Preliminary Design Review

Supersonic Air-Breathing Redesigned Engine Nozzle

Customer: Air Force Research Lab
Advisor: Brian Argrow
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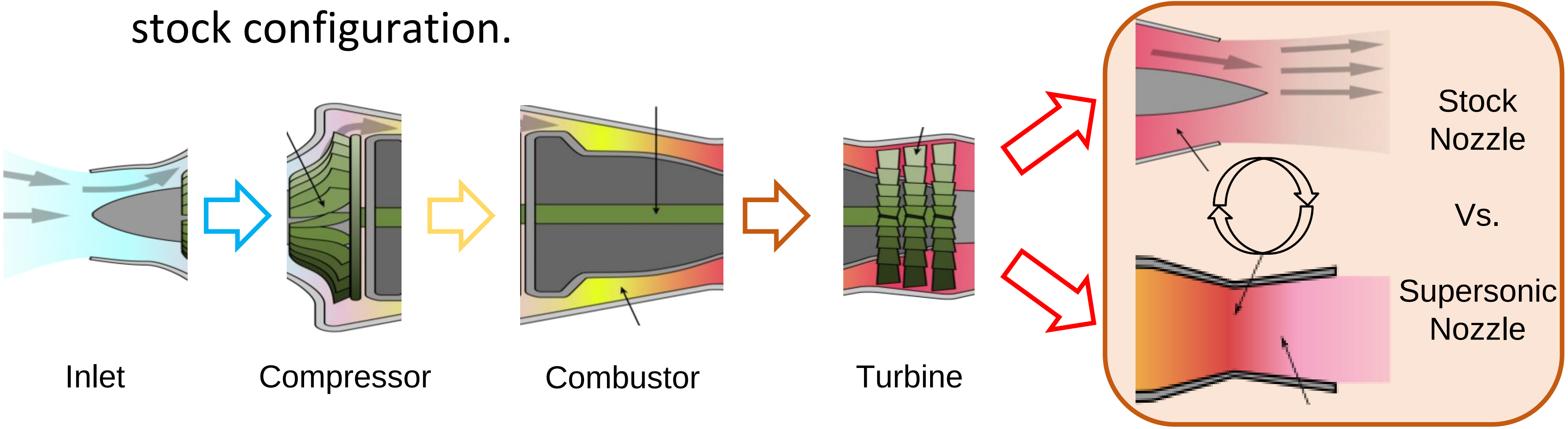
Jack Oblack, Andrew Quinn, Andrew Sanchez, Grant Vincent, Nathaniel Voth

Project Description

Model, manufacture, and **verify** an **integrated nozzle** capable of accelerating subsonic exhaust to **supersonic exhaust** produced from a **P90-RXi JetCat** engine for **increased thrust and efficiency** from its stock configuration.



Inlet

Compressor

Combustor

Turbine

Stock Nozzle

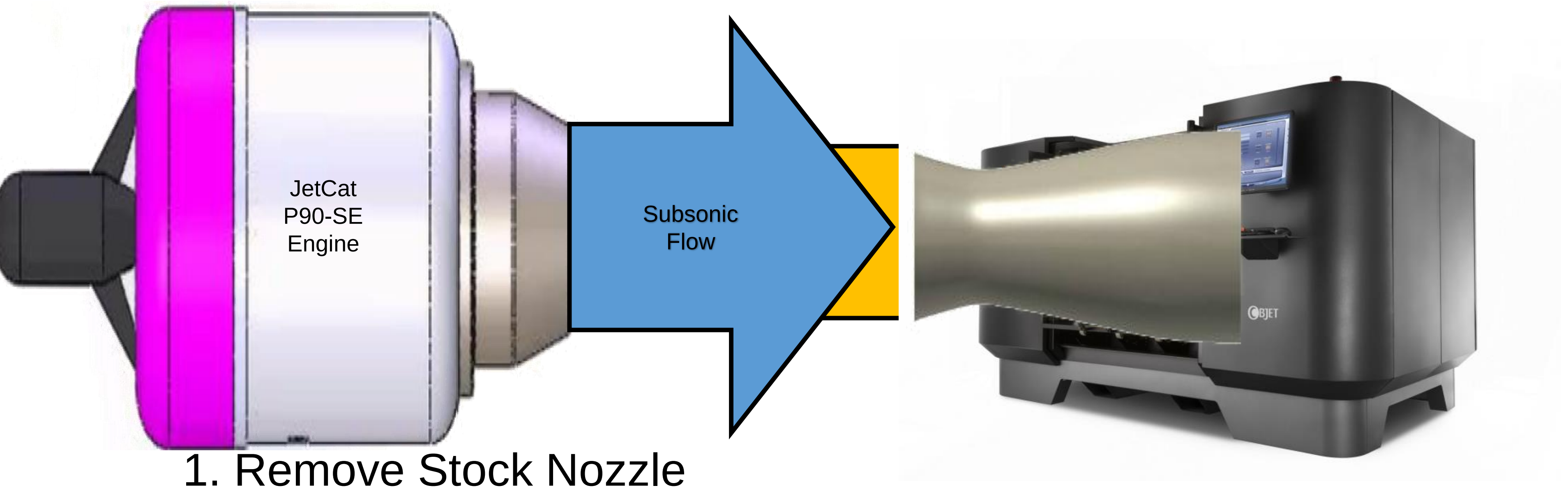
Vs.

Supersonic Nozzle

Objectives/Requirements

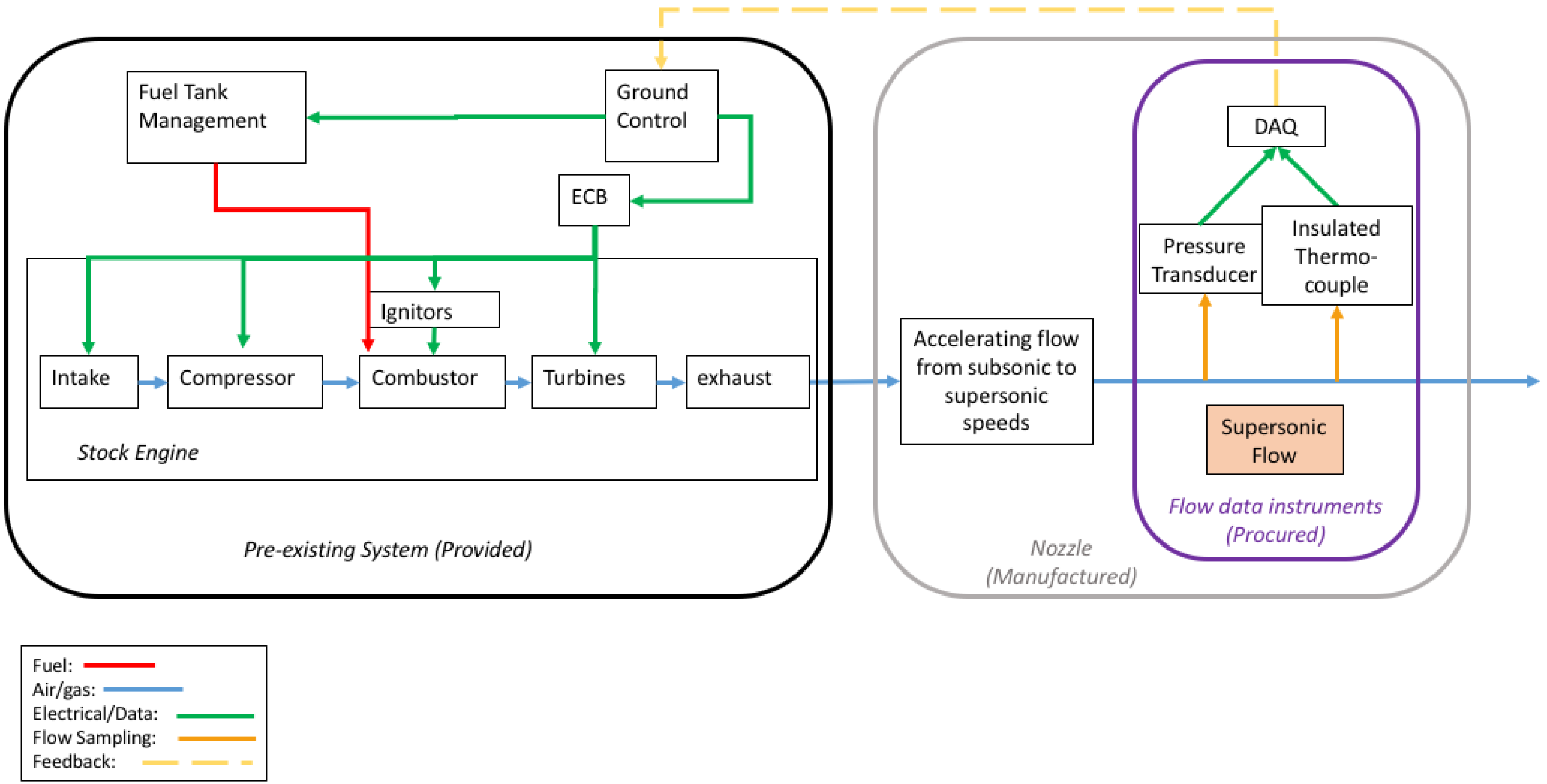
- **FR 1:** The Nozzle Shall accelerate the flow from subsonic to supersonic conditions.
- **FR 2:** The Nozzle shall not decrease the Thrust-to-Weight Ratio.
- **FR 3:** The Nozzle shall be designed and manufactured such that it will integrate with the JetCat Engine.
  - **DR 3.1:** The Nozzle shall be manufactured using additive manufacturing.
  - **DR 3.4:** Successful integration of the nozzle shall be reversible such that the engine is operable in its stock configuration after the new nozzle has been attached, tested, and detached.
- **FR4:** The Nozzle shall be able to withstand engine operation for at least 30 seconds.

Concept of Operations



1. Remove Stock Nozzle
2. Additive Manufactured 3-D Nozzle
3. Integrate Nozzle to JetCat 4. Operate Supersonic Engine

Engine FBD



Fuel Tank Management

Ground Control

ECB

Ignitors

Intake

Compressor

Combustor

Turbines

exhaust

Stock Engine

Pre-existing System (Provided)

Accelerating flow from subsonic to supersonic speeds

DAQ

Pressure Transducer

Insulated Thermo-couple

Supersonic Flow

Flow data instruments (Procured)

Nozzle (Manufactured)

Fuel:

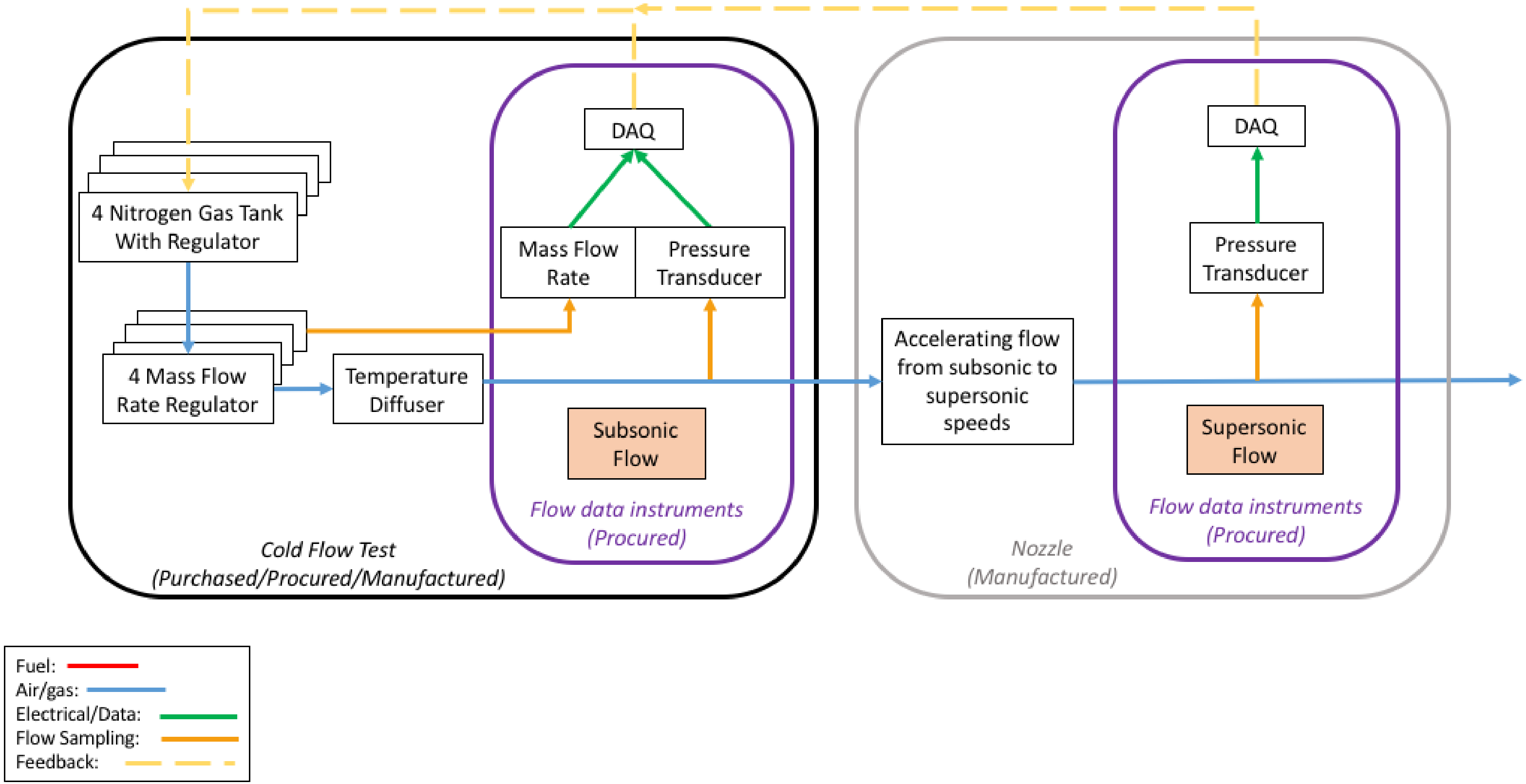
Air/gas:

