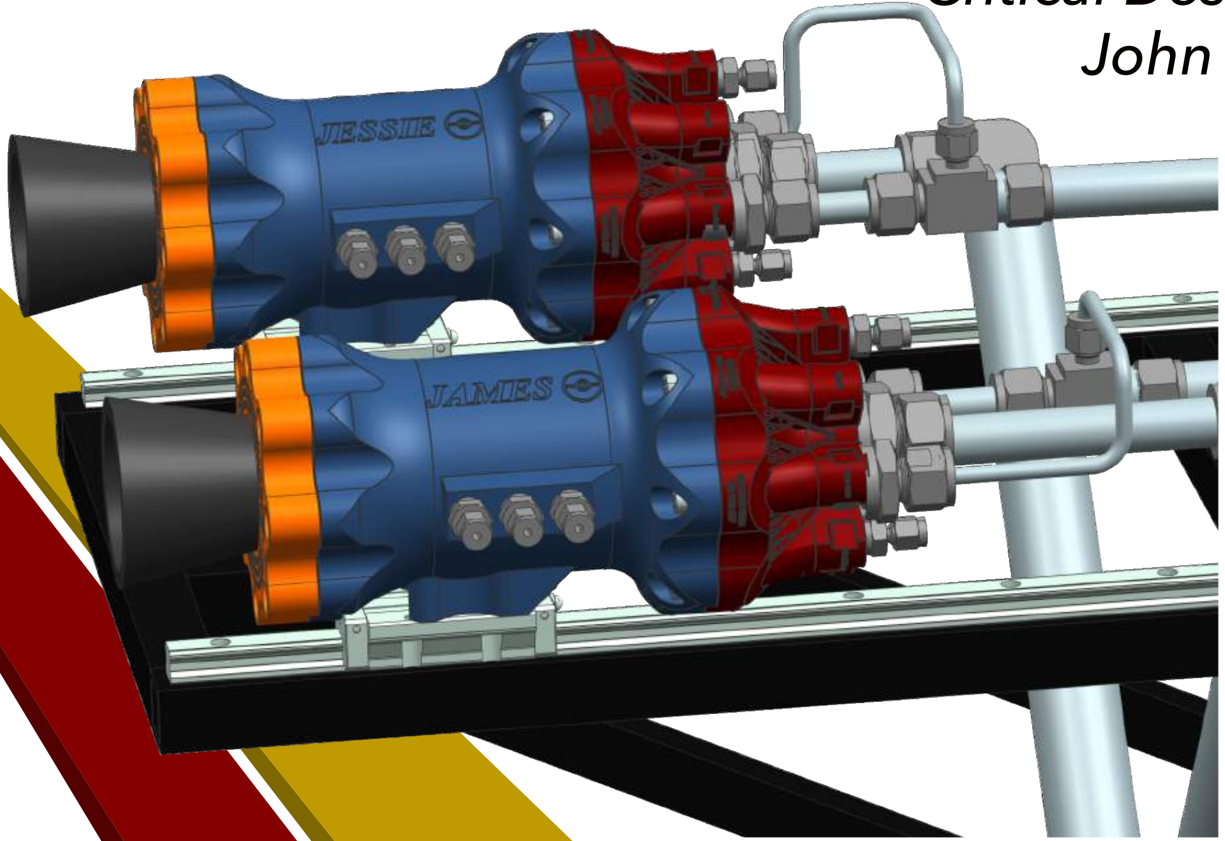
USC Viterbi School of Engineering

Jessie & James

Critical Design Review – March 30, 2018

John Targonski & Michael Moruzzi



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Agenda

Introduction & Motivation

-Discoveries

-Design Considerations

-Trade Studies

-Operating Conditions

J&J Design & Analysis

-Engine Design Tool (GUI)

