Liquid Rocket Initiative

PRELIMINARY DESIGN REVIEW

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AIAA
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Project Overview and Objectives

About Us:
The Liquid Rocket Initiative is a new student group at UIUC within the school's AIAA chapter, founded with the intent of applying system thinking to expand the presence of liquid rocket technology at UIUC, accelerating humanity's expansion into the solar system. We are doing this by creating a technical project that will bring students face-to-face with a real world rocket engineering challenge.

Primary Objective: Develop and test a 750 lbf liquid rocket engine (combustion chamber and injector)

Secondary Objective: Optimize the engine for flight and integrate with a small rocket. *This will not be the main focus of our efforts until we can successfully fire our first engine.*

Engine Requirements

1. The engine shall produce 750 lbf of thrust

2. The engine shall maintain a chamber pressure of 400 psi

Engine Performance Estimates

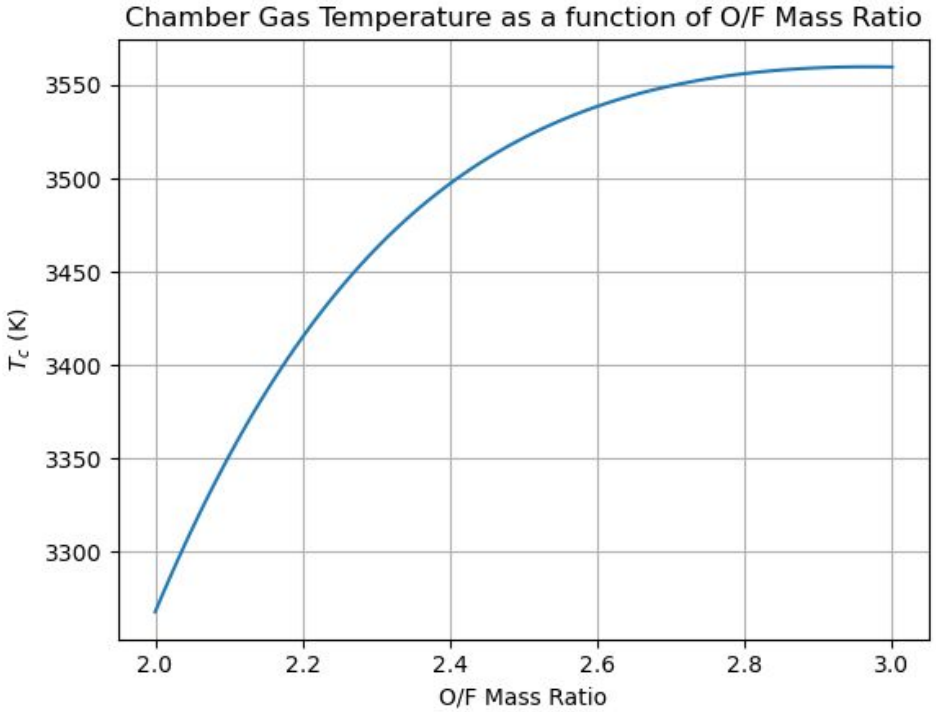
Thrust and mixture ratio were specified in Rocket Propulsion Analysis v.2.3

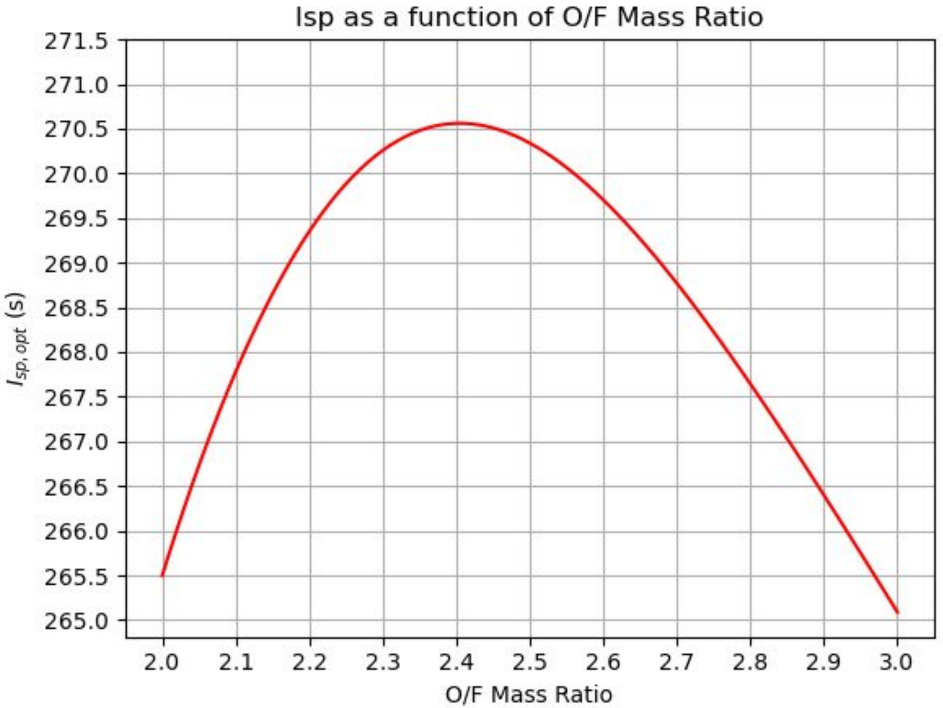
- Determined Mass Flow Rates and combustion properties
- Estimated combustion and nozzle efficiency for specified geometry and O/F ratio