Electrical/Data:

Flow Sampling:

Feedback:

Cold Flow Analog FBD



4 Nitrogen Gas Tank With Regulator

4 Mass Flow Rate Regulator

Temperature Diffuser

DAQ

Mass Flow Rate

Pressure Transducer

Subsonic Flow

Flow data instruments (Procured)

Cold Flow Test (Purchased/Procured/Manufactured)

Accelerating flow from subsonic to supersonic speeds

DAQ

Pressure Transducer

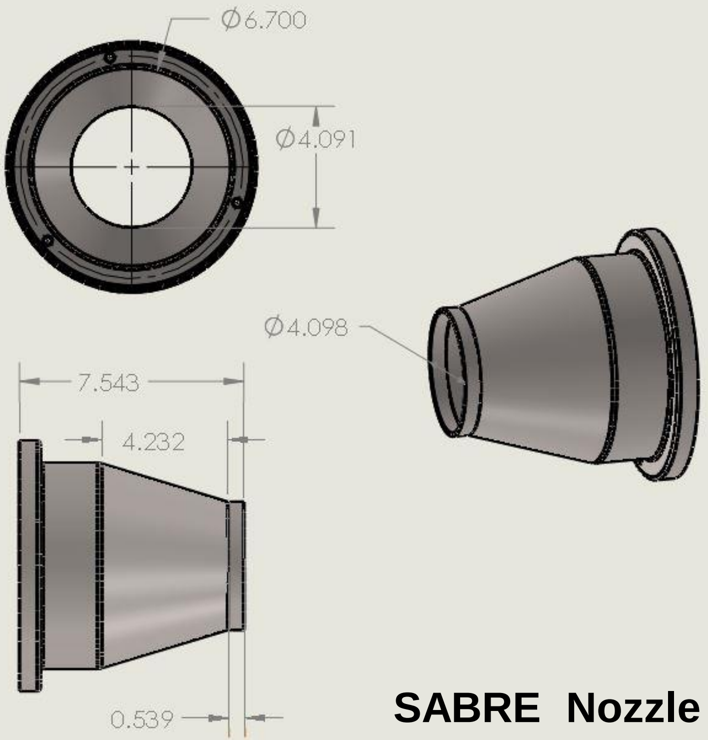
Supersonic Flow

Flow data instruments (Procured)

Nozzle (Manufactured)

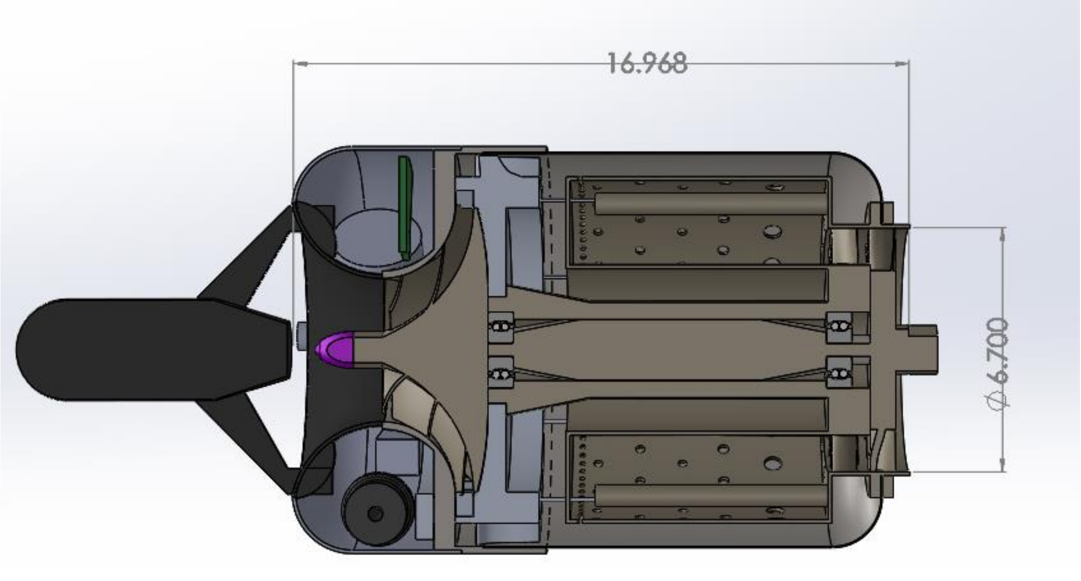
Fuel:
Air/gas:
Electrical/Data:
Flow Sampling:
Feedback:

Nozzle Aerodynamics Baseline Design



SABRE Nozzle

JetCat P90-RXi



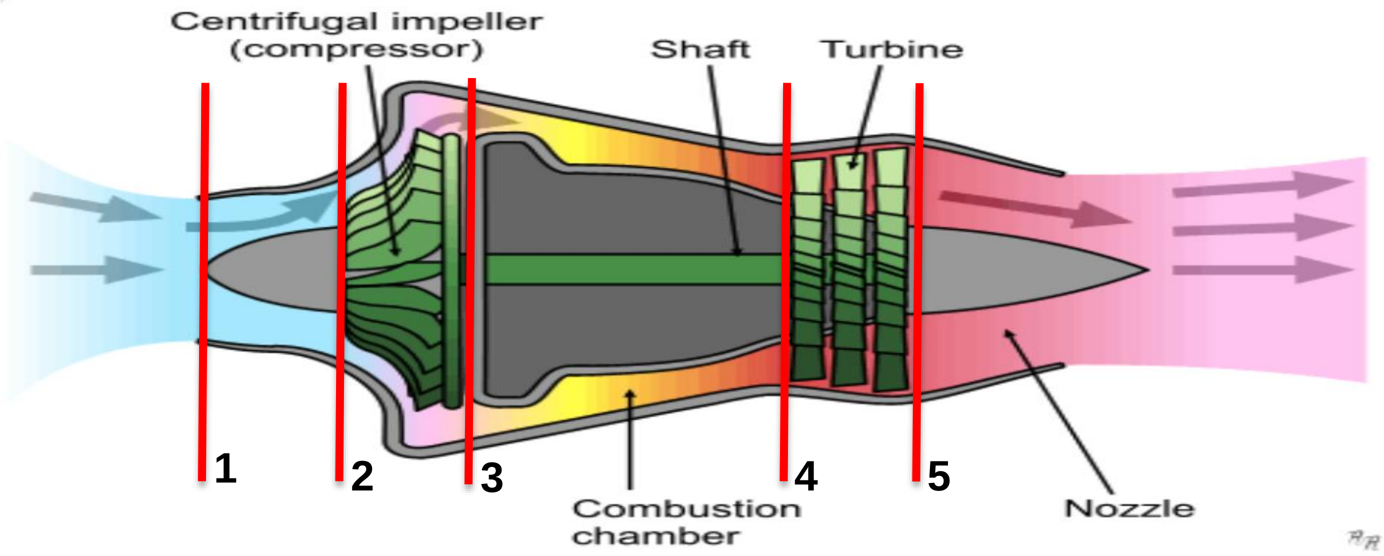
All units in cm

Nozzle Aerodynamics Feasibility

- Nozzle design concept trade study:
  - Most Critical Considerations:
    1. Weight
    2. Cost
    3. Complexity
  - Highest scoring designs:
    1. Minimum Length Nozzle(MLN)
    2. De Laval

	Weighting	**Minimum Length**	**de Laval**
Weight	0.4	5	4
Cost	0.3	5	4
Complexity	0.25	4	5
Altitude Envelope	0.05	1	1
Total	**5**	**4.55**	**4.1**

Nozzle Aerodynamics Feasibility

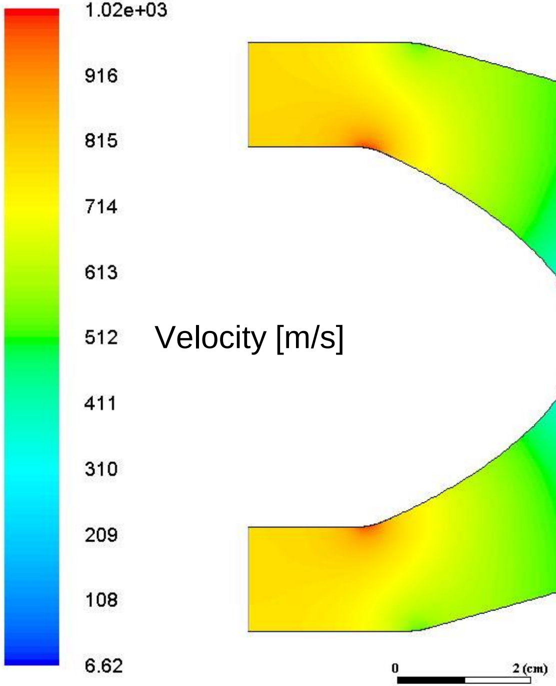


T_{T1} = 291 K	**T_{T2} = 291 K**	**T_{T3} = 382.3 K**	**T_{T4} = 1214.8 K**	**T_{T5} = 1125.2 K**
P_{T1} = 84 kPa	P_{T2} = 84 kPa	P_{T3} = 218.4 kPa	P_{T4} = 218.4 kPa	**P_{T5} = 167 kPa**

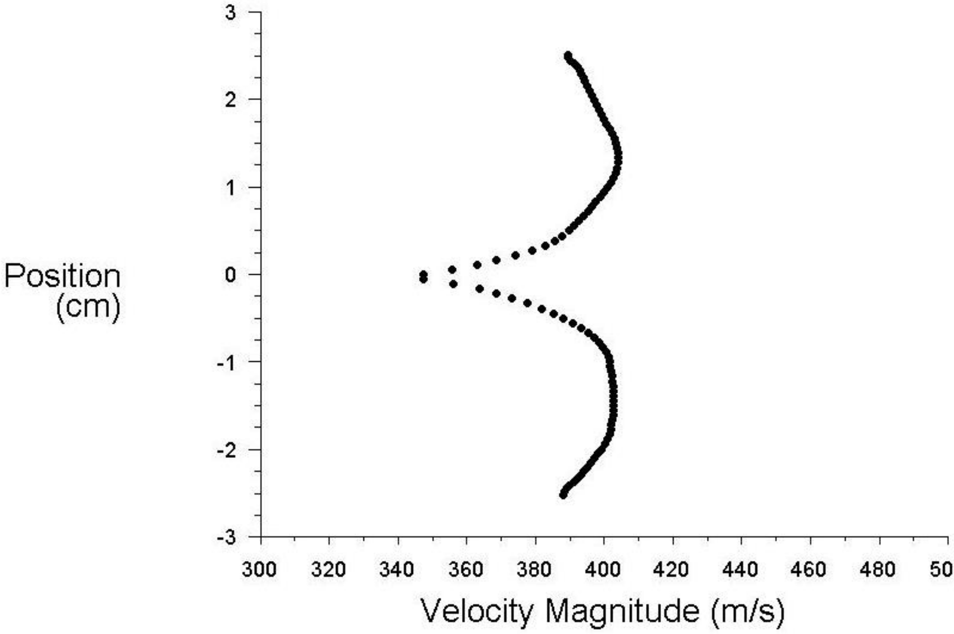
Nozzle Aerodynamics Feasibility

Stock Nozzle with Plug

Velocity Contour



Velocity Profile at Exit



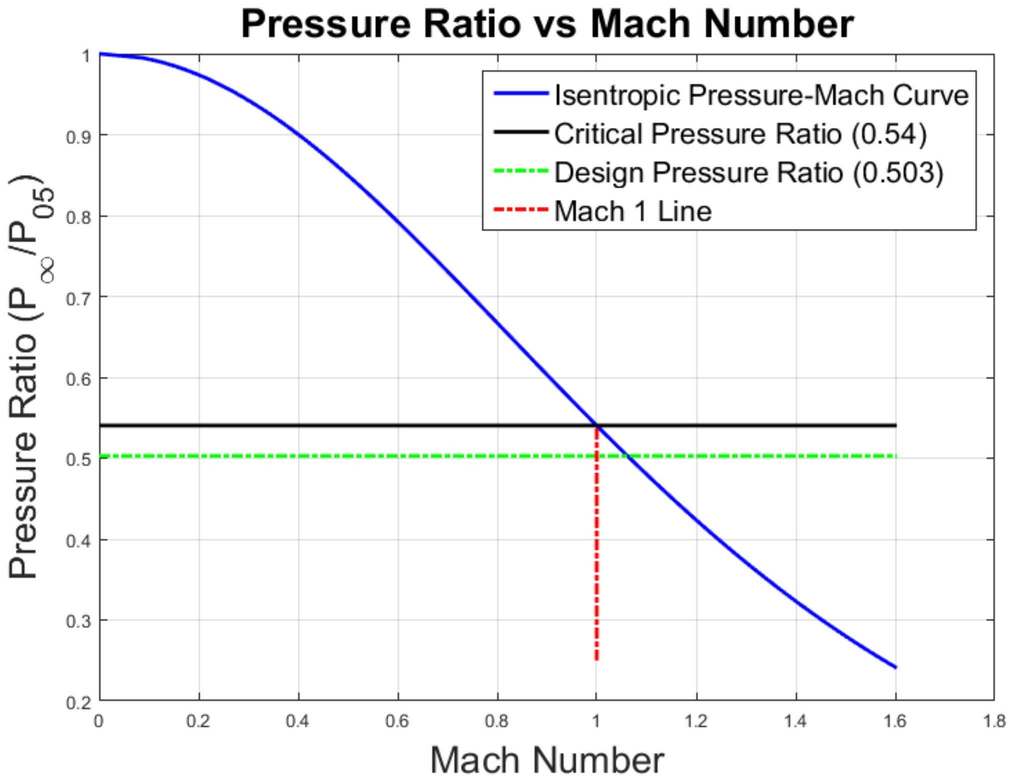
Nozzle Aerodynamics Feasibility

- Quasi 1-D Analysis shows tolerances are very small

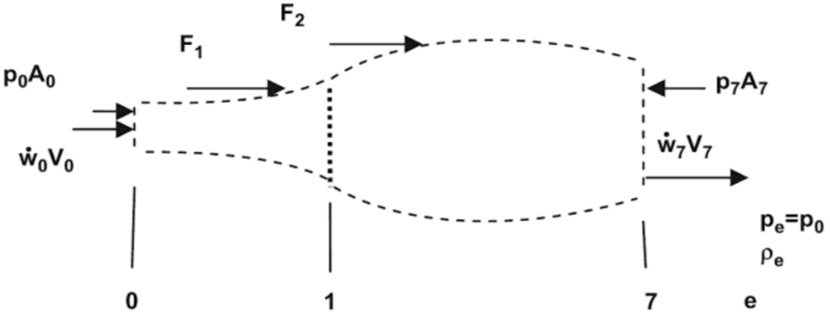
- Critical Pressure Ratio for Sonic Flow: **0.540**

