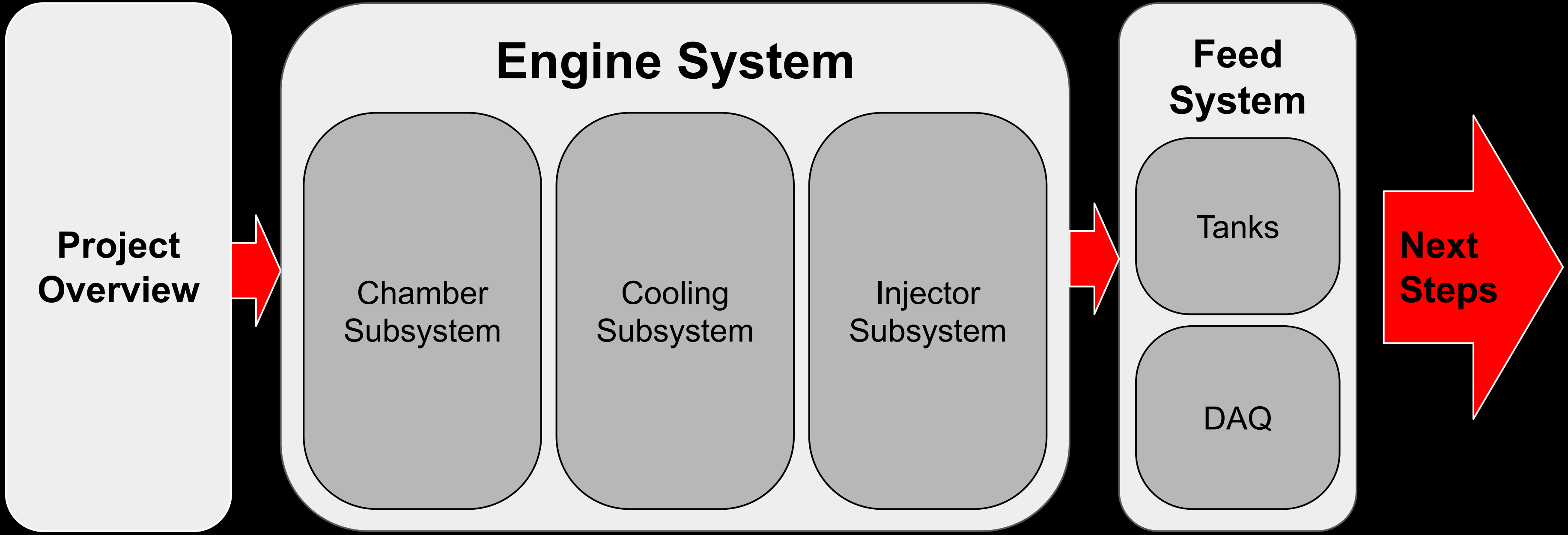
Romulus PDR

Liquid Propulsion Subteam

Presentation Timeline



Project Romulus: Overview

Primary Goals:

- Develop a more complex engine that uses active cooling methods.
- Employ more in-depth models for engine design.

Secondary Goals:

- Explore more complex injector schemes
- Update test stand to have more robust infrastructure
- Define a design structure for future Liquid Propulsion projects.

Project Timeline

IAP 2021

Planning
Research
Conceptualization
Initial system design

END GOAL:

SRR

Early Spring 2021

Component design
Initial CAD models
Parts list
Final system choices
Initial cost figures
Manufacturing plans

END GOAL:

PDR

Late Spring 2021

Final cost figures
Component analysis
Drawings
Hotfire ops
Safety protocols

END GOAL:

CDR

Fall 2021

Machine parts
Post-process engine
System dry runs
Pressure tests
Cold flow tests
Test data analysis

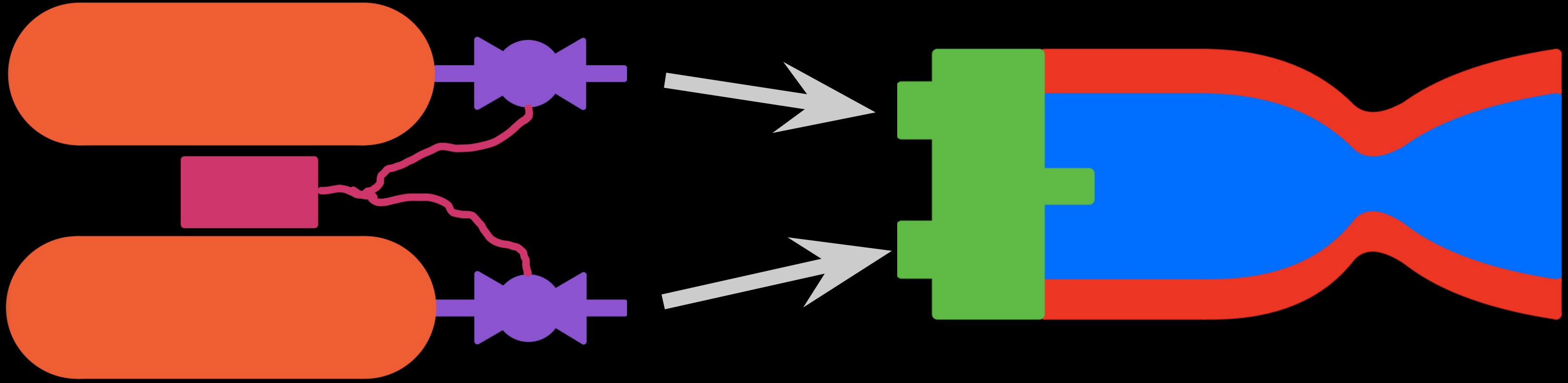
END GOAL:

HRR*

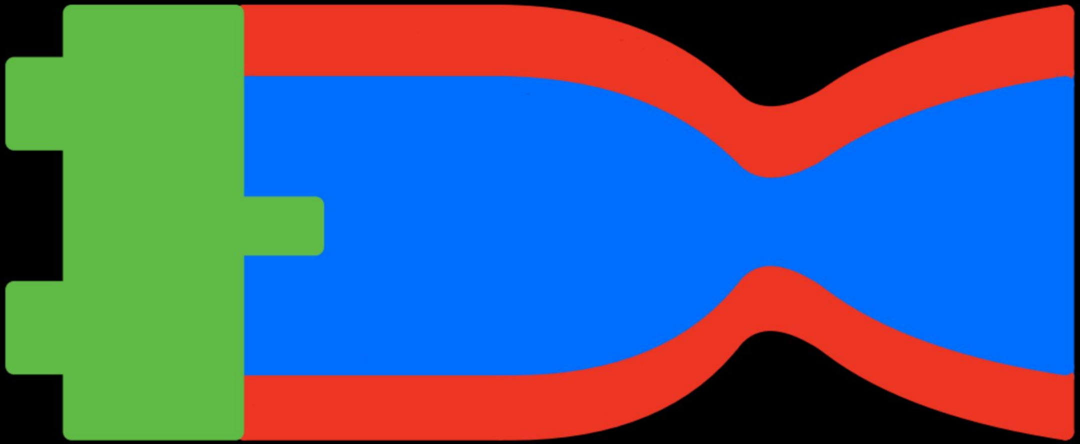
*HRR = hotfire readiness review

Feed System

Engine System



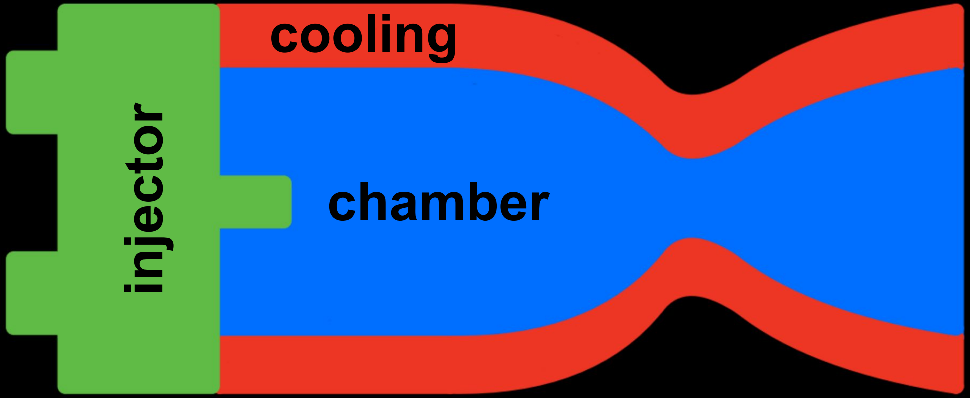
Engine System



Engine System Overview

Function: Generate thrust for duration of fire

Subsystems: injector, chamber, cooling

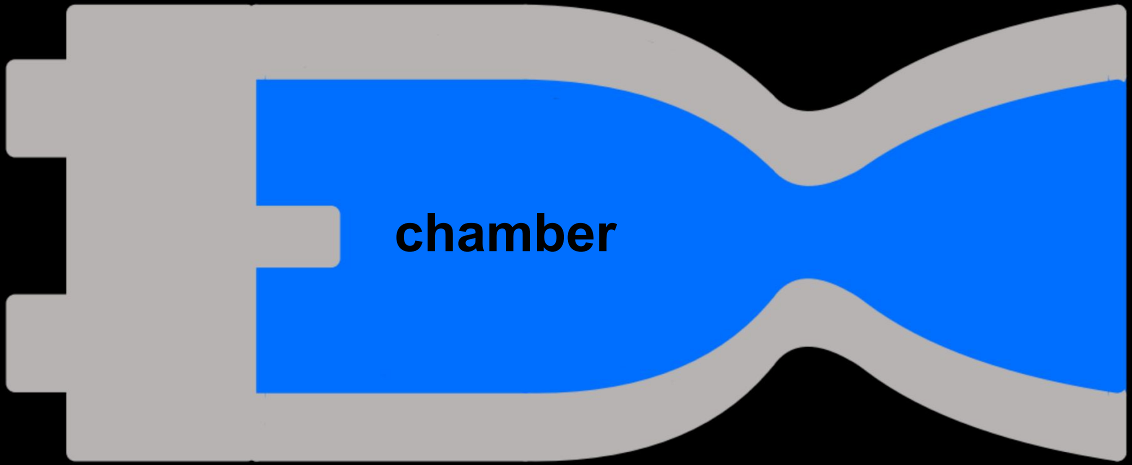


System Requirements

Engine system requirements are defined to provide a backbone for design verification and a structured set of goals

Engine	Requirements	Responsible Systems
ESR.100	Engine shall safely fire for desired duration of up to 10 seconds	Chamber, Cooling, Feed System
ESR.101	Engine shall produce _ Newtons of thrust	Chamber
ESR.102	Engine can be fired a minimum of _ times	Chamber, Cooling
ESR.103	Engine shall maintain structural integrity for the duration of testing	Chamber
ESR.104	Engine shall produce stable combustion throughout firing	Chamber, Injector
ESR.105	Engine shall be able to be manufactured in a reasonable and cost effective manner	Chamber, Cooling, Injector

Chamber Subsystem



Chamber Subsystem Overview

- Involves the design of engine geometry, flange design
- Design process:
  - Establish major design considerations/parameters
  - Define design constraints and criteria
  - Use models, research, and case studies to inform initial design decisions

Subsystem Requirements

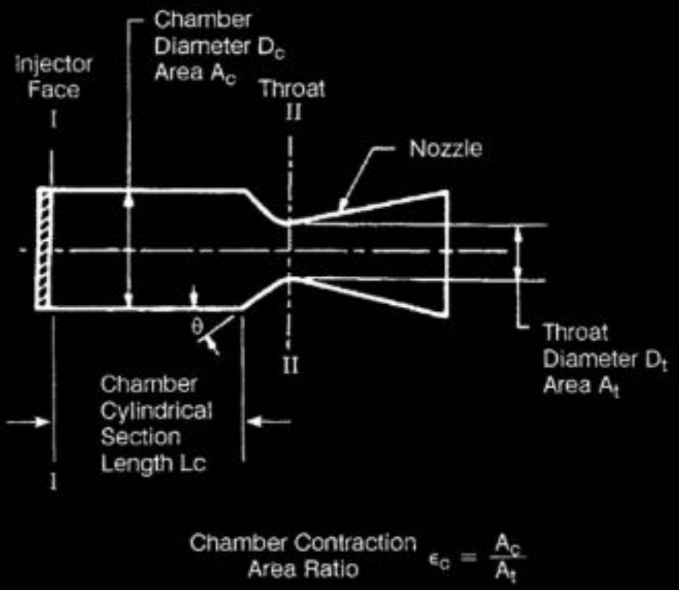
Chamber requirements are established to meet the overall goals of a robust engine and satisfactory subsystem interaction.

Chamber	Requirements	Parent Requirements	Verification Process
ESR.210	Chamber shall be able to withstand expected pressures	ESR.103	Hand calcs, FEA
ESR.211	All sealing surfaces can withstand expected pressures	ESR.103	Hand calcs, FEA
ESR.212	Propellant is sufficiently mixed before desired combustion zone	ESR.104	Hand calcs, Research
ESR.213	Chamber shall be able to be manufactured in a reasonable and cost effective manner	ESR.105	Review available tooling

Major Design Considerations

Our design focuses on creating an engine that can be reliably manufactured and cooled, while worrying less about performance metrics. The design process began with the following parameters:

- propellant choice
- mixture ratio
- L*
- contraction ratio
- chamber pressure
- mass flow



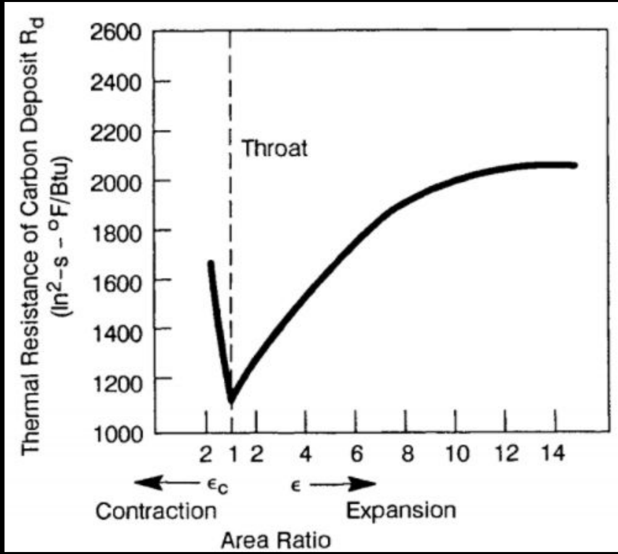
Choosing Propellant

Oxidizer: **LOX**

- Existing test stand infrastructure and prior experience

Fuel: kerosene (RP-1) vs. ethanol

- Prior experience with ethanol
- RP-1 results in carbon deposits, improving cooling
- Lots of literature on RP-1/LOX

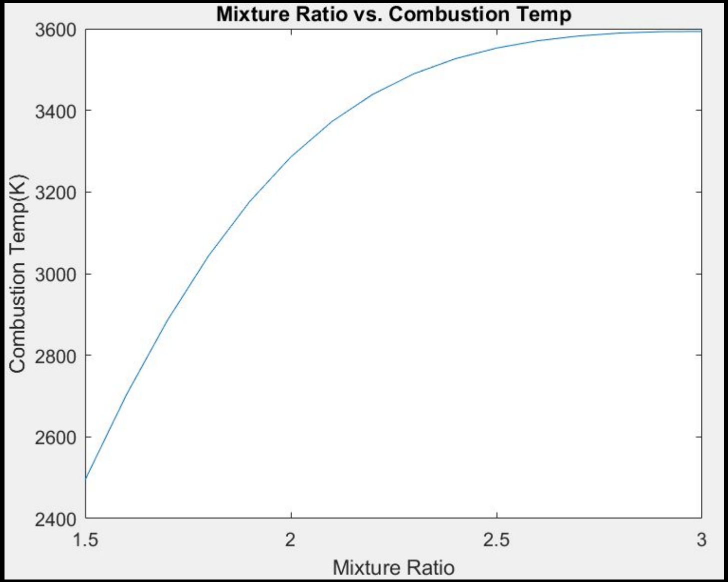


→ Final propellant choice of **LOX and RP-1**.