-Engine , Injector Sizing, & Nozzle Sizing

-Overall Engine Design

-Thermal Control

-Engine Interfaces

-Modular Features

-Fasteners & Sealing

J&J Build & Test

-Print Design

-Post Machining

-Assembly

-Tolerance Stack Ups

-Engine Checkouts

Future Modifications

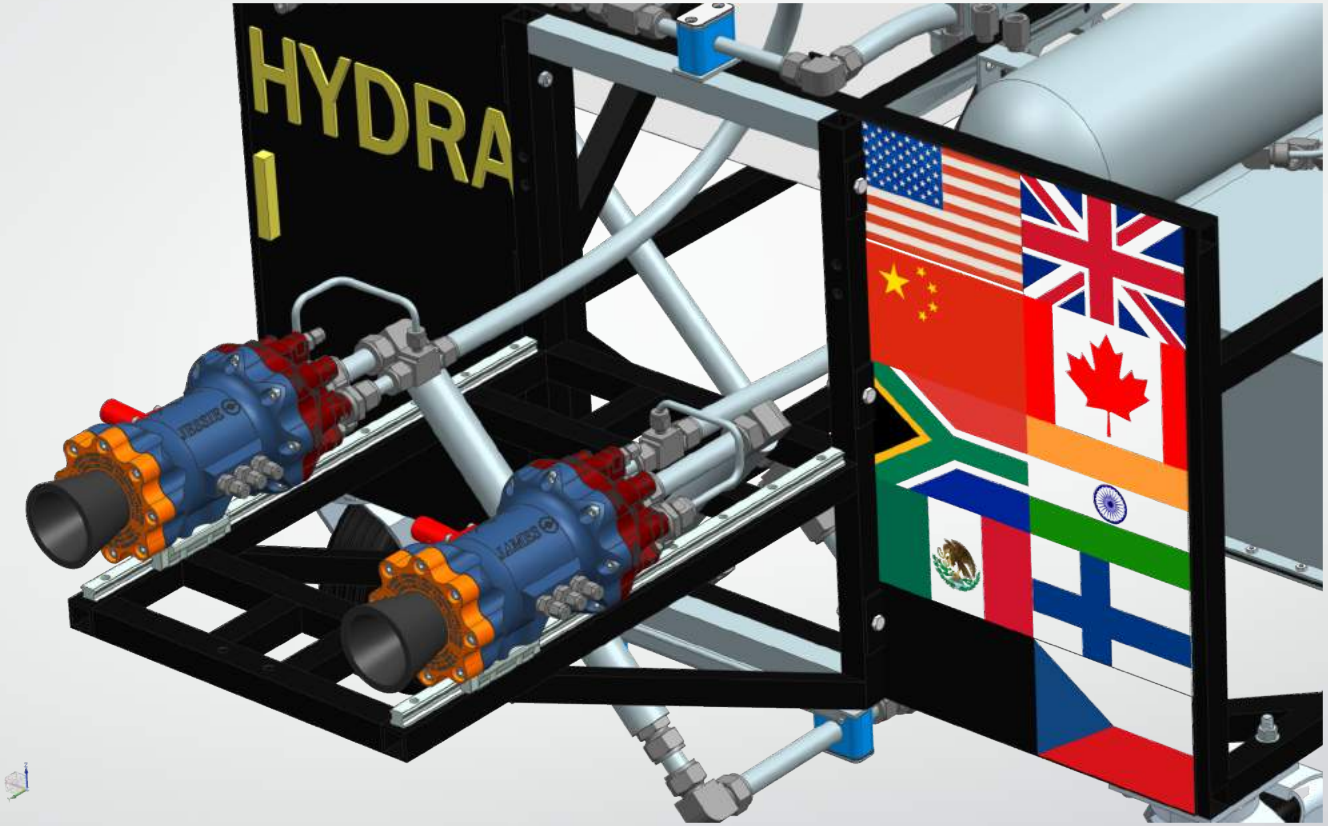
Supplementary Material

-MEL, Cost, Schedule

MOTIVATION & INTRODUCITON

Introduction & Motivation

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)

Introduction & Motivation

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Why Continue Building GOX rocket engines?

