Jessie & James
Critical Design Review - March 30, 2018
John Targonski & Michael Moruzzi
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MOTIVATION & INTRODUCTION
Meet Jessie & James

Jessie & James (J&J) – Pair of 3D printed Maraging Steel Kerosene/Gaseous Oxygen Liquid Rocket Engines that feature ablative & film cooling that will integrated and tested on our mobile thrust stand (Hydra)
Why Continue Building GOX rocket engines?

- Hydra (our mobile thrust stand) is not cryo-rated and would require significant resources and funding to make the transition.
- Keep Hydra Operational (Hydra doesn’t currently have an engine to test)
  - Blue Steel 2.0 (previous engine) was only intended to be fired once
- J&J/Hydra can serve as a morale booster, learning tool for new members & help give experience to our test & operations team
- Enable the LPL the ability to test rocket engines with no dependences on hardware
  - Balerion will require renting a test stand in order to conduct tests
Motivation & Introduction
Discoveries from Inaugural Hydra Static Fire

• The inaugural static fire of (12/02/18) was to test Hydra (mobile test stand) while using the labs originally built rocket engine (Blue Steel)

• Hydra featured a student designed & built kerosene/gaseous oxygen (GOX) feed system and data acquisition/control unit

• Hydra was designed to provide convenient way to perform static fires at FAR in the Mojave desert and future plans are to help accelerate the “learning curve” for new members by performing modifications on this relatively simple system

The J&J rocket engines have been designed to integrate onto Hydra and enable the LPL the ability to perform static fire with 100% LPL designed hardware
Motivation & Introduction
Discoveries from Inaugural Hydra Static Fire

Injector Deterioration

• The injector experienced serve deterioration (Could have been a result of excessive BKNO3 and/or chamber temperature
• This limited the lifetime of this injector to 1 static fire
• Injector is not a long term solution as fabrication time took ~3 weeks and total cost of material and labor was ~ $3,5000

New J&J injector would be designed to lower both the cost and lead time
Motivation & Introduction

Discoveries from Inaugural Hydra Static Fire

Nozzle Ablation

• The nozzle experienced a significant amount of ablation during the 5 second static fire
• This ablation of the nozzle resulted in a throat area that was 2.1 times larger than the initial throat area
• As the throat area increased, the chamber pressure had to decrease in order to compensate, which in turn lead to an increase in mass flow rate throughout the static fire

J&J would be designed to mitigate this phenomena

\[
\frac{A_t(\text{after})}{A_t(\text{before})} = 2.1
\]
Introduction & Motivation

Jessie & James Design Considerations

- Designed to be integrated & tested on LPL’s mobile test stand Hydra
- Design to be LPL’s workhorse engine
  - Ability to be fired at various operating conditions
  - Ability to be fired separately or in tandem
- Simplified design that is 3D printed
  - Minimal parts, fabricated in a relatively short lead time and at a low cost
- Reusable with minimal maintenance and hardware changes
  - One injector design that can be used at various operating conditions
  - Nozzle with minimal ablation
Introduction & Motivation

*How to determine a operating condition for Jessie & James?*

- Attempt to squeeze max performance out of Hydra
  - Design to the max mass flow rate Hydra can deliver while staying in a reliable range
- Push the boundaries for a student run university lab
  - First university to design, print (using USC’s new Center of Advanced Manufacturing), assemble, and test an additive manufactured rocket engine in house
  - Operate an engine at the highest chamber pressure ever designed & tested by a university (1,000 psi) (69 bar)
  - Become the first university to perform a dual engine static fire
Introduction & Motivation

Why two Rocket Engines?

- LPL’s partnership with the Kyushu Institute of Technology (Kyutech) to design, build, and integrate a propulsion system on their vehicle which will feature 2 flight engines
- Allows the LPL an opportunity to get over any growing pains of firing multiple engines simultaneously before completely building the Kyutech flight propulsion system
- Allows the LPL the ability to conduct dual engine tests in a relatively cheap, safe, and less complex manner
  - No cryogens
  - Cheap & rapid engine production (in the event of an anomaly)
Motivation & Introduction
Jessie & James Trade Study

Derivation to show how mass flow rate and pressure affect injector sizing for J&J

\[ \dot{m} = c_d A \sqrt{2 \rho \Delta P} \]

Fuel Line (Incompressible Fluid)

\[ \dot{m}_f = c_d A_f \sqrt{2 \rho_f (P_{inj,f} - P_c)} \]

Where
- \( c_d = 0.7 \) (square edge oriface)
- \( A_f = \text{injector orifice total area} \)
- \( \rho_f = 810 \text{ kg/m}^3 \)
- \( P_{inj,f} = \text{Fuel injector pressure} \)
- \( P_c = \text{chamber pressure} \)

Oxygen Line (Compressible Fluid)

\[ \dot{m}_o = c_d A_{i,o} \sqrt{2 \rho_o (P_{inj,o} - P_c)} \]

\[ \rho_o = \frac{P_{inj,o}}{R_0 T_0} \]

\[ \dot{m}_o = c_d A_{i,o} \sqrt{2 \left( \frac{P_{inj,o}}{R_0 T_0} \right) (P_{inj,o} - P_c)} \]

Where
- \( c_d = 0.7 \) (square edge oriface)
- \( A_{i,o} = \text{oxygen injector orifice total area} \)
- \( R_0 = 259.8 \text{ oxygen gas constant} \)
- \( P_{inj,f} = \text{fuel injector pressure} \)
- \( T_0 = \text{oxygen temperature} \)
- \( P_c = \text{chamber pressure} \)
Motivation & Introduction
Jessie & James Trade Study

Derivation to show how mass flow rate and pressure affect injector sizing for J&J

**Oxygen Line (Compressible Fluid)**

\[ A_i = \left( \frac{m}{c_d} \right) \sqrt{\frac{R_0 T_0}{2 P_{i,0} (P_{i,o} - P_c)}} \]

Where

\[ P_{i,0} = \text{oxygen injection pressure} \]
\[ P_d = \% \text{ pressure drop} \]
\[ P_{i,o} = P_c (1 + P_d) \]

Substitute and after some algebra...

\[ A_i = \frac{m}{P_c} \left( \frac{1}{P_d^{1.5} c_d} \right) \sqrt{T_0 R_0} \]

\[ ∴\text{ Keeping } A_i \text{ and } P_d \text{ constant } m \text{ and } P_d \text{ scale proportionally} \]

**Fuel Line (Incompressible Fluid)**

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

Where

\[ P_{i,f} = \text{fuel injection pressure} \]
\[ P_d = \% \text{ pressure drop} \]
\[ P_{i,f} = P_c (1 + P_d) \]

Substitute and after some algebra...

\[ A_i = \frac{m}{P_c^{0.5} P_d^{0.5}} \left( \frac{1}{c_d} \right) \sqrt{\left( \frac{1}{2 \rho} \right)} \]

\[ ∴\text{ Keeping } A_i, \text{ double } m \text{ and } P_c, \text{ and the percent } P_d \text{ will double} \]
Jessie & James Trade Study

Injector Design:

Engine Injectors initial sized for a 20% pressure drop for the fuel & a 20% pressure drop for oxygen orifices and at 50% of Hydra max mass flow rate (Dual Engine Conditions)

Using the same injector for at 100% of Hydra’s max mass flow rate will result in a 20% pressure drop through the oxygen side of the injector and a 40% pressure drop through the fuel side. (Single Engine Conditions)
Maximizing Hydra’s Performance

1. Calculate max oxygen mass flow rate $\dot{M}_o \max$ for $P_{chamber}$
2. Pick a fuel mass flow rate $\dot{M}_F$
3. Make these the flow rate and $P_{chamber}$ for single engine conditions
4. Size injector orifices for DE conditions for a 20% pressure drop $\frac{1}{2} \dot{M}_T, \frac{1}{2} P_c$
5. Determine pressure drop through injector at SE operating conditions
6. Compare regulate pressure to see if it is above or below pressure/fuel line MAWP
7. Determine regulate pressure to provide necessary regulator outlet pressure and $\dot{m}_N$ (account for droop)
8. Determine $\dot{m}_N$ to provide necessary $\dot{m}_F$ for the fuel injection pressure
9. Determine injector pressure necessary for fuel and oxygen at SE operating conditions
10. Pick lower $\dot{M}_F$
11. Check
12. Above MAWP?
   - Yes: Pick higher $\dot{M}_F$
   - No: At MAWP
13. Hydra’s max performance

SE: Single Engine
DE: Dual Engine
MAWP: Max Allowable Working Pressure
**Motivation & Introduction**

### SCFM to Mass Flow Rate

SCFM (Standard Cubic Feet per Minute)

\[
\text{CFM} = \text{SCFM} \times \frac{P_{\text{atm}}}{P} \times \frac{T}{T_{\text{atm}}}
\]

\[
\dot{m} = (\text{CFM})\rho
\]

\[
\rho = \frac{P}{TR} \quad \text{(gas )}
\]

where: CFM (cubic feet per minute)

### Fluid Correction Factor

\[
F_G = \sqrt[SG_{\text{ref}}]{SG_{\text{act}}}
\]

where: \(SG = \text{specific gravity}\)

\(SG_{\text{act}}\) is the specific gravity of your system fluid.