Choosing Mixture Ratio

Choice of mixture ratio is informed by our larger engine goal which prioritizes cooling over performance.

- Developed Tc vs. MR relation in CEA/MATLAB
- Low ratio of 1.5 chosen
    - Increased coolant mass flow
    - Lower combustion temp
    - Loss of performance is expected and acceptable
    - MR used for USC Balerian engine
    - Literature did not indicate concerns with combustion stability

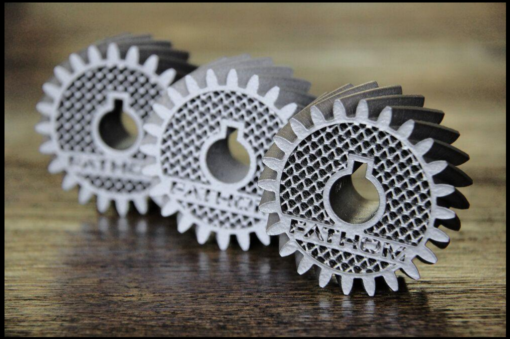


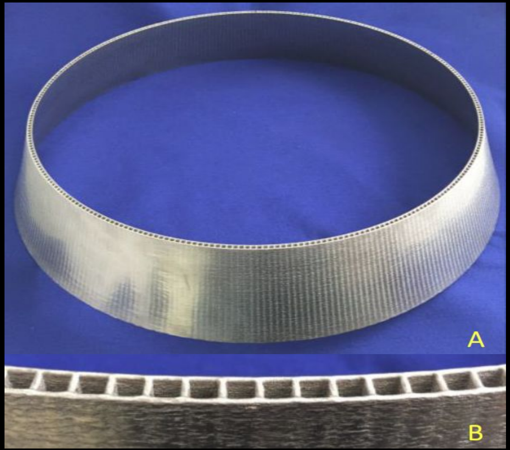
CEA and MATLAB used to evaluate MR vs. combustion temp

Additive Manufacturing

The engine will be additively manufactured using DMLS printing by Fathom Inc.

- Capable of small, complex geometries desirable for coolant channels on the scale of our engine (ESR.213)
- Design considerations:
    - Informs geometric parameters
    - Rough surface finish

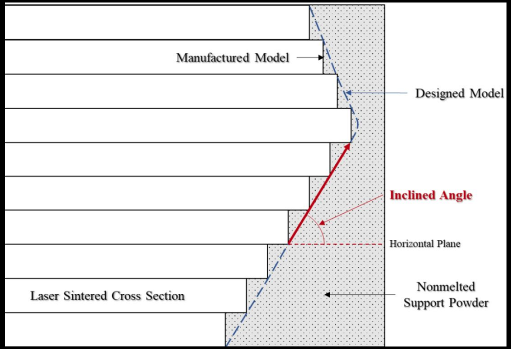




Geometric Constraints

Additive manufacturing contrains geometry:

- Max part size 9.85 x 9.85 x 8.5 inches
  - Engine length **5.9in**
    - Buffer for build volume
    - Lower pressure drop through channels
    - Easier to cool
- Max contraction angle 45°
- Chamber diameter ≥ 3in due to injector sizing

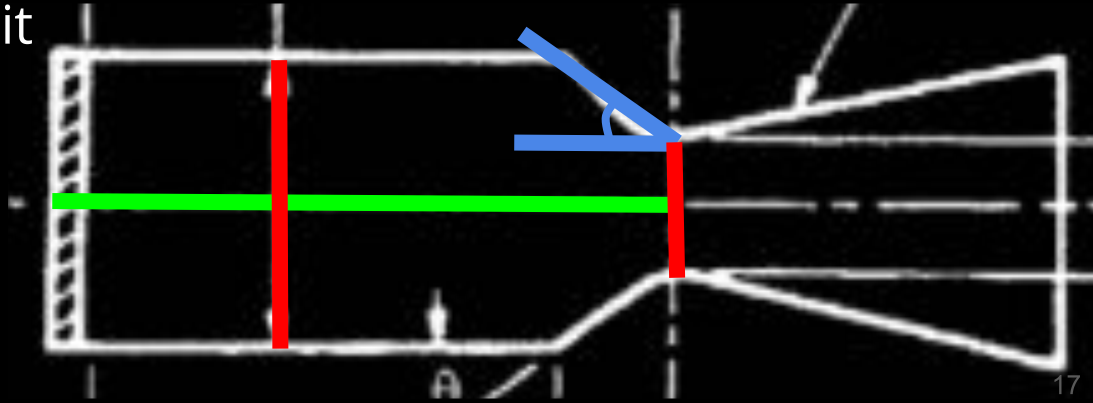


Initial Sizing Considerations/Decisions

Initial sizing was mostly limited by manufacturing constraints and injector requirements.

- Small L*
  - **1.00m**, on the lower end for LOX/RP-1
- Contraction ratio and angle
  - **16**, large to accommodate shorter design and injector design
  - **40°**, just under 45° limit

Green = chamber length
Red = contraction ratio
Blue = contraction angle



Chamber Pressure

- Chamber pressure driving design with mass flow as a result
- High limit set by feed system constraints: **500psi**
  - Relief valve sets feed system pressure limit - 800psi (700 psi with safety factor)
  - 100 psi drop (conservative) through feed system
  - Assume 20% drop through injector and regen circuit respectively
- Low limit set by performance requirements: **200psi**

Design Spreadsheet

Chosen P_c = **300psi**

B	C
[] denotes variable in functions	
blue for inputs, green for outputs	
Engine Inputs:	
Propellant Properties:	
[MixtureRatio] Mixture Ratio (ox/fuel)	1.5
[gamma] Specific heat ratio* (-)	1.25
[Rprop] Propellant Gas Constant* (R/m)	471
Chamber Properties:	
[Thrust] Thrust (N)	1750
[Tc] chamber stagnation temp (K)	2486
[Pc] chamber stagnation pressure (Pa)	2.06E+06
Exit Condition:	
[Pe] exit pressure (Pa)	101000
Firing Time:	
[BurnTime] engine firing duration (s)	

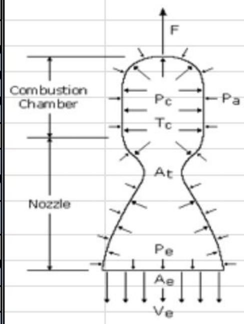


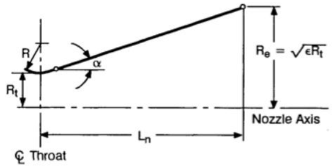
Figure 1.1

B	C
Important Constants:	
[gravity] gravitational acceleration (m/s^2)	9.81
[Runiversal] universal gas constant (J/(mol*K))	8.3145

B	C
Performance Outputs:	
[Isp] Specific impulse (s)	234.7354066
[Cstar] Characteristic velocity (m/s)	1644.342797
[ThrustCoefficient] Thrust coefficient (-)	1.400410147
[MassFlowRate] Mass flow rate (kg/s)	0.7599594844
[ExpansionRatio] Expansion ratio (-)	3.45E+00
[ExhaustVelocity] Exhaust velocity (m/s)	2302.754339

	B	C
2	**Geometry Inputs**	
3	**Combustion Chamber Side:**	
4	[ContractionRatio] Contraction Ratio (-)	16
5	[Lstar] L* (m)	1
6	[ContractionAngle] Contraction Angle (deg)	40
7	**Nozzle Side:**	
8	[DivergentAngle] Divergent Half Angle (deg)	15
9	[ThroatDiameter] Throat Diameter (m)	0.02779155511

Conical Nozzle Shape:

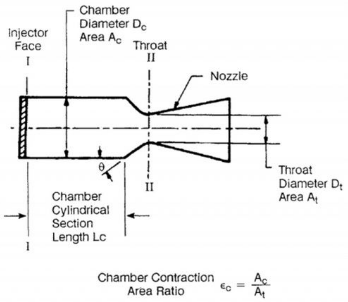


	B	C
21	**Combustion Chamber Geometry**	
22	**Full Chamber Geometry:**	
23	[ChamberVolume] Chamber Volume from L* (m^3)	6.07E-04
24	[ChamberDiameter] Chamber Diameter (m)	0.1111662204
25	[ChamberLength] Chamber Length (m)	9.47E-02
26	[ChamberSA] Chamber Surface Area (m^2)	4.53E-02
27	**Cylindrical Section:**	
28	[CylindricalVolume] Cylindrical Volume (m^3)	3.63E-04
29	[CylindricalLength] Cylindrical length (m)	3.74E-02
30	**Converging Section**	
31	[ConvergingVolume] Converging Volume (m^3)	0.000243176645
32	[ConvergingLength] Converging Length (m)	0.05726750259

	B	C
34	**Nozzle Geometry (Conical)**	
35	[ConvArcRadius] Converging Arc Radius (m)	0.02084366633
36	[DivArcRadius] Diverging Arc Radius (m)	0.005308187026
37	[NozzleLength] Nozzle Length (m)	0.04722063033

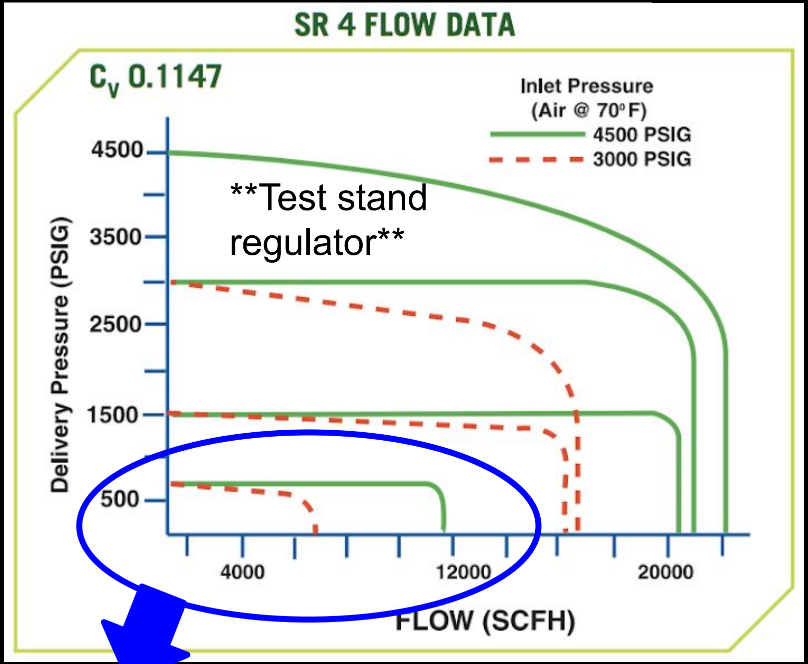
E	F
Outputs in Imperial	
Lengths:	
Chamber Length (in)	3.728857095
Nozzle Length (in)	1.859079934
Cylindrical Length (in)	1.474231009
Converging length (in)	2.254626086
Diameters:	
Chamber Diameter (in)	4.376622852
Throat Diameter (in)	1.094155713
Exit Diameter (in)	2.032537196
Volumes:	
Chamber Volume (in^3)	37.01812601
Cylindrical Volume (in^3)	22.17857662
Converging Volume (in^3)	14.83954939
Surface Area:	
Chamber Surface Area (in^2)	70.19870982

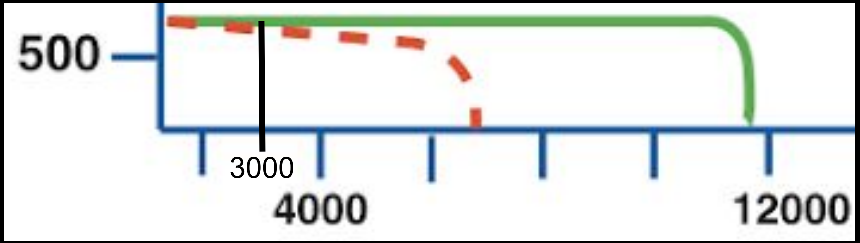
Conical Nozzle Geometry Diagram:



Flow Constraints

- Mass flow is constrained by regulator
- Wish to confirm design flow rates (established by pressure cases)
- Estimate pressure drop during steady-state flow
    - Initial flow estimate of 3000 SCFH



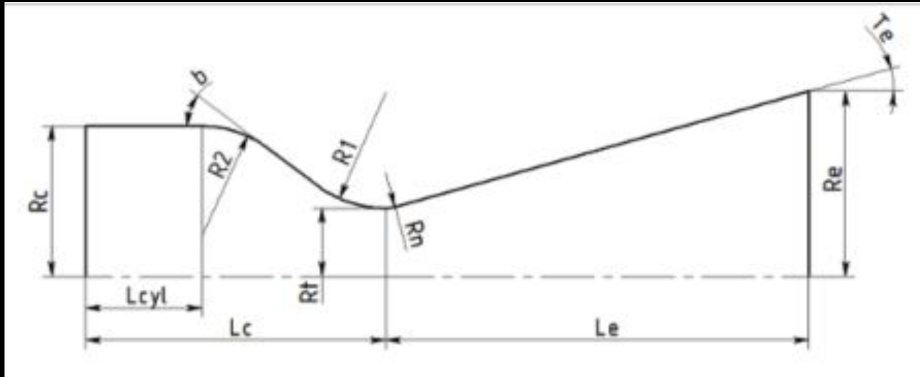


Chamber - Initial Design Choices Summary

- Pressure: **300 psi**
- Mass Flow: **0.81 kg/s**
- Mixture Ratio: **1.5**
- Contraction Angle: **40°**
- Contraction Ratio: **16**
- L*: **1.00 m**
- Nozzle Shape: **Conical**

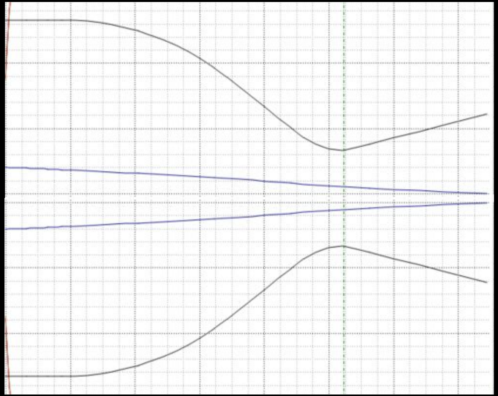
Plug into RPA & MATLAB models

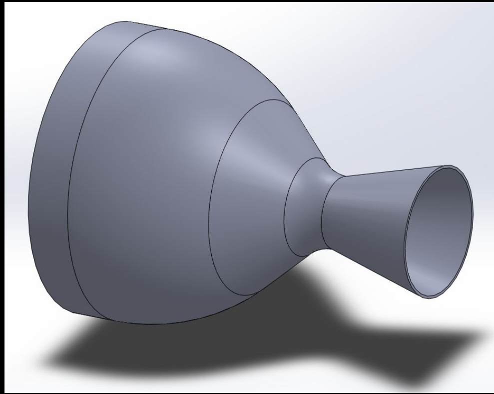
Initial Geometry



Geometry of thrust chamber with conical nozzle

Dc =	112.81	mm	b =	40.00	deg
R2 =	79.83	mm	R1 =	21.15	mm
L* =	1055.22	mm			
Lc =	104.61	mm	Lcyl =	17.43	mm
Dt =	28.20	mm			
Rn =	5.39	mm	Te =	15.00	deg
Le =	44.28	mm			
De =	51.55	mm			



