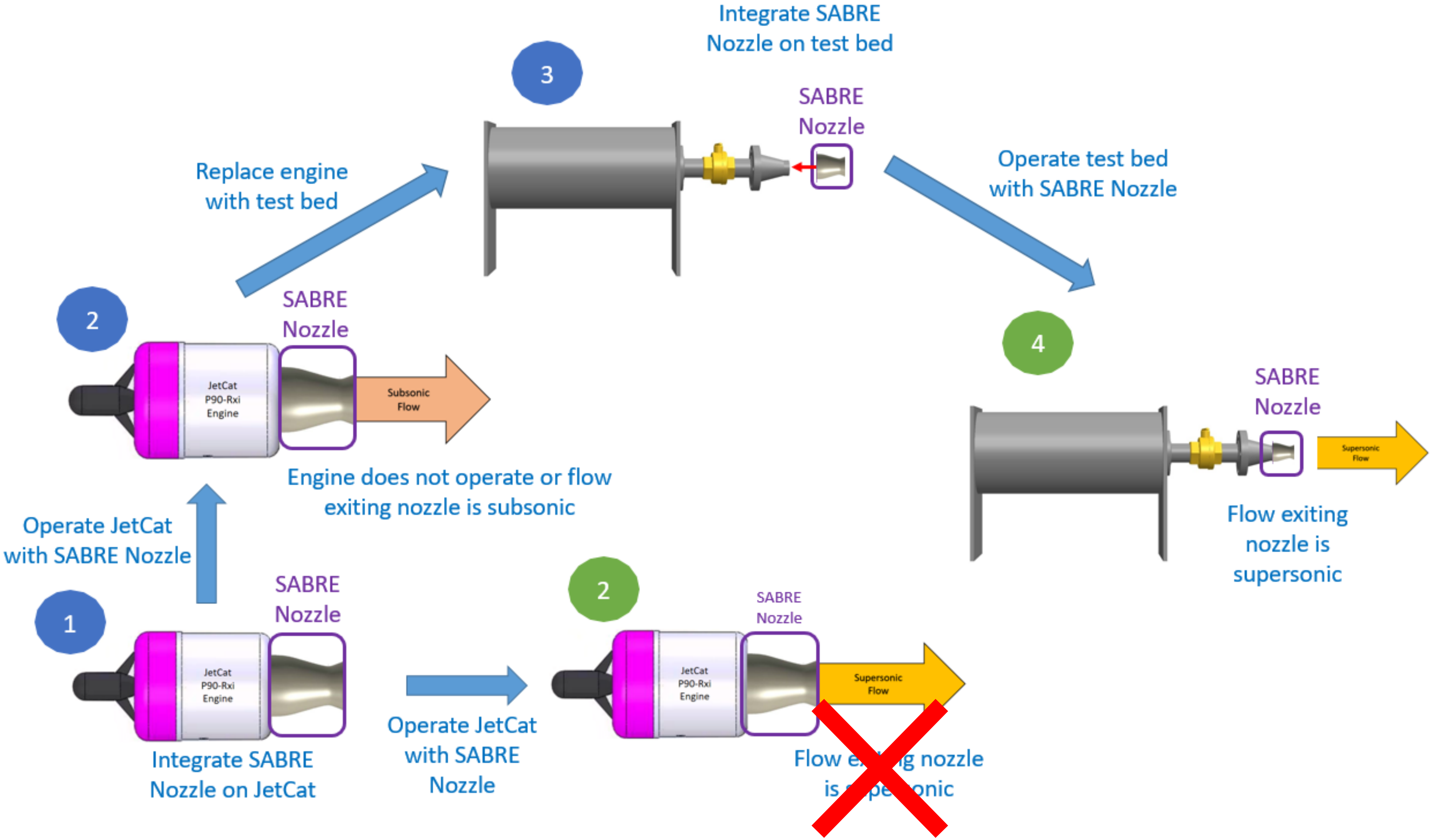
Project Overview

Project Description

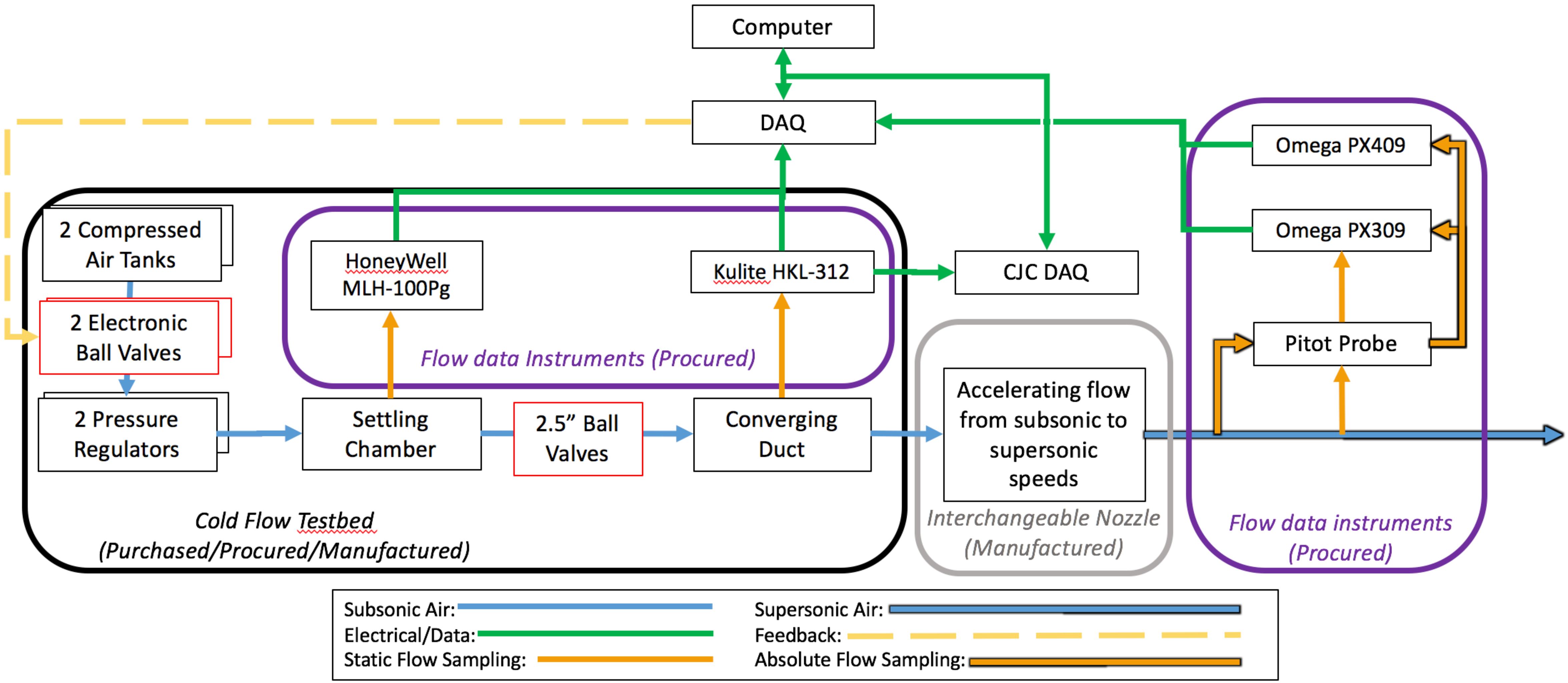
Model, manufacture, and **verify** an **additive manufactured nozzle** capable of accelerating flow to **supersonic exhaust** produced by a **P90-RXi JetCat** engine maintaining the **T/W ratio** from its stock configuration.



CONOPS

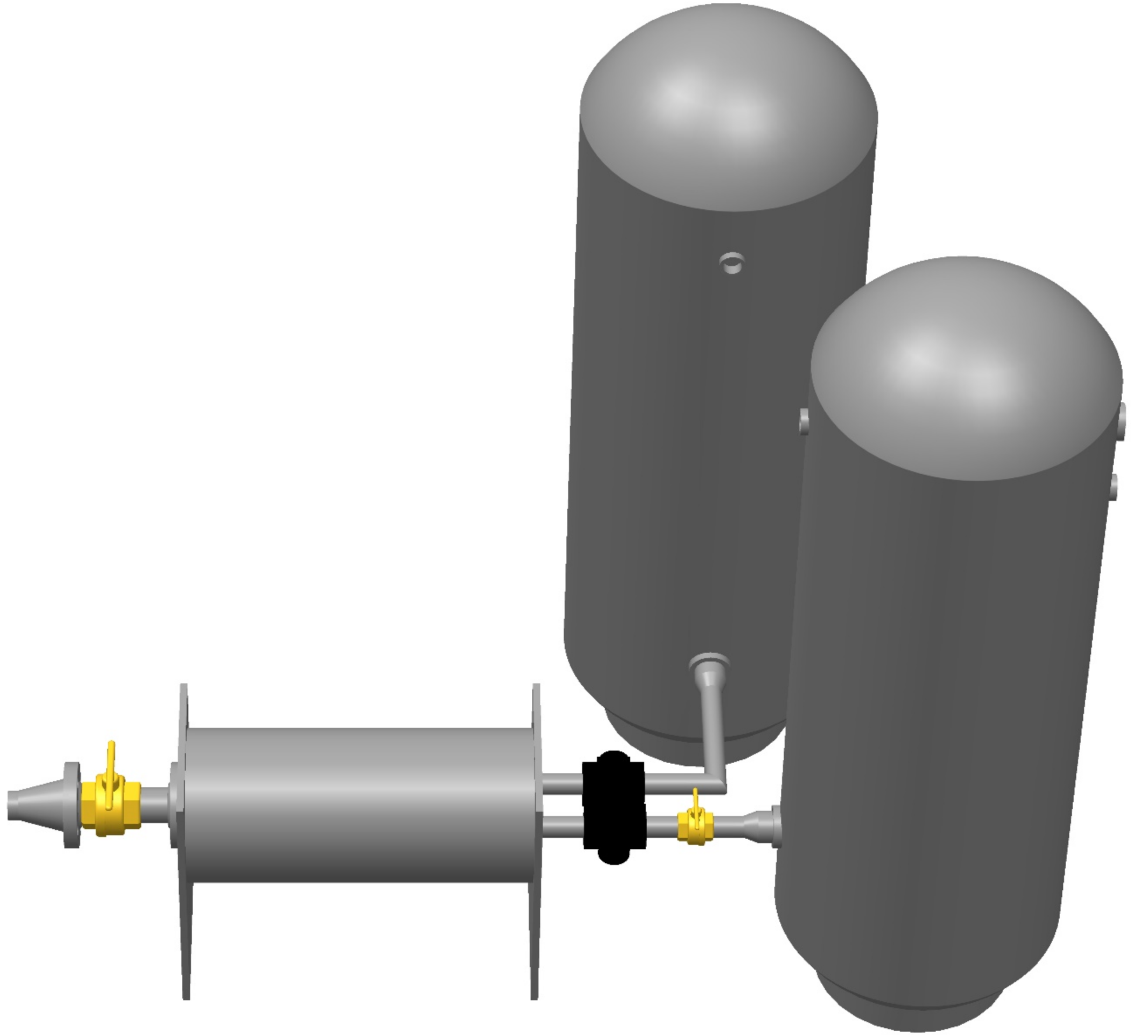

Integrate SABRE Nozzle on test bed
3
SABRE Nozzle
Replace engine with test bed
Operate test bed with SABRE Nozzle
2
SABRE Nozzle
JetCat P90-Rxi Engine
Subsonic Flow
4
SABRE Nozzle
Supersonic Flow
Engine does not operate or flow exiting nozzle is subsonic
Operate JetCat with SABRE Nozzle
Flow exiting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