- Hydra (our mobile thrust stand) is not cryo-rated and would require significate 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

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- 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

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Motivation & Introduction
Discoveries from Inaugural Hydra Static Fire

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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

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Motivation & Introduction
Discoveries from Inaugural Hydra Static Fire

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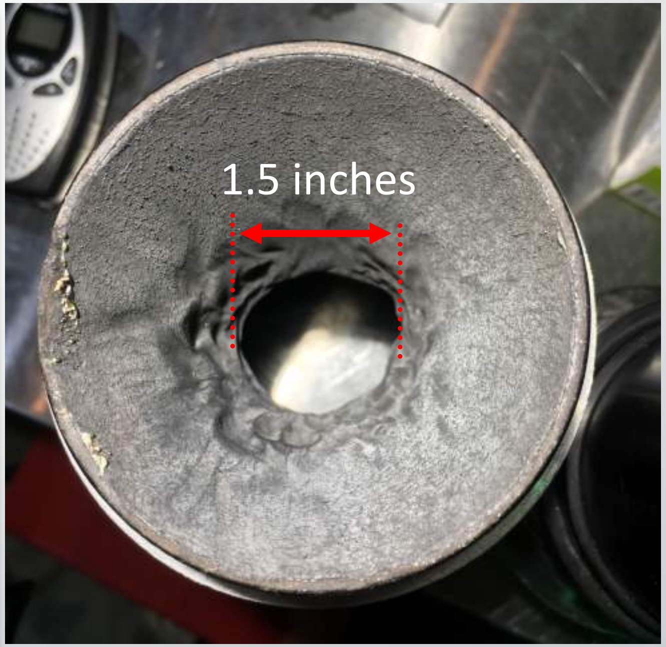
Nozzle Ablation

- 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 then the initial throat area
- As the throat area increased, the chamber pressure had to decrease in order to compensate, which in turn lead to a increase in mass flow rate throughout the static fire

$D_t(\text{before}) = 1 \text{ inch}$



$D_t(\text{after}) = 1.5 \text{ inches}$

$$\frac{A_t(\text{after})}{A_t(\text{before})} = 2.1$$

J&J would be designed to mitigate this phenomena

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Introduction & Motivation

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Jessie & James Design Considerations

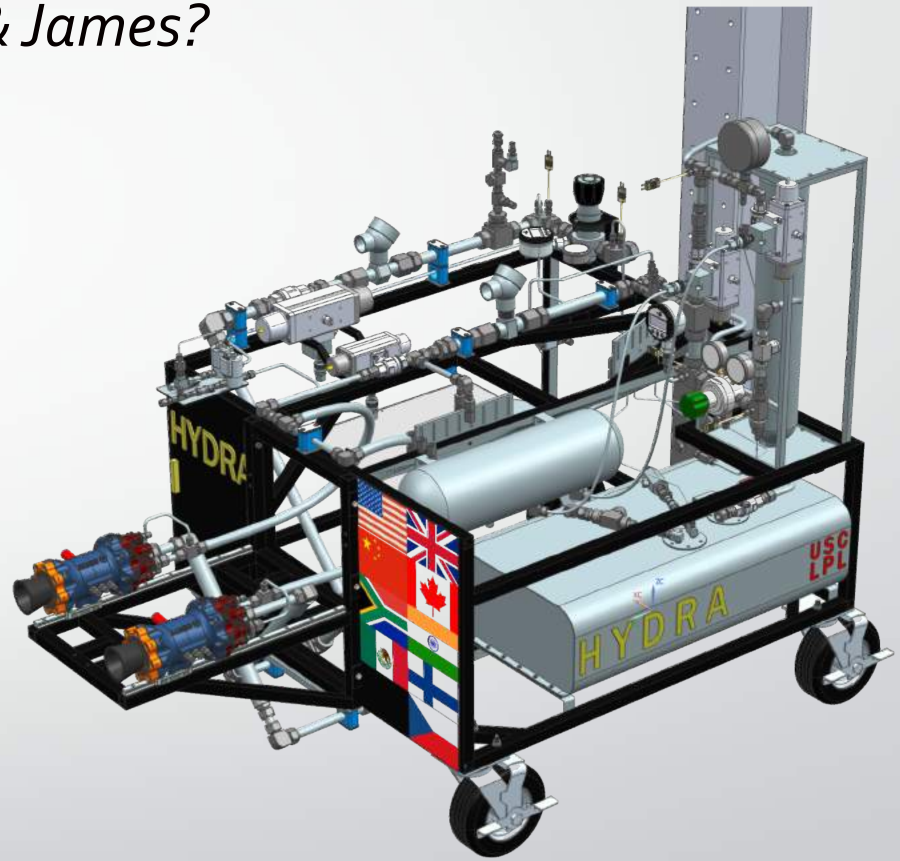
- Designed to be integrated & tested on LPL's mobile test stand Hydra
- Design to be LPL's workhorse engine
  - Ability to be fired at various operating conditions
  - Ability to be fired separately or in tandem
- Simplified design that is 3D printed
  - Minimal parts, fabricated in a relatively short 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