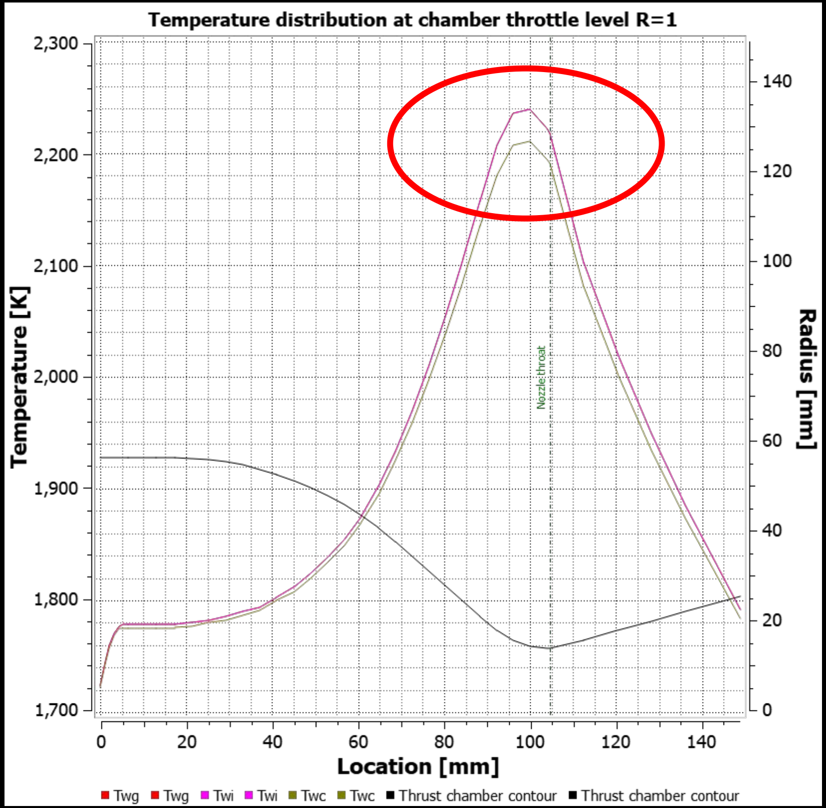


Initial Performance Outputs

- Thrust (opt): **1.743 kN**
- Isp (opt): **218.9 s**
- Mass flow: **0.8118 kg/s**

Thrust and mass flow rates

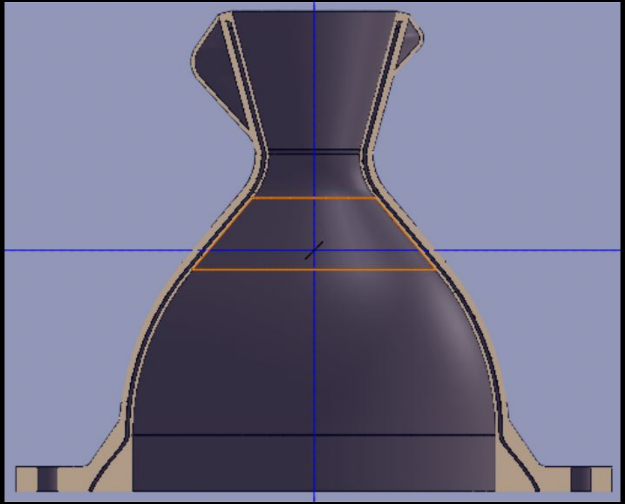
Chamber thrust (vac):	1.96156	kN
Specific impulse (vac):	246.38412	s
Chamber thrust (opt):	1.74304	kN
Specific impulse (opt):	218.93701	s
Total mass flow rate:	0.81183	kg/s
Oxidizer mass flow rate:	0.48710	kg/s
Fuel mass flow rate:	0.32473	kg/s

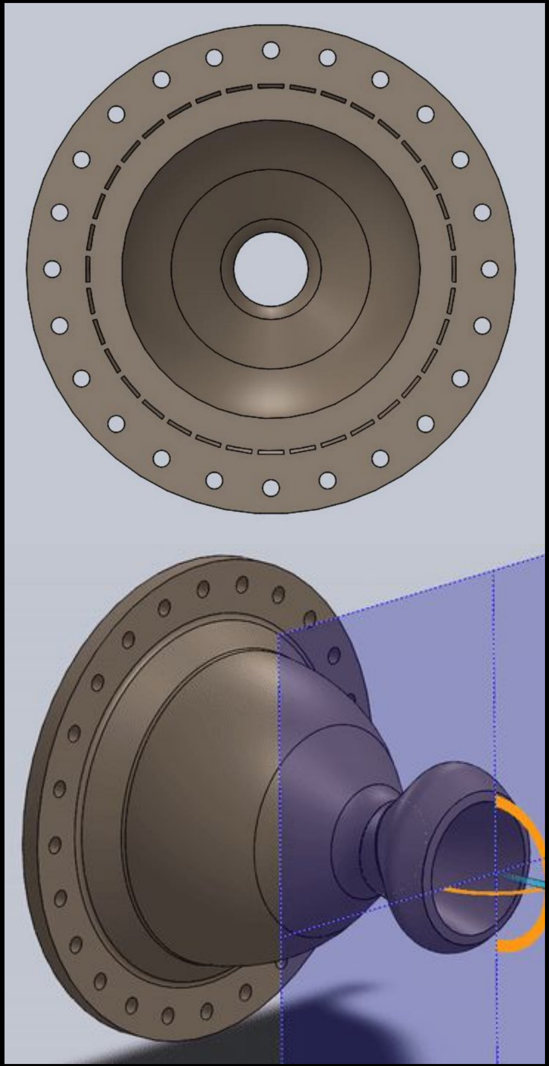


Initial Chamber CAD

Main Features

- Chamber shape outline
- Flange geometry
- Inlet manifold
- Regenerative cooling channels

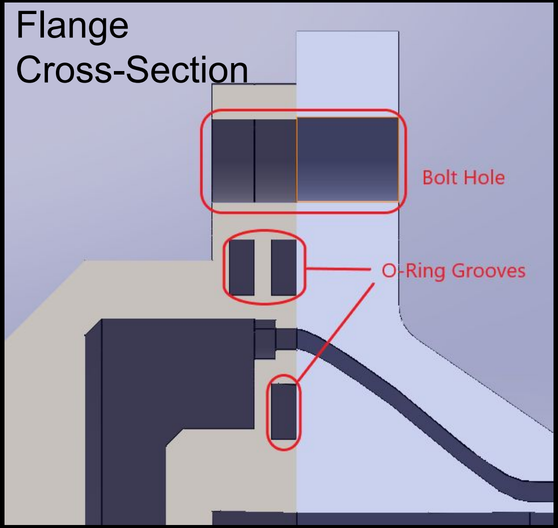


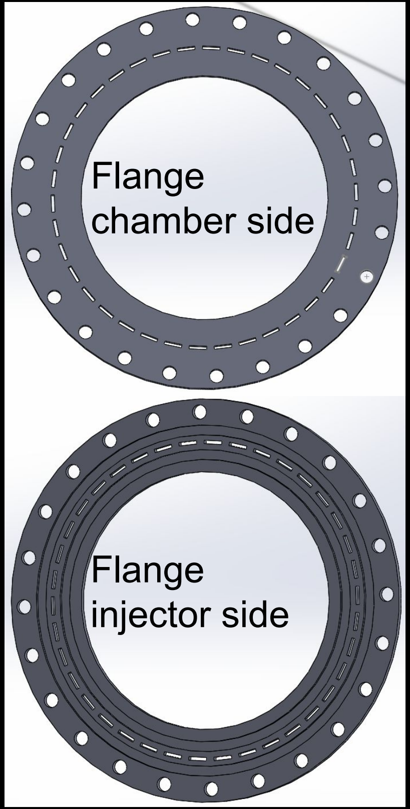


Flange Design

Challenges:

- Needed 3 Metal O-rings to stop coolant/fuel leak into atmosphere or chamber
- Must be wide enough to hold necessary number of bolts, the O-rings, and the coolant channels





Flange O-rings

Material considerations:

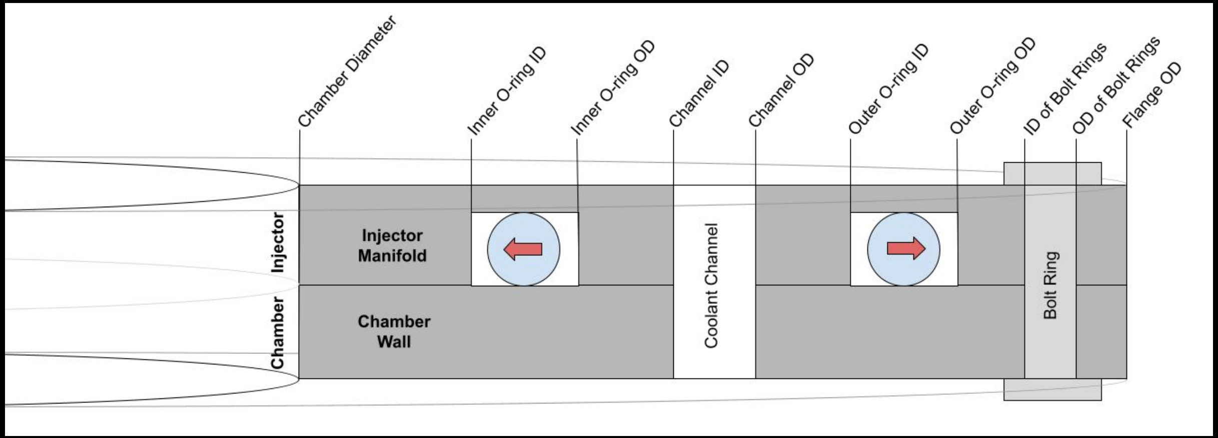
- High temperature (600K)
- High pressure (~400psi)
- LOX/RP1 compatibility

Choices:

- Plastic
  - Low temp tolerance
- Metal (Inconel 600)
  - High temp tolerance
  - Good OX resistance

Sizing:

- Fit between wall/channels/bolts
- Depends on o-ring type
- Nonstandard metal o-ring sizing
- ~10,000 lbf est. load per ring



Flange Bolt Design

- Created a bolt design spreadsheet
- Constraints:
  - Clamping force of bolts constrained by required clamping force on metal O-rings
  - Strength of bolts
  - Max bolt spacing
- Chosen Bolt Design:
  - 24 Grade 8 Steel ¼”-20 bolts
  - Bolt ring diameter of ~6.5 in.
  - Flange thickness of 0.25 in.

$$P_s = 2d+T \qquad (9\text{-}10)$$

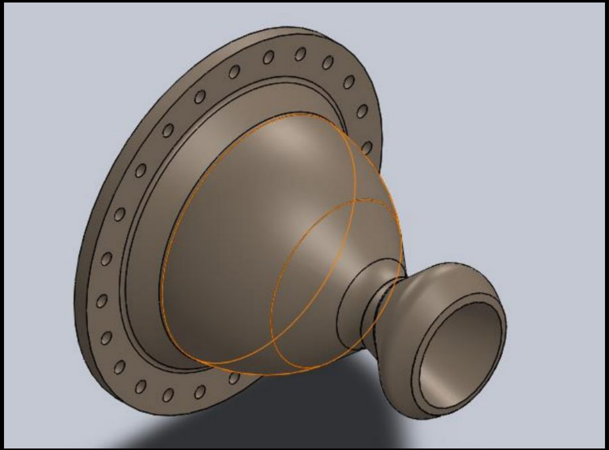
where P_s = maximum bolt spacing, in.; d = nominal bolt diam, in.; and T = flange thickness, in. The gener-

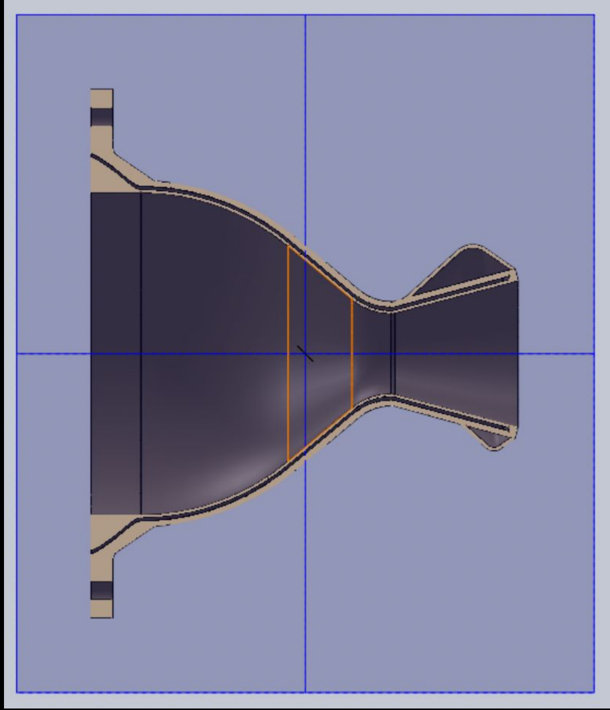
Bolt Circle Inputs	Metric Value	Metric Units	Imperial Value	Imperial Units
Vessel Info				
[VesselPressure] Vessel Pressure	2068427	Pa	300	psi
[VesselDiameter] Vessel Diameter	112.8	mm	4.44	in
[OuterORingOuterDiameter] Outer ORing Outer Diameter	152.40	mm	6.00	in
[PressureArea] "Pressure" area	0.018	m^2	0.7182	in^2
Bolt Setup				
[BoltQuantity] # of bolts	24	-	-	-
[BoltNominalDiameter] Bolt Diameter (nominal)	6.35	mm	0.25	in
Bolt Characteristics				
[MinorDiameter] Minor Diameter	4.83	mm	0.19	in
[PitchDiameter] Pitch diameter	5.52	mm	0.22	in
[BoltThread] Bolt Thread (per inch)	0.787	1/mm	19.99	1/in
[NutDiameter] Nut Diameter	12.7	mm	0.5	in
[BoltContactDiameter] Contact Diameter	9.525	mm	0.375	in
[BoltYieldStress] Bolt Allowable Yield Stress	1172.1	MPa	170000	psi
[FoSBoltTension] Factor of Safety – Bolt Tension	2	-	-	-
[FoSSeperation] Factor of Safety - Seperation	2	-	-	-
Assembly Torque				
[AppliedTorque] Torque Applied	6000	N*mm		

Outputs:	Value	Units	Value	Units
[PressureForce] Vessel pressure force	37731.2	N	8482.3	lbf
[BoltPressureForce] Pressure force (per bolt)	1572.13	N	353.4	lbf
Clamping Force (per bolt)				
[BoltAssemblyClampingForce] Clamp Force On Assembly	4303.0	N	967.4	lbf
[BoltPressurizedClampingForce] Clamp Force Once Pressure Applied	2730.9	N	613.9	lbf
Bolt Tension (per bolt)				
[AssemblyBoltTension] On Assembly	4303.0	N	967.4	lbf
[PressurizedBoltTension] Once Pressure Applied	5875.1	N	1320.8	lbf
Bolt Tensile Stress				
[StressArea] "Stress area"	21.0	mm^2	0.03	in^2
[AssemblyTension] Tension (Assembly)	204.6	MPa	29.7	ksi
[PressurizedTension] Tension (Once Pressure Applied)	279.3	MPa	40.5	ksi
Margins				
Tensile Margin of Safety	1.10	-	-	-
Seperation Margin of Safety	0.37	-	-	-
Bolt Shear Stress				
[AssemblyShearStress] On Assembly	2926.0	Pa	0.42	psi
[PressureizedShearStress] Once Pressure Applied	1353.9	Pa	0.20	psi