Test bed FBD



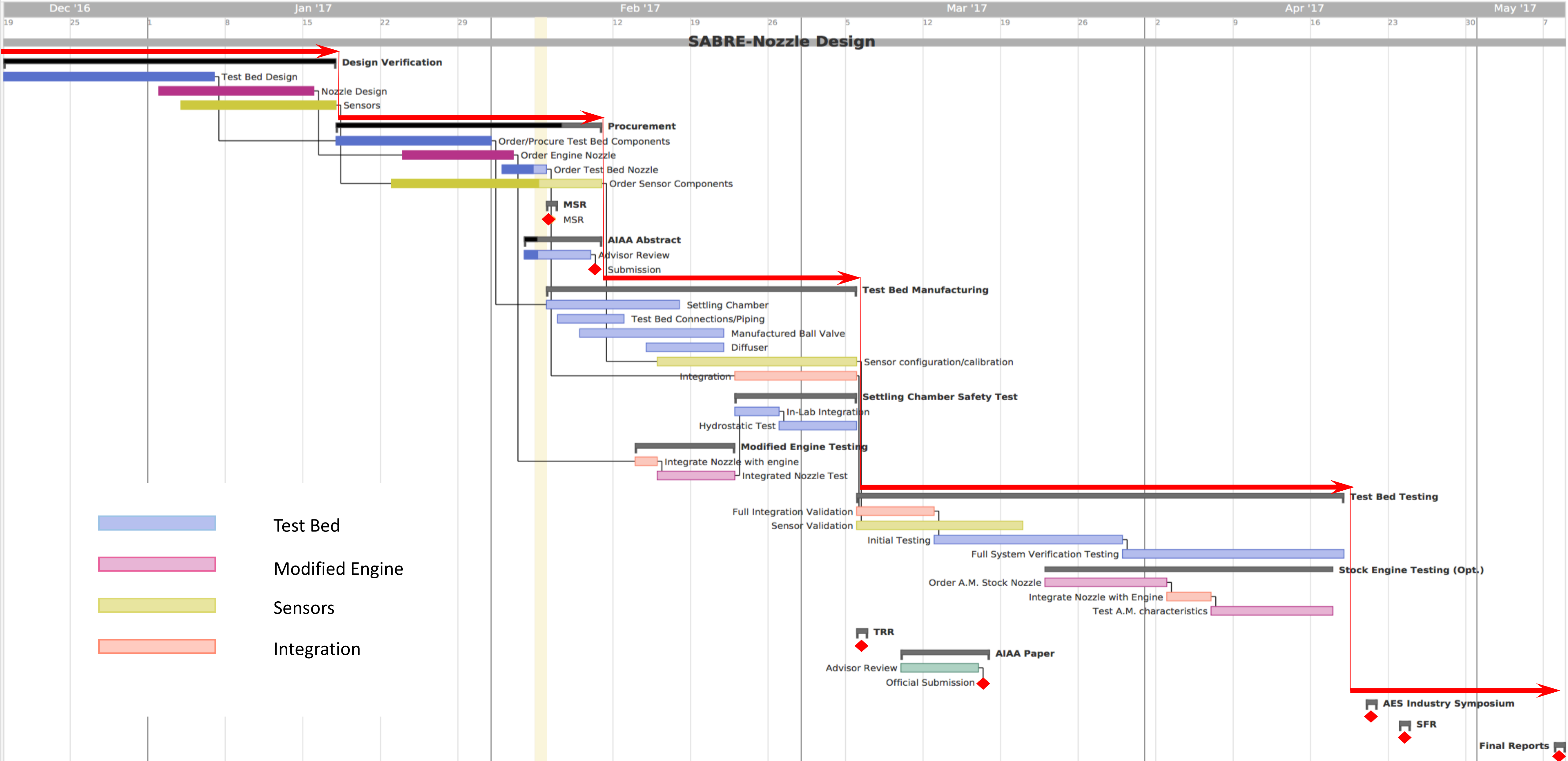
Computer
DAQ
2 Compressed Air Tanks
2 Electronic Ball Valves
2 Pressure Regulators
HoneyWell MLH-100Pg
Kulite HKL-312
Flow data Instruments (Procured)
Settling Chamber
2.5" Ball Valves
Converging Duct
Cold Flow Testbed (Purchased/Procured/Manufactured)
CJC DAQ
Accelerating flow from subsonic to supersonic speeds
Interchangeable Nozzle (Manufactured)
Omega PX409
Omega PX309
Pitot Probe
Flow data instruments (Procured)
Subsonic Air:
Supersonic Air:
Electrical/Data:
Feedback:
Static Flow Sampling:
Absolute Flow Sampling:

Testbed Design

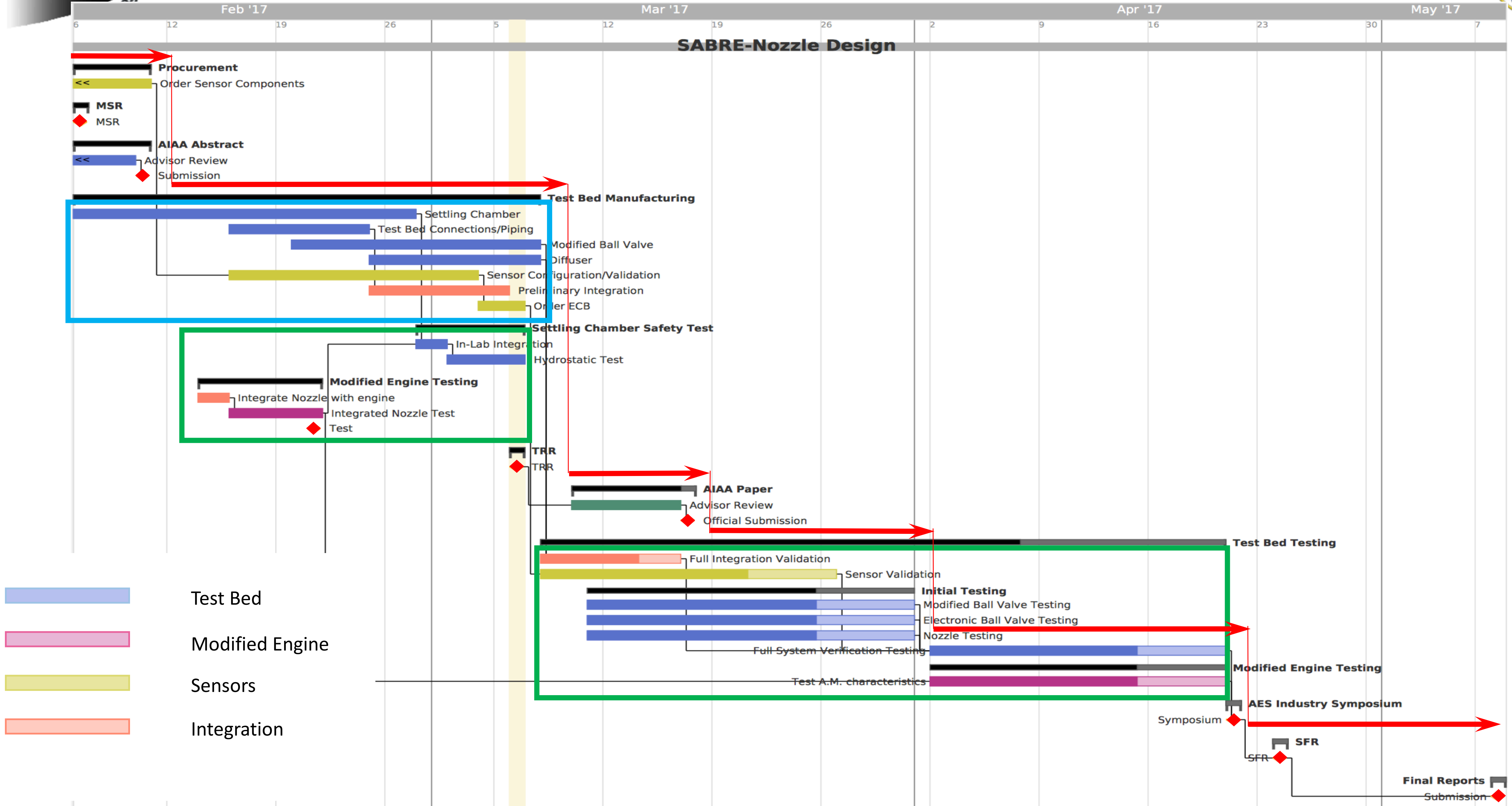


Project Schedule

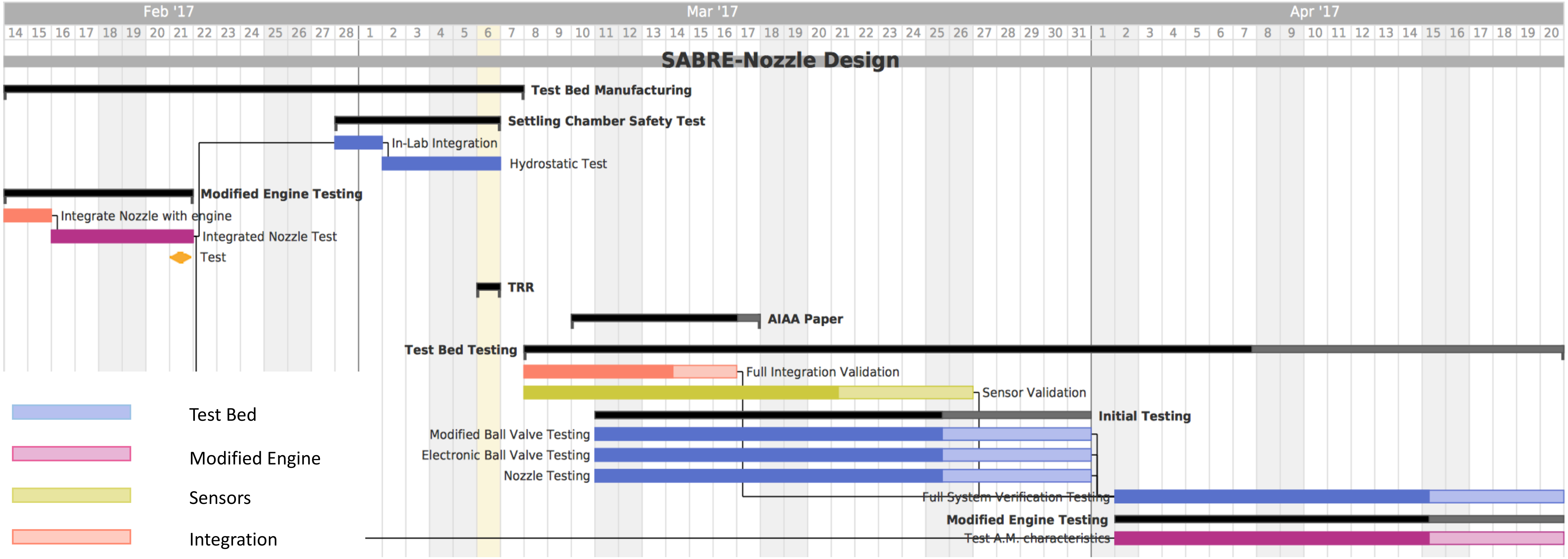
MSR Overview Schedule



TRR Overview Schedule



Testing Schedule



Project Testing

Testing Overview

- **Completed Testing**
  - Modified Engine Test
  - Hydrostatic Test
- **Upcoming Testing**
  - Full System Test
  - Further Modified Engine Test