Thrust	750 lbf (3336 N)
Chamber Pressure	400 psi (27.6 bar)
Isp	255 s
Nominal O/F Ratio	2.25
c*	1749.10 m/s
Estimated Combustion Efficiency	97.5%
Oxidizer Mass Flow Rate	0.918 kg/s
Fuel Mass Flow Rate	0.408 kg/s
Total Mass Flow Rate	1.326 kg/s

O/F Ratio

O/F Ratio chosen for manageable Tc with acceptable Isp





Engine Design Status

1. **Injector**
   a. Waiting on initial quotation from manufacturer
   b. Working on characterizing injector face heating
   c. Sorting out potential annular gap tolerance issues

2. **Combustion Chamber**
   a. Initial chamber profile has been determined
   b. Contact has been established with Compositex

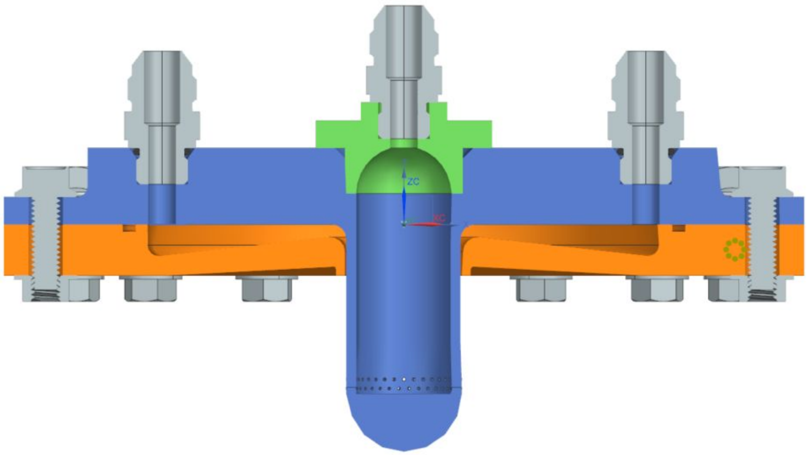
3. **Interface with Zucrow Labs Test Stand**
   a. Ready to begin defining structural and data interfaces

Injector Design

Stage: Quotation

Functional Requirements

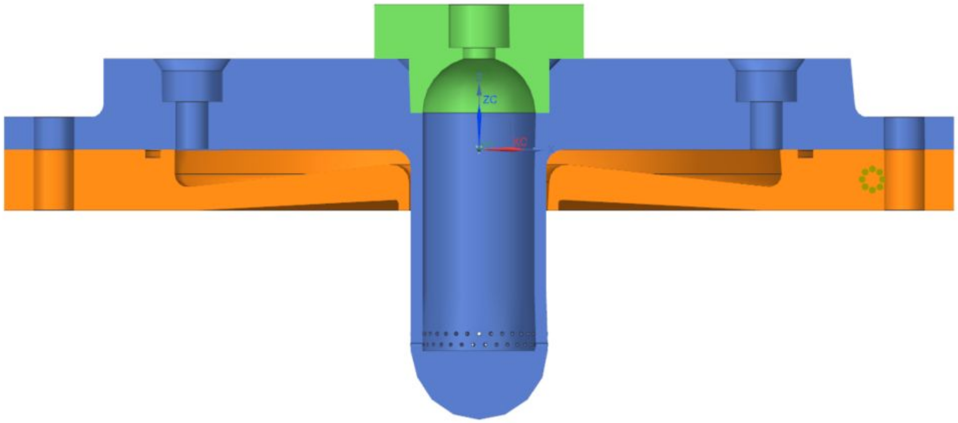
1. The injector shall provide the predetermined O/F ratio to the combustion chamber
2. The injector components shall withstand the combustion chamber temperature
3. The injector components shall withstand the startup pressure differential
4. The injector shall provide a pressure drop of at least 15% of the chamber pressure
5. The injector shall mix the propellants