- Ambient Pressure to Turbine Exit Pressure Ratio: **0.503**

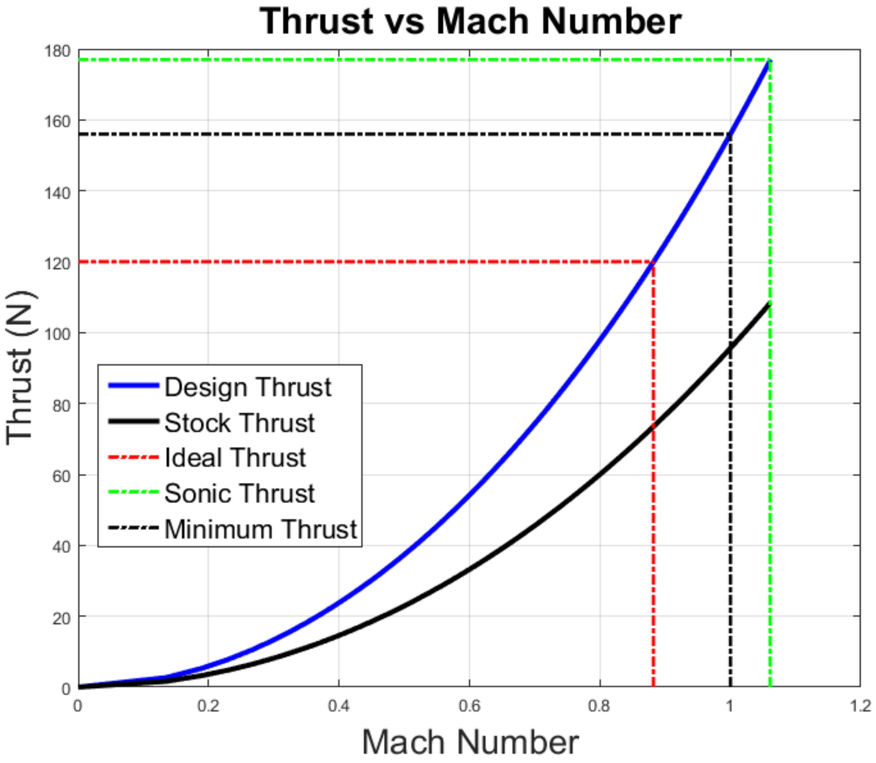
- Maximum Mach: **1.06**



Nozzle Aerodynamics Feasibility

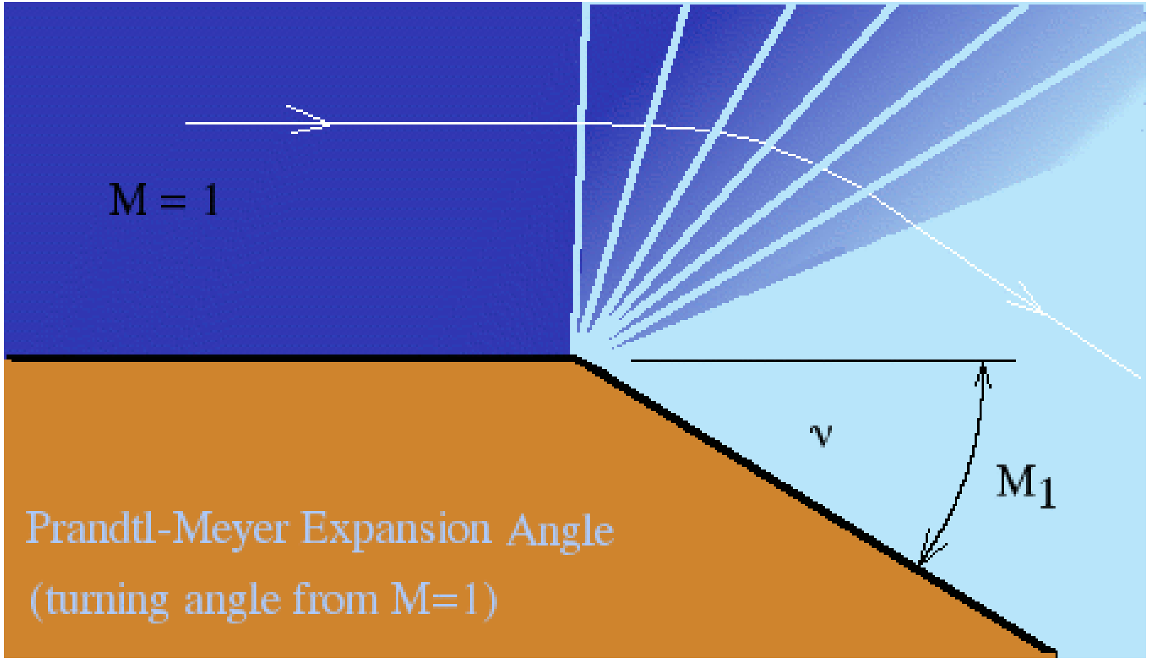


$$F = \left[\frac{\dot{w}_0 + \dot{w}_f}{g}V_7 - \frac{\dot{w}_0}{g}V_0 + A_7(p_7 - p_0)\right] - [p_0(A_0 - A_7) + F_1 + F_4]$$



Nozzle Aerodynamics Feasibility

- Prandtl-Meyer Expansion Fan Angle (v) = **0.65 deg**.
- Entrance Mach (M) = 1
- Exit Mach (M1) = **1.06**



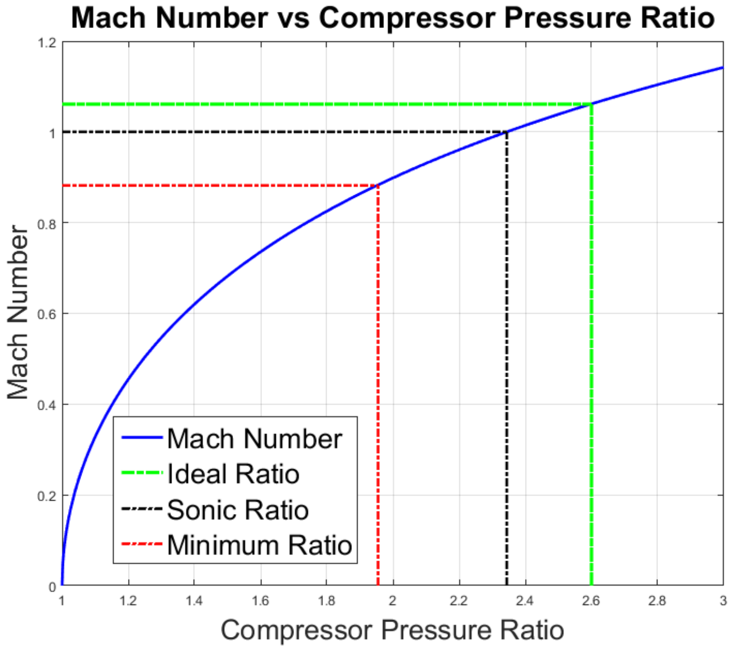
Nozzle Aerodynamics Feasibility

- Ideal Compressor Ratio = **2.6**
Total pressure at compressor exit = **218.40** kPa

- Critical (sonic) Compressor Ratio = **2.34**
Total pressure at compressor exit = **196.56** kPa

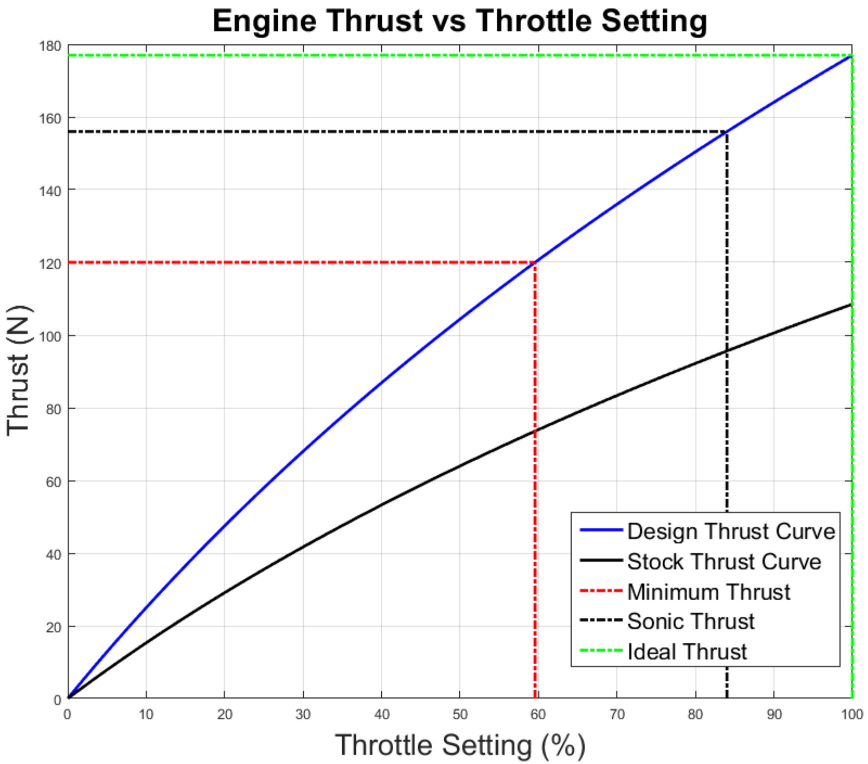
- Small Margin: A drop in total pressure greater than **21.84** kPa causes for the flow to never reach sonic or supersonic speeds

- **Minimum for Thrust Requirement = 1.95**



Nozzle Aerodynamics Feasibility

- Old Max Thrust: **105 N**
- New Max Thrust: **177 N**
- Design Point: **120 N** (FR2)



Test Bed CPE's

Simulate flow conditions from engine at the turbine exit

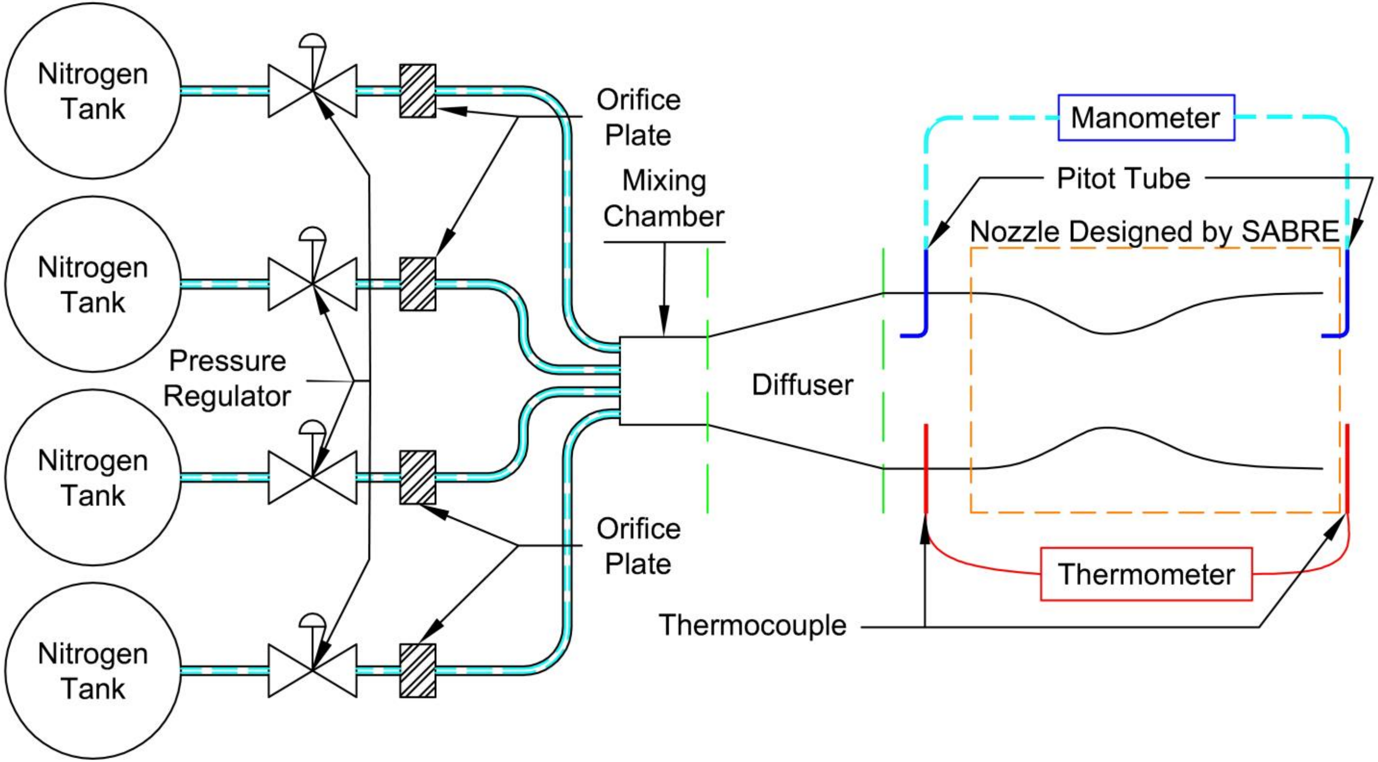
Conditions to model:

- Mass flow rate (0.26 kg/s from engine data sheet)
- Exit pressure of the turbine (167 kPa based off of Brayton cycle analysis)
- Mach number, which determines velocity
- Area is constrained by the above conditions $\dot{m} = \rho A V$

Assumptions

- Flow is laminar through the pipe
- No acceleration of fluid in hoses
- Steady flow

Test Bed Design



Test Bed Feasibility

Necessity:

$\dot{m}$ = 0.26 kg/s and $D_{orifice}$ < 1.905 cm (¾ in.) → High p_1 → Temp through hose too extreme (> 500 K)

$$\dot{m} = CAp_1\sqrt{\frac{\gamma}{RT_1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

$$\frac{0.528p_1}{\rho R}$$

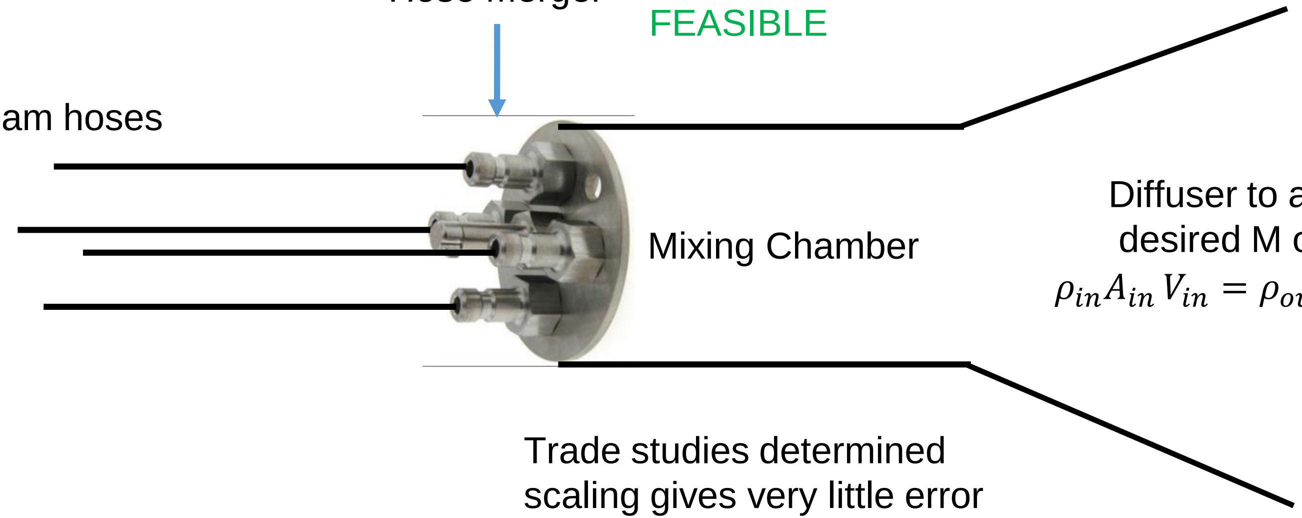
When $\dot{m}$ = 0.065 and $D_{orifice}$ < 1.905 cm (¾ in.) → p_1 = 46 psi → Highest temp through hose < 500 K

- If area is multiplied by X, mass flow rate is multiplied by X
- Multiple hoses coming together would sum mass flow rates to get total mass flow rate

$$\dot{m} = \rho AV$$

FEASIBLE

Test Bed Feasibility



Hose Merger can be manufactured and assembled
FEASIBLE

Diffuser to achieve desired M of 0.65

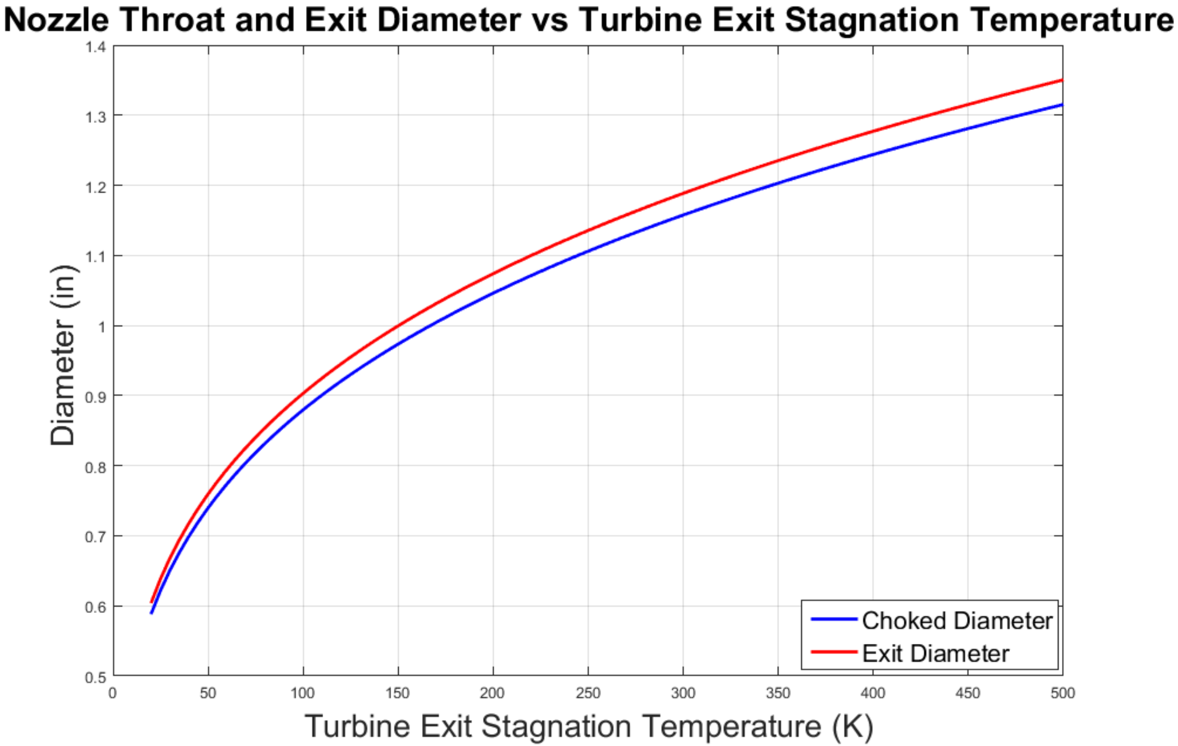
$$\rho_{in} A_{in} V_{in} = \rho_{out} A_{out} V_{out}$$

Trade studies determined scaling gives very little error
FEASIBLE

Test Bed Feasibility

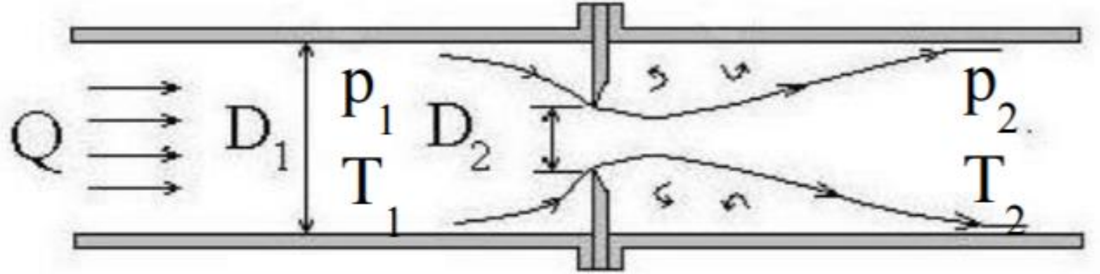
- Stagnation temperature affects the optimal throat and exit areas of the nozzle.
- Cold flow test requires nozzle designed to operate at cold flow stagnation temperature
- Same design method can be used to design cold flow nozzle

FEASIBLE



Test Bed Feasibility

- Forces a mass flow rate
- Works similarly to a convergent divergent nozzle



$\dot{m}$= 0.065 kg/s
p_1= 317 kPa (46 psi)
C (orifice plate coefficient) = 0.77 (common value)
T_1 = 293 K (room)

For choked flow:

$$\dot{m} = CAp_1\sqrt{\frac{\gamma}{RT_1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

Solving:
$D_{orifice}$ is 1.21 cm, which is **less than** a common hose diameter of 1.905 cm (3/4 in.)
FEASIBLE

Nozzle Integration CPE's

- Additive Manufacturing Process
  - Tolerances within 25.4 µm (0.001 in)

- Nozzle Mass
  - Less than 291 g at 120 N design point to maintain T/W ratio

- Interfacing with Engine
  - No extensive modifications to stock engine and its parts
  - No further flow impedance than that of the stock design
  - Interchangeability between nozzle designs for engine

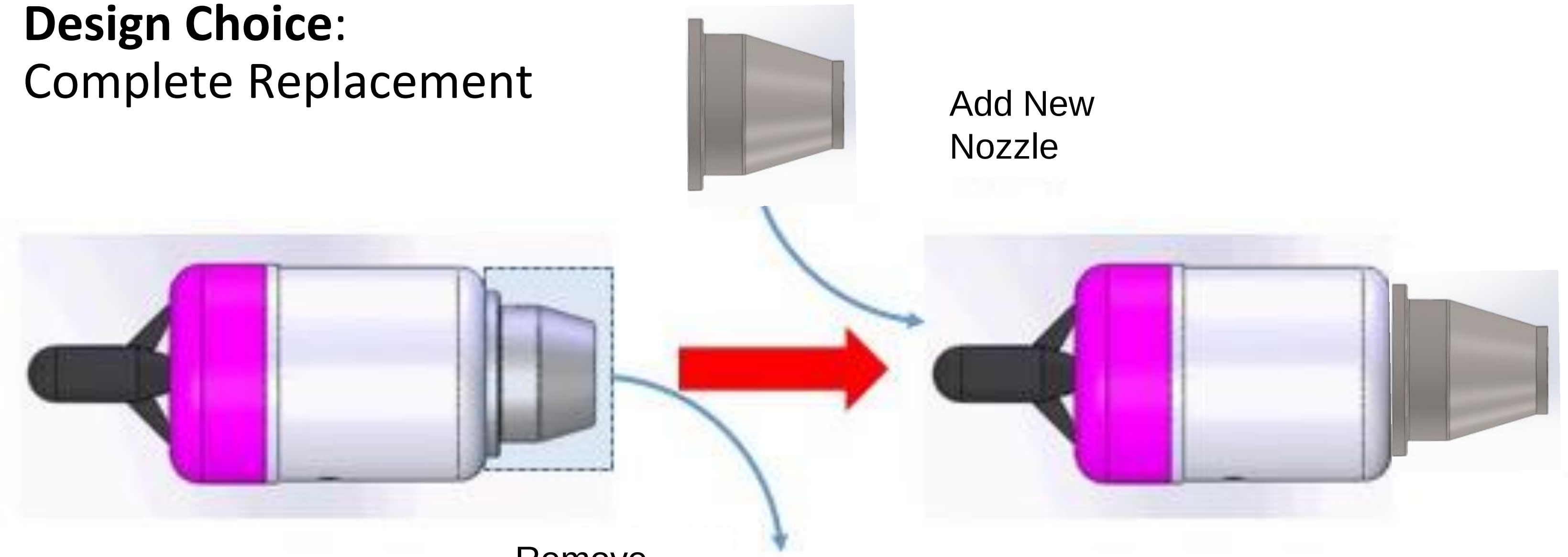
Nozzle Integration Feasibility

- Nozzle Integration Trade Study:
  - Highest scoring designs:
    1. Complete Replacement
    2. Dome Replacement

	Weighting	Replacement	Attachment	Sock	Dome Replacement
Work Cost	0.25	5	2	3	5
Mass	0.3	5	3	1	4
Flow Impedance	0.15	5	3	3	5
Interchangeability	0.2	5	1	4	5
Tolerance	0.1	4	2	3	2
Total	**5**	**4.9**	**2.25**	**2.6**	**4.4**

Nozzle Integration Feasibility

Design Choice:
Complete Replacement



Add New
Nozzle

Remove
New Nozzle

Nozzle Integration Feasibility

Design Choice: Complete Replacement

- One piece Design
  - Additional 44 g anticipated with stock material, 130 g nozzle design
  - Very low complexity of integration; identical to stock integration

- No permanent alteration/damage to stock engine components
  - Stock Nozzle can be interchanged with SABRE-Nozzle
  - No added mounting equipment

Nozzle Integration Feasibility

Integration Dome Transfer

- 3 screw-Bolt system
  - Low Complexity
  - Tolerance of 0.5 mm (0.02")

- Velocity profile at exit uniform despite presence

- Main purpose to cover turbine bearings

SABRE-Nozzle Design

Preliminary Design Document
- Problem Statement
- Conops, FBD, Objectives
- PDD Content
- Revisions
- PDD Submission