Modified Engine Test

- **Purpose:** Evaluate functionality of SABRE Nozzle on JetCat P90-RXi
- **Level of success achieved:**
  - Complete (Level 1-3) success in Design/Manuf.
- **Main Testing Equipment:**

  JetCat P-90RXi, SABRE nozzle, Omega PX137, Pitot probe
- **Risk Reduction:** Shows nozzle designed can integrate with engine
- **Results Expected:** Engine inoperable/supersonic flow not achieved

Engine Testing Requirements Addressed

FR 1	The Nozzle shall accelerate the flow from subsonic to supersonic conditions.
DR 1.1	The flow through the nozzle shall be choked such that the nozzle exit flow Mach is greater than 1.

FR 2	The Nozzle shall not decrease the Thrust/Weight ratio.
DR 2.2	The thrust of the engine shall be increased to 120 N.

FR 3	The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.
DR 3.1	The Nozzle shall be manufactured with additive manufacturing.
DR 3.4	Successful integration of the nozzle shall not render the engine inoperable after the nozzle is detached and the engine is returned to its stock configuration.

FR 4	The Nozzle shall be able to withstand engine operation for at least 30 seconds.
DR 4.1	The nozzle shall have a melting point higher than 1100K.
DR 4.4	The thrust of the engine shall not decrease over a 30 second span.
DR 4.5	The nozzle shall survive the pressure and forces of engine operation.

Critical Project Elements

CPE 1: Engine Operation

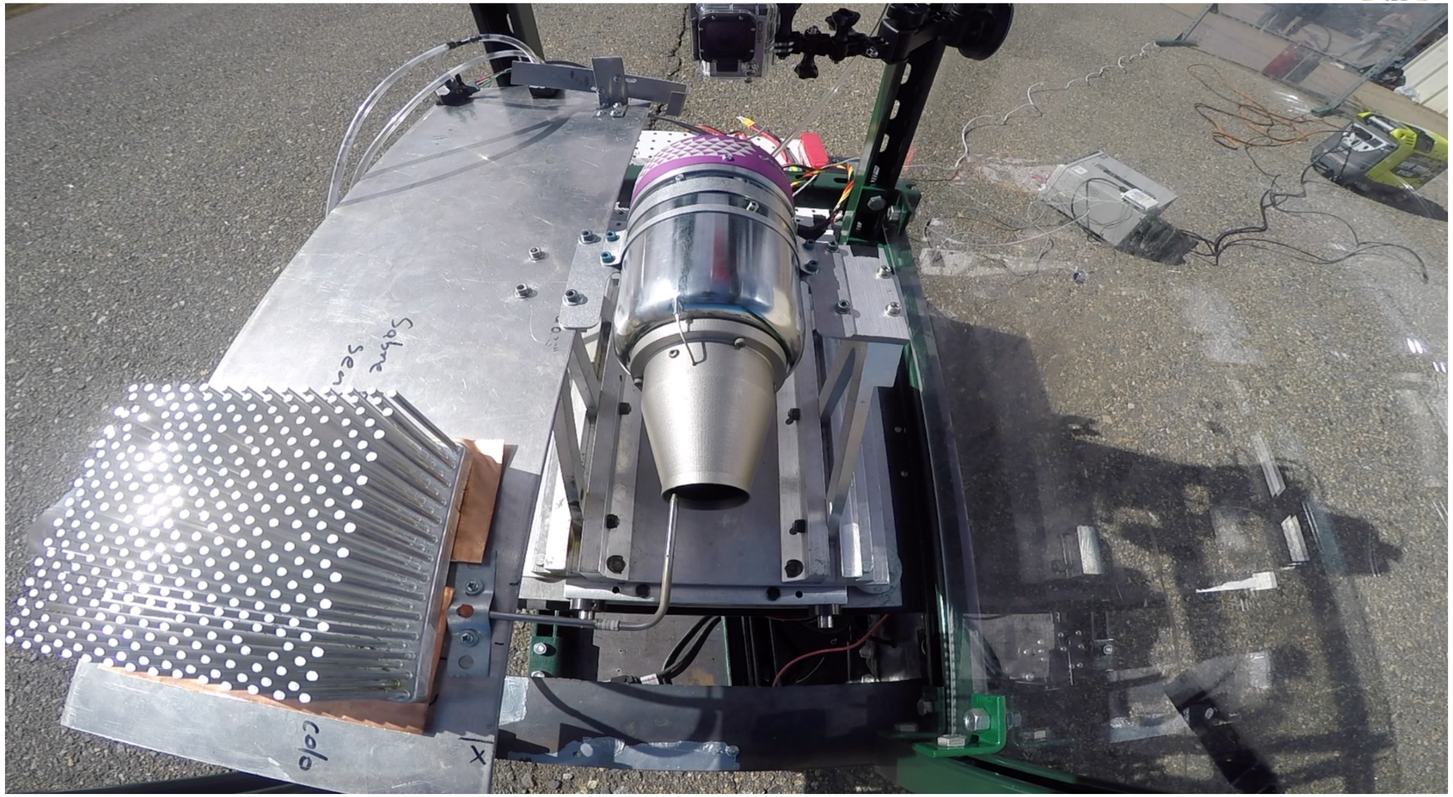
Stock Test & Modified Test

Modified Nozzle Verification

Additive Manufacturing Validation & Survivability

Modified Engine Test

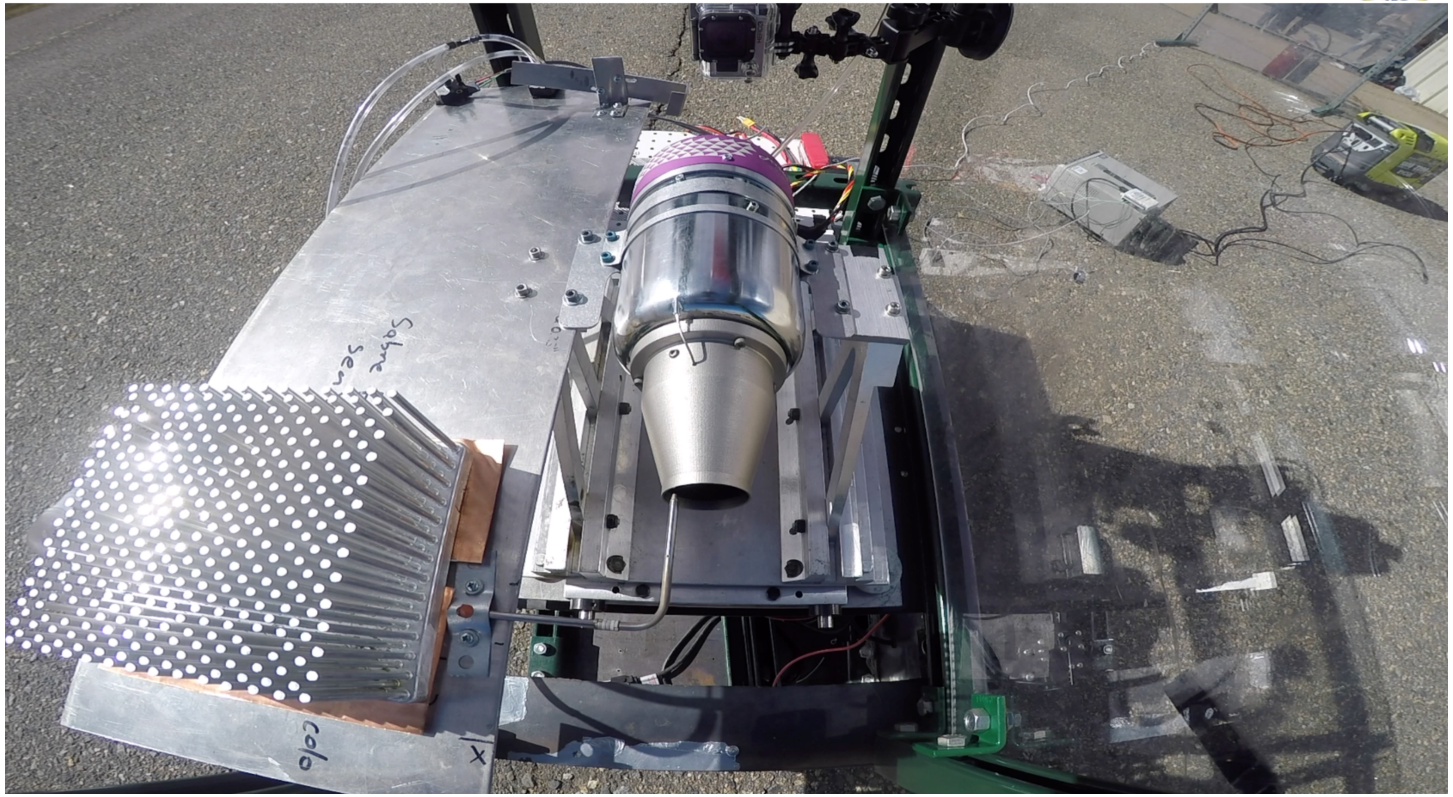
- Feb 21st
- Boulder Airport
- Testing Safety:
  - Procedure
  - Distance
  - Blast Shields
  - Equipment
  - Fire Suppression



- **Results:** Partial Success; Engine operated with SABRE nozzle (although not fully), but did not achieve supersonic flow