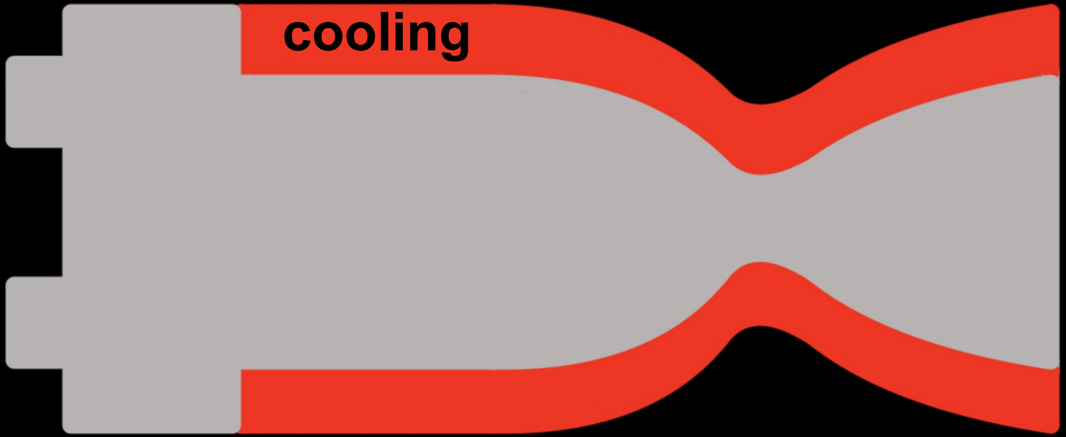
Future Work

- Finalize CAD
- Reevaluate bolt design for o-rings
- Run FEA for flange and chamber
- Finalize printing costs





Cooling Subsystem



Cooling Subsystem Overview

- Involves design of the chamber's regenerative cooling channels, cooling inlet manifold, film cooling, and material choices
- Design process was carried out as follows:
  a. Outline known design constraints
  b. Define driving parameters and decisions
  c. Create and analyze a design space for chosen parameters by modeling resulting temperature/structural profiles
     - Decisions informed and justified by research and modeling in RPA, MATLAB, and CEA.

Subsystem Requirements

Cooling subsystem requirements are defined to bound the design space for the cooling scheme, and ensure baseline functionality.

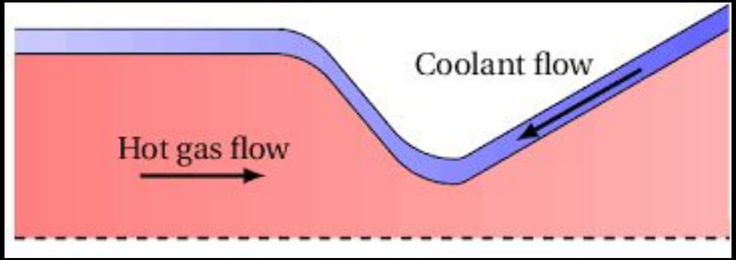
Cooling	Requirements	Parent Requirements	Verification Process
ESR.207	Chamber wall is kept below material limit (850Mpa at 950K) for repeated firing by cooling	ESR.100, ESR.102	Model analysis, CFD
ESR.208	Pressure drop through cooling circuit is below 300 psi	ESR.101, ESR.104	Model analysis, CFD
ESR.209	Cooling channels can be manufactured reliably and effectively	ESR.105	Review available tooling

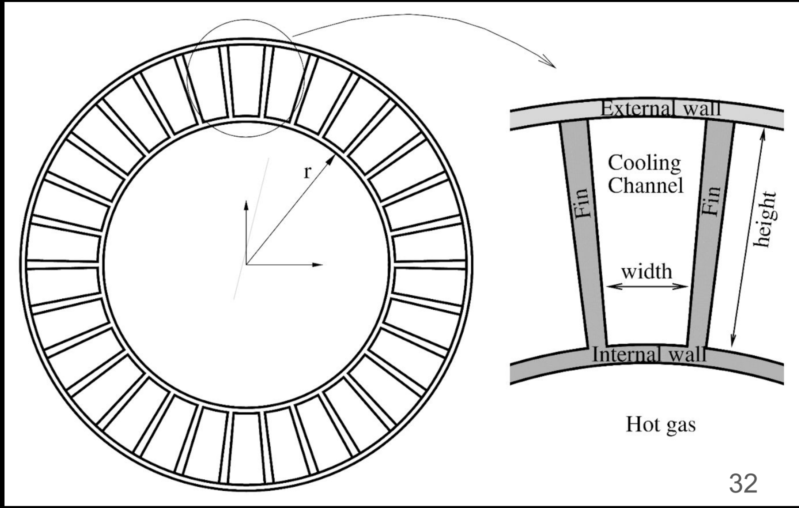
note: regenerative cooling was a predefined choice for the cooling scheme

Major Design Parameters

Biggest design challenge is the conflicting effects of cooling capability, manufacturability, and pressure drop.

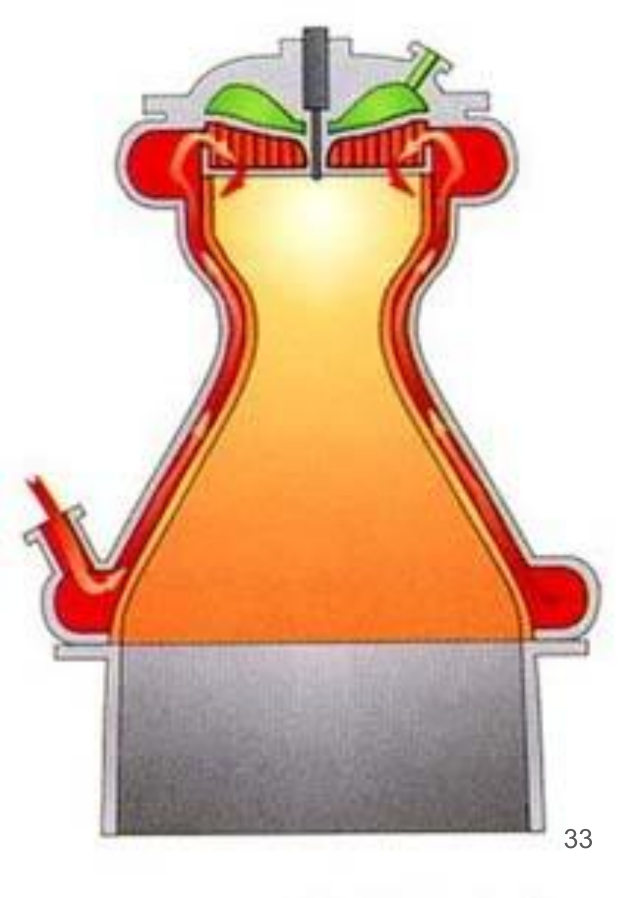
- Coolant choice
- Material choice
- Channel geometry
- Channel configuration (passes, entry point)
- Number of channels
- Chamber wall thicknesses





Choosing Coolant

- Fuel, oxidizer, external (water)
- Regenerative→RP-1 or LOX ?
  - LOX: reacts/combusts with hot metal
  - RP-1: less cooling, more stable
- Considerations for RP-1:
  - Boiling temp @.1MPa = **525K** (conservative)
  - Carbon deposits can aid in cooling
  - Properties change with temp



Material Trades

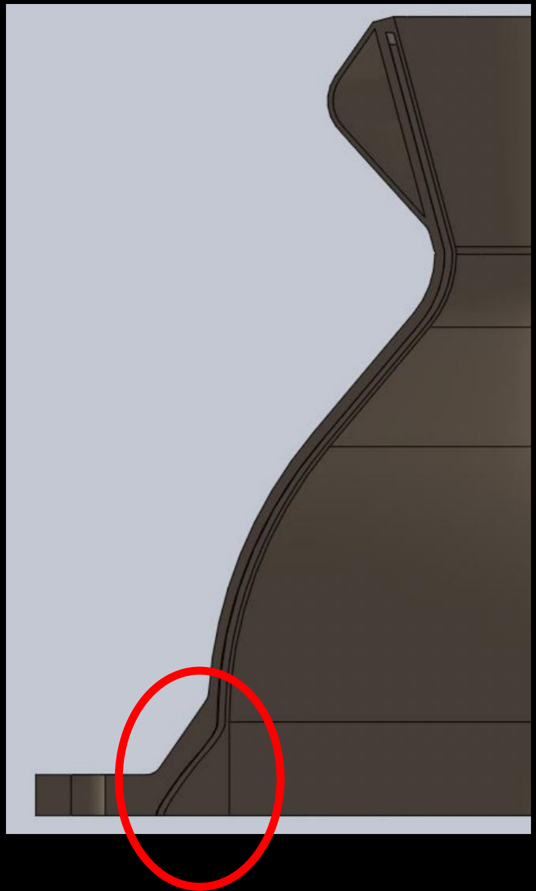
- Need material with **high strength at high temperatures**
  - Up to ~900K wall temp at throat
- Also need to consider material conductivity

Fathom's DMLS Inconel 718	
Properties at ~900°K	
Melting Temp (°K)	~1700°K
Conductivity (W/m*K)	~20 W/m*K
.2% Yield Strength (MPa)	862 MPa (min) 970 MPa (typical)
Max operating temp for parts under load (°K)	923°K
Modulus of Elasticity (ksi*10^3)	23.7 ksi*10^3

**Data from Fathom material data sheet and Inconel alloy 718 (Sept 07) Web.qxd (specialmetals.com)

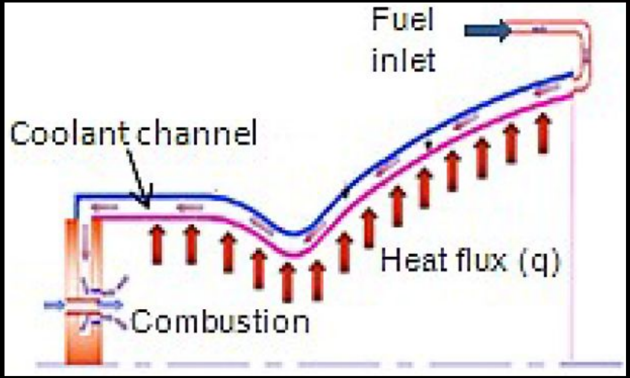
Manufacturing Considerations

- From *Fathom* Inconel 718 Data:
  - Minimum wall thickness: **.4mm**
  - Part accuracy: **.04-.06mm**
  - Z-direction surface roughness: **.02-.05mm**
- 45° overhang constraint
- Need to move channels out for flange joint
- (ESR.209)



Channel Shape & Configuration

- Chose **single pass design:** Fuel enters at nozzle exit
  - Simpler design
  - Lower pressure drop
  - Lower coolant boiling risk
- Designing **rectangular channels**:
  - Easier to model fin effects
  - Design cleared by manufacturer (ESR.209)



1D Heat Transfer Model

Conduction through inner wall

$$q = -\frac{k}{d}(T_2 - T_1)$$

Convection on either side of inner wall

$$q = h(T_{adiab,wall} - T_s)$$

- Hot side boundary layer (Bartz)

$$h_g = \left[\frac{0.026}{D_t^{0.2}}\left(\frac{\mu^{0.2}C_p}{Pr^{0.6}}\right)_{ns}\left(\frac{(p_c)_{ns}g}{c^*}\right)^{0.8}\left(\frac{Dt}{R}\right)^{0.1}\right] \times \left(\frac{A_t}{A}\right)^{0.9}\sigma \qquad (4\text{-}13)$$

- Coolant side boundary layer (Kerosene)

$$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \quad \text{at } Re > 2 \cdot 10^4$$

$$Nu = \text{Nusselt number} = \boxed{h_c d/k}$$

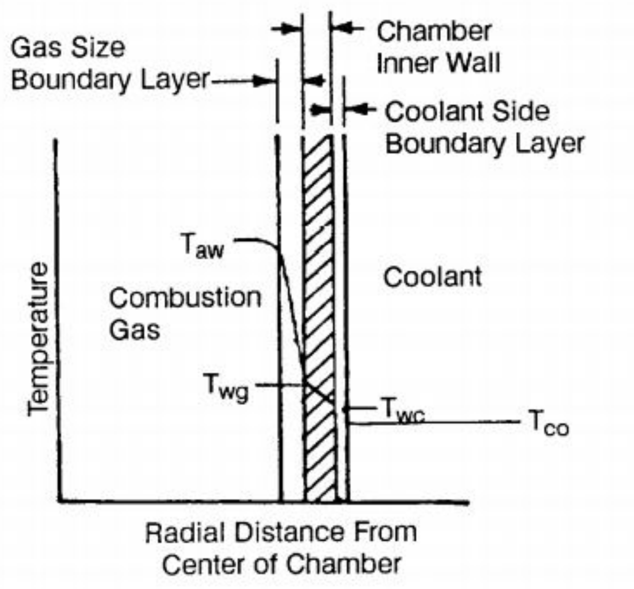
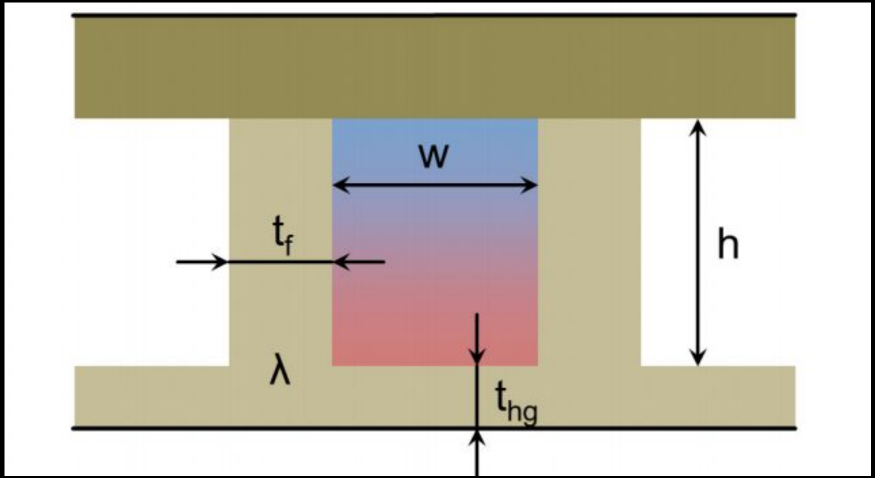


Fig. 4-30 Heat transfer schematic for regenerative cooling.