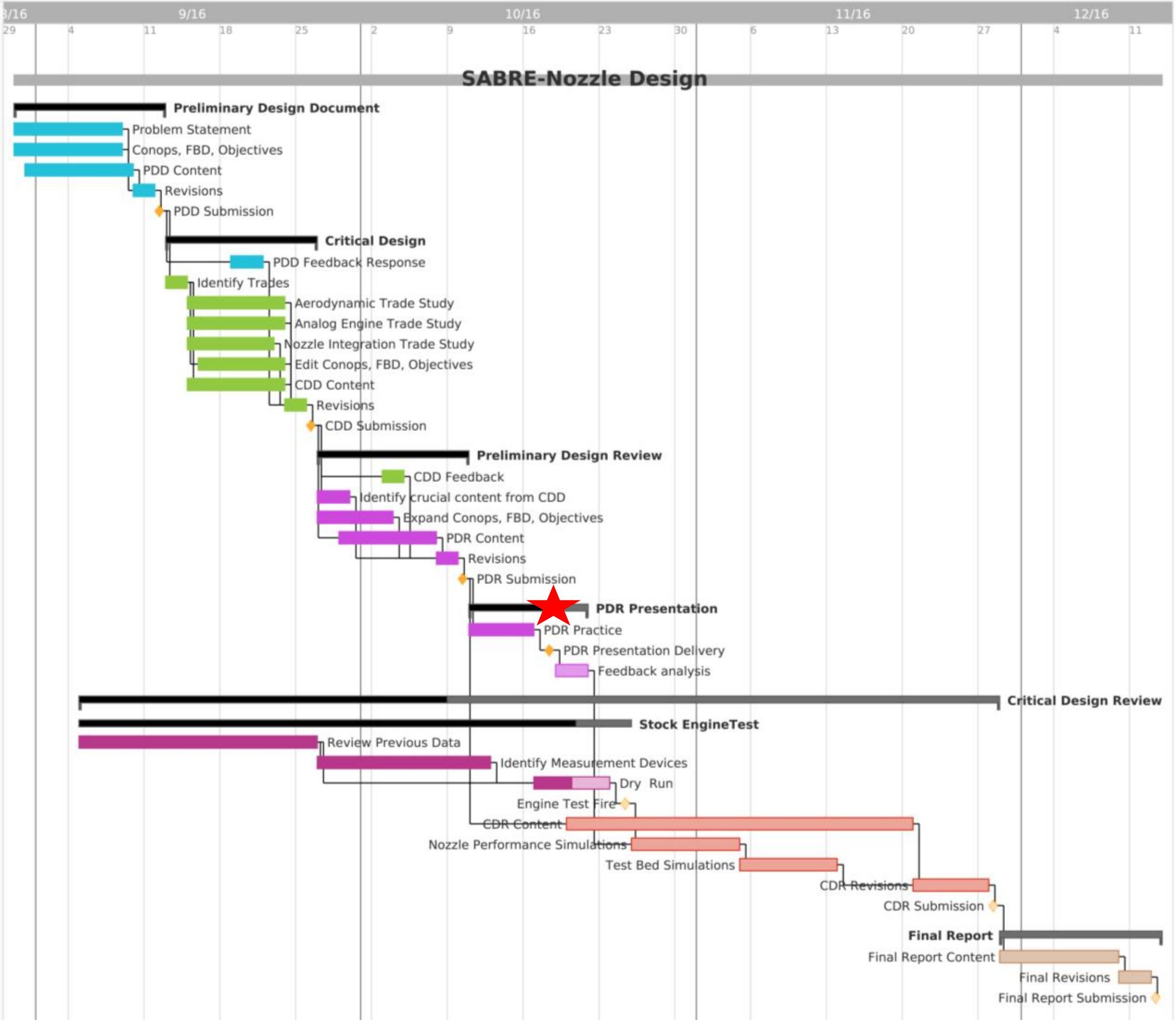
Critical Design
- PDD Feedback Response
- Identify Trades
- Aerodynamic Trade Study
- Analog Engine Trade Study
- Nozzle Integration Trade Study
- Edit Conops, FBD, Objectives
- CDD Content
- Revisions
- CDD Submission

Preliminary Design Review
- CDD Feedback
- Identify crucial content from CDD
- Expand Conops, FBD, Objectives
- PDR Content
- Revisions
- PDR Submission

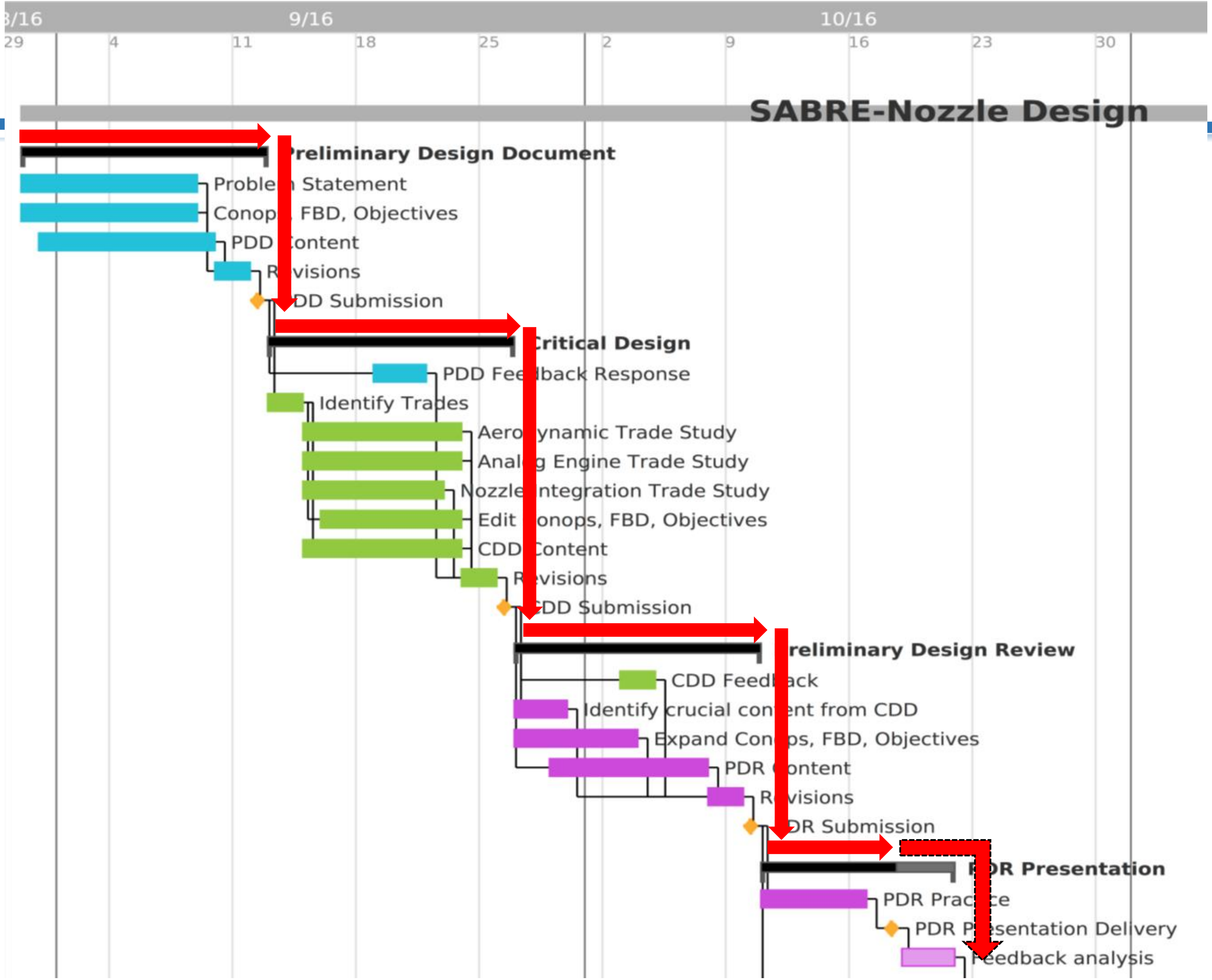
PDR Presentation
- PDR Practice
- PDR Presentation Delivery
- Feedback analysis

Critical Design Review
- **Stock EngineTest**
  - Review Previous Data
  - Identify Measurement Devices
  - Dry Run
  - Engine Test Fire
- CDR Content
- Nozzle Performance Simulations
- Test Bed Simulations
- CDR Revisions
- CDR Submission

Final Report
- Final Report Content
- Final Revisions
- Final Report Submission



SABRE-Nozzle Design



Nozzle Manufacturing

- Direct Metal Laser Sintering (DMLS)
  - Additive Manufacturing Technique
  - Laser binds layers of sinter powdered material together
  - Accuracy: 0.0005-0.001"
    - Manufactured: 20-30µm
    - Finished: down to 1µm
  - Feasible (Budget, Time, Accuracy)

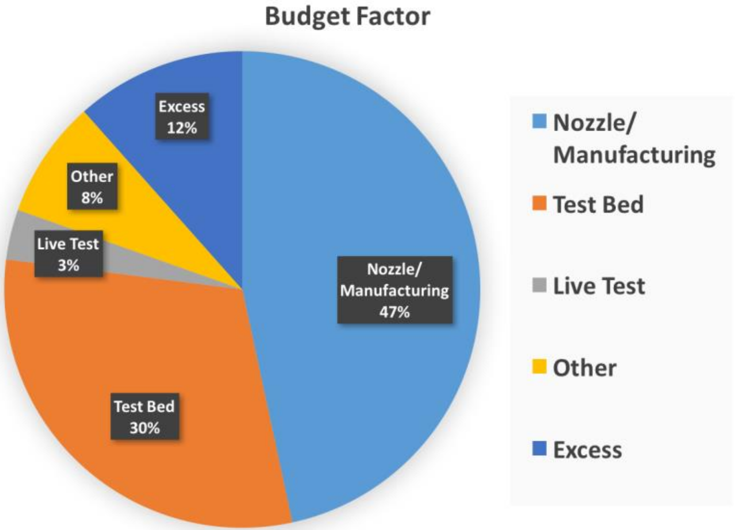
DMLS	Cobalt Chrome	Inconel 718
Price	$727	$662
Temperature Rating	2100 °F (1422 K)	1200 °F (922 K)
Density	8.5 g/cm^3	8.22 g/cm^3
Mass of Current Nozzle Design	137.2 g	132.7 g

Status Report

Budget/Financial

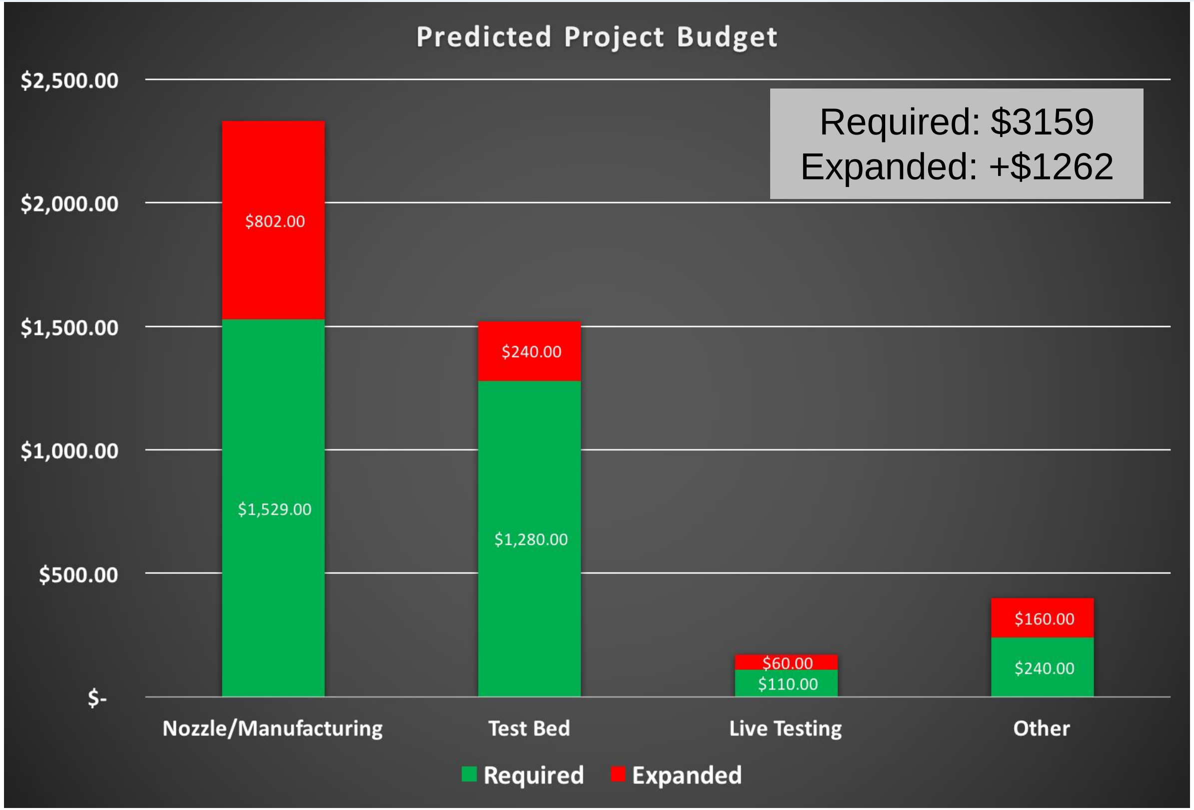
- Includes cost of 3 nozzles and 2 testing nozzles

Category	Cost
Nozzle/Manufacturing	$2331
Test Bed	$1520
Live Testing	$170
Other/Miscellaneous	$400
Grand Total	**$4421**



Project Description → Baseline Design → Nozzle Aerodynamics → Nozzle Test Bed → Nozzle Integration → Project Summary

Status Report cont.