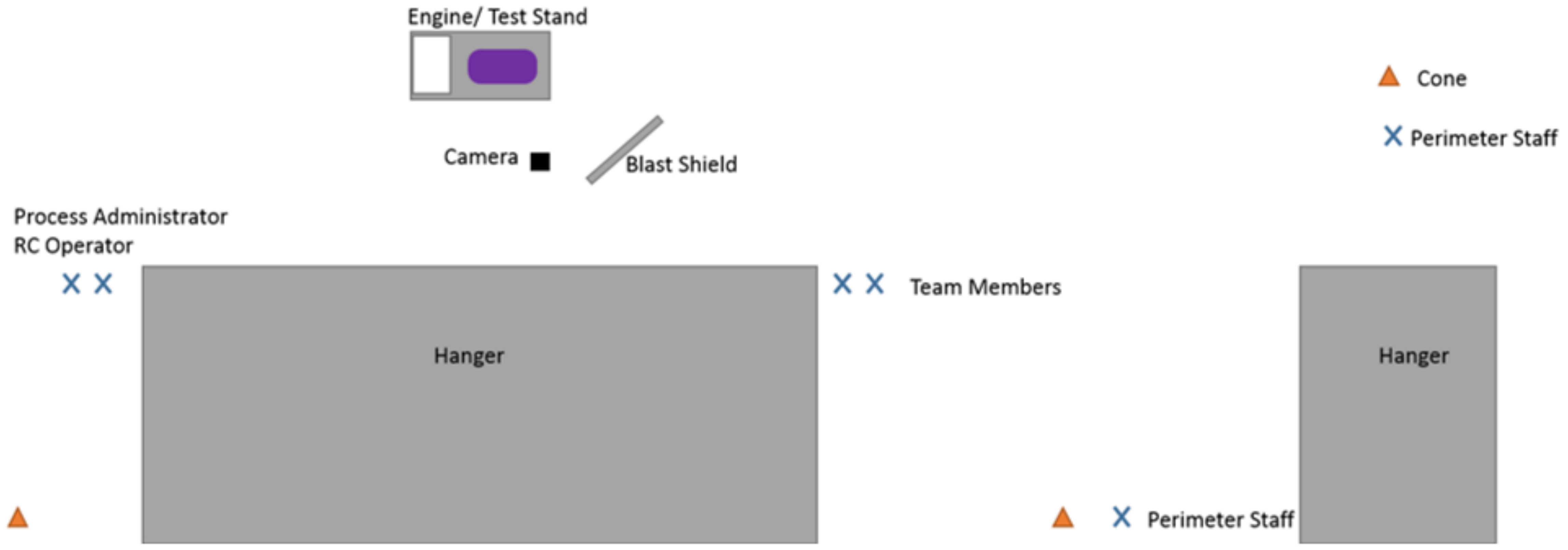
Modified Engine Test

- April ??
- Boulder Airport
- Testing Safety:
  - Procedure
  - Distance
  - Blast Shields
  - Equipment
  - Fire Suppression



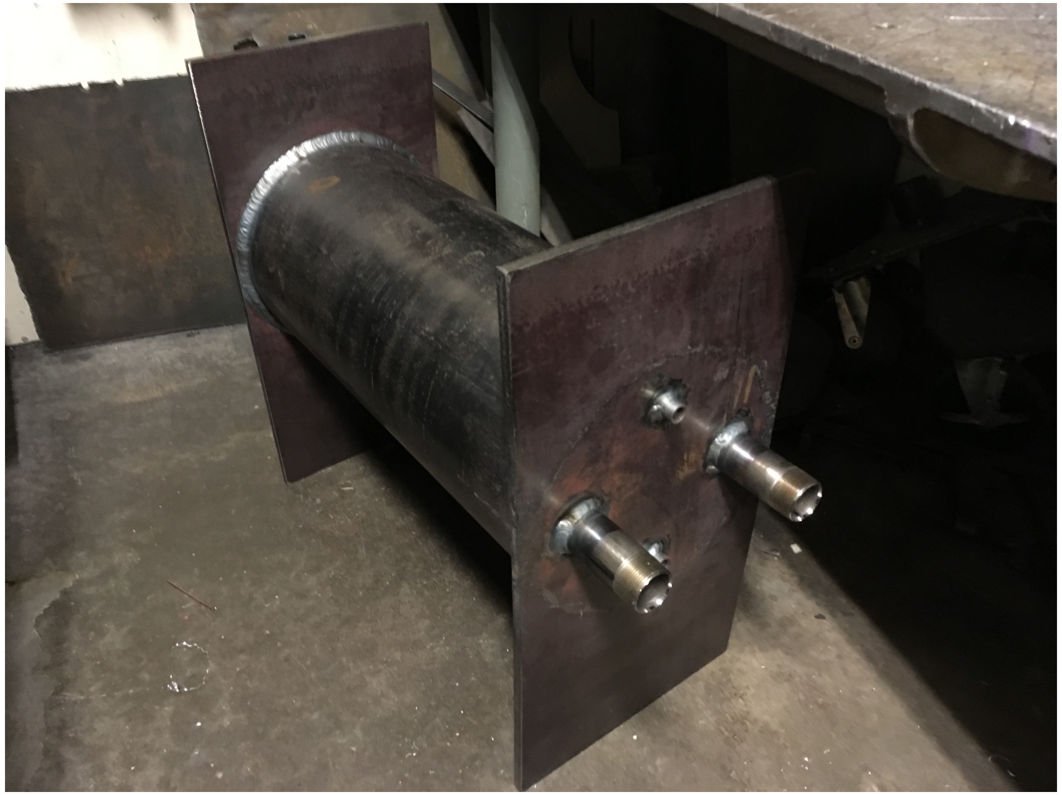
- **Future Tests:**
  - Longer duration, specific fuel consumption, thrust at specific RPM’s

Modified Engine Test Schematic



Hydrostatic Test

- **Date:** March 6, 2017
- **Location:** Aerospace Machine Shop
- **Purpose:** Leak test and determine a maximum pressure for the settling chamber



Hydrostatic Test

- **Verification & Validation:** Provides a maximum pressure rating for the settling chamber which informs a safety margin for testing (with max worst-case pressure of 175 psi in the system)
- **Main Testing Equipment:** SABRE Testbed settling chamber, analog pressure regulator, pump
- **Risk Reduction:** Allows project to proceed to testing and clears safety risks associated with welding in-house
- **Results Expected:** The weld does not fail at 200 psi

Hydrostatic Testing Requirements Addressed

FR 4	The Nozzle shall be able to withstand engine operation for at least 30 seconds.

FR 5	The Nozzle's performance shall be validated/verified through the use of a cold-flow test bed.
DR 5.1	The test bed shall provide the same pressure and mass flow rate as the engine exit within 5% adjusted for temperature

Critical Project Elements

CPE 2: Test Bed Operation

Test Bed Verification

Nozzle Design Verification

Testing Safety & Protocol

Supersonic Validation

Full System Test (Cold Flow Test Bed)

- **Purpose:** Measure exhaust velocities of the M=1.3 nozzle and the scaled down SABRE nozzle. Measure test conditions to achieve level 3 testing success 1-3
- **Verification and Validation:** Validating testbed with 1.3 Mach nozzle, validating SABRE 1.06 nozzle with testbed
- **Main testing equipment:**
  - SABRE testbed
  - Scaled SABRE 1.06 1.3 Mach nozzles
  - Kulite HKL/T-312M
  - Honeywell MLH-100PG
  - Omega PX309
  - Omega PX409

Full System Test

- **Risk Reduction:** As we do not currently have an engine which can produce supersonic conditions, the test bed will validate our ability to design supersonic convergent-divergent nozzles
- **Results Expected:** Supersonic flow exhaust (M=1.06 & M=1.3) produced by plastic manufactured nozzles

Test Bed Testing Requirements Addressed

FR 1	The Nozzle shall accelerate the flow from subsonic to supersonic conditions.
DR 1.1	The flow through the nozzle shall be choked such that the nozzle exit flow Mach is greater than 1.

FR 4	The Nozzle shall be able to withstand engine operation for at least 30 seconds.
DR 4.4	The thrust of the engine shall not decrease over a 30 second span.
DR 4.5	The nozzle shall survive the pressure and forces of engine operation.

FR 5	The Nozzle's performance shall be validated/verified through the use of a cold-flow test bed.
DR 5.1	The test bed shall provide the same pressure and mass flow rate as the engine exit within 5% adjusted for temperature

Full System Test

- **Location:** Boulder County Explosives Disposal
- **Contact:** Officer Scott Little
- **Test Safety**
  - Procedure
  - Distance
  - Earth Berms
  - Blast Shields
  - Equipment

Full System Test

- **Location:** Redstone College
- **Contact:** Jacob Martinez
- **Test Safety**
  - Procedure
  - Concrete Walls
  - Blast wall
  - Blast Shields
  - Equipment