LPL

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

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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)

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Motivation & Introduction

Jessie & James Trade Study

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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)

$A_f = injector\ oriface\ total\ area$

$\rho_f = 810\ kg/m^3$

$P_{inj,f} = Fuel\ injector\ pressure$

$P_c = chamber\ pressure$

Oxygen Line (*Compressible Fluid*)

$$\dot{m}_o = c_d A_{i,o} \sqrt{2\rho_o (P_{inj,o} - P_c)} \qquad \rho_0 = \frac{P_{inj,o}}{R_0 T_0}$$

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

Where

$c_d = 0.7$ (square edge oriface)

$A_{i,o} = oxygen\ injector\ oriface\ total\ area$

$R_0 = 259.8\ oxygen\ gas\ constant$

$P_{inj,f} = fuel\ injector\ pressure$

$T_0 =$ oxygen temperature

$P_c = chamber\ pressure$

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Motivation & Introduction

Jessie & James Trade Study

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

Oxygen Line (*Compressible Fluid*)

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

Where

$P_{i,0}$ = oxygen injection pressure

P_d = % pressure drop

$$P_{i,o} = P_c(1 + P_d)$$

Substitute and after some algebra…

$$A_i = \frac{\dot{m}}{P_c}\left(\frac{1}{P_d{}^{1.5} c_d}\right)\sqrt{T_o R_o}$$

∴ Keeping A_i and P_d constant $\dot{m}$ and P_d scale proportionally

Fuel Line (*Incompressible Fluid*)