Channel Sizing Considerations

- Minimize wall thickness
  - Lower dT better for thermal stress
  - Constrained by manufacturing limit
- Keep $T_{aw} - T_{wg}$ high
  - High h_c/h_g ratio
  - High coolant velocity
  - Lower chamber pressure
- Design many small channels
  - Increased fin efficiency
  - Geometric limitation at throat
  - LARGE dp if channels too small



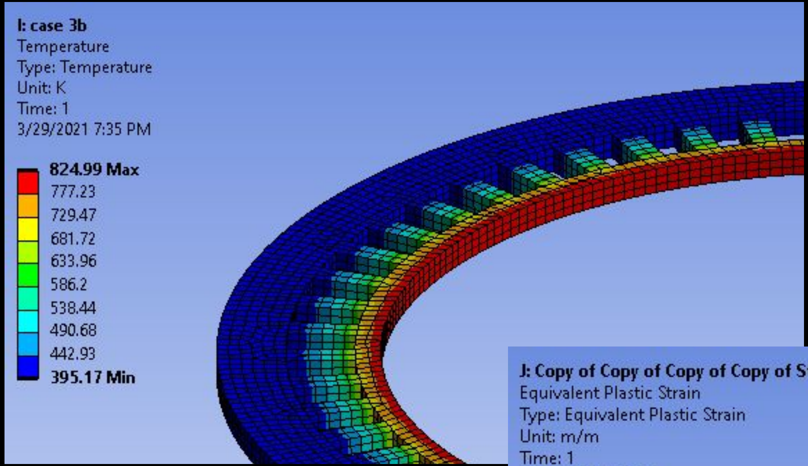
Stress Considerations

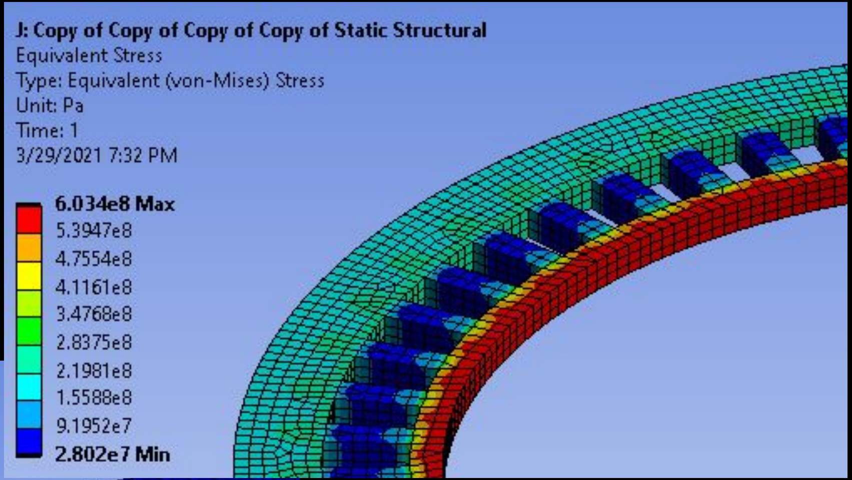
- Thermal Stresses dominate pressure stresses
  - Scales inversely with wall thickness
- Linear hand calcs did not give accurate prediction of expected stresses
- Non-linear FEA (thermal + structural) model performed at throat
  - Yielding expected on inner wall
  - Good strength margins on outer wall
- Material limit for Inconel 718: **862MPa** (minimum)

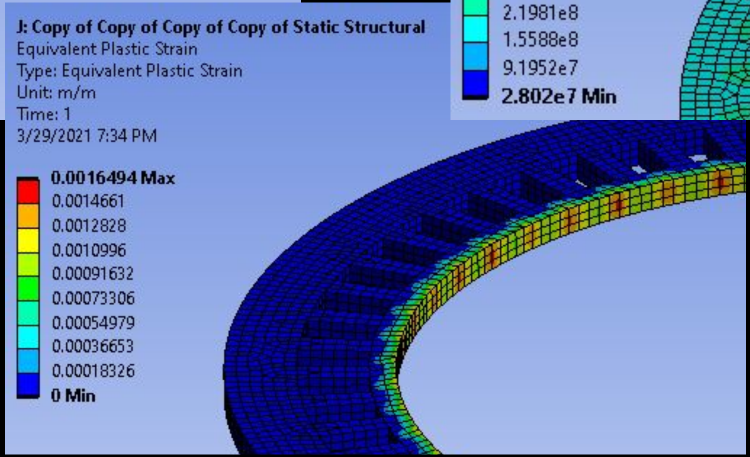
Calculating Thermal Stress on Inner and Outer Material		-		
[thickness_1] Outer Cooling Manifold Wall Thickness	0.003	m	0.12	in
[thickness_2] Inner Wall Thickness	0.001	m	0.04	in
[thickness_l] Cooling Channel Thickness	0.0015	m	0.06	in
[Wall_length] Inner Wall Section Length	0.001	m	0.04	in
[E_1] Outer Wall Young's Modulus	2.86E+11	Pa	4.15E+07	psi
[E_2] Inner Wall Young's Modulus	2.86E+11	Pa	4.15E+07	psi
[T_0] Assembly Temperature	300	K	80.33	F
[T_i] Coolant Temperature	300	K	80.33	F
[nu] Poisson's Ratio	0.3	-		
[h_i] Coolant Heat Transfer Coeff	5000	W/m^2/K		
[h_g] Hot Gas Heat Transfer Coeff	1500	W/m^2/K		
[alpha_1] Thermal Expansion Coeff Outer Wall	1.45E-05	1/C		
[alpha_2] Thermal Expansion Coeff Inner Wall	1.45E-05	1/C		
[T_aw] Adiabatic Wall Temp	2500	K		
[T_wc] Cool Side Wall Temp	710			
[T_wh] Hot Side Wall Temp	1003	K		
[k_2] Conduction Coeff Inner Material	15	W/m/K		
[q_2] Heat Transfer Through Inner Wall	2357142.857	W/m^2		
[P_g] Chamber Pressure	2068427.19	Pa	300	psi
[P_l] Coolant Pressure	4136854.38	Pa	600	psi
[Margin of Safety] Margin of Safety (Percentage)				

Stress Outputs				
[sigma_1] Outer Wall Stress	8.23E+02	MPa	1.19E+05	psi
[sigma_2c] Inner Wall Stress (Coolant Side)	-1.97E+03	MPa	-2.86E+05	psi
[sigma_2h] Inner Wall Stress (Hot Side)	-2.90E+03	MPa	-4.21E+05	psi
[sigma_2buckle] Inner Wall Buckling Stress	9.41E+05	MPa	1.36E+08	psi

Stress Considerations (cont.)

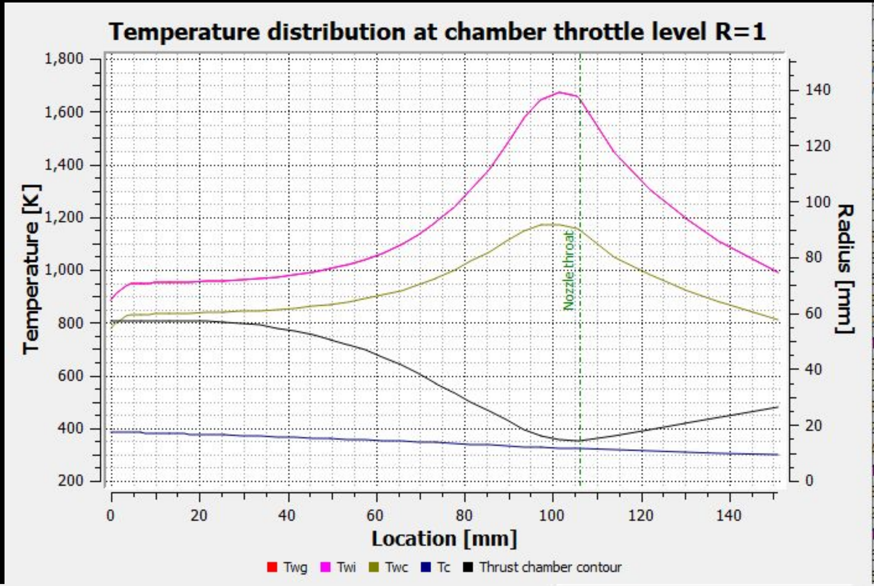




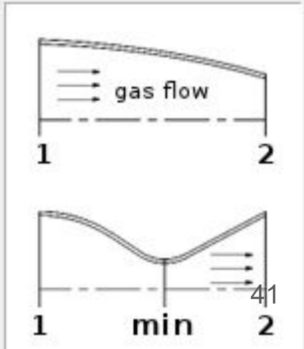


RPA Engine Modeling

- Rocket Propulsion Analysis
- Define engine, get performance
- Regenerative, film, radiative cooling
- Case studies of channel geometry
- Referenced results with paper detailing RPA's methodology: [LINK]

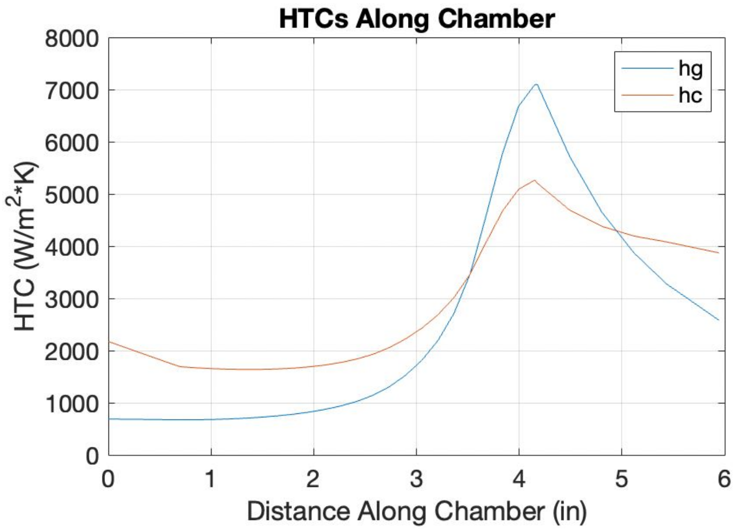


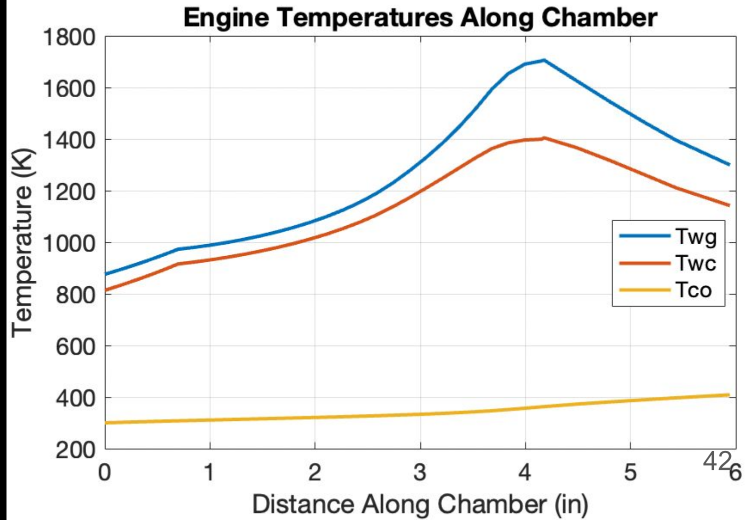
Rib height (hc1):	1.5	mm
Rib height (hc min):	1.5	mm
Rib height (hc2):	1.5	mm
Width of channel (a1):	1.5	mm
Width of channel (a min):	1.5	mm
Width of channel (a2):	1.5	mm
Number of channels:	40	



MATLAB Regen Engine Model

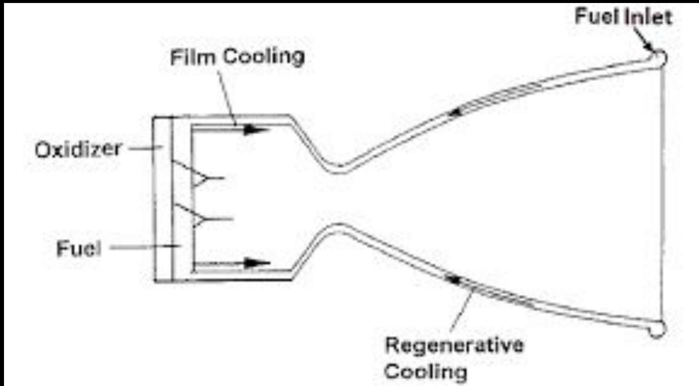
- Models regenerative cooling
- Input engine, coolant, cooling design
- Outputs properties array at location
- Compare results with RPA
- Calculates Channel pressure drops