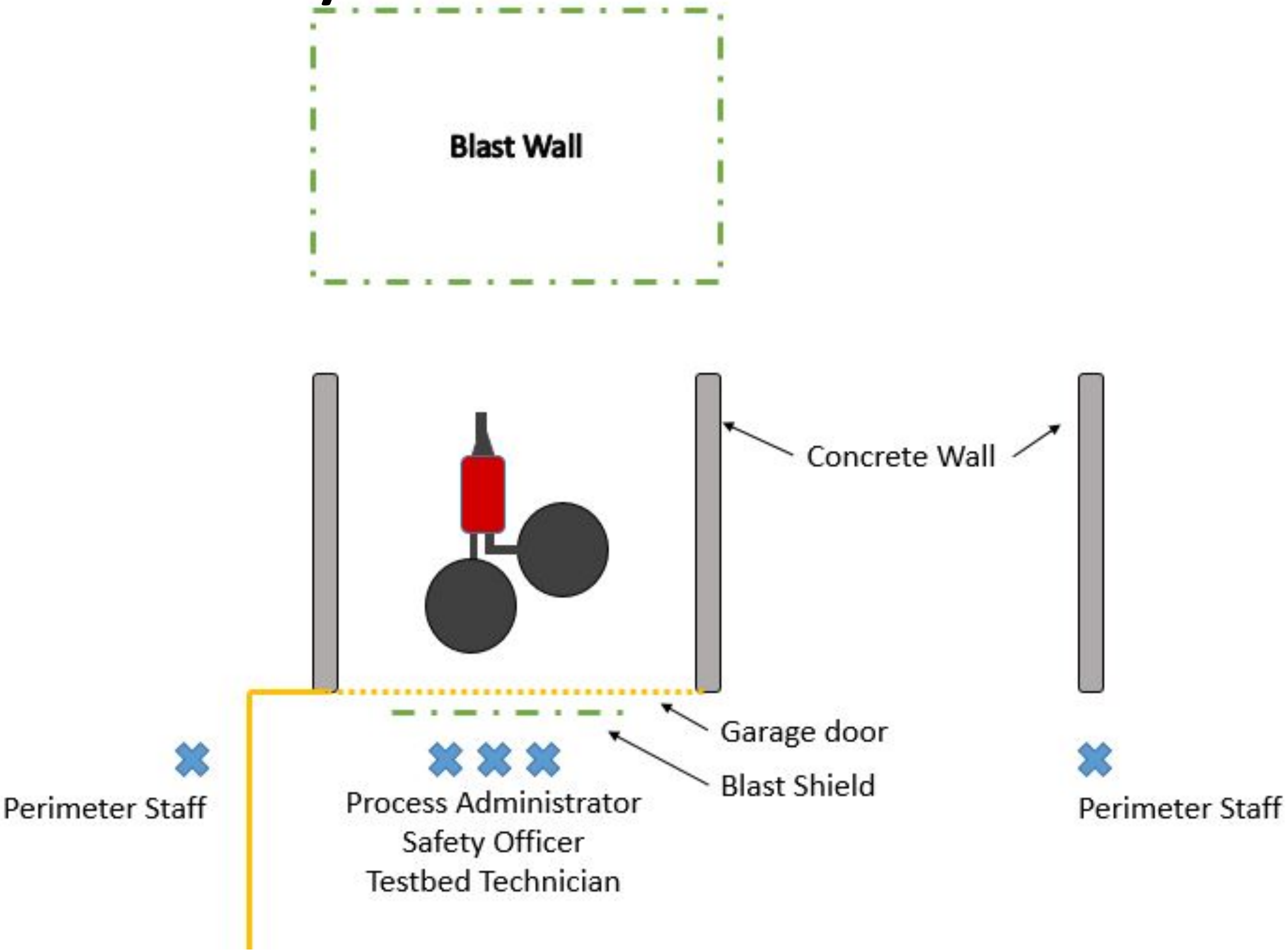
Full System Test

- **Location:** Redstone College



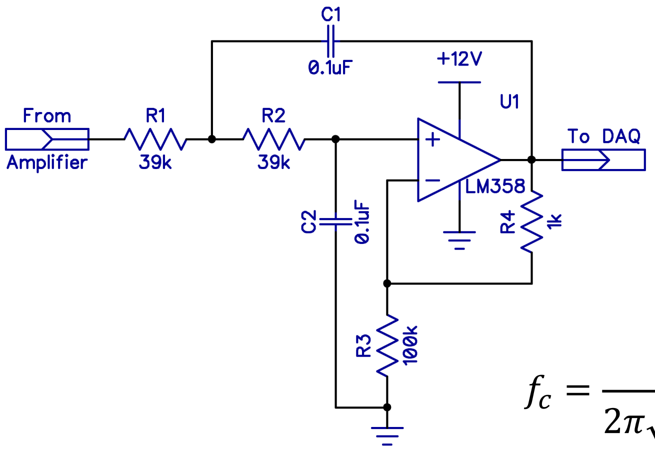
- **Date:** First week of April (after Spring break) and flexible scheduling for the weeks after

Full System Test Schematic



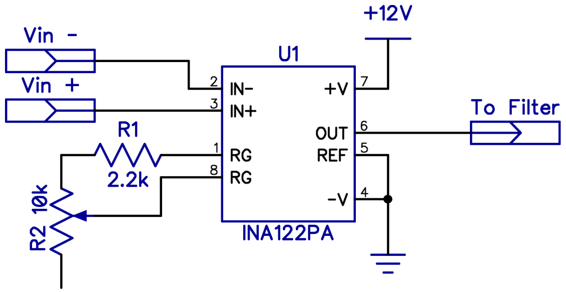
Electronics Testing

- **Purpose:** Increase DAQ Resolution by amplification and filtering
- **Verification and Validation:**
  - INA122 instrument amplifier
  - 2nd order active low-pass filter



$$G_f = 1 + \frac{R_4}{R_3}$$

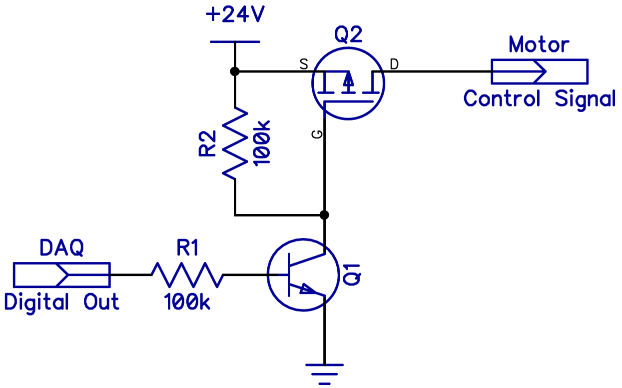
$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{2\pi R_1 C_1}$$

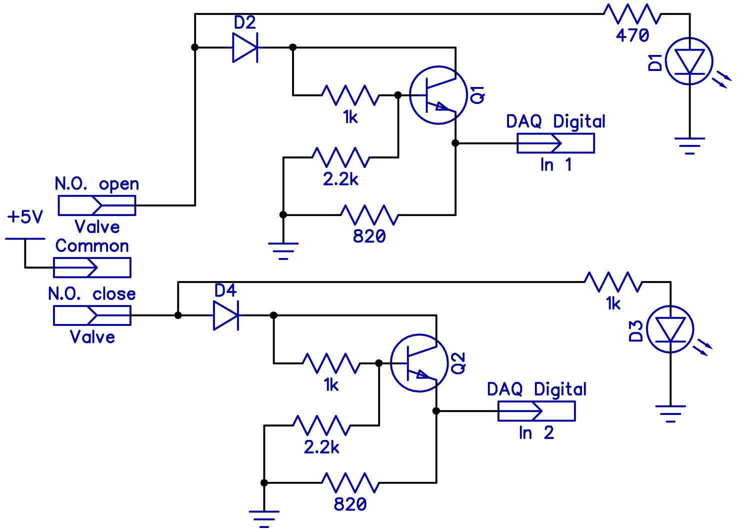


$$G_A = 5 + \frac{200000}{R_1 + R_2}$$

Electronics Testing

- **Purpose:** Control Electronic Ball Valves though NI DAQ's digital output
- **Verification and Validation:**
  - Test Ball valves circuit to determine operating time, and MOSFET switch performance. Provide option for automatic control of test bed electronic ball valves.





Project Overview | Schedule | Testing | Budget

Electronics Testing

- **Equipment Needed:**
  - NI-USB6009
  - Assured Automation 1-1/4” SM series motorized Ball vales
  - Various Electronic components
  - Custom Printed PCBs
  - 4-channel power supply
- **Risk Reduction:** Reduces sensor error caused by outside noises, allows for electronic ball valves to be remote controlled
- **Results Expected:** Better results from pressure transducers, automatic control of ball valves with control feedback

Electronics Testing Requirements Addressed

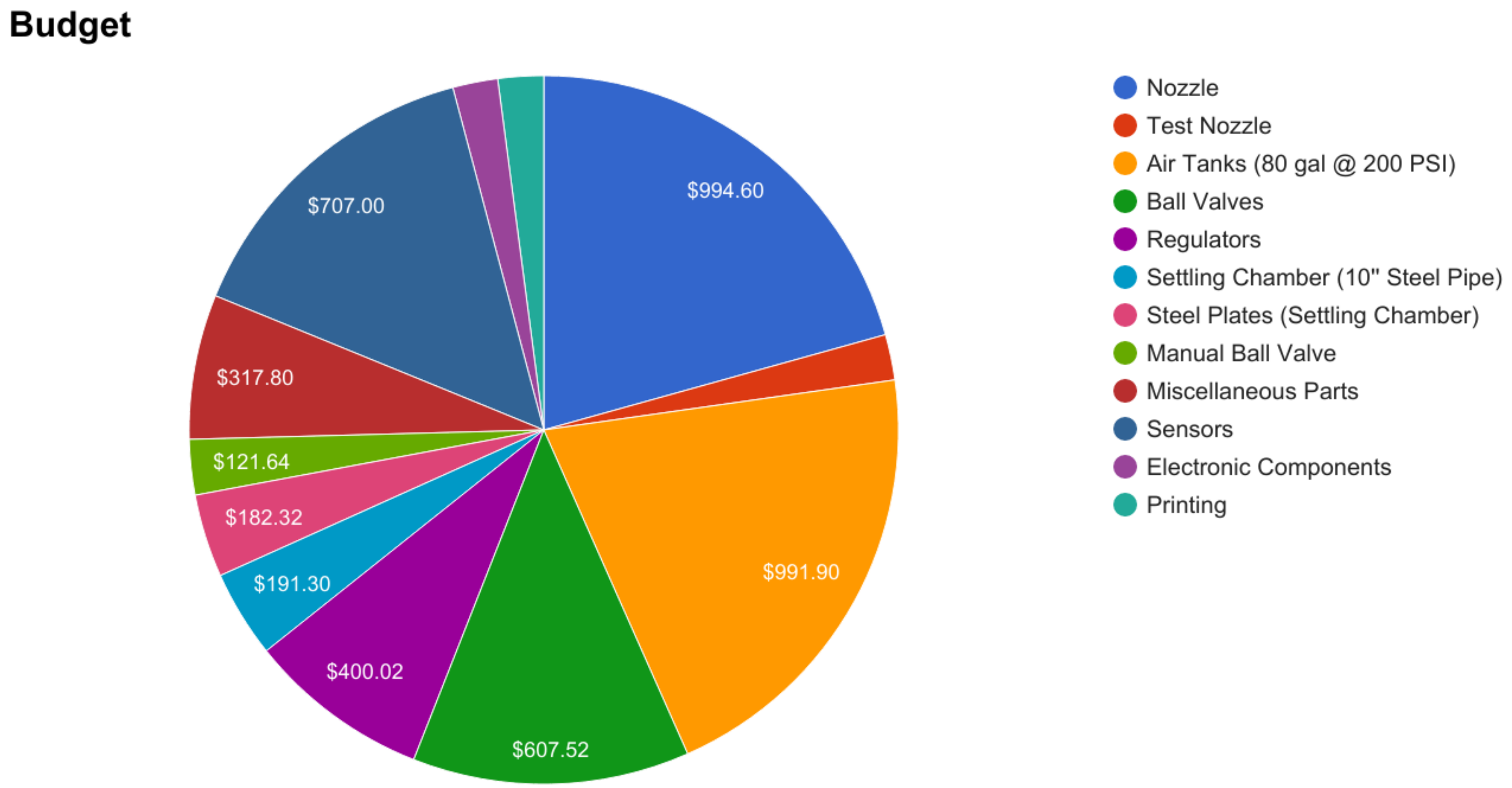
FR 1	The Nozzle shall accelerate the flow from subsonic to supersonic conditions.
DR 1.1	The flow through the nozzle shall be choked such that the nozzle exit flow Mach is greater than 1.