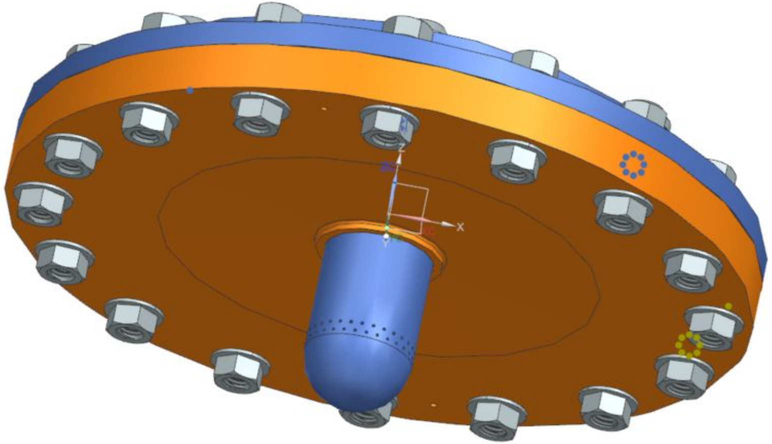
Overall Design

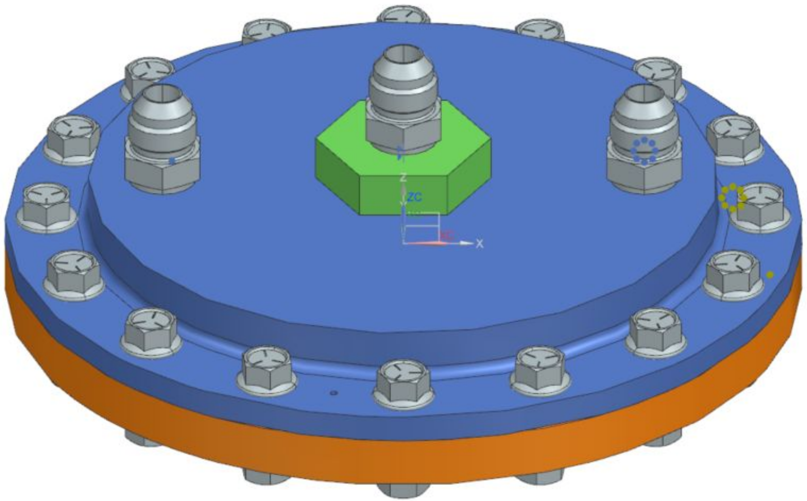
For our injector design, we have chosen to use a single element pintle injector. This decision was motivated by several factors:

1. **Simplicity**
    a. Axisymmetric—easy to lathe
    b. All holes are drilled normal to surface
2. **Combustion Stability**
    a. Recirculation zones provide acoustic damping
    b. Quasi-axisymmetric combustion
3. **Availability of Documentation**
4. **Zucrow Labs Experience**



Architecture (Water Flow)

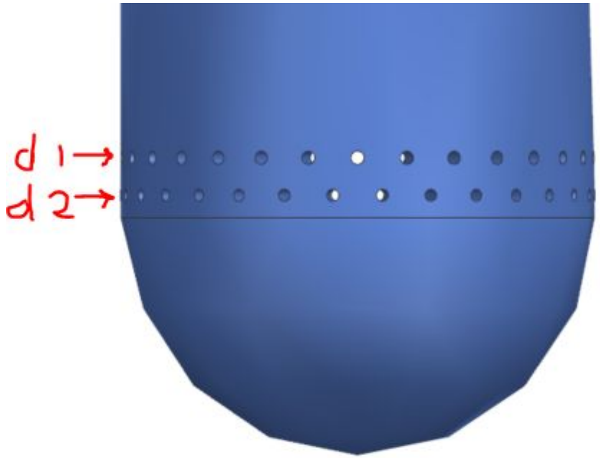




- Chose 80 psi pressure drop (20% of chamber pressure)
- C_d assumed to be 0.75 (for sharp-edged orifice)
- Assuming density of LOx at boiling point = 1141 kg/m^3
  - A = 34.506 mm^2
- Two rows, second with smaller diameter
- Orifice diameters match available drill bit sizes
  - Needs to be quickly and reliably provided by shop

$$A = \frac{\dot{m}}{C_d\sqrt{2\rho\Delta p}}$$

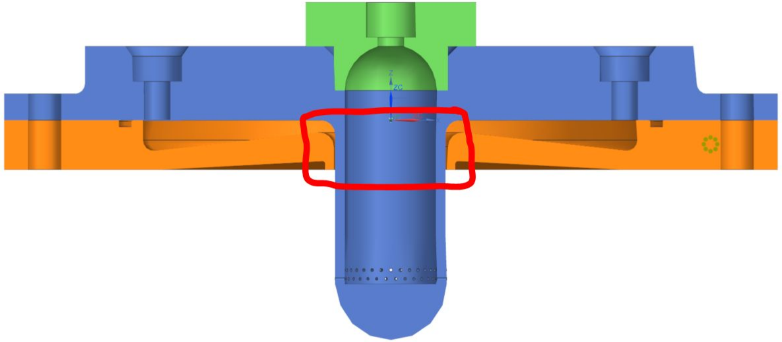
# of orifice pairs	30
Primary row diameter (d1)	0.9065 *mm*
Secondary row diameter (d2)	0.8125 *mm*
Length of Orifice	≥2*d1 at minimum
Blockage Factor	0.51