- \(SG_{\text{oxygen}} = 1.1044\)
- \(SG_{\text{Nitrogen(pure)}} = 0.9669\)
- \(SG_{\text{air}} = 1.0\)
Motivation & Introduction

Single Engine Oxygen Mass Flow Rate to SCFM

\[
SCFM = \dot{m} \frac{P}{P_{atm}} \frac{T_{atm}}{T} \frac{RT}{P}
\]

\[
SCFM = \dot{m} \frac{T_{atm} R}{P_{atm}}
\]

\[\text{Note: Cylinders Pressures & Temperatures Cancel Out}\]

\[\text{Note: Don't forget about units!}\]

\[\text{(SCFM is in English units)}\]

\[\dot{m}_0 = 1.65 \ \text{lbm/s} \ (0.75 \ \text{kg/s})\]

\[\frac{m^3}{s} \text{O}_2 = (0.75) \ \text{kg/s} \text{(298)K}(259.8) \frac{j}{Kg-K} \left(\frac{1}{1.0155}\right) \frac{1}{Pa} = 0.57 \ \frac{m^3}{s}\]

\[SCFM_{O_2} = (0.57) \ \frac{m^3}{s} \left(\frac{1}{0.30483}\right) \frac{f}{m^3} \left(\frac{60}{1}\right) \frac{s}{\text{min}}\]

\[SCFM_{O_2} = 1214\]

\[SCFM_{Air} = SCFM_{O_2} \sqrt{\frac{SG_{O_2}}{SG_{Air}}}\]

\[SCFM_{Air} = 1214 \sqrt{1.1044} \]

\[SCFM_{Air} = 1276\]

\[\text{Note: For a better estimate take into account atmospheric temperature for the time of year}\]

\[\text{(desert has hot summers and cold winters)}\]

\[T_{atm} = 40 \ F \ (277 \ K) \rightarrow 1190 \ SCFM_{Air}\]

\[T_{atm} = 100 \ F \ (311 \ K) \rightarrow 1336 \ SCFM_{Air}\]
For a cylinder pressure of 2600 psi and a desired flow rate of 1276 SCFM_{air}, setting the regulator to 1500 psi will result in an outlet pressure of about 1260 psi.
Motivation & Introduction

Determining Nitrogen Mass Flow Rate

Volmetric Flow\(_{N,I}\) = Volmetric Flow\(_{F,I}\)
Volmetric Flow = \(\dot{m}/\rho\)
\[\dot{m}_N/\rho_{N,I} = \dot{m}_F/\rho_{F,I}\]
\(\rho_F = 810 \text{ kg/m}^3\)
\(P_{N,I} = \rho_{N,I}R_{N,I}T_{N,I}\)
\[\dot{m}_N = \frac{\dot{m}_FP_{N,I}}{\rho_{F,I}R_{N,I}T_{N,I}}\]
Motivation & Introduction

**Single Engine Nitrogen Mass Flow Rate**

**Volmetric Flow**

\[ \text{Volmetric Flow}_{N,I} = \text{Volmetric Flow}_{F,I} \]

\[ \text{Volmetric Flow} = \dot{m}/\rho \]

\[ \dot{m}_N/\rho_{N,I} = \dot{m}_F/\rho_{F,I} \]

\[ \rho_F = 810 \text{ kg/m}^3 \quad P_{N,I} = \rho_{N,I}R_{N,I}T_{N,I} \]

\[ \dot{m}_N = \frac{\dot{m}_F P_{N,I}}{\rho_{F,I} R_{N,I} T_{N,I}} \]

NOTE: Temperature at nitrogen interface \( T_{N,I} \) will change the require \( \dot{m}_N \) and needs to be taken into account. Also \( \rho_{F,I} \) may vary slightly.

For \( T_{N,I} = 40 \text{ F (277 K)} \) → \( \dot{m}_N = 0.06 \frac{\text{kg}}{\text{s}} \)

For \( T_{N,I} = 100 \text{ F (311 K)} \) → \( \dot{m}_N = 0.053 \frac{\text{kg}}{\text{s}} \)

\[ \dot{m}_F = 0.88 \text{lbf/m} \cdot (0.4 \frac{\text{kg}}{\text{s}}) \]

\[ \rho_F = 810 \text{ kg/m}^3 \]

\[ P_{N,I} = 1450 \text{ psi (10 Mpa)} \]

\[ T_{N,I} = 75^\circ \text{F (297 K)} \]

\[ R_{N,I} = (296.8 \frac{J}{\text{kg} \cdot \text{K}}) \]

\[ \dot{m}_N = \frac{0.4(10E6)}{(810)(296.8)(297)} \]

\[ \dot{m}_N = 0.123 \text{ lbf/s} (0.056 \frac{\text{kg}}{\text{s}}) \]
**Motivation & Introduction**

**Single Engine Nitrogen Mass Flow Rate to SCFM**

\[ SCFM = \dot{m} \frac{P}{P_{atm}} \frac{T_{atm}}{T} \frac{RT}{P} \]

\[ SCFM = \dot{m} \frac{T_{atm} R}{P_{atm}} \]

where \( T_{atm} = 298 \text{ K} \quad P_{atm} = 1.01 \times 10^5 \text{ Pa} \)

Note: Don’t forget about units!

(SCFM is in English units)

\[ \dot{m}_N = 0.123 \text{ lbm/s} \quad (0.056 \text{ kg/s}) \]

\[ 0.049 \text{ m}^3/s = (0.056) \frac{kg}{s} (298) K (296.8) \left( \frac{1}{Kg-K} \right) \left( \frac{1}{1.01E5} \right) \text{ Pa} \]

\[ SCFM_{N2} = (0.049) \frac{m^3}{s} \left( \frac{1^3}{0.3048^3} \right) \frac{ft^3}{s} \left( \frac{60}{1} \right) \frac{s}{min} \]

\[ SCFM_{N2} = 104 \]

Note: Variations in \( T \) for the Nitrogen DOES effect the overall SCFM because it changes the required \( \dot{m}_N \).

(desert has hot summers and cold winters)

For \( T_{atm} = 40 \text{ F (277 K)} \rightarrow \dot{m}_N = 0.06 \frac{kg}{s} \rightarrow 111 \text{ SCFM}_{N2} \)

\( T_{atm} = 100 \text{ F (311 K)} \rightarrow \dot{m}_N = 0.053 \frac{kg}{s} \rightarrow 98 \text{ SCFM}_{N2} \)
Desired Regulator Outlet Pressure – 1450 psi (40% pressure drop over injector and 50 psi estimated line loss)

Setting the regulator to 2,000 psi would result in a pressure drop of about 200 psi at 104 SCFM

Therefore, if we want an outlet pressure of 1,450 psi we should set the regulator to 1,650 psi.
# Motivation & Introduction

## Jessie & James Operating Condition Summary

<table>
<thead>
<tr>
<th>Single Engine Operating Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{M}_{TOT} = 1.15 \text{ kg} )</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
</tr>
<tr>
<td>( Injectors %P_a = 40 % )</td>
</tr>
<tr>
<td><strong>Cylinder Pressure = 2600 psi</strong></td>
</tr>
<tr>
<td>( P_{\text{regulate}} = 1650 \text{ psi} )</td>
</tr>
<tr>
<td>( P_{\text{supply}} = 1450 \text{ psi} )</td>
</tr>
<tr>
<td>( P_{\text{injector}} = 1400 \text{ psi} )</td>
</tr>
<tr>
<td>( P_{\text{chamber}} = 1000 \text{ psi} )</td>
</tr>
</tbody>
</table>
Motivation & Introduction

Dual Engine Oxygen Mass Flow Rate to SCFM

\[ SCFM = \dot{m} \frac{P}{P_{atm}} \frac{T_{atm} RT}{T \cdot P} \]

\[ SCFM = \dot{m} \frac{T_{atm} R}{P_{atm}} \]

Note: Don’t forget about units!