FR 5	The Nozzle's performance shall be validated/verified through the use of a cold-flow test bed.
DR 5.1	The test bed shall provide the same pressure and mass flow rate as the engine exit within 5% adjusted for temperature

Project Budget

Current Finances

- Margin: $187.10
- Applied for additional funding from EEF

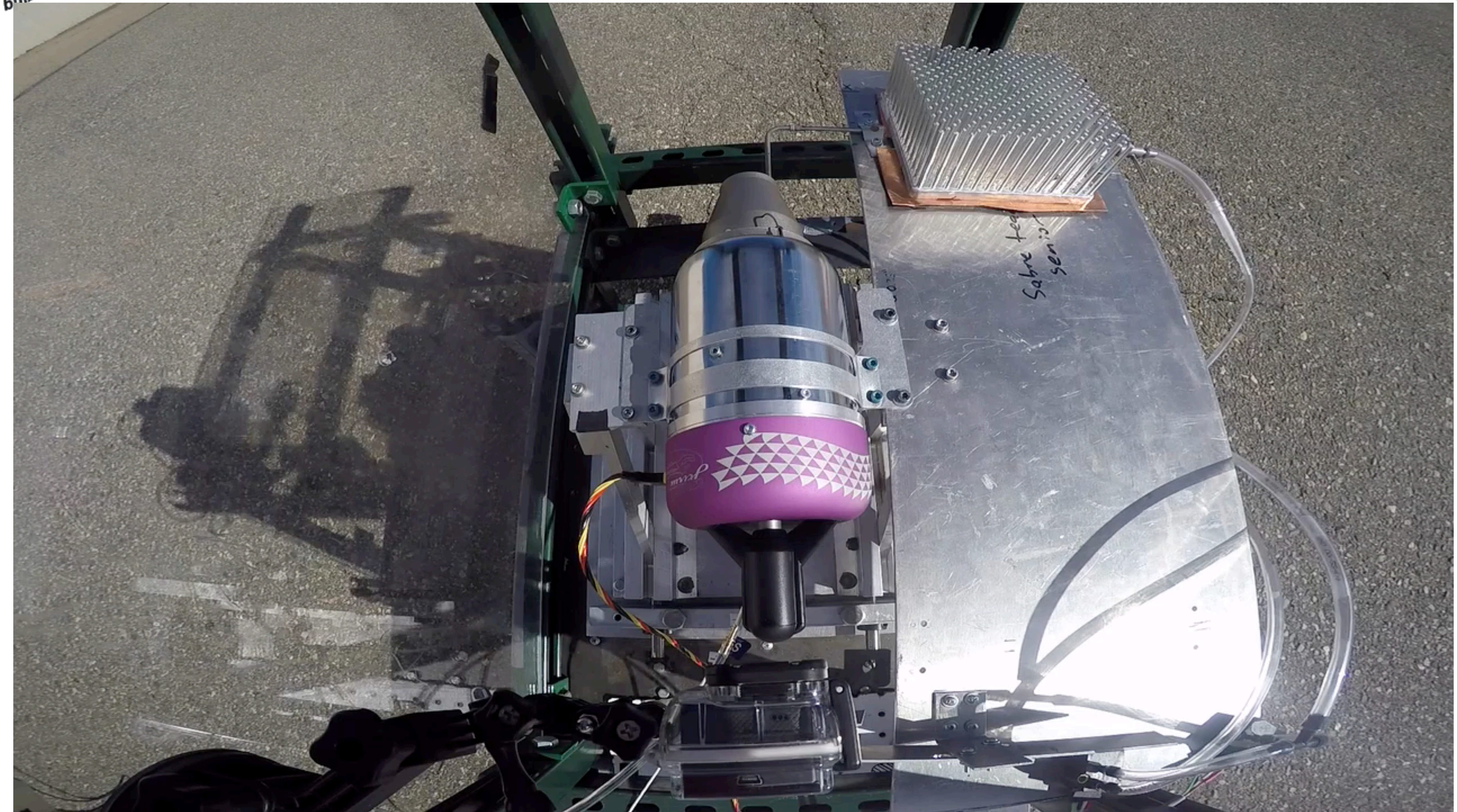


Procurement Status

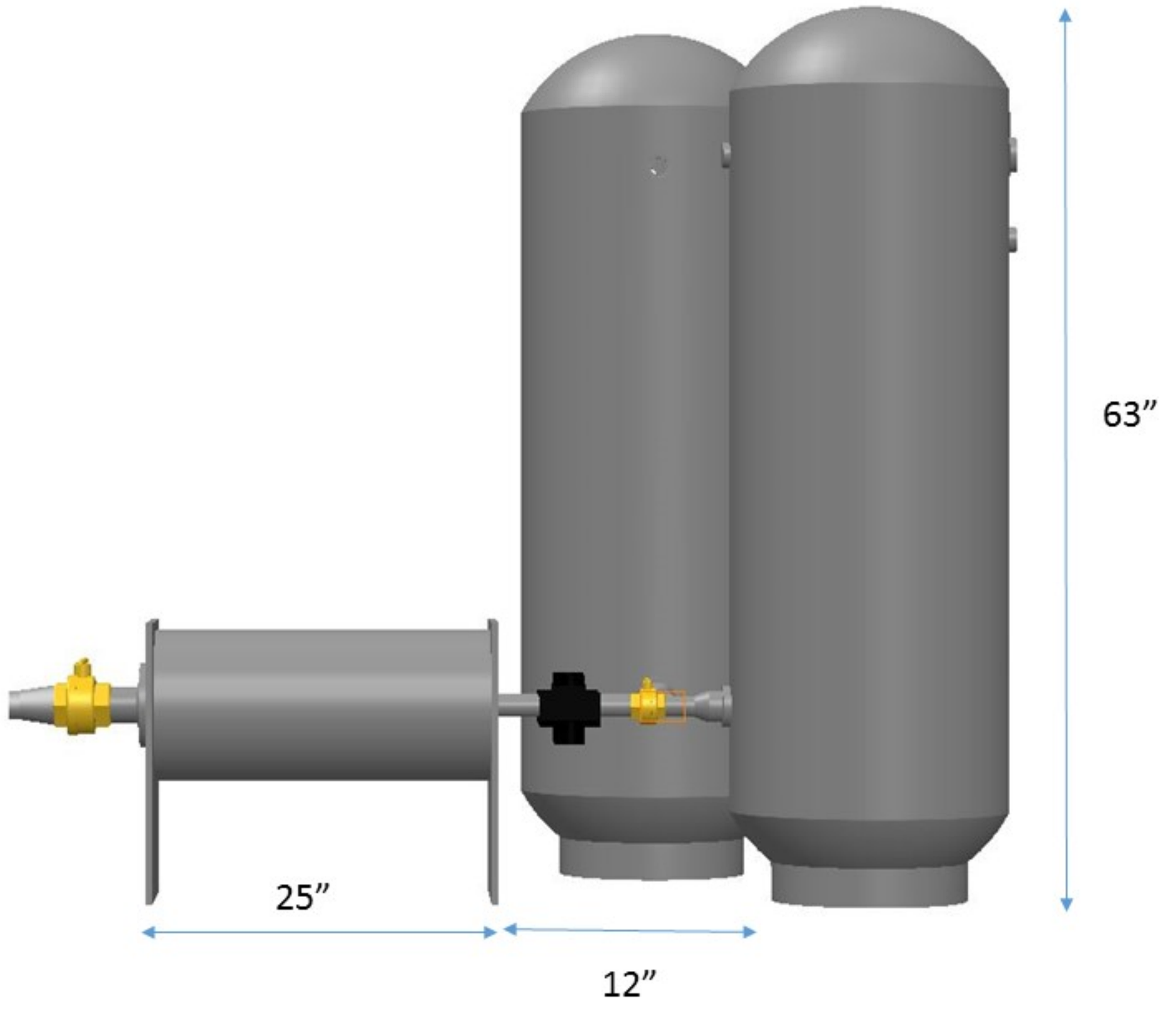
Nozzles		
	Delivered	Nozzle
	Delivered	Test Nozzle
Test Bed		
	Delivered	Air Tanks (80 gal @ 200 PSI)
	Delivered	Ball Valves
	Delivered	Regulators
	Delivered	Settling Chamber (10" Steel Pipe)
	Delivered	Steel Plates (Settling Chamber)
	Delivered	Manual Ball Valve
	Delivered	Miscellaneous Parts
	Delivered	Sensor (PX309)
	Delivered	Sensor (PX409)
	Ordered	Electronic Components

Appendix

Modified Engine Test



Test Bed Dimensions



Hydrostatic Testing

- Pressurize vessel to FOS test pressure with incompressible liquid
- Investigate pressure drop and leaks
- Investigate any permanent deformations
- Benefit of non-explosive rupture
- NWIS Hydrostatic Burst November 21, 2014

Safety: Energy and Blast

- Energy Stored in Settling Chamber: 79501 J = 0.01374 Lbs. TNT

$$W = p_o v_o \left(ln \frac{p_o}{p_a} - 1\right) + p_a v_o$$

- FEMA: Unit IV Explosive Charges
  - Shatters windows: 160 ft.
  - Eardrum rupture: 30 ft.
  - 1% fatality point: 10 ft.
- "Blast Overpressure and Survivability Calculations for Various Sized of Explosive Charges"
  - Threshold lung damage facing blast: 9 ft.
  - Threshold lung damage facing sideways to blast: 6 ft.