Required: $3159
Expanded: +$1262

Moving Forward

- Test current stock engine Nozzle
- Nozzle Simulations (CFD: Thermal and Aerodynamic)
- Test Bed functionality/Design
  - Conduct critical design experiments

References

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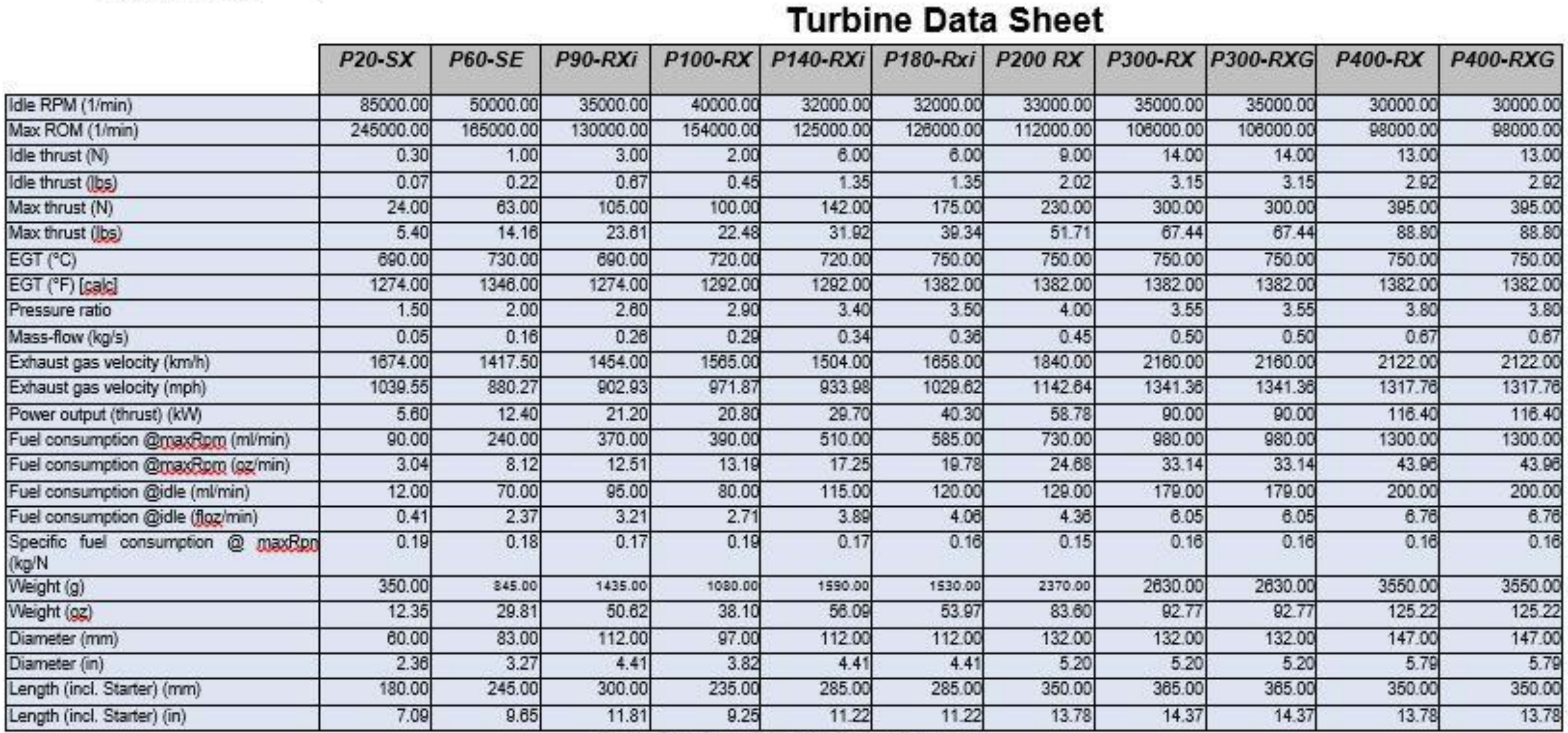
Back-Up
Slides

Appendix: Data Sheet

Data converted to ISA: 15°C and 101,325 Pa

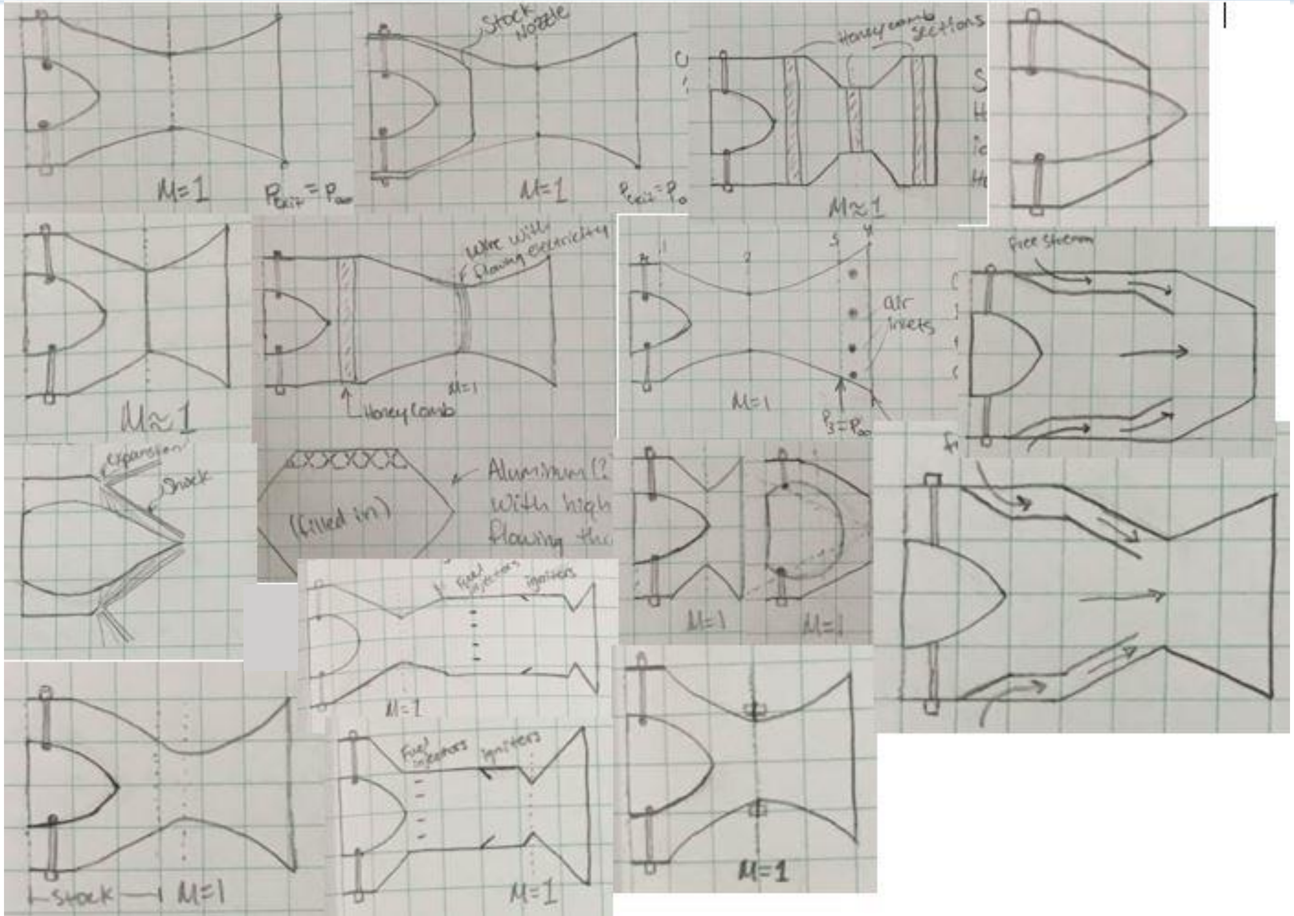


Turbine Data Sheet

	P20-SX	P60-SE	P90-RXi	P100-RX	P140-RXi	P180-Rxi	P200 RX	P300-RX	P300-RXG	P400-RX	P400-RXG
Idle RPM (1/min)	85000.00	50000.00	35000.00	40000.00	32000.00	32000.00	33000.00	35000.00	35000.00	30000.00	30000.00
Max ROM (1/min)	245000.00	165000.00	130000.00	154000.00	125000.00	126000.00	112000.00	106000.00	106000.00	98000.00	98000.00
Idle thrust (N)	0.30	1.00	3.00	2.00	6.00	6.00	9.00	14.00	14.00	13.00	13.00
Idle thrust (lbs)	0.07	0.22	0.67	0.45	1.35	1.35	2.02	3.15	3.15	2.92	2.92
Max thrust (N)	24.00	63.00	105.00	100.00	142.00	175.00	230.00	300.00	300.00	395.00	395.00
Max thrust (lbs)	5.40	14.16	23.61	22.48	31.92	39.34	51.71	67.44	67.44	88.80	88.80
EGT (°C)	690.00	730.00	690.00	720.00	720.00	750.00	750.00	750.00	750.00	750.00	750.00
EGT (°F) [calc]	1274.00	1346.00	1274.00	1292.00	1292.00	1382.00	1382.00	1382.00	1382.00	1382.00	1382.00
Pressure ratio	1.50	2.00	2.60	2.90	3.40	3.50	4.00	3.55	3.55	3.80	3.80
Mass-flow (kg/s)	0.05	0.16	0.26	0.29	0.34	0.36	0.45	0.50	0.50	0.67	0.67
Exhaust gas velocity (km/h)	1674.00	1417.50	1454.00	1565.00	1504.00	1658.00	1840.00	2160.00	2160.00	2122.00	2122.00
Exhaust gas velocity (mph)	1039.55	880.27	902.93	971.87	933.98	1029.62	1142.64	1341.36	1341.36	1317.76	1317.76
Power output (thrust) (kW)	5.60	12.40	21.20	20.80	29.70	40.30	58.78	90.00	90.00	116.40	116.40
Fuel consumption @maxRpm (ml/min)	90.00	240.00	370.00	390.00	510.00	585.00	730.00	980.00	980.00	1300.00	1300.00
Fuel consumption @maxRpm (oz/min)	3.04	8.12	12.51	13.19	17.25	19.78	24.68	33.14	33.14	43.96	43.96
Fuel consumption @idle (ml/min)	12.00	70.00	95.00	80.00	115.00	120.00	129.00	179.00	179.00	200.00	200.00
Fuel consumption @idle (floz/min)	0.41	2.37	3.21	2.71	3.89	4.06	4.36	6.05	6.05	6.76	6.76
Specific fuel consumption @ maxRpn (kg/N	0.19	0.18	0.17	0.19	0.17	0.16	0.15	0.16	0.16	0.16	0.16
Weight (g)	350.00	845.00	1435.00	1080.00	1590.00	1530.00	2370.00	2630.00	2630.00	3550.00	3550.00
Weight (oz)	12.35	29.81	50.62	38.10	56.09	53.97	83.60	92.77	92.77	125.22	125.22
Diameter (mm)	60.00	83.00	112.00	97.00	112.00	112.00	132.00	132.00	132.00	147.00	147.00
Diameter (in)	2.36	3.27	4.41	3.82	4.41	4.41	5.20	5.20	5.20	5.79	5.79
Length (incl. Starter) (mm)	180.00	245.00	300.00	235.00	285.00	285.00	350.00	365.00	365.00	350.00	350.00
Length (incl. Starter) (in)	7.09	9.65	11.81	9.25	11.22	11.22	13.78	14.37	14.37	13.78	13.78

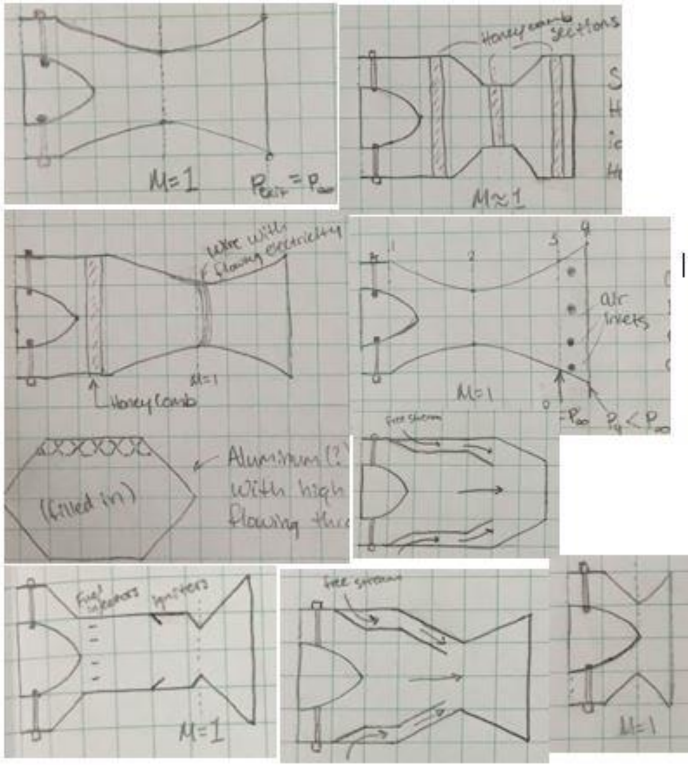
Engine Data Sheet 7-14-2015 Without Prices.xlsx