(SCFM is in English units)

Note: Same Oxygen Mass Flow & SCFM rate as Single Engine Fire

\[ \dot{m}_o = 1.65 \ \text{lbm/s} (0.75 \ \text{kg/s}) \]

\[ 0.57 \left( \frac{m^3}{s} \right) = (0.75) \ \frac{kg}{s} (298) \text{K} (259.8) \left( \frac{1}{kg-k} \right) \left( \frac{1}{Pa} \right) \]

\[ SCFM_{O2} = (0.57) \left( \frac{m^3}{s} \right) \left( \frac{1^3}{0.3048^3} \right) \left( \frac{ft}{m} \right) \left( \frac{60}{s} \right) \left( \frac{s}{min} \right) \]

\[ SCFM_{O2} = 1214 \]

\[ SCFM_{Air} = SCFM_{O2} \sqrt{SG_{O2} \over SG_{Air}} \]

\[ SCFM_{Air} = 1214 \sqrt{1.1044} \]

\[ SCFM_{Air} = 1276 \]

Note: For a better estimate take into account atmospheric temperature for the time of year

(desert has hot summers and cold winters)

For \( T_{atm} = 40 \ \text{F} (277 \ \text{K}) \rightarrow 1190 \ SCFM_{Air} \)

\( T_{atm} = 100 \ \text{F} (311 \ \text{K}) \rightarrow 1336 \ SCFM_{Air} \)
Dual Engine Oxygen Regulator Set Pressure

Desired Regulator Outlet Pressure – 650 psi (20% pressure drop over injector and 50 psi estimated line loss)

For a cylinder pressure of 2600 psi and a desired flow rate of 1276 SCFM\textsubscript{air}, \(\approx 300\) psi drop for regulator set to 800 psi and about 200 psi for regulator set at 1000 psi.

Therefore setting regulator to 900 psi may result in desired outlet pressure \(P_{out} \approx 650\) psi

Flow test needed for more accurate set pressure!
Motivation & Introduction

Dual Engine Nitrogen Mass Flow Rate

Volmetric Flow \( N,I = \text{Volumetric Flow} \_F,I \)

Volmetric Flow = \( \dot{m}/\rho \)

\[
\dot{m}_N/\rho_{N,I} = \dot{m}_F/\rho_{F,I}
\]

\( \rho_F = 810 \text{ kg/m}^3 \)

\( P_{N,I} = \rho_{N,I}R_{N,I}T_{N,I} \)

\[
\dot{m}_N = \frac{\dot{m}_F P_{N,I}}{\rho_{F,I} R_{N,I} T_{N,I}}
\]

NOTE: Temperature at nitrogen interface \( T_{N,I} \) will change the require \( \dot{m}_N \) and needs to be taken into account. Also \( \rho_{F,I} \) may vary slightly

For \( T_{N,I} = 40 \text{ F (277 K)} \) \( \rightarrow \dot{m}_N = 0.027 \frac{\text{kg}}{\text{s}} \)

For \( T_{N,I} = 100 \text{ F (311 K)} \) \( \rightarrow \dot{m}_N = 0.024 \frac{\text{kg}}{\text{s}} \)

\( \dot{m}_F = 0.88 \text{ lbm/s (0.4 } \frac{\text{kg}}{\text{s}} \) \)

\( \rho_F = 810 \text{ kg/m}^3 \)

\( P_{N,I} = 650 \text{ psi (4.48 Mpa)} \)

\( T_{N,I} = 75^\circ \text{F (297 K)} \)

\( R_{N,I} = (296.8 \frac{J}{Kg-K}) \)

\[
\dot{m}_N = \frac{(0.4)(4.48E6)}{(810)(296.8)(297)}
\]

\( \dot{m}_N = 0.551 \text{ lbm/s (0.025 } \frac{\text{kg}}{\text{s}} \)
Motivation & Introduction

Dual Engine Nitrogen Mass Flow Rate to SCFM

$$SCFM = \dot{m} \left( \frac{P}{P_{atm}} \right) \left( \frac{T_{atm}}{T} \right) \left( \frac{RT}{P} \right)$$

$$SCFM = \dot{m} \left( \frac{T_{atm} R}{P_{atm}} \right)$$

Note: Don’t forget about units!

(SCFM is in English units)

$$\dot{m}_N = 0.551 \ \text{lbm/s} \ (0.025 \ \text{kg/s})$$

$$0.0218 \left( \frac{m^3}{s} \right) = (0.025) \left( \frac{kg}{s} \right) (298) \left( \frac{K}{296.8} \right) \left( \frac{J}{kg \cdot K} \right) \left( \frac{1}{0.0105 \ Pa} \right)$$

$$SCFM_{N2} = (0.0218) \left( \frac{m^3}{s} \right) \left( \frac{1}{0.3048^3} \right) \left( \frac{ft}{m^3} \right) \left( \frac{60}{1} \right) \left( \frac{s}{min} \right)$$

$$SCFM_{N2} = 46$$

Note: Variations in $T$ for the Nitrogen DOES effect the overall SCFM because it changes the required $\dot{m}_N$.

(desert has hot summers and cold winters)

For $T_{atm} = 40 \ F (277 \ K) \rightarrow \dot{m}_N = 0.027 \ \text{kg/s} \rightarrow 50 \ SCFM_{N2}$

$T_{atm} = 100 \ F (311 \ K) \rightarrow \dot{m}_N = 0.024 \ \text{kg/s} \rightarrow 45 \ SCFM_{N2}$
Desired Regulator Outlet Pressure – 650 psi (20% pressure drop over injector and 50 psi estimated line loss)

Setting the regulator to 1,000 psi would result in a pressure drop of about 200 psi at 46 SCFM. Therefore, if we want an outlet pressure of 650 psi we should set the regulator to around 900 psi.
### Dual Engine Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{M}_{TOT}$</td>
<td>0.575 kg</td>
</tr>
<tr>
<td>$OF$</td>
<td>1.875</td>
</tr>
<tr>
<td>Fuel</td>
<td>OX</td>
</tr>
<tr>
<td>Injector $%P_d = 20%$</td>
<td></td>
</tr>
<tr>
<td>Cylinder Pressure = 2600 psi</td>
<td></td>
</tr>
<tr>
<td>$P_{regulate} = 900$ psi</td>
<td></td>
</tr>
<tr>
<td>$P_{supply} = 650$ psi</td>
<td></td>
</tr>
<tr>
<td>$P_{injector} = 600$ psi</td>
<td></td>
</tr>
<tr>
<td>$P_{chamber} = 500$ psi</td>
<td></td>
</tr>
</tbody>
</table>
J&J DESIGN & Analysis
J&J DESIGN & Analysis
GUI Tool
J&J DESIGN & Analysis
Engine & Injector Sizing
### J&J Design & Analysis

**Engine & Injector Sizing**

**Single Engine Design Point**

<table>
<thead>
<tr>
<th>Design Point J&amp;J</th>
<th>Thermochemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{M}_{TOT} = 1.15 \text{ kg/s}$</td>
<td>From NASA CEA</td>
</tr>
<tr>
<td>OF ratio= 1.875</td>
<td>Chemistry: Kerosene/Gaseous Oxygen (GOX)</td>
</tr>
<tr>
<td>$P_c = 6.895 \text{ MPa, (1000 psi, 69 bars)}$</td>
<td>$T_c = 3266 \text{ K, (5418 °F)}$</td>
</tr>
<tr>
<td>$P_e = 101352.9 \text{ Pa (14.7 psi, 1.01325 bars)}$</td>
<td>$\bar{M} = 20.05 \text{ kg/kmol}$</td>
</tr>
<tr>
<td>$L^* = 1.27 \text{ m, (50 inches)}$</td>
<td>$\gamma = 1.187$</td>
</tr>
</tbody>
</table>
Propellant Mass Flow Rates

\[
\frac{\dot{m}_o}{\dot{m}_F} = 1.875
\]

\[
\dot{m}_o + \dot{m}_F = 1.15 \text{ kg/s}
\]

\[
\dot{m}_F = 1.15 - \dot{m}_o \frac{\dot{m}_o}{1.15 - \dot{m}_o} 1.875
\]

\[
\dot{m}_o = 1.875(1.15 - \dot{m}_o)
\]

\[
\dot{m}_F = 0.4 \text{ kg/s}
\]

\[
\dot{m}_o = 0.75 \text{ kg/s}
\]

Throat Area

\[
A^* = \frac{\dot{M}_{TOT}}{P_0} \sqrt{\frac{T_0 R}{\gamma}} \left( 1 + \frac{\gamma - 1}{2} \right)^\frac{\gamma+1}{\gamma-1}
\]

\[
A^* = \frac{1.15}{6.895 \text{ MPa}} \sqrt{\frac{(3265.5)(414.66)}{1.187}} \left( 1 + \frac{1.187 - 1}{2} \right)^\frac{1.187+1}{2(1.187-1)}
\]

\[
A^* = 300.4 \text{ mm}^2, (0.466 \text{ inch}^2)
\]
J&J Design & Analysis
Engine & Injector Sizing
Single Engine