Safety: Shrapnel

- Maximum Speed of Smallest Object: 1628 m/s = 3642 mph

$$E_{kinetic} = \frac{1}{2}mv^2$$

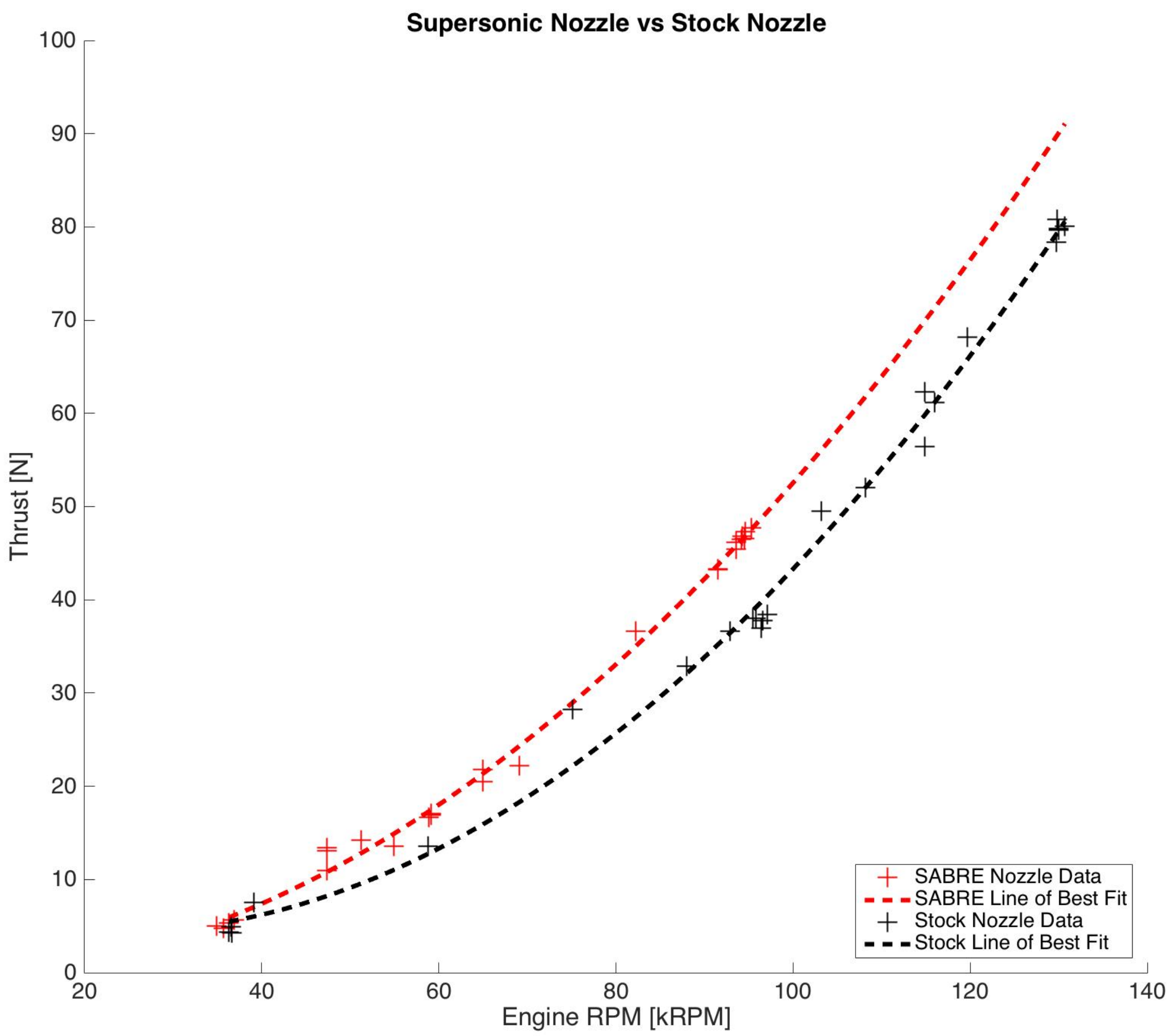
- Terminal Velocity: 29.86 m/s = 66.79 mph

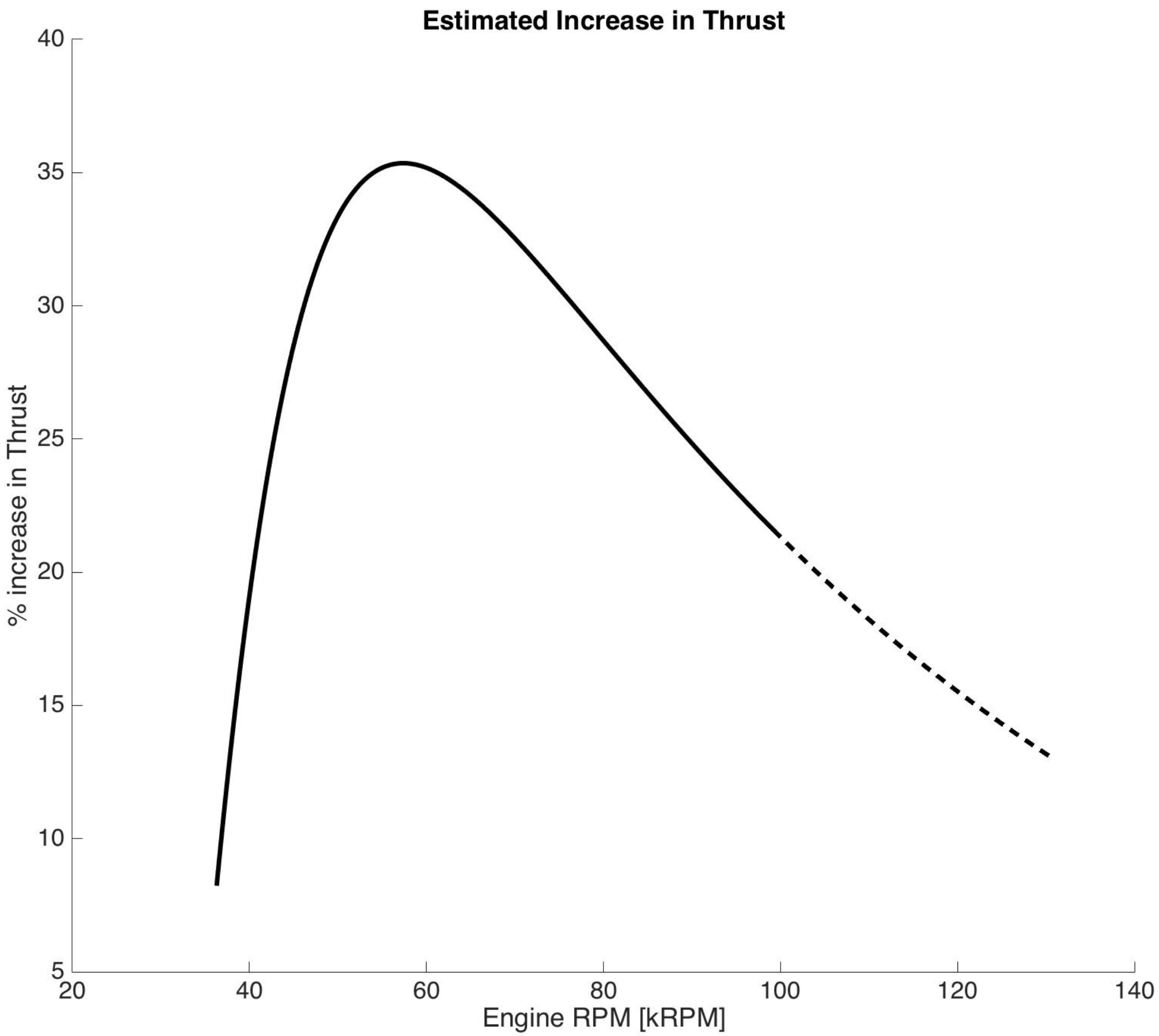
$$v_t = \sqrt{\frac{2mg}{\rho A c_d}}$$

- Maximum Horizontal Distance of Travel: 3683 m = 2.289 mi

$$x_{max} = \frac{v_o v_t cos(\theta)}{g}$$

Supersonic Nozzle Performance

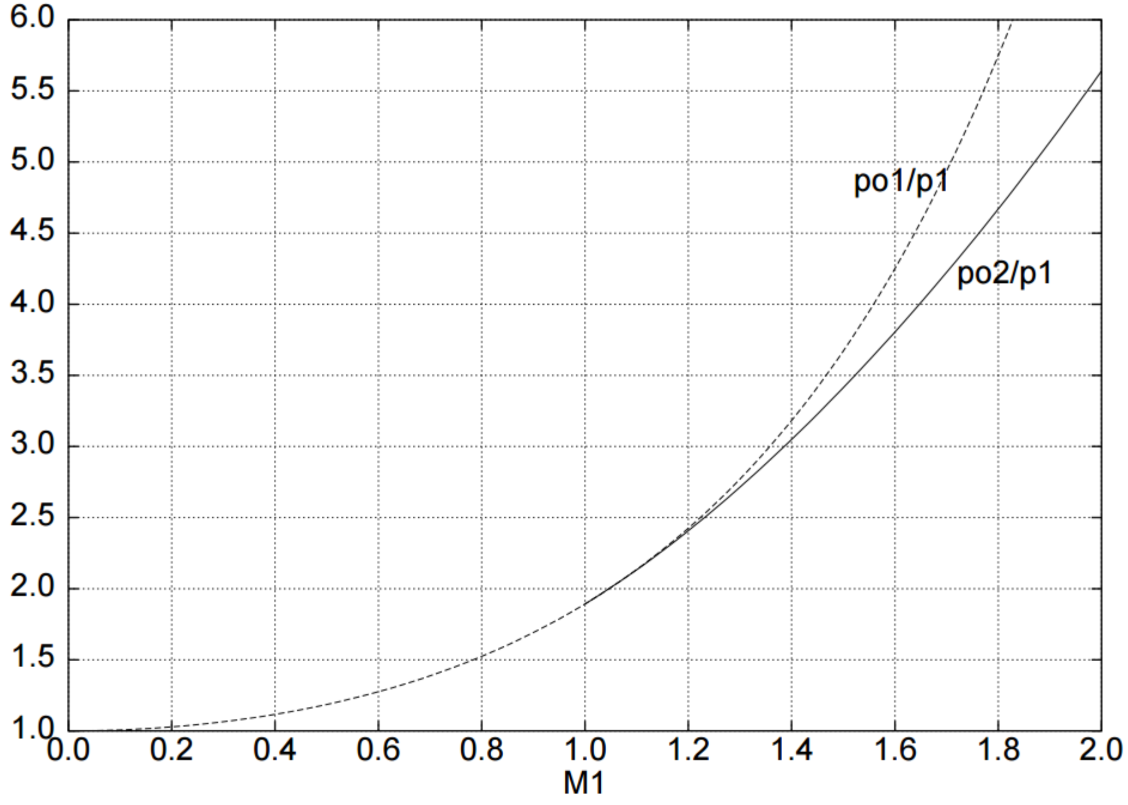




Error Propagation Analysis

$$\delta P0_2 = P1 * \sqrt{(\frac{\partial P0_2}{\partial M}\frac{\partial M}{\partial A/A}\delta A/A)^2 + (\frac{\partial P0_2}{\partial M}\frac{\partial M}{\partial A/A}\frac{\partial A/A}{\partial \dot{m}}\delta \dot{m})^2 + (\frac{\partial P0_2}{\partial M}\frac{\partial M}{\partial A/A}\frac{\partial A/A}{\partial P0}\delta P0)^2}$$

- 0.075 psi of Error with 0.5% Mathematical Error
- Required 0.12 psi of Resolution to Capture 0.004 +/- Mach
- Ideal 0.04 psi of Resolution to Capture 0.0013 +/- Mach



Testing Roles- Test Bed

Role	Team Member	Description
Process Administrator	1.	- Walks team through each step of the process - Delegates commands to the test bed operator during engine operation.
Safety Officer	2.	- Ensures the proper safety operation is carried out. - Hands out earplugs and safety glasses.
RC Operator	3.	- Operates the LabView program
Testing Tech(s)	4. 5.	- Ensure proper set-up of the test bed - Pressurized test bed
Data Engineer	6.	- Records video and data from test. - Walkie Talkie communicator
Perimeter Staff	7. 8. 9.	- Alert people of test bed testing - Establish and enforce secure perimeter