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

Where

$P_{i,f}$ = fuel injection pressure

P_d = % pressure drop

$$P_{i,f} = P_c(1 + P_d)$$

Substitute and after some algebra…

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

∴ Keeping A_i , double $\dot{m}$ and P_c, and the percent P_d will double

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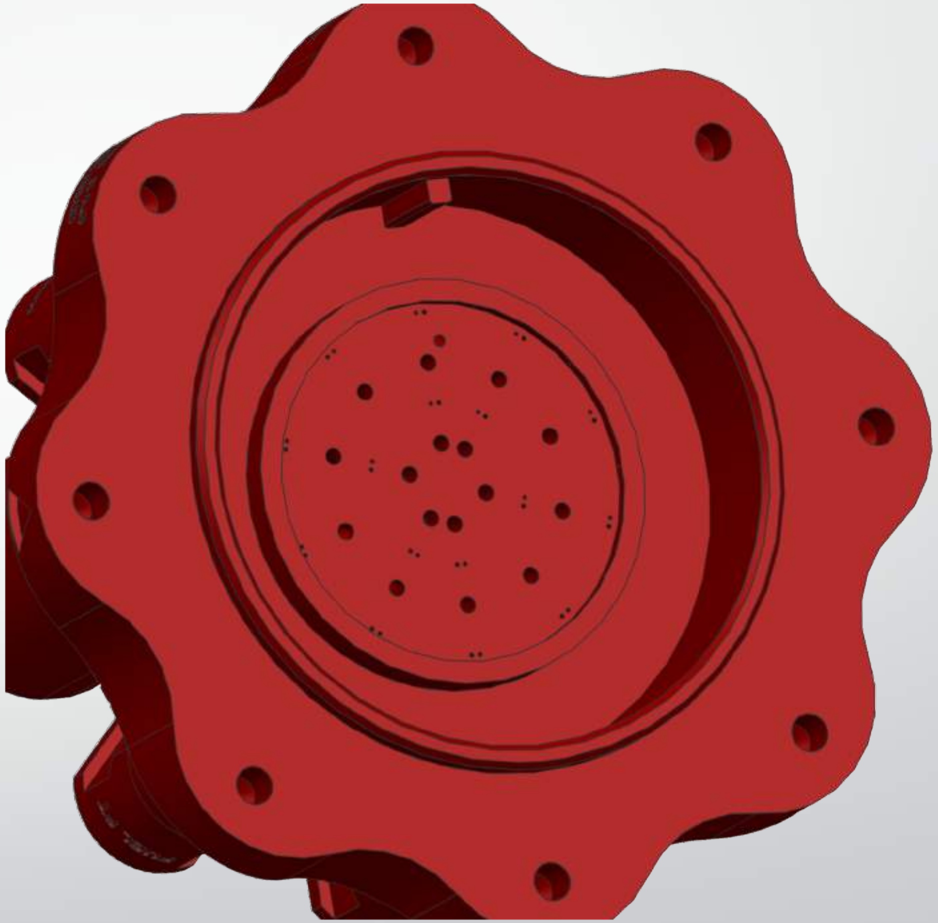
Jessie & James Trade Study

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)