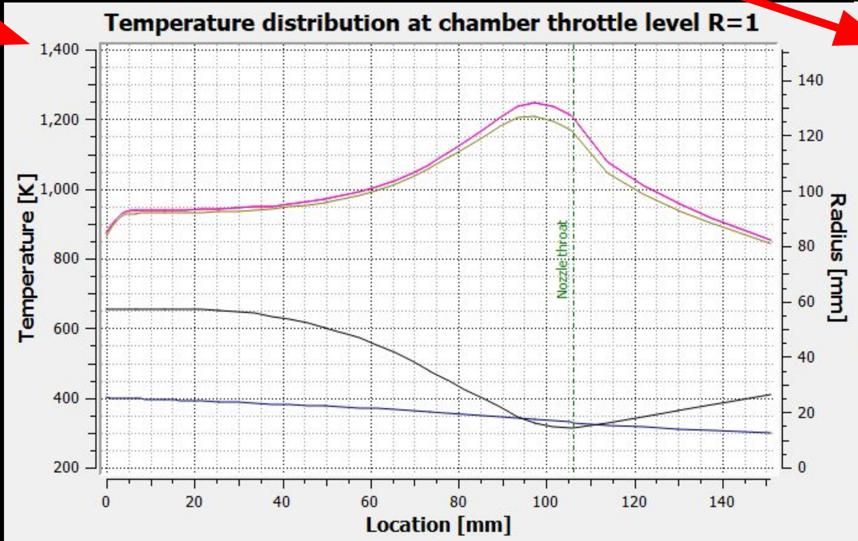


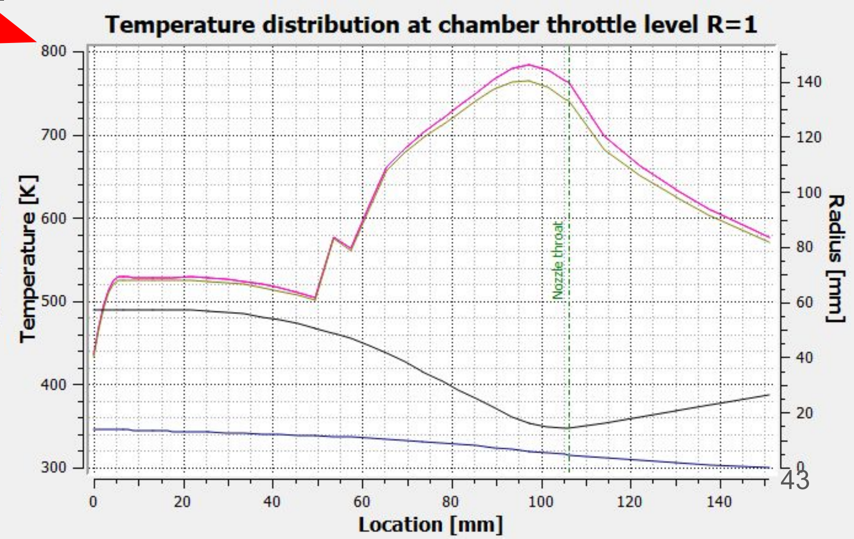


Film Cooling Motivation

- Complement regenerative cooling
- Relatively simple
- Easily modeled



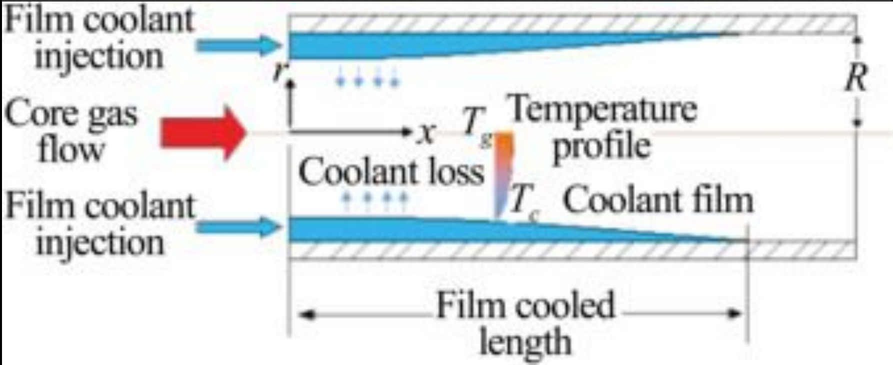


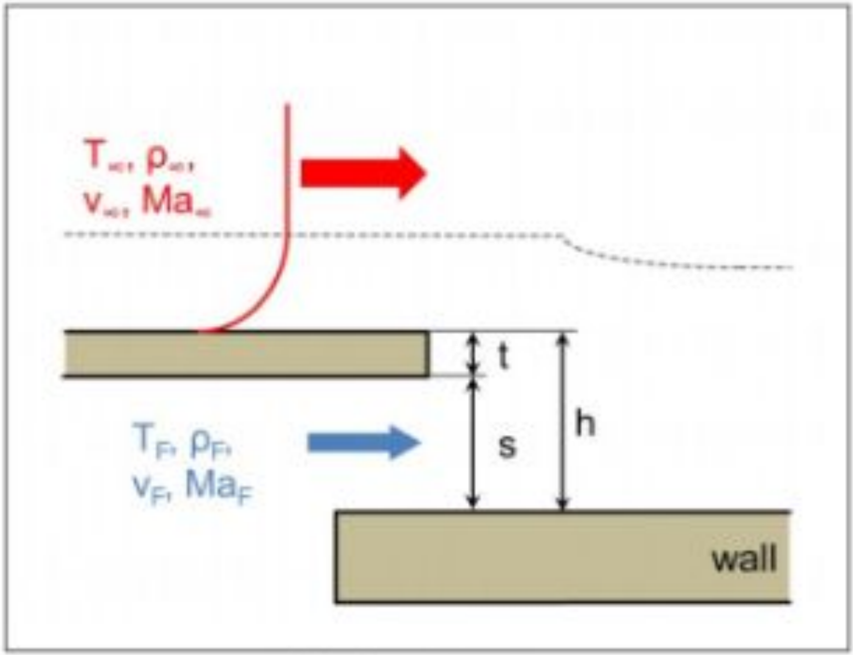


Film Cooling Considerations

- Film cooling effectiveness
- Geometry
- Coolant mass flow
  - Using **5%** of total mass flow

$$\eta_{cool} = 0.6 \left(\frac{x}{F \cdot s}\right)^{-0.3} \left(Re_s\, F\, \frac{\mu_{cool}}{\mu_{\infty}}\right)^{0.15}$$



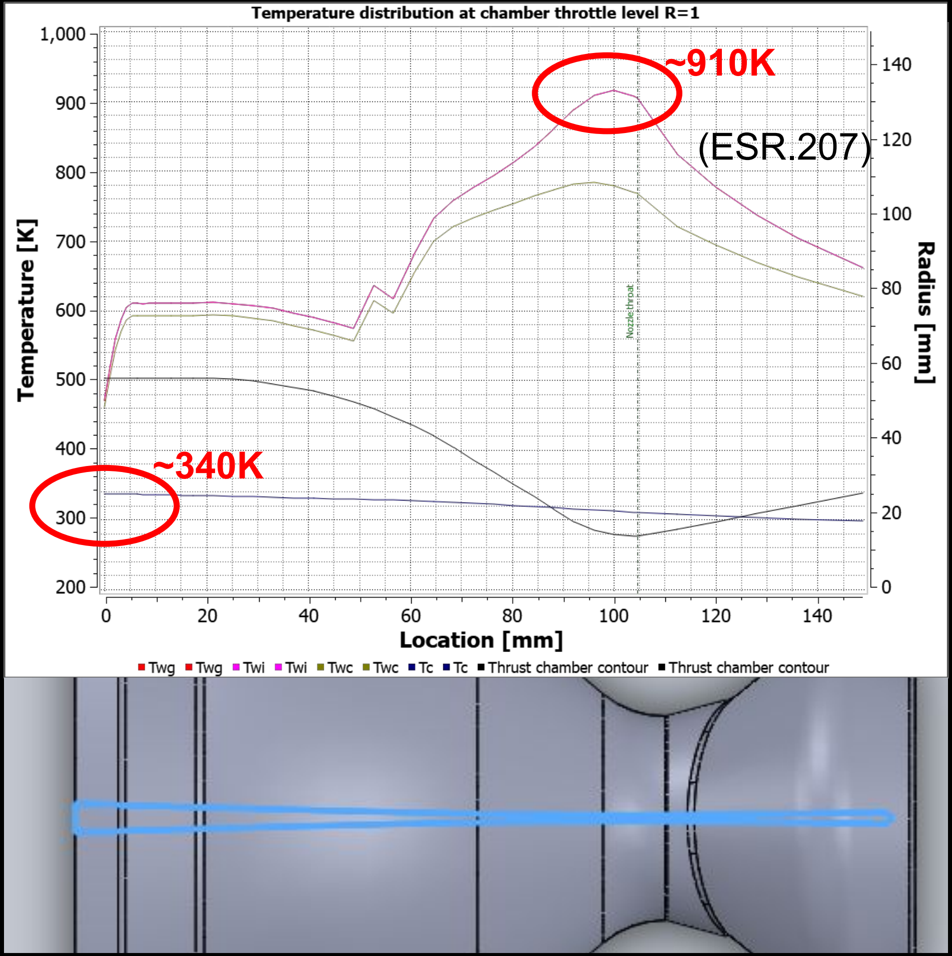


(b) slot injection

**From "Investigation on Heat Transfer in Small Hydrocarbon Rocket Combustion Chambers" - Kirchberger

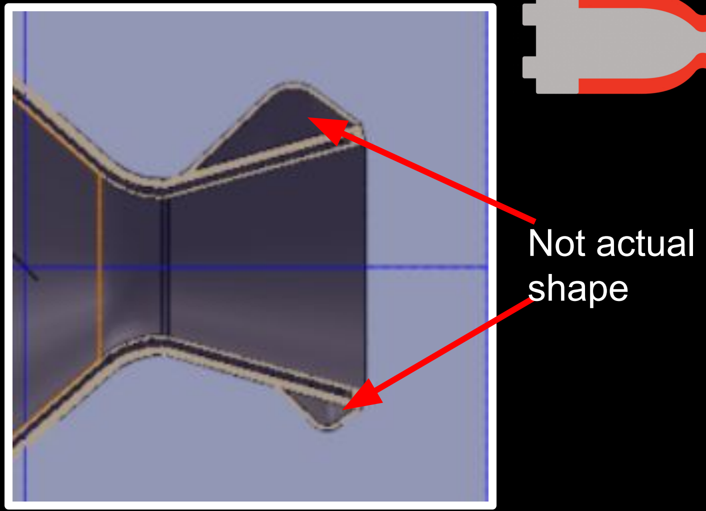
Chosen Channel Shape

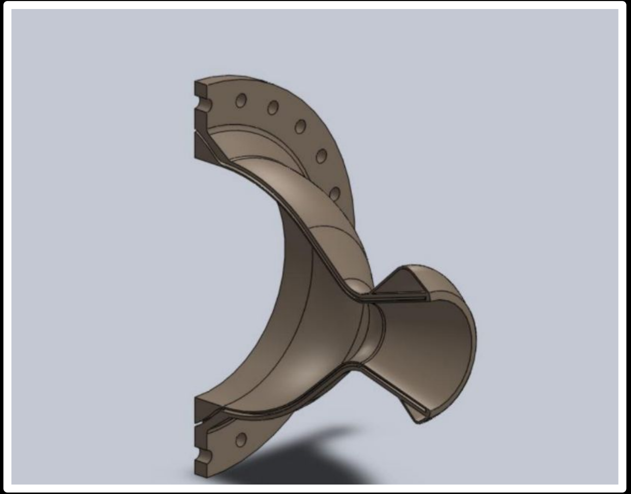
- # of Channels: **54**
- Rib Thickness: **.8 mm**
- Wall Thickness: **.75 mm**
- Channel Height Profile: **[2 mm, 2 mm, 2 mm]**
- Channel Width Profile: **[4 mm, 1 mm, 2 mm]**
- Coolant Pressure Drop: **131psi** (ESR.208)
- Film Cooling Flow Rate: **5% of total (~.04kg/s)**



Inlet Manifold Design

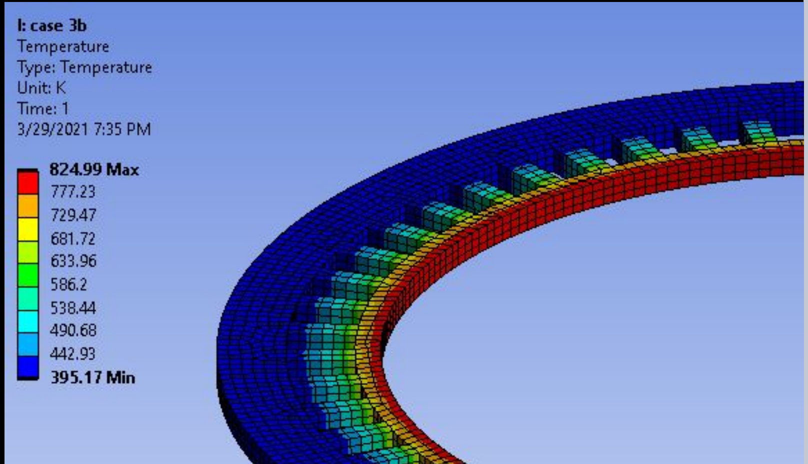
- **Goal**: evenly feed each coolant channel
- Shape of feed cross section
  - 45 degree manufacturing constraint
  - Resembles USC Balerian engine
- Variation of cross-sectional area
  - From relevant literature: $D= d_1{*}k^{(7/19)}$
    [“Manifold Design for Micro-Channel Cooling With Uniform Flow Distribution”]
  - Chose area to minimize pressure drop and fit on the nozzle

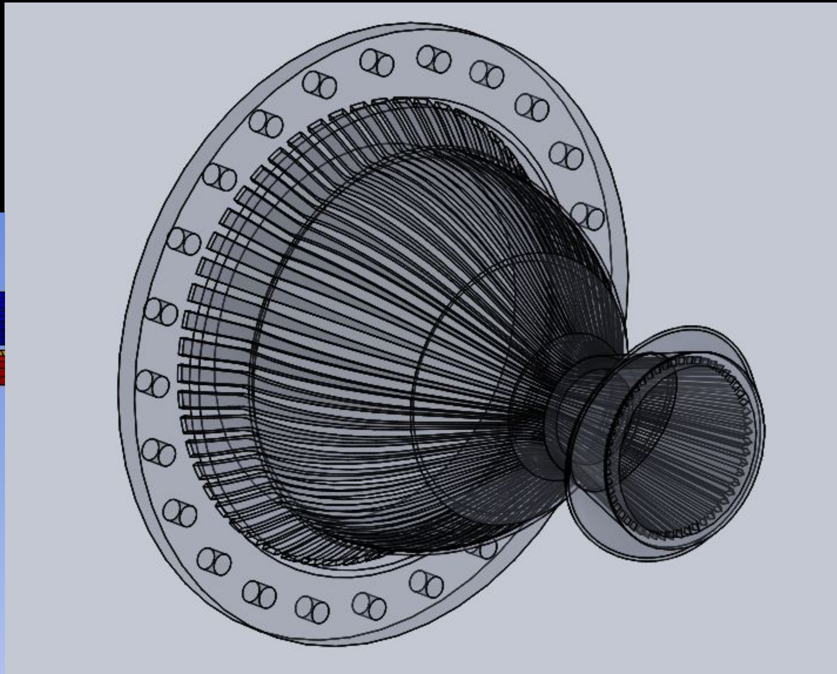




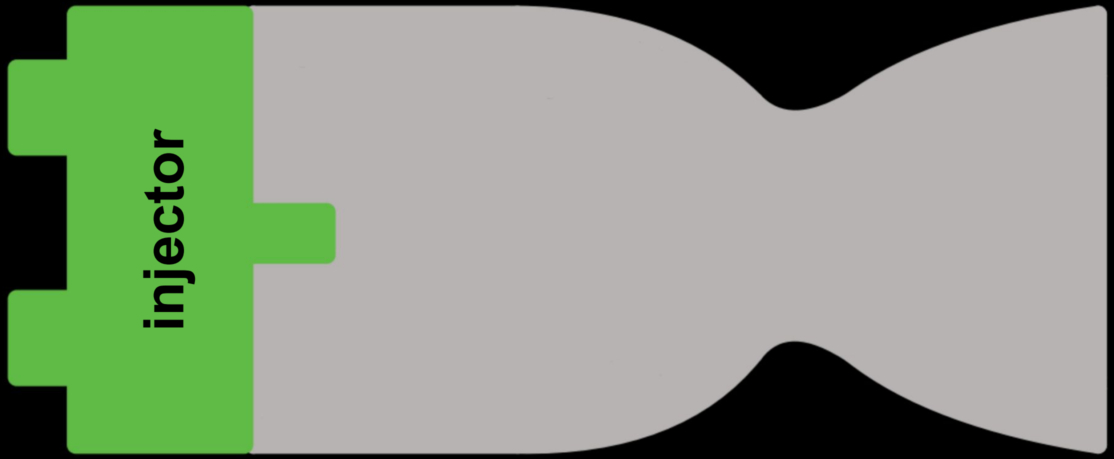
Future Work

- Verify thermal stress estimates
- Finalize chamber CAD
- Finalize manifold design
- Develop simple CFD of channel
- Finalize film cooling sizing





Injector Subsystem



Injector Subsystem Overview

- **Function:** Inject the propellants into the chamber for optimal combustion, preventing instabilities and mitigating thermal issues.
- Design process was carried out as follows:
  - Selecting an injector element type via mini trade study
    - Satisfying system requirements
  - Discussing major decisions in pintle injector design
  - Defining geometrical parameters based on upstream inputs and requirements of the subsystem
  - Designing component scheme and initial CADs

Subsystem Requirements

Injector requirements are defined to ensure the engine is capable of generating the mission thrust while minimizing structural damage.

Injector	Requirements	Parent Requirements	Verification Process
ESR.200	Propellant is injected to reduce chamber wall heating	ESR.102, ESR.103	Hand calcs, Research
ESR.201	Propellant is sufficiently mixed and atomized before desired combustion zone	ESR.104	Hand calcs, Research
ESR.202	Propellant pressure drop is sufficient to maintain stable combustion	ESR.104	Hand calcs, Research
ESR.203	Propellant is injected at the specified mass flow rates	ESR.101	Cold flow test

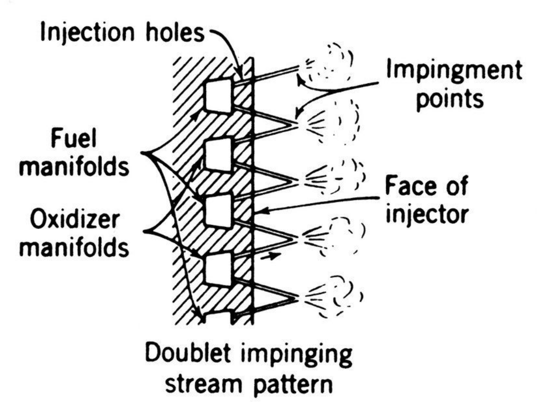
Subsystem Requirements

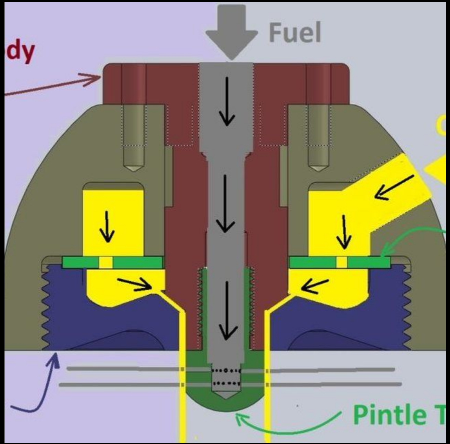
Injector requirements are defined to ensure the engine is capable of generating the mission thrust while minimizing structural damage.