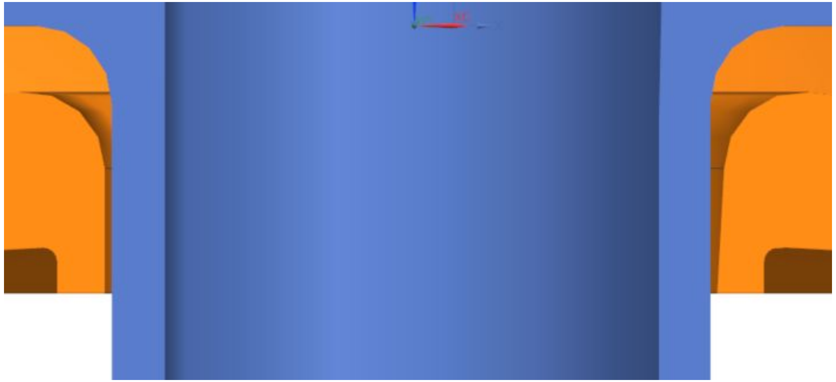


Annular Gap Sizing

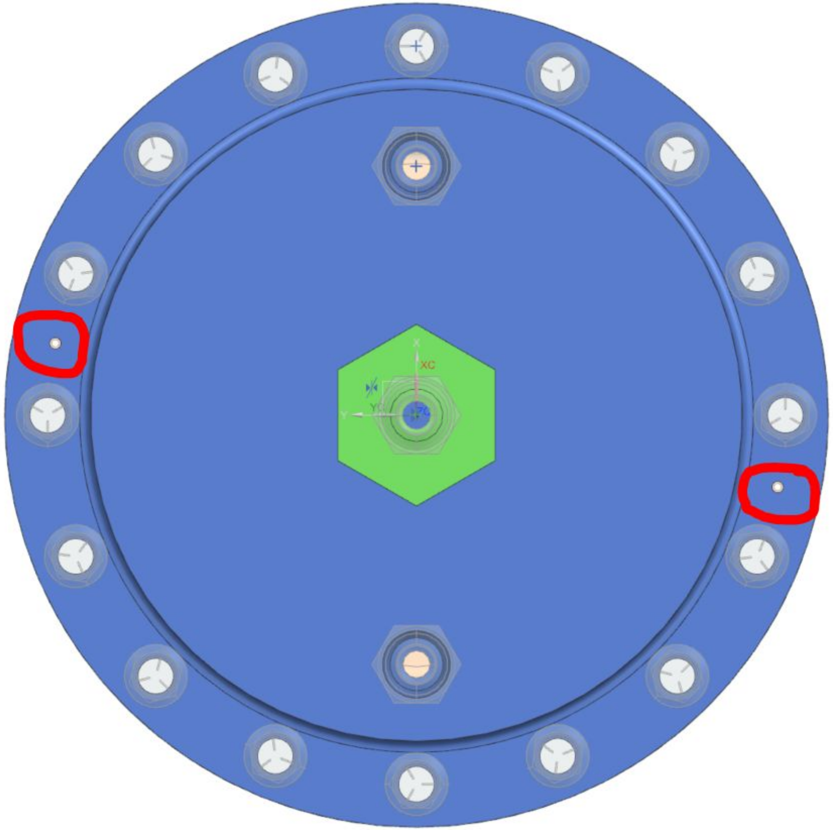
- **Sizing is super tight:** primary constraint on sizing lies in manufacturing capabilities
- Assuming C_d = 0.75 and density of RP-1 = 810 kg/m^3:
  - A = 18.2 mm^2
  - r_{gap} = 0.181 mm
- Concentricity of pintle body achieved with dowel pins (shown on next slide)
- Gap run-distance ≥ *A*Gap Size*

$$A = \frac{\dot{m}}{C_d\sqrt{2\rho\Delta p}}$$





Dowel Pins



Straight through the dome and headplate

Annular Gap Issues

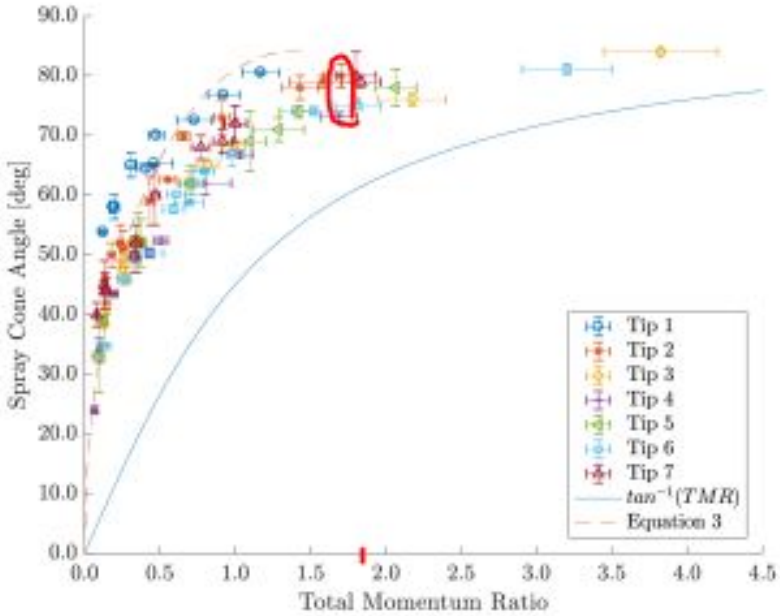
Nature of small annular gap requires tight tolerances and precise alignment