**Throat Diameter**

\[ D^* = 2 \left( \frac{A^*}{\pi} \right)^{0.5} \]

\[ D^* = (2) \left( \frac{3E - 4}{\pi} \right)^{0.5} \]

\[ D^* = 0.0195 \text{ m (0.770 inch)} \]

**Exit Mach Number**

\[ M_e = \sqrt{\frac{2 \left( \frac{p_e}{p_0} \right)^{\frac{\gamma - 1}{\gamma}} - 1}{\gamma - 1}} \]

\[ M_e = \sqrt{\frac{2 \left( \frac{101352.9}{6.895 \text{ MPa}} \right)^{\frac{1.187\text{ MPa} - 1}{1.187}} - 1}{1.187 - 1}} \]

\[ M_e = 3.178 \]
Exit to Throat Area Ratio

\[ \frac{A_e}{A^*} = \frac{1}{M} \left[ \frac{2}{\gamma + 1} \left( 1 + \frac{\gamma - 1}{2} M^2 \right) \right]^{\gamma + 1 \over 2(\gamma - 1)} \]

\[ \frac{A_e}{A^*} = \frac{1}{3.178} \left[ \frac{2}{1.187 + 1} \left( 1 + \frac{1.187 - 1}{2} \left( 3.178 \right)^2 \right) \right]^{\frac{1.187 + 1}{2(1.187 - 1)}} \]

\[ \frac{A_e}{A^*} = 9.1041 \]

Exit Velocity

\[ u_e = \sqrt{2 \frac{R \gamma T_0}{\gamma - 1 M} [1 - \left( \frac{p_e}{p_0} \right)^{\gamma - 1 \over \gamma}]} \]

\[ u_e = \sqrt{2 \frac{(8314) (1.187) 3265.5}{1.187 - 1} \frac{[1 - \left( \frac{101352.9}{6.895 \text{ MPa}} \right)^{1.187 - 1 \over 1.187}]}{20.05} \]

\[ u_e = 2889.31 \text{ m/s} , (6464.8 \text{ mph}) \]
J&J Design & Analysis
Engine & Injector Sizing

Single Engine

Specific Impulse

\[ Isp = \frac{u_{eq}}{g} \]
\[ Isp = \frac{2889.311}{9.8} \]

\[ Isp = 294.5 \text{ sec} \]

Thrust

\[ F_T = \dot{m}u_e + A_e(p_e - p_a) \]
\[ F_T = (1.15)(2889.31) + 0.0027(101352.9 - 6.895 \times 10^6) \]
\[ F_T = 3.32 \text{ kN (747 lbf)} \]
J&J Design & Analysis
Engine & Injector Sizing

Single Engine

Chamber Volume

$$V_{ch} = L^* A^*$$

$$V_{ch} = (1.27)(3.004 \times 10^{-4})$$

$$V_{ch} = 381.5 \text{ cm}^3, (23.28 \text{ inch}^3)$$
**Chamber Length**

\[ A_t = 3E - 4 \, \text{m}^2, \, (0.466 \, \text{inch}^2) \]

\[ D_t = 1.96 \, \text{cm}, \, (0.77 \, \text{inch}) \]

\[ \frac{A_c}{A_t} = 8D_t^{-0.6} + 1.25 \]

\[ \frac{A_c}{A_t} = (8)1.96^{-0.6} + 1.25 \]

\[ \frac{A_c}{A_t} = 6.59 \]

\[ A_c = 0.002 \, \text{m}^2, \, (3.10 \, \text{inch}^2) \]

\[ L_c = \frac{V_c}{A_c} \]

\[ L_c = \frac{3.815 \, E - 4 \, \text{m}^3}{0.002 \, \text{m}^2} \]

\[ L_c = 0.19 \, \text{m} \,(7.51 \, \text{inch}) \]

Use as a starting point. Ended with:

\[ L_c = 0.17 \, \text{m} \,(6.58 \, \text{inch}) \]

\[ D_c = 54 \, \text{mm} \,(2.125 \, \text{inch}) \]
Nozzle Length (Conical)

\[ L_n = \frac{D_e - D_t}{2\tan\theta_{cn}} \]

Where  

- \( L_n \) = conical nozzle length  
- \( D_t \) = nozzle throat diameter  
- \( \theta_{cn} \) = nozzle cone half angle (15°)

\[ L_n = \frac{0.059 - 0.02}{2\tan(15°)} \]

\[ L_n = 2.87 \text{ in (72.8 mm)} \]

Diagram is for a parabola shaped nozzle. J&J used this diagram for sizing the converging & diverging part of the nozzle.
Engine & Injector Sizing

Chamber Wall Thickness

\[ t_w = \frac{FSP_c r_c}{\sigma_y} \]

Where

- \( t_w \) = wall thickness
- \( r_c \) = Chamber Radius 0.027 m (1.5 inch)
- \( p_c \) = chamber pressure = 6.895 Mpa (1000 psi)
- \( \sigma_y \) = Yield Strength = 1000 Mpa (145 ksi)
- FS = Safety Factor

\( t_w = 4.06 \text{mm} (0.160 \text{ inch}) \) [@ chamber wall] FS = 15.5

\( t_{w \text{ pressure channel}} = 1.32 \text{ mm} (0.052 \text{ inch}) \) [@ injector pressure port wall] FS = 5

\( t_{w \text{ logo}} = 1.04 \text{ mm} (0.041 \text{ inch}) \) [on wall where chamber pressure channel crosses over logo] FS = 4
## Summary of Engine Specifications
### Single Engine Static Fire

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Kerosene</th>
<th>Gaseous Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OF ratio</strong></td>
<td>1.875</td>
<td></td>
</tr>
<tr>
<td>( \dot{M}_{TOT} )</td>
<td>1.15 ( km/s )</td>
<td>2.5 ( lbm/s )</td>
</tr>
<tr>
<td>( P_c )</td>
<td>6.895 ( MPa )</td>
<td>1000 ( psi )</td>
</tr>
<tr>
<td>( P_e )</td>
<td>101352.9 ( Pa )</td>
<td>14.7 ( psi )</td>
</tr>
<tr>
<td>( L^* )</td>
<td>1.27 ( m )</td>
<td>50 ( inches )</td>
</tr>
<tr>
<td>( D^* )</td>
<td>19.6 ( mm )</td>
<td>0.770 ( inch )</td>
</tr>
<tr>
<td>( T_c )</td>
<td>3266 ( K )</td>
<td>5418 ( ^\circ )F</td>
</tr>
<tr>
<td>( A^* )</td>
<td>0.3004 ( mm^2 )</td>
<td>0.466 ( inch^2 )</td>
</tr>
<tr>
<td>( A/A^* )</td>
<td>9.1041</td>
<td></td>
</tr>
<tr>
<td><strong>Isp</strong></td>
<td>294.5 ( s )</td>
<td></td>
</tr>
<tr>
<td>( F_T )</td>
<td>3.32 ( kN )</td>
<td>750 ( lbf )</td>
</tr>
<tr>
<td>( V_{ch} )</td>
<td>381.5 ( cm^3 )</td>
<td>23.286 ( inch^3 )</td>
</tr>
<tr>
<td>( L_c )</td>
<td>0.17 ( m )</td>
<td>6.58 ( inch )</td>
</tr>
<tr>
<td>( D_c )</td>
<td>54 ( mm )</td>
<td>2.125 ( inch )</td>
</tr>
<tr>
<td>( L_n )</td>
<td>72.8 ( mm )</td>
<td>2.87 ( inch )</td>
</tr>
<tr>
<td>( T_w )</td>
<td>3.81 ( mm )</td>
<td>0.15 ( inch )</td>
</tr>
</tbody>
</table>
# J&J Design & Analysis
## Engine & Injector Sizing