Appendix: Nozzle Designs

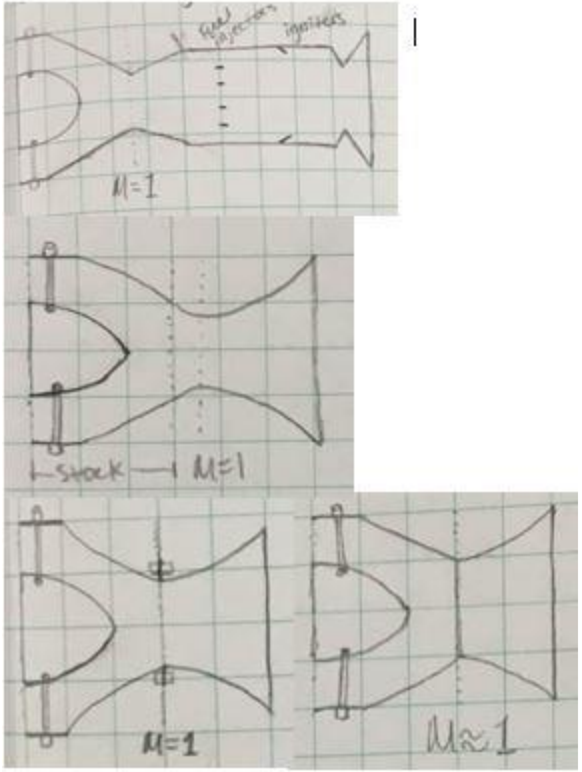


Appendix: Nozzle Integration

Replacement

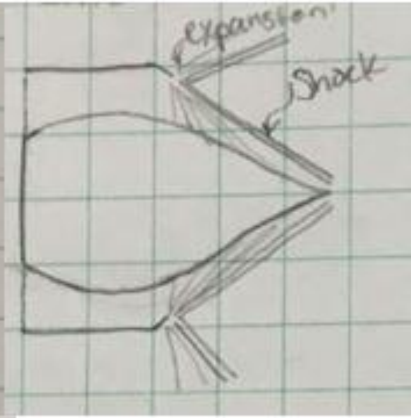


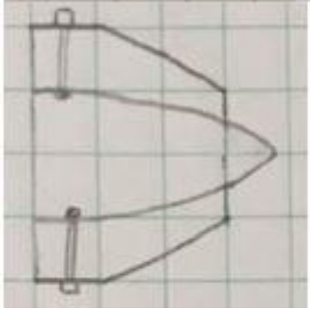
Attachment



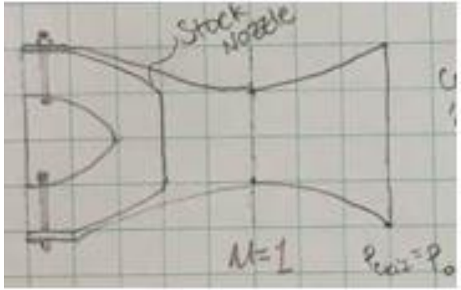
Appendix: Nozzle Integration

Dome Replacement





Sock

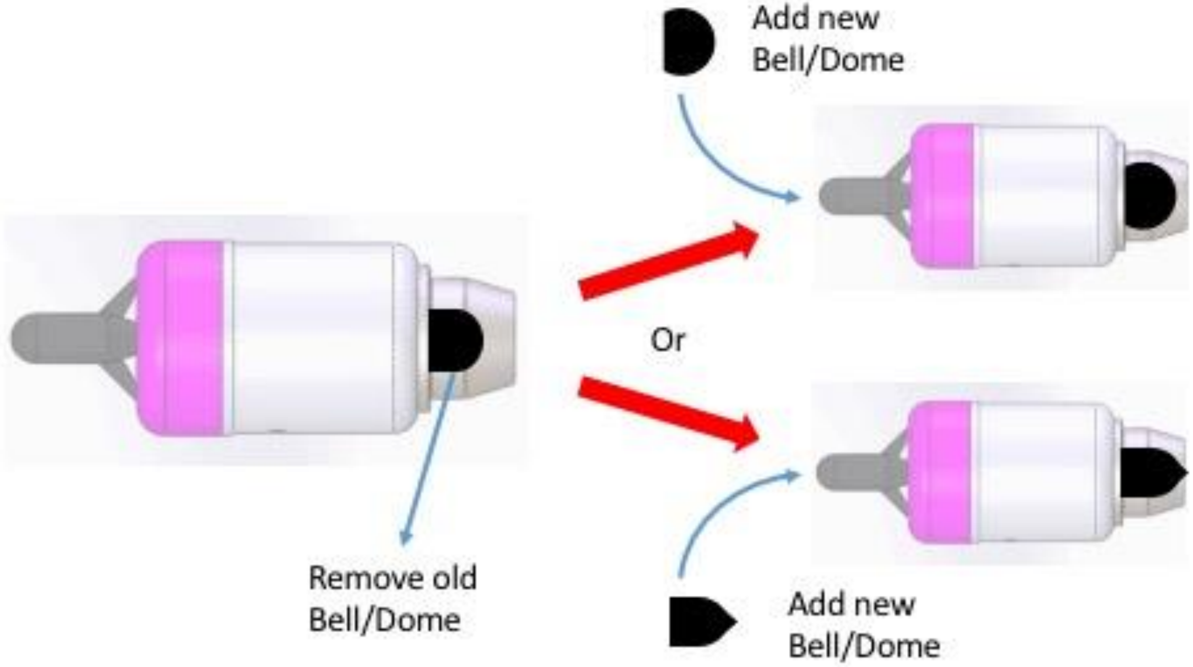


Appendix: Nozzle Integration Feasibility

Design consideration: Dome Replacement

- Stock nozzle maintained
- Small Size
  - Low mass cost; additional 9 g anticipated
  - Cost Savings in manufacturing
  - Easy to implement in large scale product change
- Aerodynamic Complexity
  - Small length to work with (stock nozzle)

Appendix: Nozzle Integration Feasibility



Appendix: Nozzle Integration Feasibility

Design Consideration: Nozzle 'Sock'

- Stock nozzle maintained
- Manufacturing complexity
- Tolerances of integration design
- Additional 130 g anticipated

Design Consideration: Nozzle Extension

- Stock engine not maintained
- Connection Vulnerability
- Less manufacturing material required
- Additional 44 g anticipated for nozzle, additional supports required

Appendix: Pressure Regulator

- Pressure output of Nitrogen tank: 15.168 MPa (2200 psi)
- Ideal pressure output of regulator: 317 kPa (46 psi)

Praxair 4095 Pressure Regulator
Inlet Range: up to 27.58 MPa (4000 psi)
Output Range: up to 2.068 MPa (300 psi)

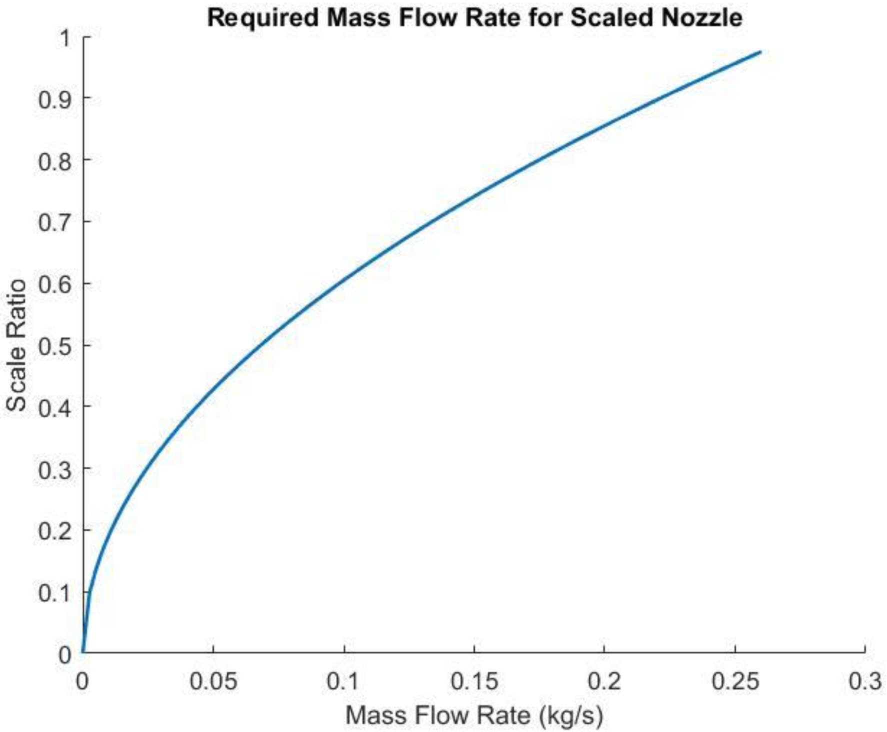
FEASIBLE

Appendix: Nozzle Scalability

$$\left(\frac{A_e}{A^*}\right)^2 = \frac{1}{M_e^2}\left(\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M_e^2\right)\right)^{\frac{\gamma+1}{\gamma-1}}$$

$$\dot{m}^* = \frac{p_0 A^*}{\sqrt{T_0}}\sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

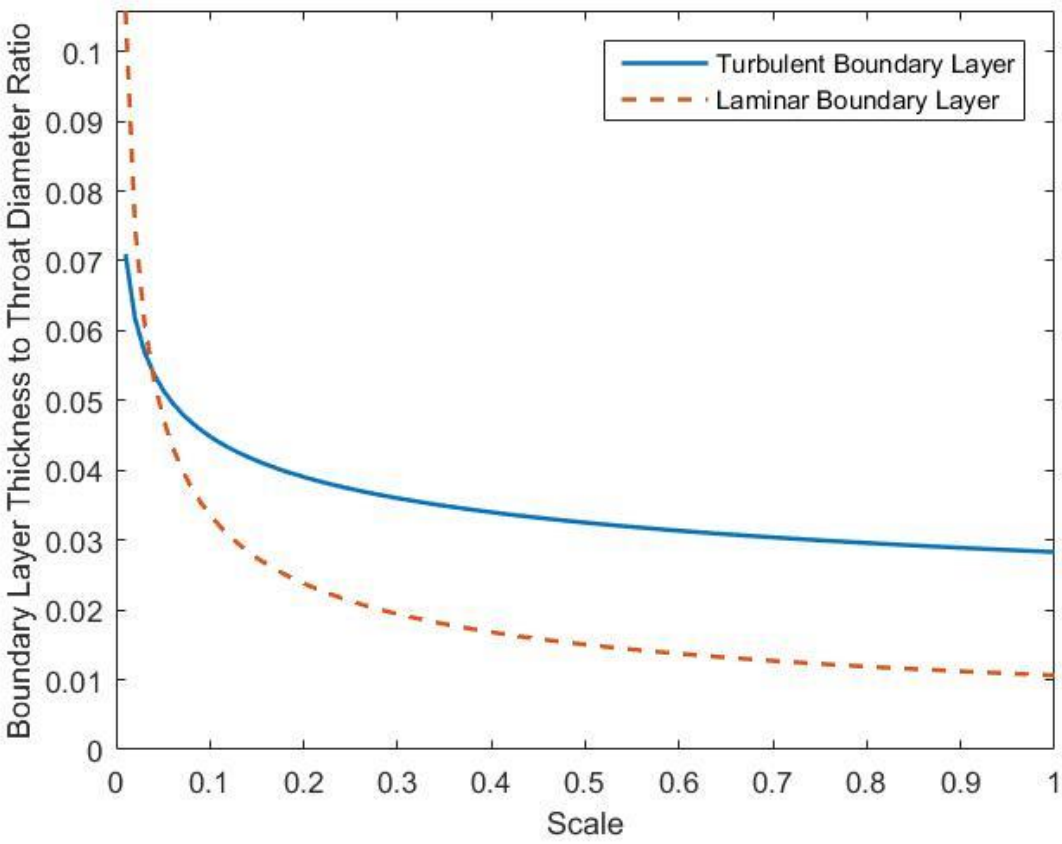
$$A^* = \frac{\dot{m}\sqrt{T_0}}{p_0\sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}$$



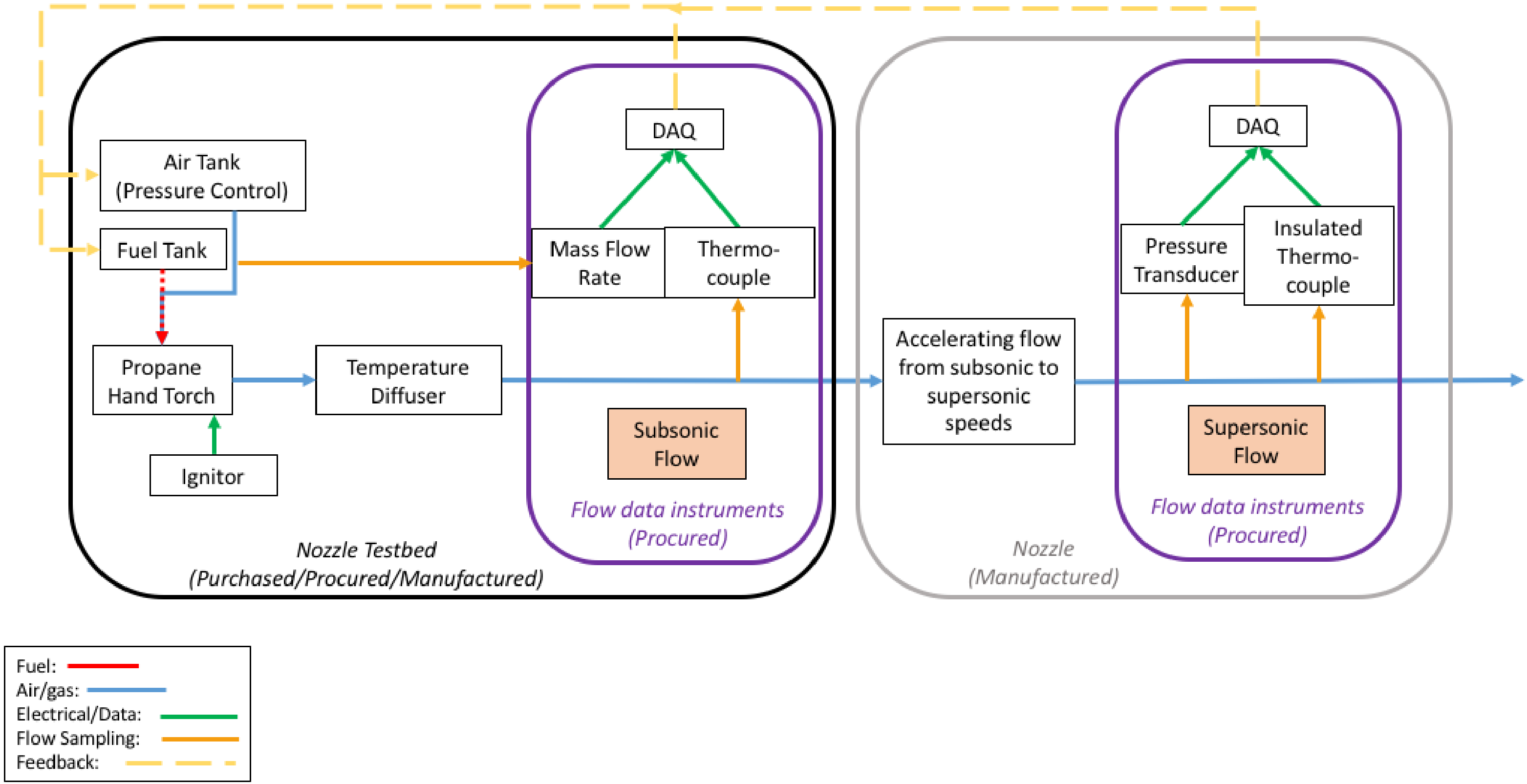
Appendix: Nozzle Scalability

$$\delta \approx 5.0x/\sqrt{\mathrm{Re}_x}$$

$$\delta \approx 0.37x/{\mathrm{Re}_x}^{1/5}$$



Appendix: FBD Hot Flow (Level 2 Success)