- Currently using tolerance requirement of +/- 10% (0.0181 mm)
  - Working with machine shop to assess approach for tightest tolerance
- Concerned about thermal expansion of injector manifold changing annular gap size
- Requires precise alignment of upper manifold to lower manifold
  - Current plan: use dowel pins for alignment

CURRENT Impingement Parameters

LOx exit velocity = 23.32 m/s
RP1 exit velocity = 27.69 m/s

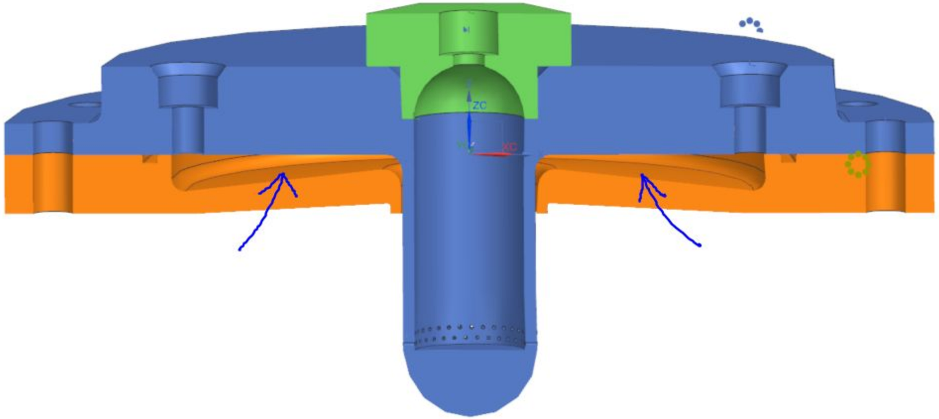
Total Momentum Ratio = 1.89
Approximate Spray Cone Angle 70° > θ > 80°
:/



Taken from: AIAA SciTech Forum "Spray Cone Formation from Pintle-Type Injector Systems in Liquid Rocket Engines", James Blakely, Johann Freeburg, Jacob Hogge, University of Southern California

Manifold

- Toroidal cavity formed by putting the dome and headplate together
- Upwardly-sloped to gradually transition fluid flow into the annular gap
- Single EPDM O-ring
- Current sizing is empirical



Propellant Connections

- 2, ½" fuel lines, SAE(ORB) to JIC
- 1, 1/2" ox line, SAE (ORB) to JIC

Injector Thermal Analysis

Several hurdles have been encountered in simulating the heat flow on our injector face:

1. Modeling mantle recirculation zone
   a. Quasi-1D Flow Assumption: easiest to model, unsure of actual flow behavior
   b. Estimating gas-side heat transfer coefficient
   c. Sharp corner between chamber wall and injector face
2. Hotspot near ablative wall where jet impinges

Pintle body concerns:

1. Need sufficiently low T_c to accommodate LOx in pintle
2. Concerned about hotspot at pintle tip
3. Lack accurate simulations of gas flow around pintle and in core recirculation zone

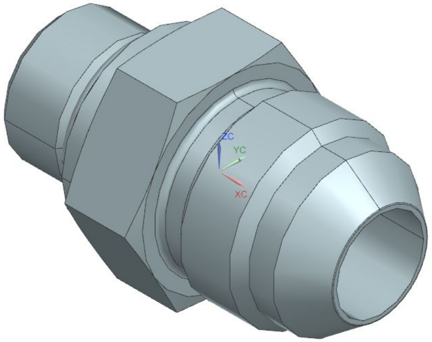
Structural Analysis

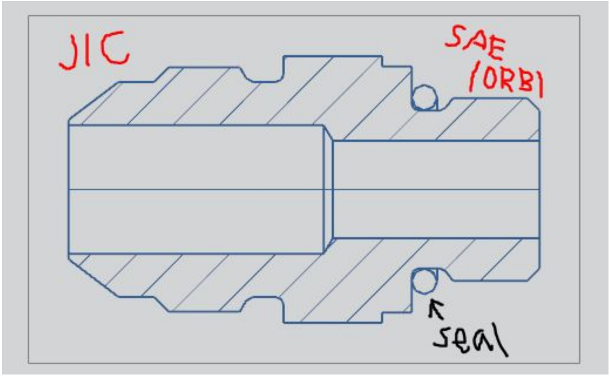
Preliminary calculations performed; modelled injector face as a flat washer

- Considered max. pressure difference across injector face during startup
- Considered pressure on radial surface of annular gap
    - suggests manifold thickness is more than sufficient for expected structural loads using 304 stainless steel

Fittings

- For our fuel and oxidizer inlets, we plan to use ½" diameter SAE(ORB)/JIC fittings to connect the injector manifold to the feed system.
- This will allow us to easily attach and detach the engine from the feed system, while providing a good seal between the injector manifold and feed tubing.
- The SAE Straight Thread side will be attached to the manifolds, while the JIC fitting will be attached to the feed tubing.