### Summary of Engine Specifications
#### Dual Engine Static Fire

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Kerosene</th>
<th>Gaseous Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OF ratio</strong></td>
<td>1.875</td>
<td></td>
</tr>
<tr>
<td>$M_{TOT}$</td>
<td>0.575 $kg/s$</td>
<td>1.3 $lbm/s$</td>
</tr>
<tr>
<td>$P_e$</td>
<td>3.45 $MPa$</td>
<td>500 $psi$</td>
</tr>
<tr>
<td>$P_e$</td>
<td>101320 $Pa$</td>
<td>14.7 $psi$</td>
</tr>
<tr>
<td>$L^*$</td>
<td>1.27 $m$</td>
<td>50 inches</td>
</tr>
<tr>
<td>$A^*$</td>
<td>0.300 $mm^2$</td>
<td>0.465 inch$^2$</td>
</tr>
<tr>
<td>$D^*$</td>
<td>19.6 mm</td>
<td>0.770 inch</td>
</tr>
<tr>
<td>$T_c$</td>
<td>3222 $K$</td>
<td>5340 °F</td>
</tr>
<tr>
<td>$A/A^*$</td>
<td>5.4902</td>
<td></td>
</tr>
<tr>
<td>$I_{sp}$</td>
<td>275.9 s</td>
<td></td>
</tr>
<tr>
<td>$F_T$</td>
<td>1.56 $kN$</td>
<td>350 $lbf$</td>
</tr>
<tr>
<td>$V_{ch}$</td>
<td>338.18 $cm^3$</td>
<td>23.286 $inch^3$</td>
</tr>
<tr>
<td>$L_c$</td>
<td>0.16 m</td>
<td>6.283 inch</td>
</tr>
<tr>
<td>$D_c$</td>
<td>54 mm</td>
<td>2.125 inch</td>
</tr>
<tr>
<td>$L_n$</td>
<td>49 mm</td>
<td>1.93 inch</td>
</tr>
<tr>
<td>$T_w$</td>
<td>3.81 mm</td>
<td>0.15 inch</td>
</tr>
</tbody>
</table>
J&J DESIGN & Analysis
Top Level Engine Design
J&J Design & Analysis
Overall Engine Design

J&J Overview

Isomolded Graphite Nozzle

Retention Ring (2 Pieces)

Combustion Chamber

Injector

5" (12.7 cm)

11" (28 cm)
The design of Jessie & James is identical besides for the pressure block & injector which is rotated by 180°.

This simplifies the routing of feed & sensor lines.
J&J Design & Analysis

Overall Engine Design

J&J Overview

**Engine Components**

Each engine will be made up of the following components:

1. Injector
2. Chamber
3. Nozzle Retention Ring ½
4. Nozzle Retention Ring 2/2
5. Chamber Ablative Insert (Graphite)
6. Ablative Nozzle (Graphite)
7. 1 Dash 153 O-ring
8. 2 Dash 337 O-rings
9. 16 ¼”-28 5/8” screws
Overall Engine Design

Jessie – Injector Ports

**Oxygen Inlet** - SS-1210-1-OR
\(\frac{3}{4}''\) Tube OD X 1 1/16-12 Male-O-Seal SAE/MS Straight Thread

**Fuel Inlet** - SS-810-1-OR
\(\frac{1}{2}''\) Tube OD x \(\frac{3}{4}-16\) Male O-Seal SAE/MS Straight Thread

**Film Cooling Inlet** - SS-400-1-OR
\(\frac{1}{4}''\) Tube OD x 7/16-20 Male O-Seal SAE/MS Straight Thread

**Sensor Ports** - SS-200-1-OR
\(\frac{1}{8}''\) Tube OD x 5/16-24 Male O-Seal SAE/MS Straight Thread
Chamber Pressure Sensors

J&J will have 3 pressure sensors that are equally spaced around the circumference of the combustion chamber.

The 3 pressure sensor ports are routed to the pressure sensor block.

Sensor Ports - SS-200-1-OR
1/8” Tube OD x 5/16-24 Male O-Seal
SAE/MS Straight Thread
The Nozzle geometry is a function of the chamber pressure & total mass flow rate

J&J design allows you to swap different nozzles by removing retention ring.
<table>
<thead>
<tr>
<th>Mechanical properties of parts at 20 °C (68 °F) As Built</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
</tr>
<tr>
<td>- in horizontal direction (XY)</td>
</tr>
<tr>
<td>- in vertical direction (Z)</td>
</tr>
<tr>
<td>typ. 1100 ± 100 MPa (160 ± 15 ksi)</td>
</tr>
<tr>
<td>typ. 1100 ± 100 MPa (160 ± 15 ksi)</td>
</tr>
<tr>
<td>Yield strength (Rp 0.2 %)</td>
</tr>
<tr>
<td>- in horizontal direction (XY)</td>
</tr>
<tr>
<td>- in vertical direction (Z)</td>
</tr>
<tr>
<td>typ. 1050 ± 100 MPa (typ. 152 ± 15 ksi)</td>
</tr>
<tr>
<td>typ. 1000 ± 100 MPa (145 ± 15 ksi)</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>- in horizontal direction (XY)</td>
</tr>
<tr>
<td>- in vertical direction (Z)</td>
</tr>
<tr>
<td>typ. 160 ± 25 GPa (23 ± 4 Msi)</td>
</tr>
<tr>
<td>typ. 150 ± 20 GPa (22 ± 3 Msi)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>typ. 15 ± 0.8 W/m°C</td>
</tr>
<tr>
<td>(104 ± 6 Btu in/(h ft°C °F))</td>
</tr>
</tbody>
</table>
J&J DESIGN & Analysis
Injector Design
Both Jessie & James will feature the same injector design and will be used for both single and dual engine static fires.

The injector has been sized for dual engine testing conditions with a 20% pressure drop seen for the fuel, oxygen, and film cooling orifices.

For single engine firing conditions, the oxygen orifices will maintain a 20% pressure drop while the pressure drop for the fuel & film cooling orifices will be 40%.
Since this injector will be 3D printed, any overhangs more than ~45 degrees require a support structure of some sort. This can be designed in, or formed in the pre-3D printing software. In this case, a support “tree” has been designed in to reduce the mass of the printed part.

Other overhangs are kept below 45 degrees, such as internal manifolds.

Threaded holes have also been opted for in the engine flange to eliminate the need for post-machining of the flange support structure (to allow room for a bolted joint).
J&J Design & Analysis
Engine & Injector Sizing

Injector

- Const. Velocity Manifold
- Maximum area > 4A_f

Film Cooling Channels

Fuel Fluid Flow Volume

Top View Slice through Fuel Manifold
J&J Design & Analysis

Engine & Injector Sizing

Injector

Film Cooling Channels

- Const. Velocity Manifold
- Maximum area > $4 A_{film}$
J&J Design & Analysis
Engine & Injector Sizing
Injector
The orifice arrangement is similar to the Blue Steel 2.0 Injector (machined).

Oxygen Orifices form a shower-head in two concentric rings.

Fuel orifices are arranged in like doublets, impinging at 30 degrees from axial. They also form two concentric rings and lie on radials that intersect the oxygen orifices.

Spray from impinging pairs tends to lie in the plane perpendicular to the plane formed by the impinging jets. These are radial planes (in this case) and so better mixing should be achieved by lining orifices up in the aforementioned manner.
Fuel Injector Sizing (Based on Dual Engine Conditions)

\[ A_f = \left( \frac{m}{c_d} \right) \sqrt{\frac{1}{2\rho} \left( \frac{1}{P_{i,f} - P_c} \right)} \]

Where

\[ \rho = 810 \text{ kg/m}^3 \]

\[ c_d = 0.7 \text{ (square edge orifice)} \]

\[ A_f = \text{injector orifice total area} \]

\[ P_c = 3.447E6 \text{ Pa (500 psi)} \]

Pressure Drop 20%

\[ P_{\text{inj,f}} = 4.137E6 \text{ (600 psi)} \]

\[ \dot{m}_f = 0.17 \text{ kg/s (15% tapped off for } \dot{m}_{\text{film}}) \]

\[ \# \text{ of holes} = 32 \]

\[ A_f = \left( \frac{0.17}{0.7} \right) \sqrt{\frac{1}{2(810)} \left( \frac{1}{4.137E6 - 3.447E6} \right)} \]

\[ A_f = 7.26E - 6 \text{ m}^2 \]

\[ A_{i,f} = \frac{A_f}{\# \text{ of holes}} \]

\[ A_{i,f} = \frac{7.26E - 6}{32} \]

\[ A_{i,f} = 2.27E - 7 \text{ m}^2 \]

\[ D_f = 2 \left( \frac{2.27E - 7}{\pi} \right)^{0.5} \]

\[ D_f = 0.538 \text{ mm (0.021 inch)} \]
Film Orifice Sizing (Based on Dual Engine Conditions)

\[ A_{film} = \left( \frac{\dot{m}_{film}}{c_d} \right) \sqrt{\frac{1}{2\rho}} \left( \frac{1}{P_{i,film} - P_c} \right) \]