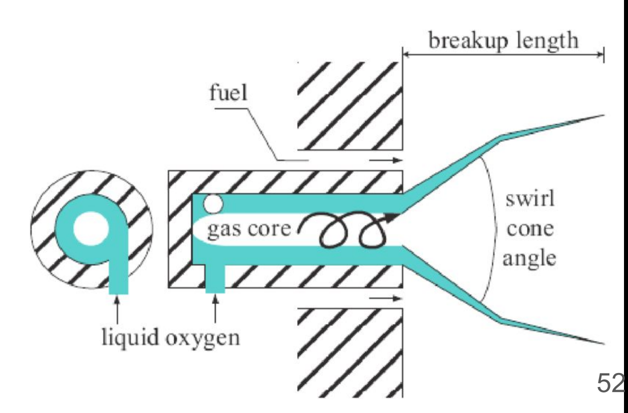
Injector	Requirements	Parent Requirements	Verification Process
ESR.204	Injector remains below material temperature limit for repeated firing	ESR.102, ESR.103	Hand calcs, Research
ESR.205	Injector sealing surfaces can withstand expected pressures	ESR.102, ESR.103	Hand calcs, Research
ESR.206	Injector elements shall be sized within manufacturing limits	ESR.105	Review available tooling

Injection Scheme Trade Study

- Injector design options:
  - Impinging jet
  - Pintle
  - Coaxial swirl
- Trade study considerations:
  - Machinability (20%)
  - Complexity of research (25%)
  - Atomization & mixing (10%)
  - Cooling (20%)
  - Research interest (25%)







Pintle Injector

The pintle injector design provides some unique advantages:

- Inherently simple design
- Combustion stability
    - Curved combustion zone
- Cooling effects
    - Recirculation zones (ESR.200)

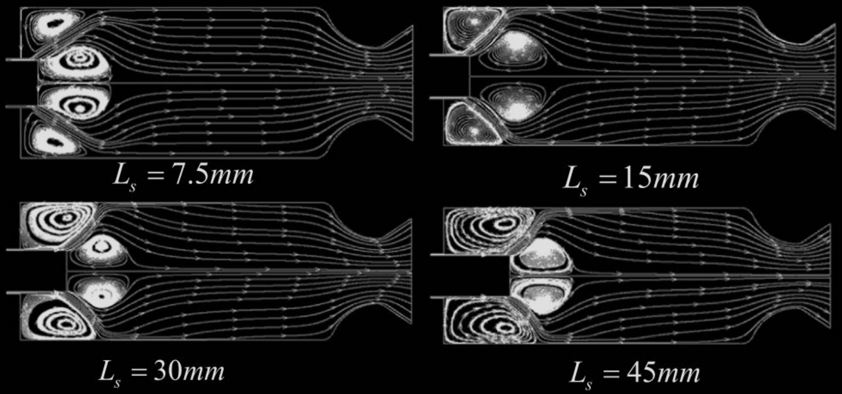


Fig. 11. Streamline for different L_s.

Pintle Tip Outlet Design

Drilled hole vs. Full annulus (at Pintle tip)

- Full annulus
  - Throttle by changing the opening area
  - Possibly require swirled flow
- Drilled hole
  - Throttle by changing skip distance & mass flow

Ox-centered injection with fuel film cooling

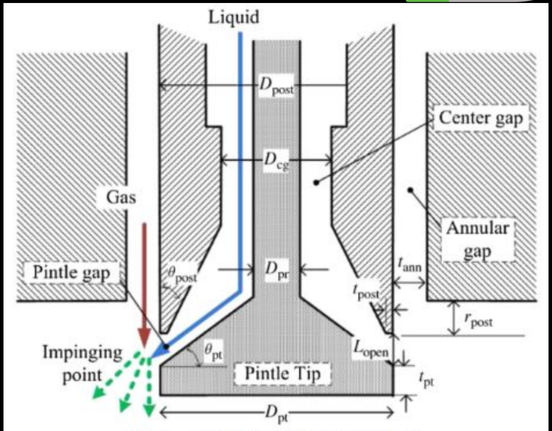
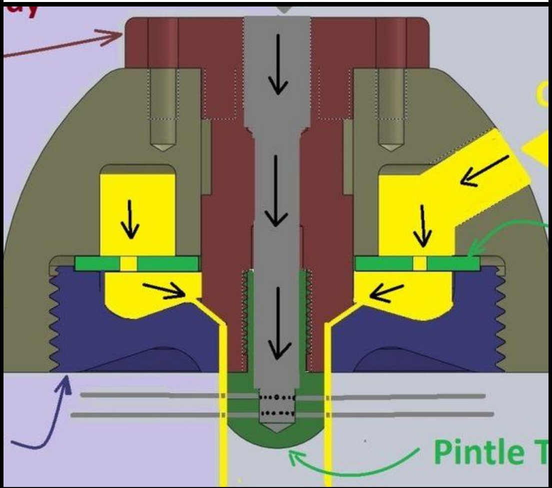


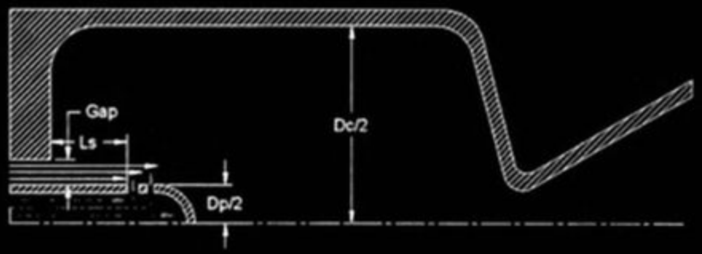
Fig. 1 Schematic of the pintle injector.

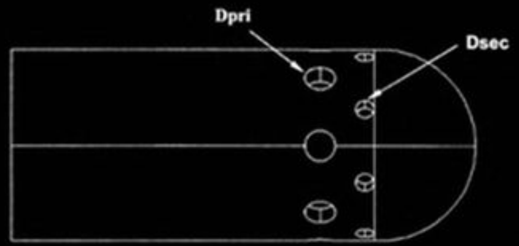


Major Design Considerations

Primary considerations of a pintle injector design revolve around appropriate mixing/combustion and minimizing damage to chamber

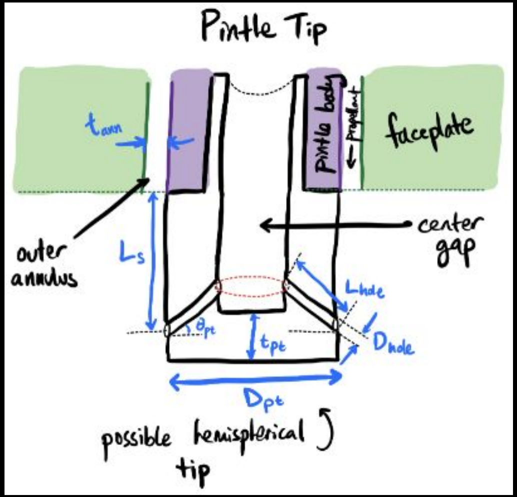
- System Mass Flow Rates (ESR.203)
- Combustion Chamber Pressure
- Total Momentum Ratio (TMR)
  - Around 0.1-0.2 to optimize performance
- Chamber to Pintle Diameter Ratio (Dc/Dp)
  - Typically 3-5
- Vaporization Length





Pintle Sizing & Geometry

- Pintle diameter
  - Based on chamber diameter & Dc/Dp
- Pintle angle
  - Able to achieve desired TMR with 0 angle
- Hole diameter & Annulus diameter
  - Calculated value based on desired TMR, mass flow & pressure drop
  - (ESR.203)
- Manufacturing constraints
  - Reasonable number of holes
  - Smallest drill bit size
  - (ESR.206)

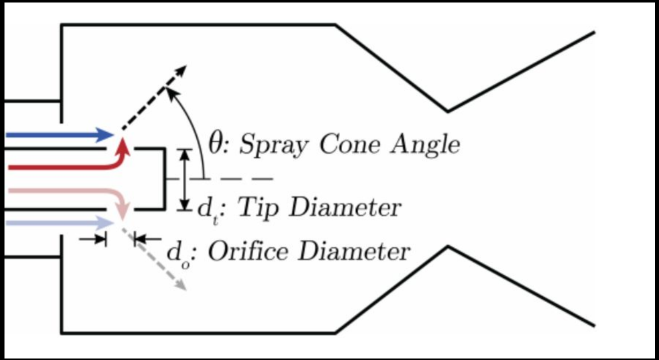


$$\frac{\rho_f V_f^2 t d}{\rho_o V_o^2 \frac{\pi d^2}{4}} = \mathrm{TMR}$$

$$A_i = \left(\frac{\dot{m}}{c_d}\right) \sqrt{\left(\frac{1}{2\rho}\right) \frac{1}{(P_{i,f} - P_c)}}$$

Stability & Combustion Considerations

- Pressure drop considerations
  - Make sure Delta_P > 100 psi for both ox and fuel
  - (ESR.202)
- Calculated atomization characteristics
  - Droplet size (SMD): ~0.1-0.2 mm
  - Spray angle: ~35-40 degrees
  - Atomization distance: ~50 mm (ox) ~ 130 mm (fuel)
  - (ESR.201)



$$D_{32} = 10^3 (L_{\text{open}})(\xi^{-1}) \exp[4.0 - q(We^{0.1})]$$

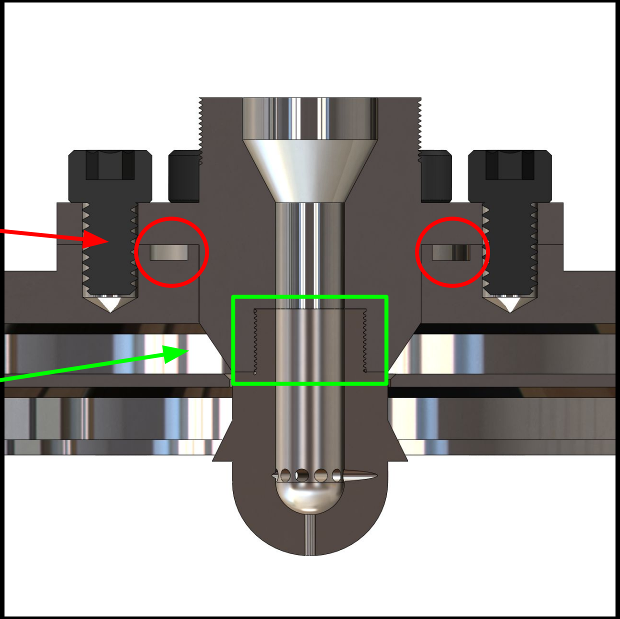
$$x^* = \left(\frac{D_{32}^2}{4}\right)\left[\frac{u_{d0}}{\sqrt{\gamma_c R_c T_c}} + \frac{3}{\Gamma}\left(\frac{A_t}{A_c}\right)\frac{S}{10}\right]\frac{c_{p,c}\rho_{\text{liq}}}{k_c}\frac{\sqrt{\gamma_c R_c T_c}}{\ell n(1+B)}\frac{1}{(2+S)}$$

Cooling & Thermal Considerations

- Material Choice
  - Copper Alloy Pintle tip
    - Higher thermal conductivity
  - 304L Stainless Steel
    - Higher melting point
- LOX cooling bypass flow at Pintle tip
- Deflected annular flow
  - Moves the actual combustion farther from the pintle tip
- (ESR.204)

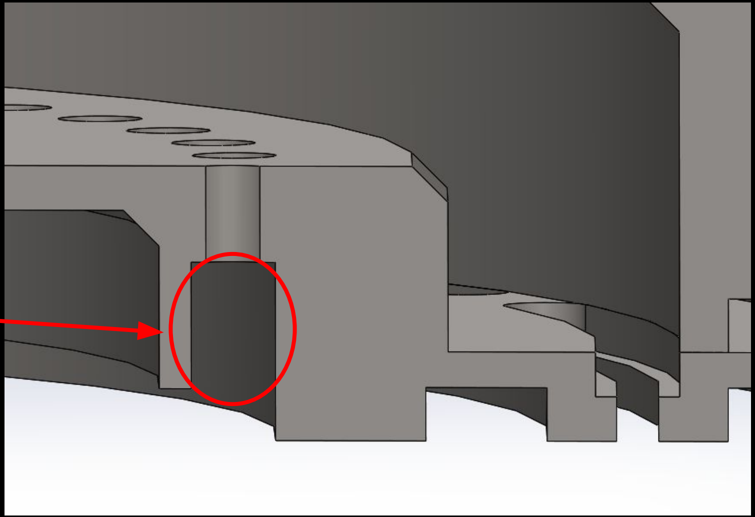
Sealing Surfaces

- Pintle Assembly
  - Pintle Body
    - Plastic O-ring
    - No LOX contact
    - Not heated
  - Pintle Tip Threading
    - PTFE Tape
  - (ESR.205)
- Manifold Assembly
  - Metal O-rings
  - Discussed on earlier slide
  - (ESR.205)

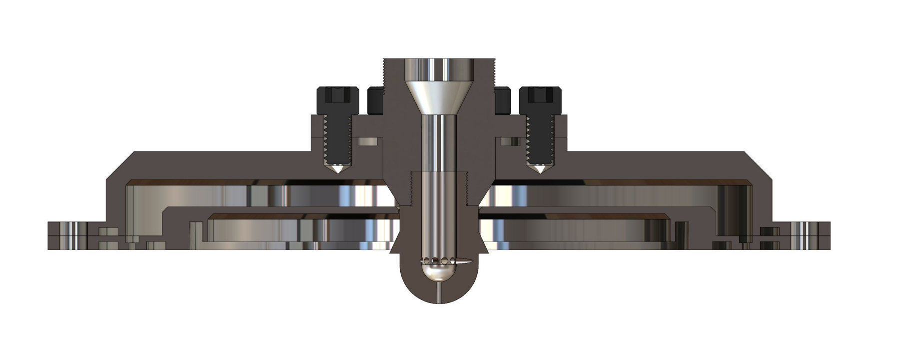


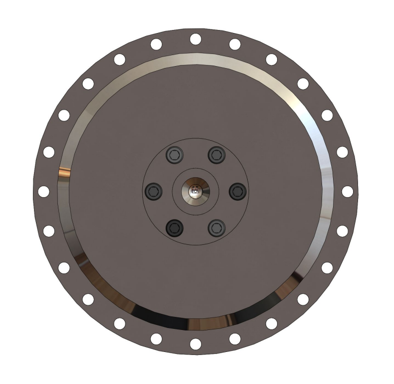
Manifold Design

- Inlets fuel from regenerative cooling channels
- Drilled hole film cooling
  - No possible annulus
  - Annular extension
- Exact manifold volume undetermined as of yet
  - Unsure of desired velocity profile