(Threads not detailed)

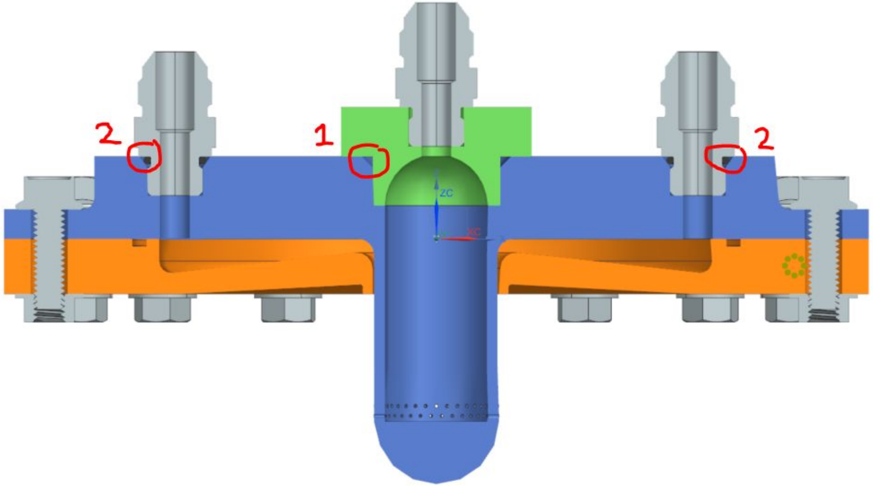
Fitting Seals

LOx inlet

- Fitting will be welded to the adapter
- Adapter will be compress an O-ring **(1)** onto dome
- Due to the cryogenic temperatures this seal will experience, elastomers are not an option for this seal. Therefore, we are currently planning on using a PTFE O-ring for this seal. This O-ring will require replacement after each use due to PTFE's inelasticity

Fuel Inlets

- These seals **(2)** will not be exposed to extreme temperatures, thus we plan on using standard EPDM O-rings to seal these connections.



Material Selection

- 304 stainless steel has been selected for the injector manifold and pintle
- Range of grades; considering using 304H for added high temperature strength

Benefits	Concerns
Good machinability	Low thermal conductivity
High strength across a wide temperature range, including cryogenic temperatures	Ignition with LOx in pintle
Corrosion-resistant	Strength quickly diminishes at high (> ~700°C) temperatures
Well-characterized	
Low-cost	

What Needs Work?

Several areas of continuing study concerning injector design:

1. **Pintle Tip Heating**
   - Hemispherical mass, relatively far from LOx in pintle
   - Searching literature for effect of chamber geometry on core recirculation zone

2. **Annular Gap Tolerancing**
   - Given possible machining tolerance for components wish to determine performance
   - What is performance with largest and smallest possible annular gap? Is it acceptable?

3. **Manifold Sizing/Pressure Drop**
   - Currently considering CFD for manifold
   - Eventual cold-flow testing to characterize injector manifold pressure drop

What Needs Work? (cont.)

4. **Injector Face Heating**
   - Also relates to manifold sizing and pressure drop determination, as injector face heats the fuel in manifold
   - Attempting to use quasi-1D heat flow model for injector face, hard to validate assumptions
5. **Structural Analysis**
   - Simulate startup loads (highest pressure differential)
   - Iterate to determine performance as a function of injector face heating
6. **Human Factors Analysis**