Where

\[ \rho = 810 \text{ kg/m}^3 \]
\[ c_d = 0.7 \text{ (square edge orifice)} \]
\[ A_{film} = \text{injector orifice total area} \]
\[ P_c = 3.447E6 \text{ Pa (500 psi)} \]
\[ \text{Pressure Drop 20\%} \]
\[ P_{inj,film} = 4.137E6 \text{ (600 psi)} \]
\[ \dot{m}_{film} = 0.03 \text{ kg/s} \text{ (15\% tapped off from } \dot{m}_f\text{)} \]
\[ \# \text{ of holes} = 10 \]

\[ A_{film} = \left( \frac{0.03}{0.7} \right) \sqrt{\frac{1}{2(810)}} \left( \frac{1}{4.137E6 - 3.447E6} \right) \]
\[ A_{film} = 1.28E - 6 \text{ m}^2 \]

\[ A_{i,film} = \frac{A_f}{\# \text{ of holes}} \]
\[ A_{i,film} = 1.28E - 6 \]
\[ A_{i,film} = \frac{10}{10} \]

\[ D_{film} = 2 \left( \frac{1.28E - 7}{\pi} \right)^{0.5} \]
\[ D_{film} = 0.404 \text{ mm (0.0159 inch)} \]
Oxygen Injector Sizing (Based on Dual Engine Conditions)

\[ A_o = \left( \frac{\dot{m}_o}{c_d} \right) \sqrt{ \frac{R_0 T_0}{2 P_{i,0} (P_{i,o} - P_c)} } \]

Where

- \( R_0 = 259.8 \frac{J}{\kappa g - k} \)
- \( T_0 = 290 \, K \)
- \( c_d = 0.7 \) (square edge orifice)
- \( A_o = \text{injector orifice total area} \)
- \( P_c = 3.447E6 \, \text{Pa} \) (500 psi)
- Pressure Drop 20%
- \( P_{i,0} = 4.137E6 \, \text{Pa} \) (600 psi)
- \( \dot{m}_o = 0.375 \frac{\text{kg}}{\text{s}} \)
- \# of holes = 16

\[ A_o = \left( \frac{0.375}{0.7} \right) \sqrt{ \frac{(259.8)(290)}{2(4.137E6)(4.137E6 - 3.447E6)} } = 6.155E - 5 \, m^2 \]

\[ A_{i,o} = \frac{A_o}{\# \text{ of holes}} = \frac{6.155E - 5}{16} \]

\[ A_{i,o} = 3.85E - 6 \, m^2 \]

\[ D_o = 2 \left( \frac{3.85E - 6}{\pi} \right)^{0.5} = 2.21 \, \text{mm} \, (0.087 \, \text{inch}) \]
J&J DESIGN & Analysis
Thermal Control
Cooling on Jessie & James

• Jessie & James will feature both ablative & film cooling
• The engine chamber will be lined with isomolded graphite
• Nozzle will be constructed with isomolded graphite
  • Isomolded graphite has a much lower ablation rate than phenolic (nozzle material for nozzle Blue Steel 2.0)
• 15% of the full will be tapped off to cool the injector
An Isomolded Graphite will be used to thermally control both the combustion chamber and nozzle.

The combustion chamber will be lined with graphite and the nozzle will be fabricated out of graphite.

An alignment feature and pathways will be machined into the chamber line to allow for chamber pressure transducers and for the torch ignitor to operate.
Isomolded Graphite

All graphite will be machined out of one 3.00” DIA X 24” L Rod

This rod is large enough to machine all components

<table>
<thead>
<tr>
<th>Jessie Graphite Parts</th>
<th>James Graphite Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Chamber Liner</td>
<td>1 - Chamber Liner</td>
</tr>
<tr>
<td>1 - 1000 psi optimum expansion nozzle</td>
<td>1 - 1000 psi optimum expansion nozzle</td>
</tr>
<tr>
<td>1 – 500 psi optimum expansion nozzle</td>
<td>1 – 500 psi optimum expansion nozzle</td>
</tr>
</tbody>
</table>
### Material data Isomolded Graphite

<table>
<thead>
<tr>
<th>Property</th>
<th>SI Units</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus *</td>
<td>7~8 GPa</td>
<td>1.015Mpsi ~1.16Mpsi</td>
</tr>
<tr>
<td>Compressive strength *</td>
<td>8963 Pa</td>
<td>13000 psi*</td>
</tr>
<tr>
<td>Density</td>
<td>0.065 lb/in³</td>
<td>1.81 gr/cm³</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>7250 psi</td>
<td>50 MPa</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>85 W/(m²·K/m)</td>
<td>49 BTU/(h·ft²·°F/ft)</td>
</tr>
<tr>
<td>CTE</td>
<td>4.6 Microns/m°C</td>
<td>2.6 in/in°F×10⁻⁶</td>
</tr>
</tbody>
</table>

* Provided by the engineer at Graphite Store as an estimate
(This has not been tested & therefore is not in datasheet)
Insulation Thickness

\[ t_{\text{insul}} = t_{\text{exp}} \dot{e}_s \]

Where

- \( t_{\text{insul}} \) = insulation thickness (m)
- \( t_{\text{exp}} \) = insulation exposure time (s)
- \( \dot{e} \) = insulation erosion rate (m/s)
- \( f_s \) = safety factor

\[ t_{\text{insul}} = (25)s(0.10) \frac{mm}{s} (4) \]

\[ t_{\text{insul}} = 10 \text{ mm (0.39 inch)} \]

\[ t_{\text{chamber liner}} = 11.11 \text{ mm (0.4375 inch)} \]

Larger due to uncertainty about graphite material properties & to allow for a larger \( \frac{A_c}{A_t} \) and longer max turn times in future modifications.

This provides enough confidence to fire for a short duration & use test results to estimate a more accurate erosion rate.
Ablative Cooling Energy Conservation

\[(\dot{Q}_{\text{rad}} + \dot{Q}_{\text{con}}) = \dot{m}_{\text{ablative}} \cdot h_{\text{ablative}}\]

Where:

\[\dot{Q}_{\text{rad}}\] = heat addition due to radiation (W)
\[\dot{Q}_{\text{con}}\] = heat addition due to convection (W)
\[\dot{m}_{\text{ablative}}\] = the mass flow of the ablative material (kg/s)
\[h_{\text{ablative}}\] = enthalpy of material ablation (J/kg)

Note: Need to know \(\varepsilon_{\text{flame}}\) & \(h_{\text{ablative}}\). Looking into this. Can estimate \(h_{\text{ablative}}\) after a static fire by measuring the amount of material that has ablated.
J&J Design & Analysis
Thermal Control

Film Cooling Energy Conservation

\[(\dot{Q}_{rad} + \dot{Q}_{con})_{in} = \dot{Q}_{wall} + \dot{m}_{film} \left( \int_{T_{vap}}^{T_{out}} c_p dT + h_{fg} + c[T_{vap} - T_{in}] \right)\]

\(\dot{Q}_{rad}\) = heat addition due to radiation (W)
\(\dot{Q}_{con}\) = heat addition due to convection (W)
\(c_p\) = heat capacity of vaporized gases at constant pressure (J/kg.K)
\(C\) = heat capacity of the prevaporized fluid (J/kg.K)
\(h_{fg}\) = heat of vaporization of the fluid (J/kg)
\(\dot{Q}_{wall}\) = heat flow into the wall (W)
\(\dot{m}_{film}\) = mass-flow rate of the wall coolant (kg/s)
\(T_{in}\) = temperature of the coolant entering the control volume (K)
\(T_{out}\) = temperature of the vaporized coolant leaving the control volume (K)

Post CDR, more research will be done to in this area
J&J DESIGN & Analysis
Engine Interfaces
Mount Interface

Mount Interface:

4

This is mount the engine to the slide rail featured on Hydra
The ignitor interface will secure and seal the ignitor onto the engine.
J&J Design & Analysis

Engine Interfaces

Milk Stool Interface

The injector houses the 3 ¼”-28 mounting points for the milk stool.