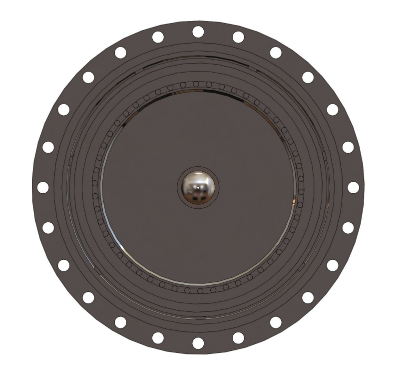


Initial CAD





Feed-system side



Chamber side

Pintle Initial Design Choices

Summary of initial design choices

TMR	0.25
Pintle angle	0°
Dc/Dp	6
Skip Distance	0.75
Pressure drop	20%
Hole length factor (L/d)	3
Number of holes (as manufactured)	11

Future Work

- Research more Pintle tip cooling
- Research manifold design
- Verify cooling effects
    - Maybe CFD
- Manufacture injector assembly
- Cold flow test

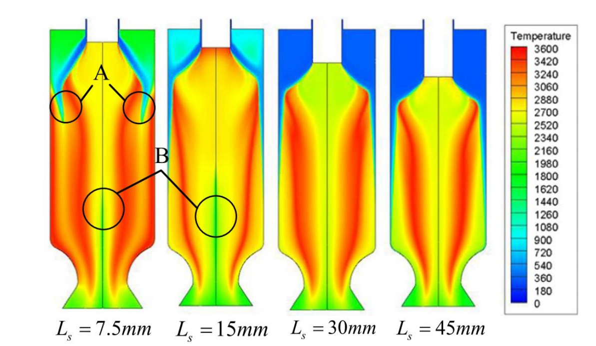
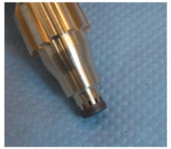
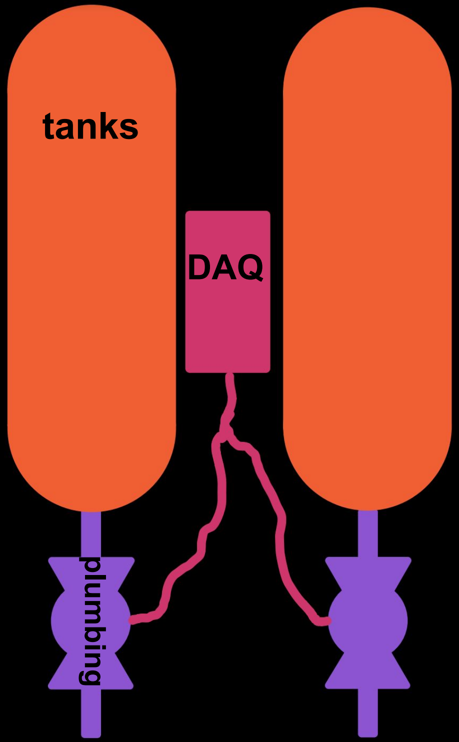


Fig. 13. Temperature fields for different L_s.

Injector	Description	Figure
1	Shortened LOX passage and reduced skip ratio	
2	Same as injector 1, incorporates active cooling of the pintle tip	
3	Use of a LCH_4 deflector for displacement of the impingement point	
4	Same as injector 2, but with a cooled pintle tip	

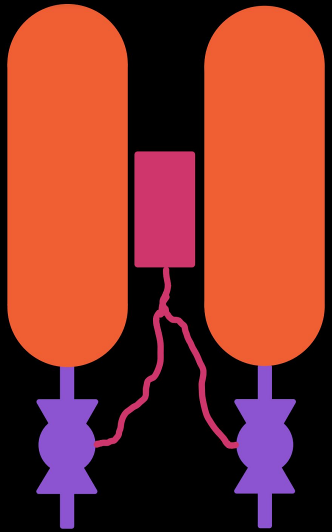
Feed System



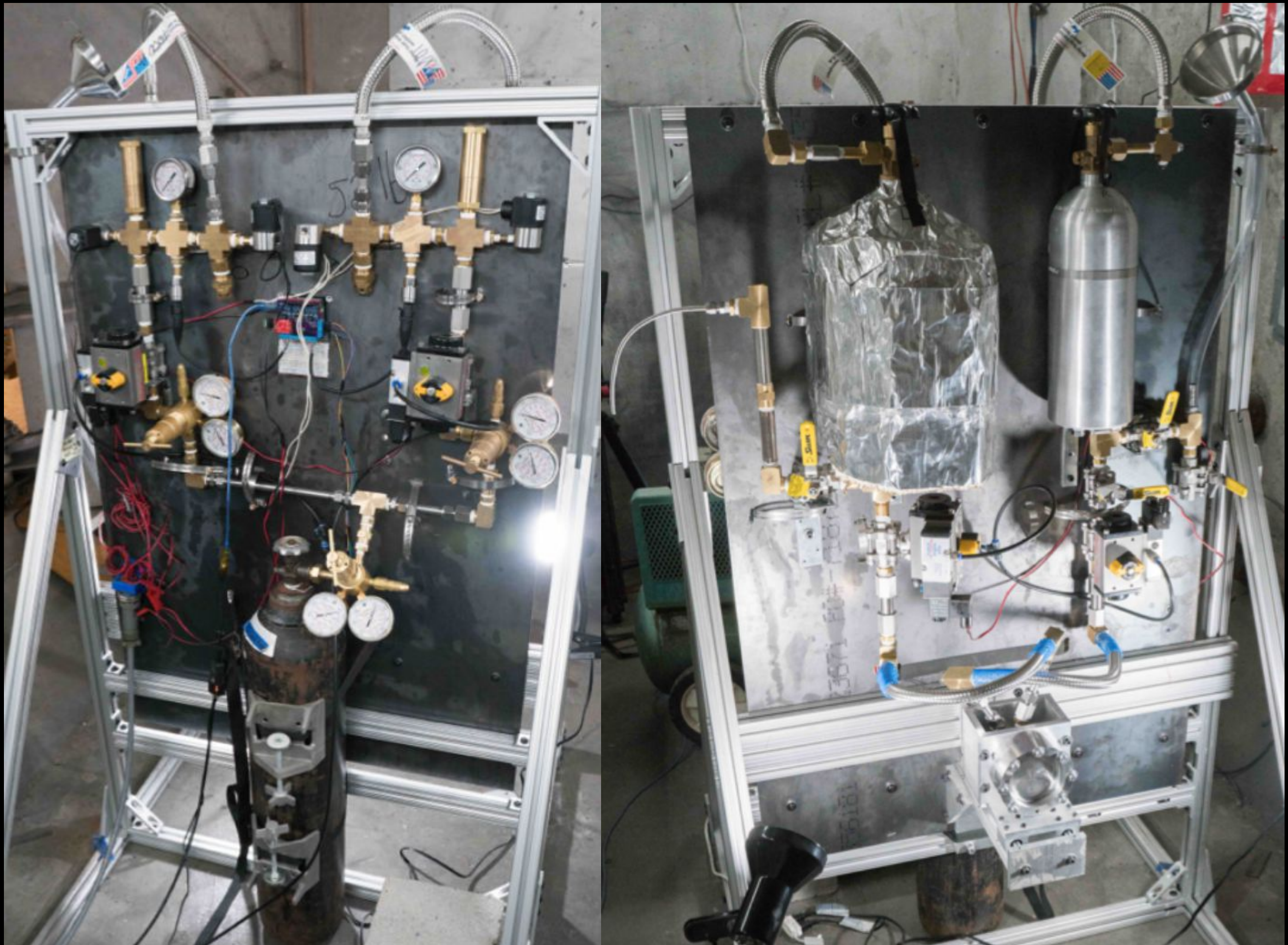
Feed System Overview

Function: Feed propellant to the engine at proper flow rate/pressure, allow safe & controlled operation, and log accurate data for all testing.

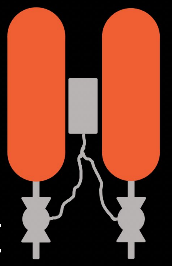
Subsystems: tanks, plumbing, DAQ



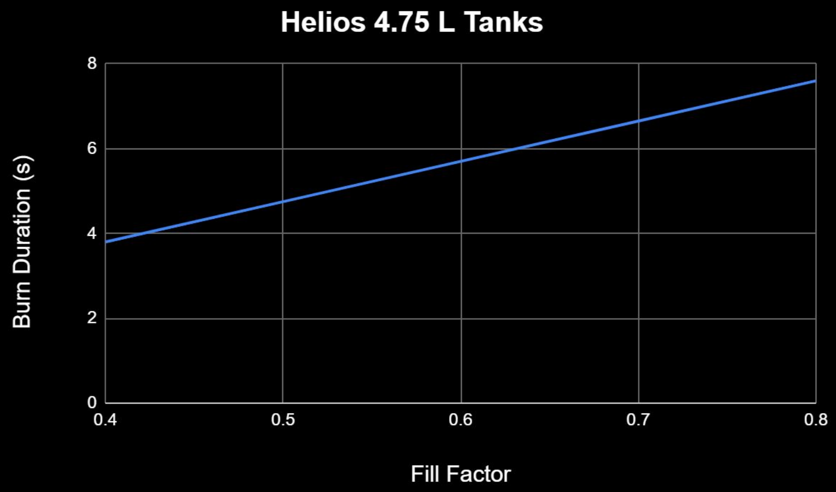
Test Stand

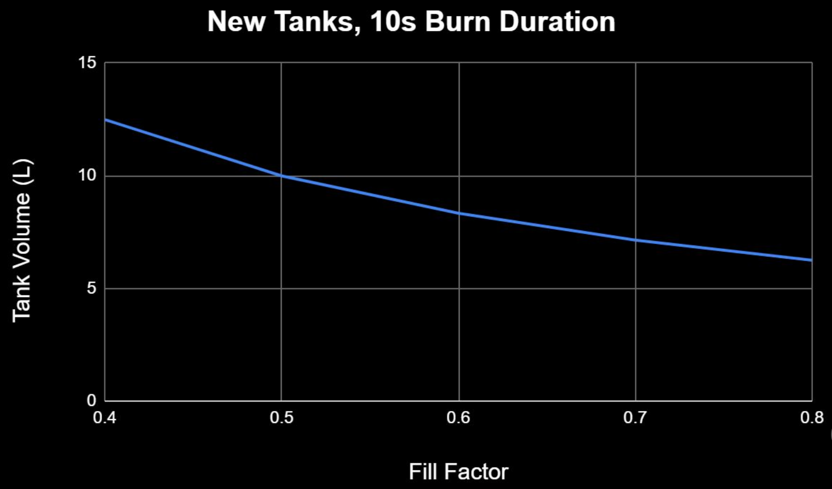


Tank Initial Design



- Larger tanks **likely** required for initial burn duration goal (10s)
- Larger tanks **definitely** required for longer burns after initial test
- **Parameters:**
  - Tank volume (Helios: 4.75 L)
  - Fill factor (Helios: 40%)
- **Likely choice:** 10 L tanks at 50% fill factor

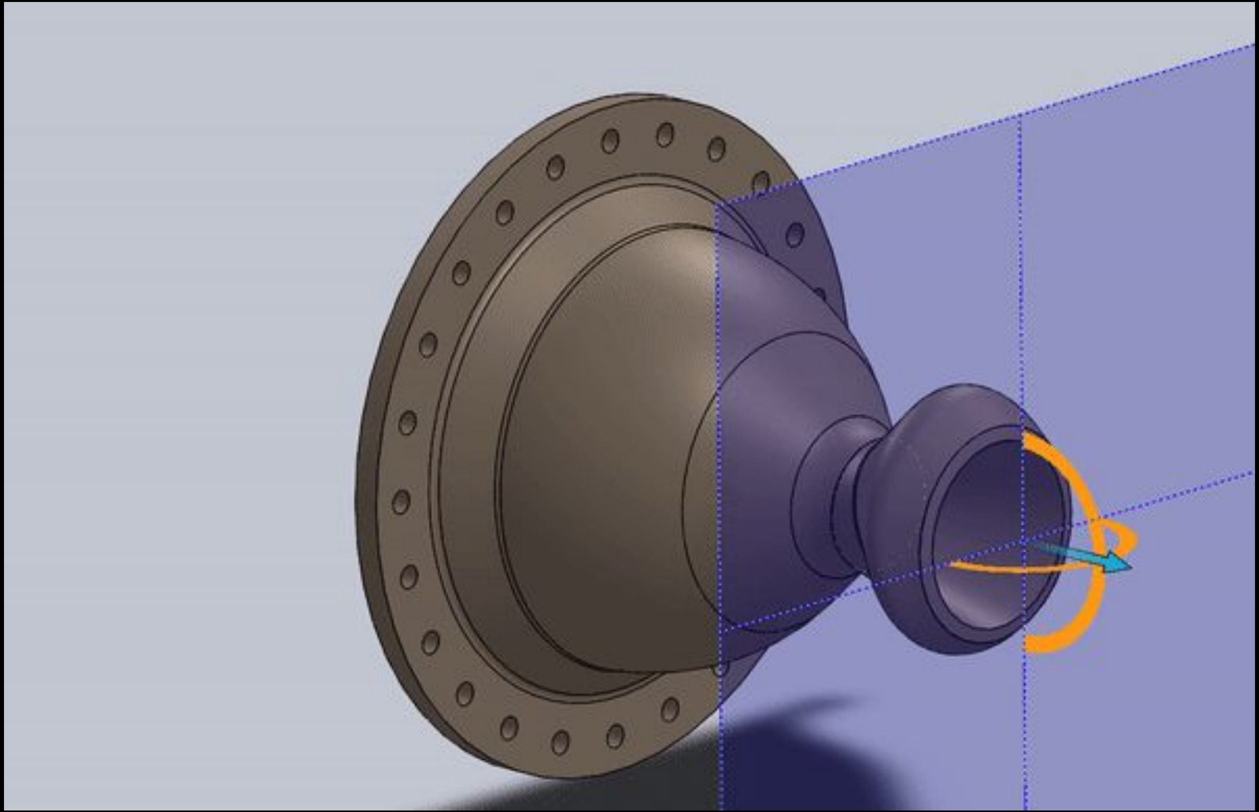




Instrumentation Considerations

- Capture system performance metrics
  - Regenerative cooling performance
    - Total heat flux into coolant
    - Engine surface temperatures
  - Engine performance
    - c* from load cell and theoretical mass flow rate
- Enable safer and more convenient testing procedures
  - Measure surface temps along LOX feed line

Thanks!



Appendix

Initial Cost Estimates (Manufacturing)

Name	Cost
DMLS Chamber Print	7000
New Tanks	1000
Material Stock	300
Test Stand Updates	700
O-rings	500
DAQ	500
Total: 10000$	

Engine Edge Case Study: Pc = 500psi

Chamber Pressure and Thrust **500 psi** - 2150 N		
Chamber Geometry	Chamber Diameter (in, min 3)	**3.63**
	Chamber Length (in, max 5.9)	**5.90**
	Throat Diameter (in)	**0.907**
Feed System	Mass Flow Rate (kg/s)	**1.01**
	Feed Pressure Requirement (psi)	**700****

Engine Edge Case Study: Pc = 200psi

Chamber Pressure and Thrust **200 psi** - 1725 N		
Chamber Geometry	Chamber Diameter (in, min 3)	**5.44**
	Chamber Length (in, max 5.9)	**5.89**
	Throat Diameter (in)	**1.36**
Feed System	Mass Flow Rate (kg/s)	**0.857**
	Feed Pressure Requirement (psi)	**280****

Instrumentation Diagram - Feed System