Chamber Design

Stage: Trade Studies

Functional Requirements

1. The combustion chamber wall shall be able to withstand the chamber temperature for the entirety of the burn duration

2. The combustion chamber shall be able to withstand the chamber pressure for the entirety of the burn duration

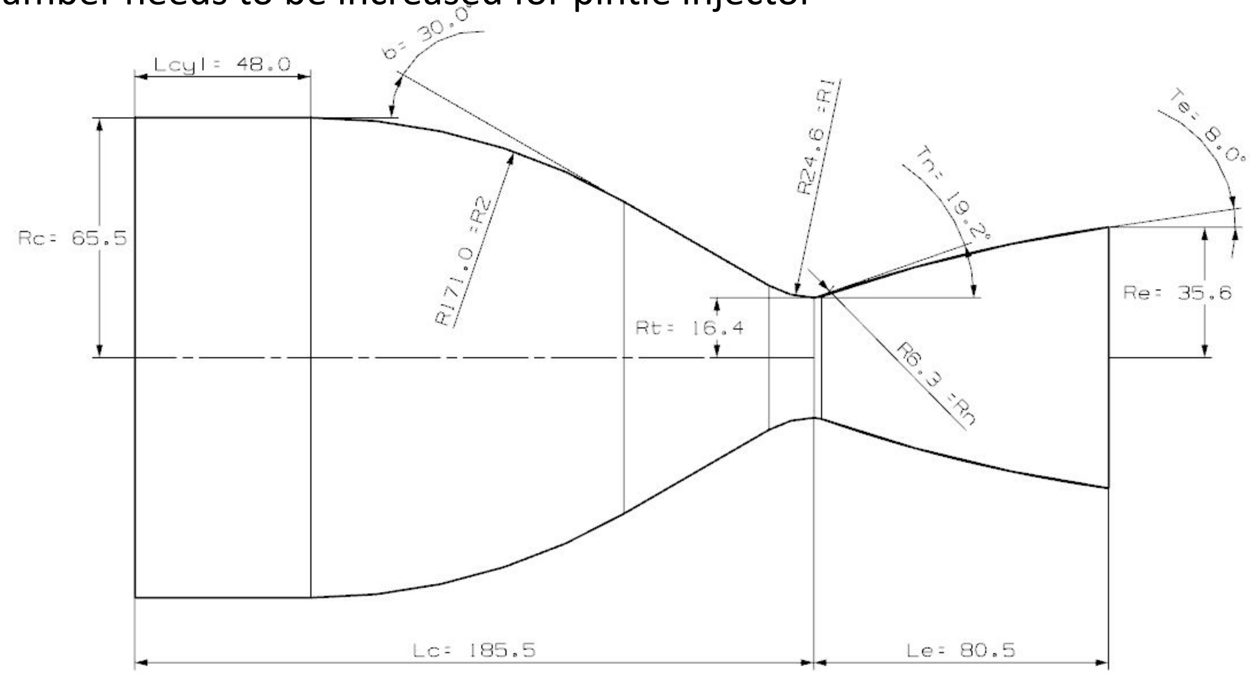
3. The combustion chamber shall produce 750 lbf of thrust

Engine Sizing

Engine is sized to produce 750 lbf thrust at sea level

- Parabolic nozzle with fixed expansion area ratio
- Approximation of bell contour used by RPA
- Aspect ratio of cylindrical chamber needs to be increased for pintle injector

Specified Parameters	
L*	2000 mm
b	30°
R1/Rt	1.5
Rn/Rt	0.382



Material Selection

- We have decided to use a silica phenolic, carbon fiber wrapped combustion chamber for our tests.
- The idea of running initial tests with a carbon steel billet, then switching over to ablative was briefly considered. The pros and cons of this approach are outlined below:

Pros	**Cons**
Provides preliminary verification of the injector design before testing with more expensive hardware	Carbon steel billet does not test our most pressing concerns (injector face burnthrough, pintle tip heating)
Carbon steel billet can be manufactured quickly	Higher overall development costs
Verifies startup procedure before testing with more expensive hardware	Longer overall development timeline

Image Credit: Compositex, Inc.

What Needs Work?

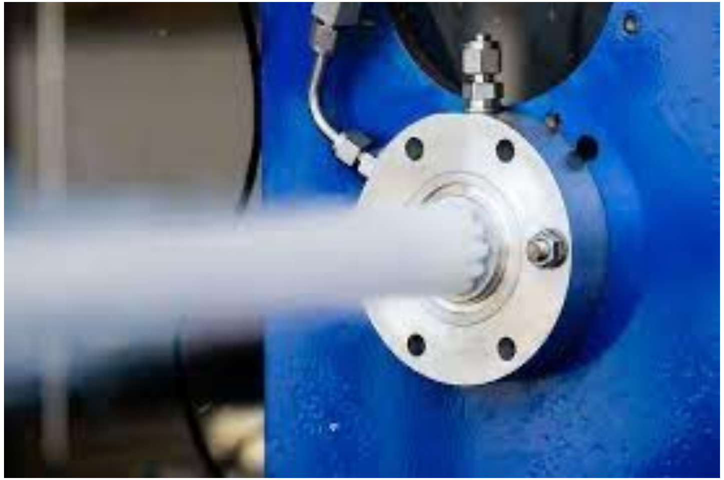
1. **Structural interface with injector**
   - Flange connecting injector and combustion chamber
2. **Thermal Analysis**
   - Pintle tip heating
   - Injector face heating
   - Throat/wall heating
3. **Human Factors Analysis**
   - Bolt torque
   - Flange assembly (including seal placement)

Testing Campaign

Test Matrix

Testing Sequence:

1. **Water flow test**
   a. Estimate injector discharge coefficients
   b. Verify flow rates
2. **Cold flow test**
   a. Determine propellant introduction times
3. **Overpressure cold flow test** (≥1.4x maximum expected operating pressure)
   a. Verify injector structural integrity under high pressure differential
4. **Hot Fire Test (Short and Long Duration)**
   a. Determine injector face ability to withstand thermal loads for longer burn durations
   b. Measure chamber ablation rates, determine hotspots
   c. Determine whether pintle geometry is suitable for long-duration burns