The milk stool is strut design that will bypass all propellant inlet lines and make contact with a load cell to provide thrust measurements.
J&J will feature a total of 16 ¾-28 5/8” fully threaded socket head screws

The first set of 8 will secure the injector to the chamber and the second set of 8 will secure the nozzle to the chamber with a 3D printed retention ring.
J&J Fasteners & Washer Material Properties

**Screws**
- Used for both retention ring and injector side
- Type: \( \frac{3}{4} \)-28
- Length: \( \frac{3}{4} ” \)
- Material: 18-8 Stainless Steel
  (fully threaded socket head screw)
- Tensile Area: 0.03640”
- Ultimate Strength: 70 ksi
- Young's Modulus: 28500 ksi

**Lock washers**
- Used for both retention ring and injector side
- 18-8 Stainless Steel Mil. Spec. Split Lock Washer
- ID: 0.260”
- OD: 0.487”
- Thickness: 0.062”
- Ultimate Strength: 73.2 ksi
- Young's Modulus: 28500 ksi
- Yield Strength: 31.2 ksi
Retention Ring, Injector, Chamber
Material: EOS Maraging Steel MS1
Yield Strength: 145 ksi (1000 MPa)
(in Z direction – lower then the XY direction)
Modulus of Elasticity: 22 Msi (150 Gpa)
(in Z direction – lower then the XY direction)

Keensert (Lightweight Insert)
Only Using on Retention Ring Side
Non-locking (Part # KN428J)
Internal Thread Class 3B 1/4-28
Material: 303 CRES (passivated)
External Thread: 3/8 – 16
Shear Engagement: 0.2371”
L: 0.37”
J&J Design & Analysis
Fasteners & Sealing

Screw Preload Force

\[
\text{Preload Force} = 0.75 \left( \sigma_{\text{proof}} \right) A_t
\]

Where \( A_t \) = Tensile Area

(0.75 is coefficient used for reusable screws)

\[
\text{Preload Force} = 0.75 \times 80 \text{ ksi} \times 0.0364 \text{in}^2
\]

\[
\text{Preload Force} = 2184 \text{ lbf} \ (9.610 \text{ kN})
\]

Screw Torque Equation

\[
T = K_t F_i D
\]

Where:

- \( T \) = torque (in-lb, ft-lb, or N-m)
- \( K_t \) = torque coefficient (0.15 lubed)
- \( F_i \) = Initial preload Force in the bolt
- \( D \) = nominal diameter of bolt

\[
T = (0.15)(2184) \text{lbf} \times (0.25) \text{in}
\]

\[
\text{Torque Preload} = 81.9 \text{ in-lbf} \ (9.25 \text{ N-m})
\]

For screws on both the injector and nozzle side
**Screw Stiffness**

\[ K_{\text{screw}} = \frac{A_t E_{\text{screw}}}{L_{\text{joint}}} \]  
(Fully Threaded screw)

- \( E_{\text{bolt}} = 28500 \text{ ksi} \)
- \( L_{\text{joint}} = 0.35 \text{ inch} \)
- \( A_t = 0.0364in^2 \)
- \( K_{\text{screw}} = \frac{0.0364in^2 \times 28500 \text{ ksi}}{0.35 \text{ inch}} \)

\[ K_{\text{screw}} = 2.964 \text{ Msi} \]

**Joint Stiffness**

\[ K_{\text{joint}} = \frac{\pi E_{\text{joint}} d_{\text{shank}}}{2ln \left( 5 \left( \frac{L_{\text{joint}} + 0.5d_{\text{shank}}}{L_{\text{joint}} + 2d_{\text{shank}}} \right) \right)} \]

- \( E_{\text{joint}} = 22000 \text{ ksi} \) (entirely maraging steel)
- \( d_{\text{shank}} = 0.281 \text{ inch} \)

\[ K_{\text{joint}} = \frac{\pi (22000 \times 0.281)}{2ln \left( 5 \left( \frac{0.35 + 0.5 	imes 0.281}{0.35 + 2 	imes 0.281} \right) \right)} \]

\[ K_{\text{joint}} = 11.5 \text{ Msi} \]
Joint coefficient of screw-load factor, \( C \)

\[
C = \frac{k_{screw}}{k_{screw} + k_{joint}}
\]

\[
C = \frac{2.964 \text{ Msi}}{2.964 \text{ Msi} + 11.5 \text{ Msi}}
\]

\[
C = 0.20
\]

The required minimum preload to prevent gapping is then

\[
F_i = P (1 - C)
\]

Factor of Safety against gapping

\[
FS_{gap} = \frac{F_i}{P(1 - C)}
\]

Where \( P \) = load

Now need to determine the load on the joint for both ends of the engine...
Determining Load on Fasteners

\[ P_{\text{Retention Ring}} = (P_0)(A_c - A_t) \]
\[ P_{\text{Retention Ring}} = (1000 \text{ psi})(3.55\text{in}^2 - 0.466\text{in}^2) \]
\[ P_{\text{Retention Ring}} = 3084 \text{lbf} \]

\[ P_{\text{screw}} = \frac{P_{\text{Retention Ring}}}{\# \text{ of Screws}} \]
\[ \# \text{ of Screws} = 8 \]
\[ P_{\text{screw}} = \frac{3084 \text{lbf}}{8} \]
\[ P_{\text{screw}} = 385.5 \text{lbf} \]
Fastening - Retention Ring Side

**The required minimum preload to prevent gapping is then**

\[ F_{i,min} = P(1 - C) = 385.5 \text{ lbf} (1 - 0.20) \]

\[ F_{i,min} = 308 \text{ lbf} \]

**Preload Force = 2184 lbf ✓**

Factor of Safety against gapping

\[ FS_{gap} = \frac{F_i}{P(1 - C)} = \frac{2184 \text{ lbf}}{385.5 \text{ lbf} (1 - 0.20)} \]

\[ FS_{gap} = 7.08 \]

**Gapping is NOT predicted!**
Determining Load on Fasteners

\[
P_{\text{Injector}} = (P_0)(A_c)
\]

\[
P_{\text{Injector}} = (1000 \text{ psi})(3.55\text{in}^2)
\]

\[
P_{\text{Injector}} = 3550 \text{ lbf}
\]

\[
\# \text{ of Screws} = 8
\]

\[
P_{\text{screw}} = \frac{3550 \text{ lbf}}{8}
\]

\[
P_{\text{screw}} = 444 \text{ lbf}
\]
Failure in tension is NOT predicted!

\[
\sigma_{screw} = \frac{P_{screw}}{\text{Tensile Area}}
\]

\[
\sigma_{screw} = \frac{444 \text{ lbf}}{0.0364 \text{in}^2}
\]

\[\sigma_{screw} = 12.2 \text{ ksi}\]

\[FS = \frac{80 \text{ ksi}}{12.2 \text{ ksi}}\]

\[FS = 6.56\]

The required minimum preload to prevent gapping is then

\[F_{i,\text{min}} = P(1 - C) = 444 \text{ lbf } (1 - 0.20)\]

\[F_{i,\text{min}} = 355 \text{ lbf}\]

**Preload Force = 2184 lbf ✓**

Factor of Safety against gapping

\[FS_{gap} = \frac{F_i}{P(1 - C)} = \frac{2184 \text{ lbf}}{444 \text{ lbf } (1 - 0.20)}\]

\[FS_{gap} = 6.15\]

Gapping is NOT predicted!
Minimum Screw Length of Engagement

\[
L_{e,\text{min}} = \frac{2\pi \left( \frac{1}{2} + 0.5775(nE_s - K_n) \right)}{K_n\max \pi \left( \frac{1}{2} + 0.5775(28)(0.1904 - 0.1857) \right)}
\]

\[
L_{e,\text{min}} = 0.217 \text{ inch}
\]

Since different materials need to get the J value

\[
J = \frac{A_s \sigma_{ult, ext}}{A_n \sigma_{ult, int}}
\]

\[
A_s = \text{Shear area of external thread (screw)}
\]

\[
A_n = \text{Shear area of internal thread (hole)}
\]

If \( J > 1 \) then the minimum length of engagement needs to be extended to:

\[
L_{e,\text{min new}} = J \times L_{e,\text{min org}}
\]

\[
A_s = \pi n L_{e,\text{min}} k_n \max \left( \frac{1}{2n} + 0.57735(E_s \min - k_n \max) \right)
\]

\[
k_n \max = \text{Maximum minor diameter of internal thread}
\]

\[
E_s \min = \text{Minimum pitch diameter of external thread}
\]

\[
n = \text{number of threads per inch}
\]

\[
A_s = \pi (28)(0.217)(0.1857)\left( \frac{1}{2(28)} + 0.57735(0.1904 - 0.1857) \right)
\]

\[
A_s = 0.073 \text{ in}^2
\]

\[
A_n = \pi n L_{e,\text{min}} D_s \min \left( \frac{1}{2n} + 0.57735(D_s \min - E_n \max) \right)
\]

\[
E_n \max = \text{Maximum pitch diameter of internal thread}
\]

\[
D_s \min = \text{Minimum major diameter of external thread}
\]

\[
A_n = \pi (28)(0.217)(0.2095)\left( \frac{1}{2(28)} + 0.57735(0.2095 - 0.1959) \right)
\]

\[
A_n = 0.103 \text{ inch}^2
\]
J&J Design & Analysis  
Fasteners & Sealing  

Checking Minimum Length of Engagement on Retention Ring Side, Not using Keenserts here

Minimum Screw Length of Engagement cont.