Test Bed Safety Checklist

3.3: Checks Before Test

Action	Check
Preliminary Checks	
Ensure that a proper perimeter has been established, marked, and manned	
Determine if weather allows testing	
Clear testing area of debris	
Air Checks	
Make sure that proper eye protection is being used	
Check all piping and make sure it is clear and unrestricted, check for leaks	
Test ball valve actuation before test bed is pressurized	
Fill reservoir tanks and make sure they are pressurized to correct value (pressure gage)	
Determine that pressure regulators are set to desired values	
Assembly Checks	
Place test bed in-line of wind	
Clear rear of test bed of obstructions	
Post-Assembly Checks	
Repair leaks/ensure there are no leaks	
Inspect piping and weld for signs of damage	
Ensure that no components are at risk of entering test bed during operation	
Final Checks	
Monitor sensors to ensure test bed and components are in safe operational limits	
Extra personnel are to go 50 feet away from engine or behind suitable cover	
Place ear and eye protection on	

Test Bed Operation Procedure

TEST PROCEDURE

*NOTE: If at any time during the test the test bed loses power and the settling chamber is still pressurized, the emergency cable will need to be pulled. This emergency cable is attached to a pin that will open the most downstream ball valve, and air can then empty out of the system. **If the settling chamber is pressurized, the test bed is not safe to approach!**

	Test Procedure		
1.	Determine that the perimeter is secured and that reservoirs are each pressurized to the correct value		
2.	Make sure everyone is behind cover		
3.	On LabView, open the two most upstream ball valves electronically. They do not need to be opened simultaneously.		
4.	Monitor the data from the settling chamber to determine when the correct pressurization has been reached, and that the pressure regulators have kept the settling chamber from over pressurizing		
5.	Once the data engineer determines that the settling chamber is properly pressurized, use LabView to actuate the manual ball valve that is downstream of the settling chamber		
6.	Let the test run until the settling chamber is fully depressurized		
7.	The data engineer will communicate to the test operator once the settling chamber is depressurized. At this point, the test operator will communicate that the test bed is safe to approach		
8.	At this point, initiate tear down or repeat the test from step 1 if another run is desired.		

Test Bed Tear Down Procedure

	Test Tear Down		
1.	Verify that the reservoir tanks are empty (check analog gage on tank)		
2.	Disconnect piping from reservoir tanks and settling chamber		
3.	Remove sensors, disconnect DAQ		
4.	Store all cables together, store all sensors together, store piping together		
5.	Check for debris in the testing area		
6.	Load test bed components, verify that items on the checklist are accounted for and transport back to CU		

Testing Roles: Engine Test

Role	Team Member	Description
Process Administrator	1.	- Walks team through each step of the process - Delegates commands to the RC operator during engine operation. - Main Walkie Talkie communicator.
Safety Officer	2.	- Ensures the proper safety operation is carried out. - Hands out earplugs and safety glasses.
RC Operator	3.	- Operates the RC controller for the engine
Engine Tech(s)	4. 5.	- Ensure proper set-up of the engine and electronics
Data Engineer	6.Andrew	- Records video and data from test. - Walkie Talkie communicator
Perimeter Staff	7. 8. 9.	- Watch for cars and alert civilians of engine testing. - Walkie Talkie communicator

Engine Test Safety Checklist

Action	Check
Preliminary Checks	
Ensure that a proper perimeter has been established, marked, and manned	
Determine if weather allows testing	
Clear testing area of debris	
Fuel Checks	
Make sure that proper eye protection is being used	
Check the fuel lines and filter and make sure they are clean with no restrictions	
Fill fuel tank(s) and make sure the main and hopper tanks are full	
Assembly Checks	
Place engine in-line of wind	
Clear rear of engine of obstructions	
Post-Assembly Checks	
Clean spills (as required) properly and repair leaks	
Ensure there are no fuel or propane leaks	
Inspect fuel gaskets for signs of damage	
Ensure that no components are at risk of entering the engine during operation	
Final Checks	
Monitor sensors to ensure engine and components are in safe operational limits	
Extra personal are to go 50 feet away from engine or behind suitable cover	
Place ear and eye protection on	

Engine Operation Procedure

*NOTE: If at any time during the test the engine needs to be immediately shut down, the emergency shut down switch is the down position of the "flap mix" switch located right above the throttle. **If there is a problem or when in doubt turn the engine off!**

	Test Procedure		
1.	To start turbine move throttle knob and throttle trim to their minimum positions		
2.	Move Throttle Trim to max position until remote controller display shows trim value at max.		
3.	Move Throttle knob to max position. The engine is now starting		
4.	Verify that I/O board LEDs are flashing in a green → red → yellow repetitive pattern. This indicates the engine has started its automated start sequence. *NOTE: if LEDs are flashing in a yellow →red → green pattern this indicates an error. Move the trim to max and the throttle back to minimum position to correct.*		
5.	Move throttle down to minimum (idle) position		
6.	When green OK LED on the GSU illuminates, engine is ready for throttle commanding *If green light doesn't illuminate, shut engine off by flipping the flap mix switch to its down position and start the start-up sequence over*		
7.	Run engine test with supersonic designed nozzle. Slowly increase throttle to half. Wait 1 minute. Slowly increase throttle to full. Wait 1 minute. Slowly ramp down to idle. Slowly ramp up to full throttle. Slowly ramp down to idle. Record data given automatically by GSU.		
8.	To Turn Off Engine: Set the flap mix switch to the up position (auto-OFF) to begin the automatic shut down and cool off process; should hear engine power down.		
9.	Wait for engine to complete its cool down sequence! ECU should automatically turn off after cool down sequence is finished. Temperature of engine can also be tracked using the GSU.		
10.	Initiate tear down sequence.		

Engine Tear Down Procedure

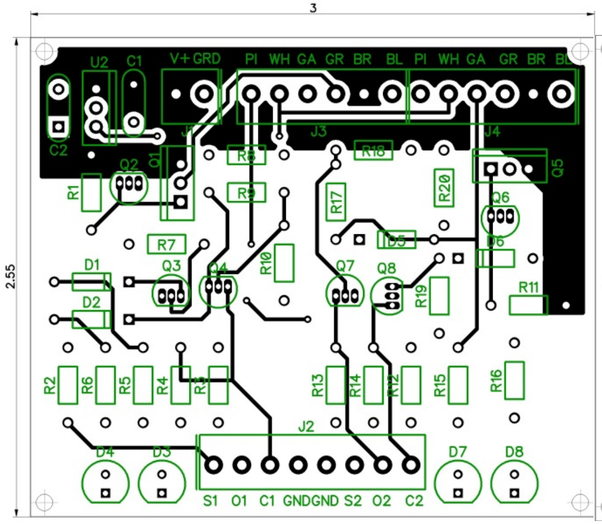
	Test Tear Down		
1.	Turn off the remote control		
2.	Turn the receiver switch off and unplug receiver battery		
3.	Unplug ECU battery from ECU		
4.	Disconnect ECU Data cable from engine		
5.	Check for residual fuel in the fuel lines before disconnecting. Disconnect fuel line from engine, hold up to allow fuel to flow back into fuel tank.		
6.	Remove fuel line from fuel tank and store in fuel line container		
7.	Unplug ECU Data cable from ECU and store		
8.	Unplug GSU from mini I/O board and store		
9.	Unplug mini I/O board from ECU and store		
10.	Unplug and store any remaining cables		
11.	Leave engine on test stand for transport from test site to CU		
12.	Once at CU, remove top engine clamp and remove and store engine		
13.	Remove test clamps and store with engine		
14.	Place fuel tank back under fume hood		

Levels of Success

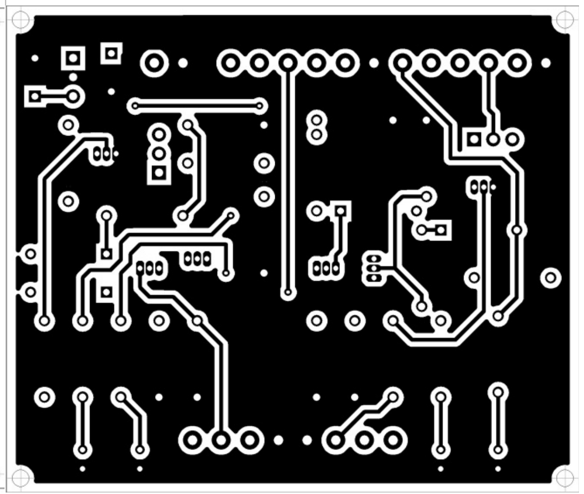
	Model/Simulation	Design/Manufacturing	Testing
Level 1	• Model stock engine exhaust with given parameters (T, P, V, $\dot{m}$) • Model air in nozzles (SABRE and plastic) changing from subsonic flow to supersonic flow • No decrease of T/W (SABRE nozzle)	• Manufacture convergent-divergent nozzle that fits and can attach 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 in thrust of 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 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 a M=1.06 and M=1.3 tests

Printed Circuit Boards

Motor Control Board



Top



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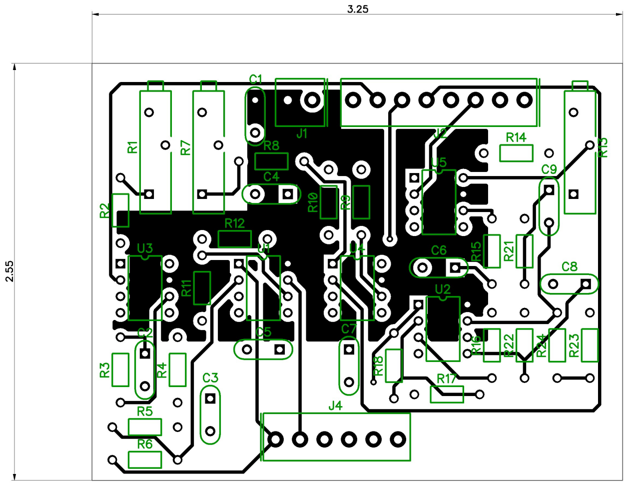
Instrument Amplifier Board



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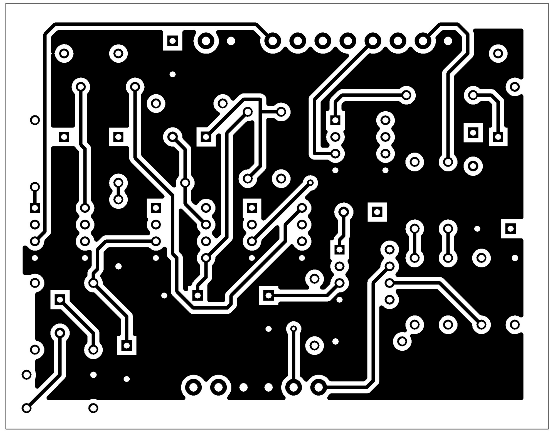

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