Link to Our Test Matrix

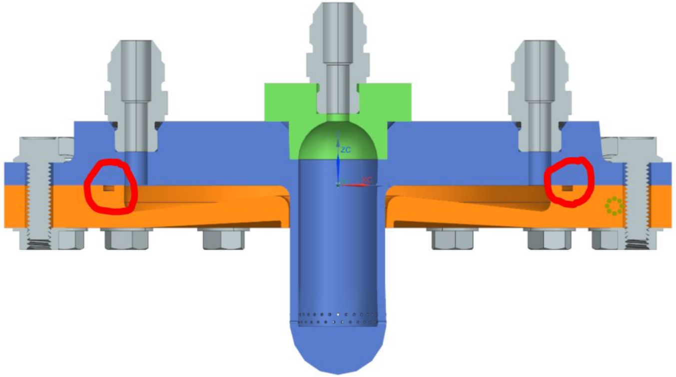
Failure Modes and Risks

Failure Mode	Severity	Likelihood	Detection	Risk Priority Number	Mitigation
Inadequate Manifold Seal	Medium	Low	Fuel leakage from manifold	8	Analyze test article after cold flow to ensure adequate sealing
Inadequate Chamber Seal	High	Medium	Chamber pressure data, hot fire test video	2	Backup O-ring, abort if a leak is observed
Pintle Tip Melting	High	Medium	Post-test inspection of pintle	4	Low burn duration initial test
Annular Flow Disconformity	Medium	Medium	Engine performance analysis, hot fire test footage	5	Tight tolerance on annular gap
Injector Face Burnthrough	High	Medium	Loss of pressure in manifold	3	Thermal modeling of injector face
Hard Start	High	Medium	Combustion chamber pressure spike	1	Measure propellant introduction timing during cold flow test and use this data to time propellant introduction correctly, start igniter prior to run valves opening
Inadequate LOX Inlet Seal	Medium	Low	LOX leakage from inlet seal	6	Examine LOX inlet seal after cold flow test
Inadequate Injector Pressure Drop	High	Low	Measurement of relative manifold and chamber pressures	7	Automatically abort test if faulty differential pressure is recorded

Seals

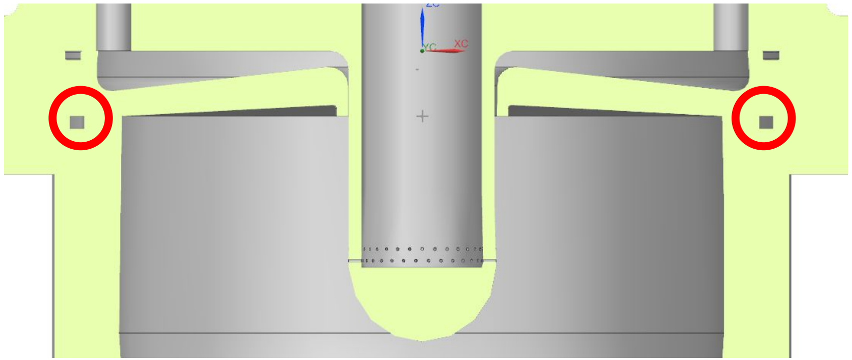
Dome/Injector Face Seal

- This seal will not be exposed to cryogenic or combustion temperatures since it is right up against the fuel manifold
- We have chosen to use an EPDM O-ring to seal this connection due to its compatibility with fuels, relatively large temperature range, and low cost



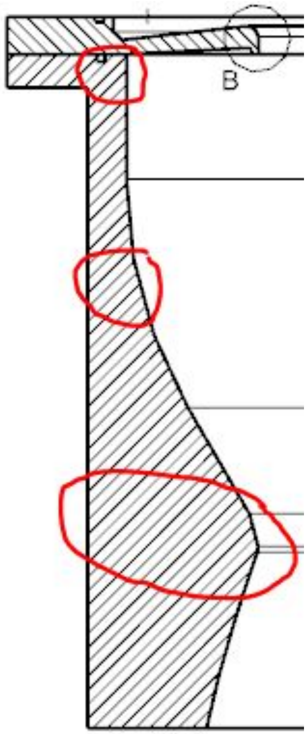
Injector Face/Combustion Chamber Seal

- Due to the high temperatures this interface will experience, the options for sealing materials are limited.
- Based on Zucrow Labs' experience, we currently believe that the best option for this seal is a PTFE O-ring used with a high-quality surface finish



Instrumentation

- Sensors needed to verify requirements:
  - Pressure Transducers
    - Ported to the chamber
    - *Thinking* about porting to manifold, but would require a re-design
  - Thermocouples
    - First at top edge in the chamber
    - Second at fan impingement point with chamber wall
    - Third at nozzle throat
  - Accelerometers



What Needs Work?

1. **Test Duration**
   - Current goal is to reach steady state, but for how long?
2. **Test Stand Structural Interface**
   - Need more information from Zucrow Labs
3. **Instrumentation**

Wrap Up