Since different materials need to get the J value

\[ J = \frac{(0.073 \text{ in}^2)(70 \text{ ksi})}{(0.103 \text{ in}^2)(145 \text{ ksi})} \]

\[ J = 0.34 \]

Since \( J < 1 \):

\[ L_{e,min} = 0.217 \text{ inch} \]

Our length of Engagement On Retention Ring Side:

\[ L_e = L_{screw} - (t_{retention\_ring} - d_{counter\_bore}) - t_{washer} \]

\[ L_e = 0.75'' - (0.75'' - 0.4'') - 0.062'' \]

\[ L_e = 0.338'' \]

On retention ring side both internal and external threads are NOT predicted to fail!
Insert Internal Thread Failure Check

\[ A_s = \frac{3\pi L_e D_{major, ext}}{4} \]

Where \( A_s = \) Thread Shear Area

\( L_e = \) Length of Thread Engagement

\( D_{major, ext} = \) Major Diameter of the mating external thread

\[ A_s = \frac{3\pi(0.338)(0.375)}{4} \]

\[ A_s = 0.30 \text{ in}^2 \]

Insert Internal Thread Failure Check

\[ P_{ult} = 12370 \text{ lb (MS51830E-202L)} \]

\[ FS_{shear\ thread\ failure} = \frac{P_{ult}}{P_{joint}} \]

For Injector Side

\[ FS_{shear\ thread\ failure} = \frac{12370 \text{ lb}}{444 \text{ lbf}} \]

\[ FS_{shear\ thread\ failure} = 27.9 \]

Insert Internal Thread Failure is NOT predicted!
J&J Design & Analysis
Fasteners & Sealing

Using Keenserts on Injector Side

Insert External Thread Failure Check

\[ P_{\text{ult}} = 8630 \text{ lb (MS51830E-202L)} \]
\[ A_s = 0.30 \text{ in}^2 \]

\[ \text{For injector side} \]

\[ FS_{\text{shear thread failure}} = \frac{8630 \text{ lbf}}{444 \text{ lbf}} \]

\[ FS_{\text{shear thread failure}} = 19.4 \]

Insert External Thread Failure is NOT predicted!

Insert Parent Material Thread Failure Check

\[ P_{\text{ult}} = (0.103 \text{ in}^2)(145 \text{ksi}) \]
\[ P_{\text{ult}} = 14,935 \text{ lbf} \]

\[ \text{For injector side} \]

\[ FS_{\text{shear thread failure}} = \frac{14935 \text{ lbf}}{444 \text{ lbf}} \]

\[ FS_{\text{shear thread failure}} = 33.6 \]

Insert Parent Material Thread Failure is NOT predicted!
Sealing Features

Jessie & James each have 3 potential leak paths

1. Nozzle & Chamber interface
2. Ignitor & Chamber interface
3. Injector & Chamber interface
Sealing Features

Nozzle & Chamber interface

Will feature two female gland piston seals

Two for redundant purposes, fine surface finish on nozzle may be hard to achieve

Multiple nozzles will be printed during Jessie & James lifetime, so O-ring groove has been placed on chamber side (less machining)
Sealing Features

Ignitor & Chamber interface

Will Feature a Face Seal

Because it is more likely to print future iterations of the ignitor, the O-ring groove has been placed on the chamber side (less machining labor)
Sealing Features

Injector & Chamber interface

Will Feature a Face Seal

Because it is more likely to print future iterations of the injector, the O-ring groove has been placed on the chamber side (less machining)
Injector-Chamber

Face Seal O-ring
Dash Number 153
Qty: 1
Size: 3/32”
Material: Viton

Nozzle-Chamber

Piston Seal O-rings
Dash Number 337
Qty: 2
Size: 3/16”
Material: Viton

Ignitor-Chamber

Face Seal O-ring
Dash Number 115
Qty: 1
Size: 3/32”
Material: Viton
The chamber insert will be fabricated to have a slightly undersized outer diameter with respect to the combustion chamber inner diameter.

This will provide ease of assembly.

The chamber insert will be sized so that during the static fire the insert will expand and make contact on the chamber inner wall, this will help transfer all of the load to the chamber wall.
J&J Build & Test
Fabrication & Assembly

Installing the Chamber insert

The axial length of the insert will be sized to be slightly larger than the engine's axial length. This will require to press fit the chamber liner during assembly.

Press fitting the chamber liner will prevent any axial movement during the static fire.

A clocking feature on the injector face will position the liner correctly, to make sure the pressure chambers and ignitor are lined up.
J&J Build & Test
J&J Build & Test
Fabrication & Assembly
J&J Build & Test
Fabrication & Assembly

Printed Pieces

Each engine will be made up 4 printed pieces:

1. Injector
2. Chamber
3. Nozzle Retention Ring ½
4. Nozzle Retention Ring 2/2
J&J Build & Test
Fabrication & Assembly

Printer: EOS M290

Design Constraints:
Max Print Height: 325 mm (12.8 inch)
Must avoid 45° overhangs
Features should be above 150 μm (0.006 inch)
J&J Build & Test
Fabrication & Assembly

Injector Print Direction
J&J Build & Test
Fabrication & Assembly

Chamber Print Direction

Print Direction
J&J Build & Test
Fabrication & Assembly

Retention Ring Print Direction
Additive Manufacturers

Will be using USC’s Center for Advance Manufacturing (CAM) to print Jessie & James.

Cheapest solution as they:

- Charge $7/hour of printing time (others ~ $100/hour)
- Only charge for the material
  - Inconel - $150/kg
  - Maraging Seel - $150/kg
J&J Build & Test
Fabrication & Assembly

J&J Engine Parts on Build Plates

Retention Ring on build plate
Injector on Build Plate
Both Chambers on Build Plate

No Support Structure Required!
Additive Manufacturers

Jessie & James Printing Cost Estimate

Print Hours
2 Combustion Chambers ~ 66 hours
2 injectors & 4 (1/2) retention rings ~ 80 hours
Total weight of printed parts 5.72 kgs (12.6lbs)

Printing Time Cost: $1,022
Material Cost: $1,716

Estimated Total Cost: $2,738
J&J Build & Test
Tolerance Stack-ups
Tolerance Stack-Up

This will be completed post CDR

Stack-ups that will be addressed:

- Graphite liner press fit
- Graphite liner radial strain during test to ensure the printed chamber takes pressure loads
- Screw socket head below flange surface

Hooke’s Law:

\[ \sigma = E \varepsilon, \quad \varepsilon = \frac{\Delta L}{L_0} \]

\[ \varepsilon_{\text{max}} = \frac{\sigma_{\text{ult}}}{E} = \frac{50 \text{ MPa}}{7 \text{ GPa}} = 0.007 \quad , \quad \varepsilon = \frac{\Delta L}{L_0} \]

\[ \Delta L = \varepsilon_{\text{max}} L_0 = (0.007)(0.11) m \]

\[ \Delta L = 7.7E - 4 m \ (0.030 \text{ inch}) \]

\[ L_0 = 0.11 m \ (4.375 \text{ inch}) \]

Can Axial or Radially Compress ~0.030 inch before failure
Questions?
Future Modifications
Hydra
Future Modifications
Jessie & James
Supplementary Material

Master Equipment List (MEL)
Supplementary Material
Master Equipment List (MEL)
Supplementary Material

Cost
The only difference in design is the injector & pressure transducer ports are rotated by 180°.
Supplementary Material
Schedule
Radiation Heat Addition

Radiation heat transfer coefficient

\[ h_{rad} = \varepsilon \sigma (T_c^2 + T_\infty^2) (T_c + T_\infty) \]

Where \( \varepsilon = \text{emissivity (flame)} \)

\[ \sigma = \text{Stefan – Boltzmann constant} = 5.67 \times 10^{-8} \left( \frac{W}{m^2 K^4} \right) \]

\( T_c = \text{chamber temperature} \)

\( T_\infty = \text{ambient temperature} \)
Motivation & Introduction

Constraints for Jessie & James

Hydra

• Bottle Pressure (limits \( \text{deltaT} \), and Mdot)
• Oxygen Regulator (Droop, max set pressure 1500 psi)
• Flow Meter
• Cylinder Orifice
• Line Velocity
• Pressurant max static line pressure (1890 psi Fuel Tank)
Motivation & Introduction

Design Constraints

Constraints with Hydra

Flow Meter Check
Motivation & Introduction
Design Constraints

Constraints with Hydra

Ox Cylinder Orifice Choke Check

Mass flow rate
\[ \dot{m} = \rho u A \]

Speed of Sound
\[ a = \sqrt{\gamma RT} \]

Mention still need to know pressure drop by orifice and particulate filter and still maintain a incoming pressure above 2000 psi.
Motivation & Introduction
Design Constraints

Constraints with Hydra
Line Velocity Check