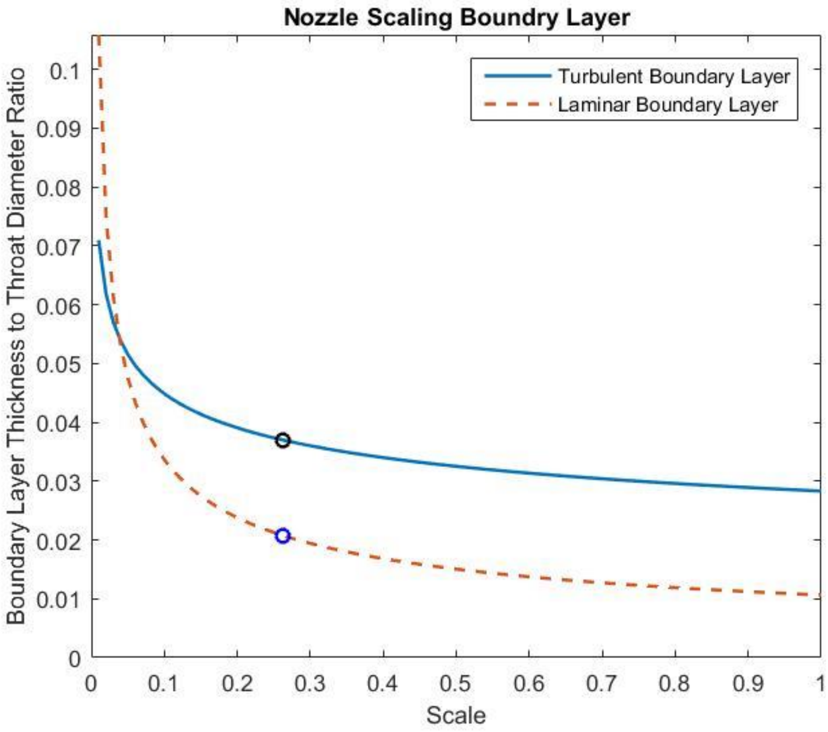


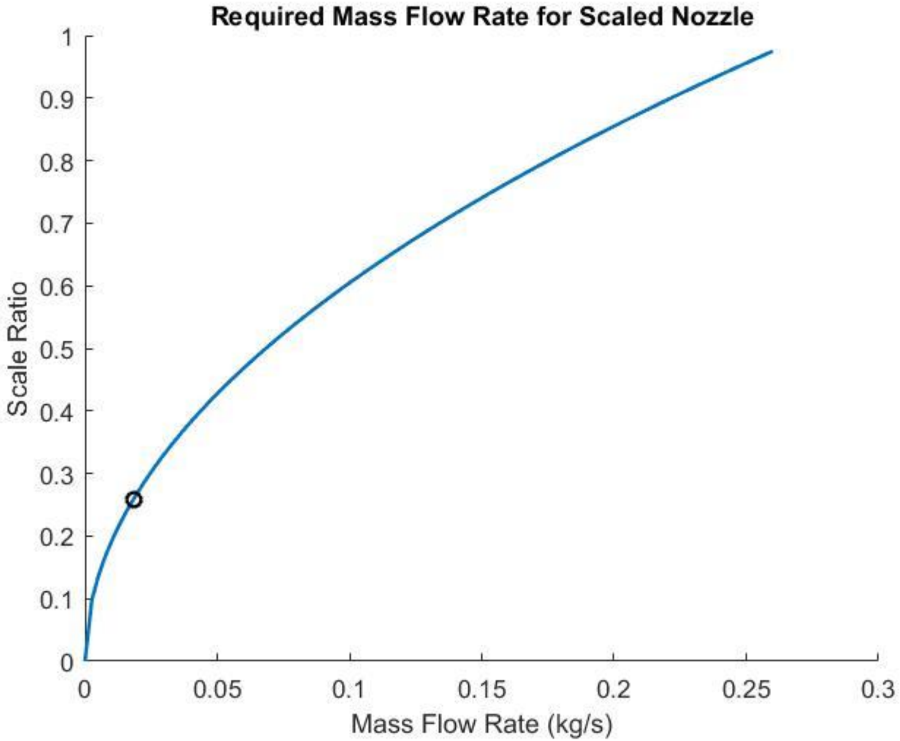
Appendix: Hot Flow Testing

	Burner	**JetCat P-90 xi**
Pressure (atm)	1.42	1.6248
Temperature (K)	1258.3	963.15
Mach	0.95	0.66
Mass flow rate(kg/s)	0.0183	0.26

- Hybrid burners' 1.25" foundry and kiln burner

Appendix: Hot Flow Testing





Appendix: Thermal Expansion

Assuming: Isentropic Flow Relations to determine static flow temperature, steady state (rate of heat transfer is constant), forced turbulent dry air convection within nozzle, natural convection outside of nozzle, nominal CoCr thermal properties

$$h_1 = 13.95 \frac{W}{m^2 K} \qquad h_2 = 11.88 \frac{W}{m^2 K}$$

$$k = 30.8 \frac{W}{m^o C} \qquad \alpha = 15.1 \frac{\mu m}{m^o C}$$

$$\Delta d = d_o \Delta T \alpha$$

Station	Inlet	Throat	Exit
Temperature(K)	871	746	734
Δd (μm)	441 (0.86%)	278 (0.68%)	271 (0.66%)

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}}$$

$$R_{total} = R_{conv,1} + R_{cond} + R_{conv,2}$$

$$= \frac{1}{2\pi r_1 L h_1} + \frac{ln(r_2/r_1)}{2\pi L k} + \frac{1}{2\pi r_2 L h_2}$$

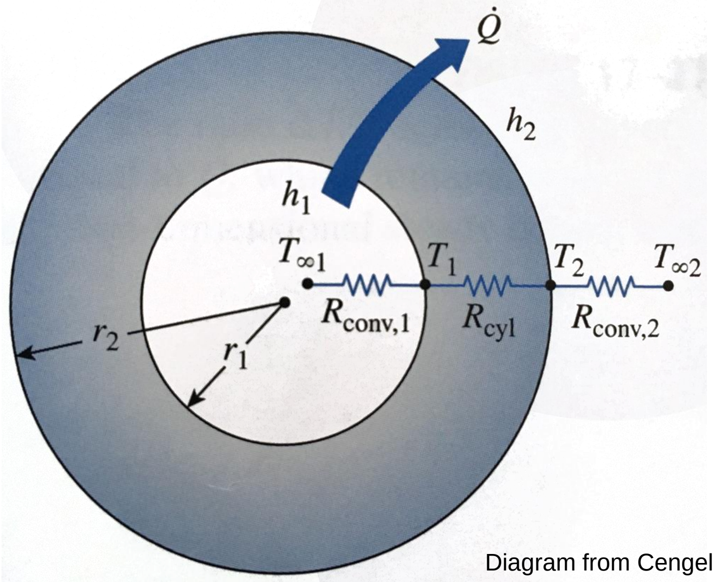


Diagram from Cengel

Appendix: Ideal Turbo-jet Analysis

- **Station 1-2: Inlet**

Total pressure and total temperature are **conserved**

$$p_{t,2} = p_{t,1}$$

$$T_{t,2} = T_{t,1}$$

- **Station 2-3: Compressor**

Isentropic Compression-

Compressor Pressure Ratio - $\pi_c = \frac{p_{t,3}}{p_{t,2}}$

$$p_{t,3} = \pi_c * p_{t,2}$$

$$T_{t,3} = T_{t,2}(\pi_c)^{\frac{\gamma-1}{\gamma}}$$

- **Station 3-4: Combustor**

Constant Pressure Combustion:

$$p_{t,4} = p_{t,3}$$

$$\frac{f}{a} = \frac{\dot{m}_{fuel}}{\dot{m}_0 - \dot{m}_{fuel}}$$

$$T_{t,4} = \frac{(\frac{f}{a} * HV + c_p * T_{t,3})}{c_p + c_p * \frac{f}{a}}$$

- **Station 4-5: Turbine**

$$\frac{p_{t,5}}{p_{t,4}} = [1 - \frac{T_{t,2}}{T_{t,4}} * \frac{1}{(1 + \frac{f}{a})} * (\pi_c^{\frac{\gamma-1}{\gamma}} - 1)]^{\frac{\gamma}{\gamma-1}}$$

$$p_{t,5} = \frac{p_{t,5}}{p_{t,4}} * p_{t,4}$$

$$T_{t,5} = T_{t,4} * (\frac{p_{t,5}}{p_{t,4}})^{\frac{\gamma-1}{\gamma}}$$

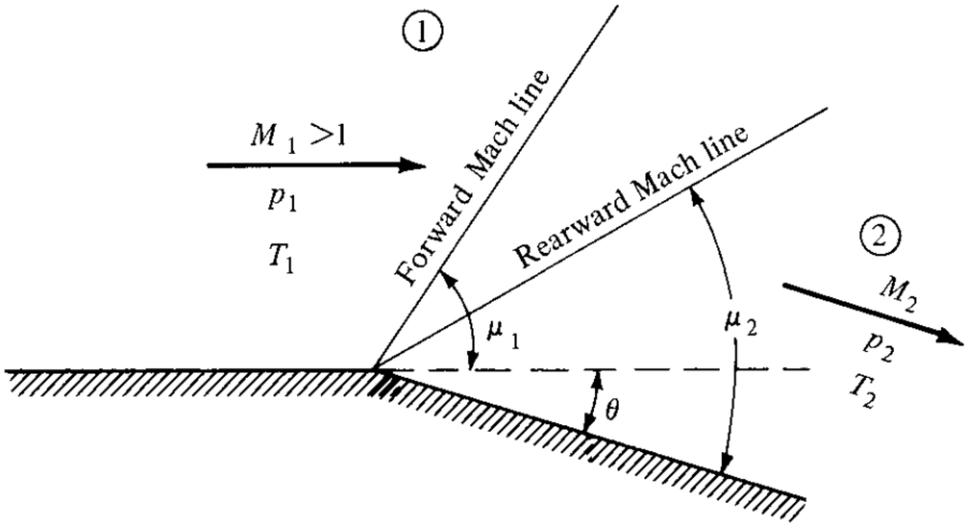
Appendix: Mass-Flow through Nozzle

$$\dot{m} = \frac{p_t A}{\sqrt{T_t}}\sqrt{\frac{\gamma}{R}}M\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

- Compression Ratio influences Stagnation Pressure and Temperature, which influence maximum Mach number.

- Critical throat area determined with a Mach number of 1, ideal isentropic Pressure and Temperature conditions, and a fixed maximum mass flow rate.

Appendix: Prandtl-Meyer Expansion



$$\nu(M) = \sqrt{\frac{\gamma+1}{\gamma-1}}\tan^{-1}\sqrt{\frac{\gamma-1}{\gamma+1}(M^2-1)} - \tan^{-1}\sqrt{M^2-1}$$

$$\theta = \nu(M_2) - \nu(M_1)$$

1: $\theta = \nu(1.06) - \nu(1)$

2: $\theta = 0.011 - 0\ (rad)$

3: $\theta = 0.654\ (deg)$

Appendix: Mach # from Pressure

Supersonic Flow

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

$$\frac{P_{02}}{P} = \left[\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}} \left(\frac{1-\gamma+2\gamma M^2}{\gamma+1}\right)$$

Where:

P_{02} = stagnation pressure after the shock wave

P = static pressure (same before or after shock wave)

M = Mach number before the shock wave

A pitot tube measures both stagnation pressure and static pressure behind the shock. Therefore, the equation above can be solved for M (the desired value to verify our designed nozzle can achieve supersonic flow).

Appendix: Mach # from Pressure

- Measuring compressible flow (still subsonic)

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

Where:

P_0 - total pressure
P - static pressure

With the pitot tube measuring the total and static pressure, M can be solved for in the above equation.

Compressible Subsonic Flow

Appendix: Expanded Budget Chart

Nozzle/Manufacturing	Nozzle	3 x $727	$2181
	Test Nozzle (Plastic)	2 x $75	$150
Test Bed	Regulator	4 x $20	$80
	Oriface	4 x $250	$1000
	Pitot Probe	2 x $20	$40
	Hose	1 x $400	$400
Live Testing	Plexiglass	1 x $50	$50
	Nitrogen Tanks	8 x $15	$120
Other	Project Management	-	$360
	Extra Piping/Tubes	-	$40
Total			$4421