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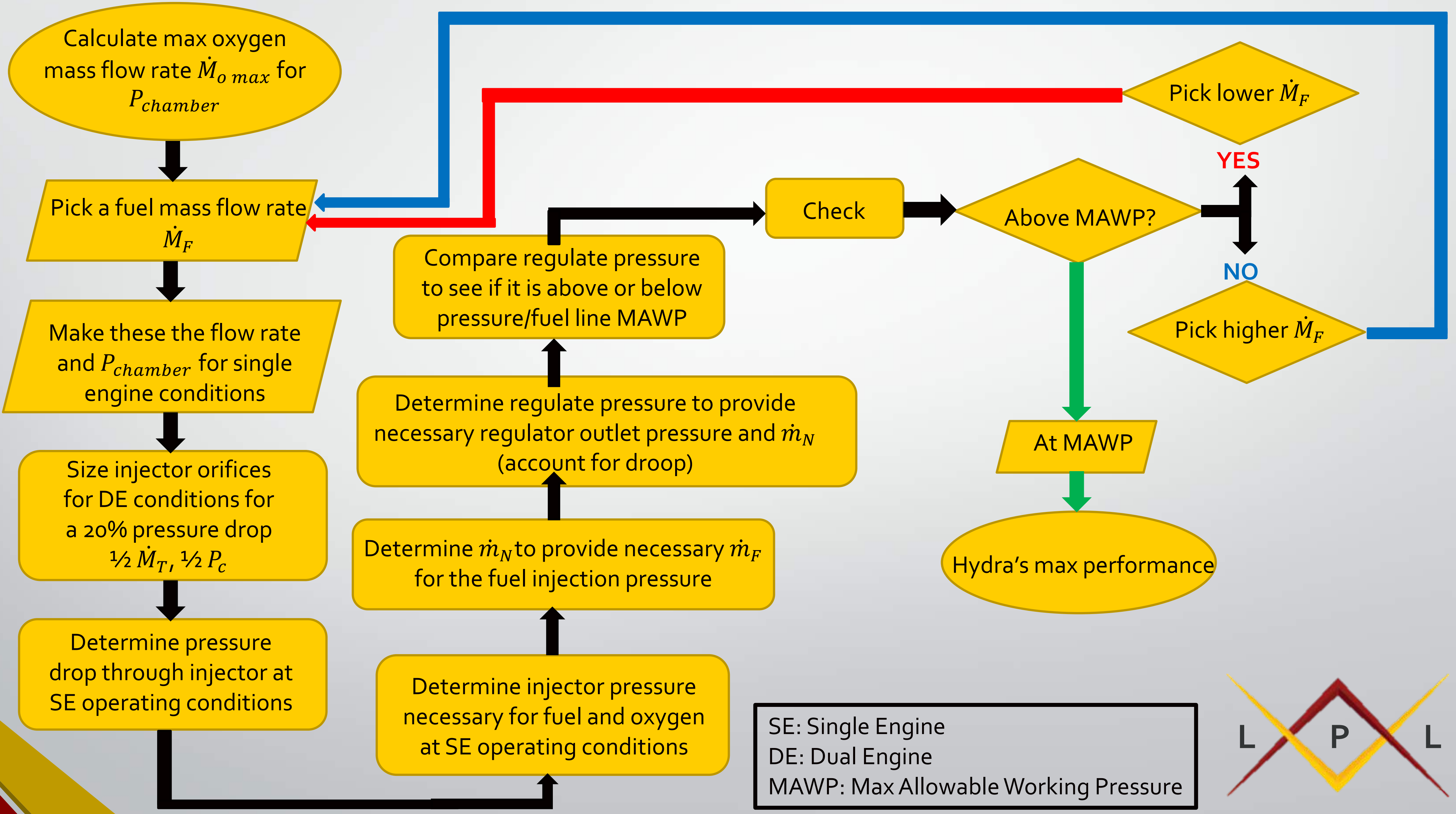
Maximizing Hydra's Performance



Motivation & Introduction

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SCFM to Mass Flow Rate

SCFM (Standard Cubic Feet per Minute)

CFM = SCFM $\times \frac{P_{atm}}{P} \times \frac{T}{T_{atm}}$

$\dot{m} = (CFM)\rho$

$\rho = \frac{P}{TR}$ (gas)

where: CFM (cubic feet per minute)

Fluid Correction Factor

$$F_G = \sqrt{\frac{SG_{ref}}{SG_{act}}}$$

where: $SG = specific\ gravity$

SG_{act} is the specific gravity of your system fluid.

SG_{oxygen} = 1.1044

$SG_{Nitrogen(pure)}$ = 0.9669

SG_{air} = 1.0

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Motivation & Introduction

Single Engine Oxygen Mass Flow Rate to SCFM

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

$$SCFM = \dot{m}\frac{T_{atm}\,R}{P_{atm}}$$

Notice: Cylinder Pressures & Temperatures Cancel Out

Note: Don't forget about units!

(SCFM is in English units)

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 F (277 K) → 1190 $SCFM_{Air}$

T_{atm} = 100 F (311 K) → 1336 $SCFM_{Air}$

$$\dot{m}_O = 1.65\ {}^{lbm}/_{s}\,(0.75\ {}^{kg}/_{s})$$

$$\left(\frac{m^3}{s}\right)_{O2} = (0.75)\frac{kg}{s}(298)K(259.8)\frac{J}{Kg-K}\left(\frac{1}{1.01E5}\right)\frac{1}{Pa} = 0.57\left(\frac{m^3}{s}\right)$$

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

$$SCFM_{O2} = 1214$$

$$SCFM_{Air} = SCFM_{O2}\sqrt{\frac{SG_{O2}}{SG_{air}}}$$

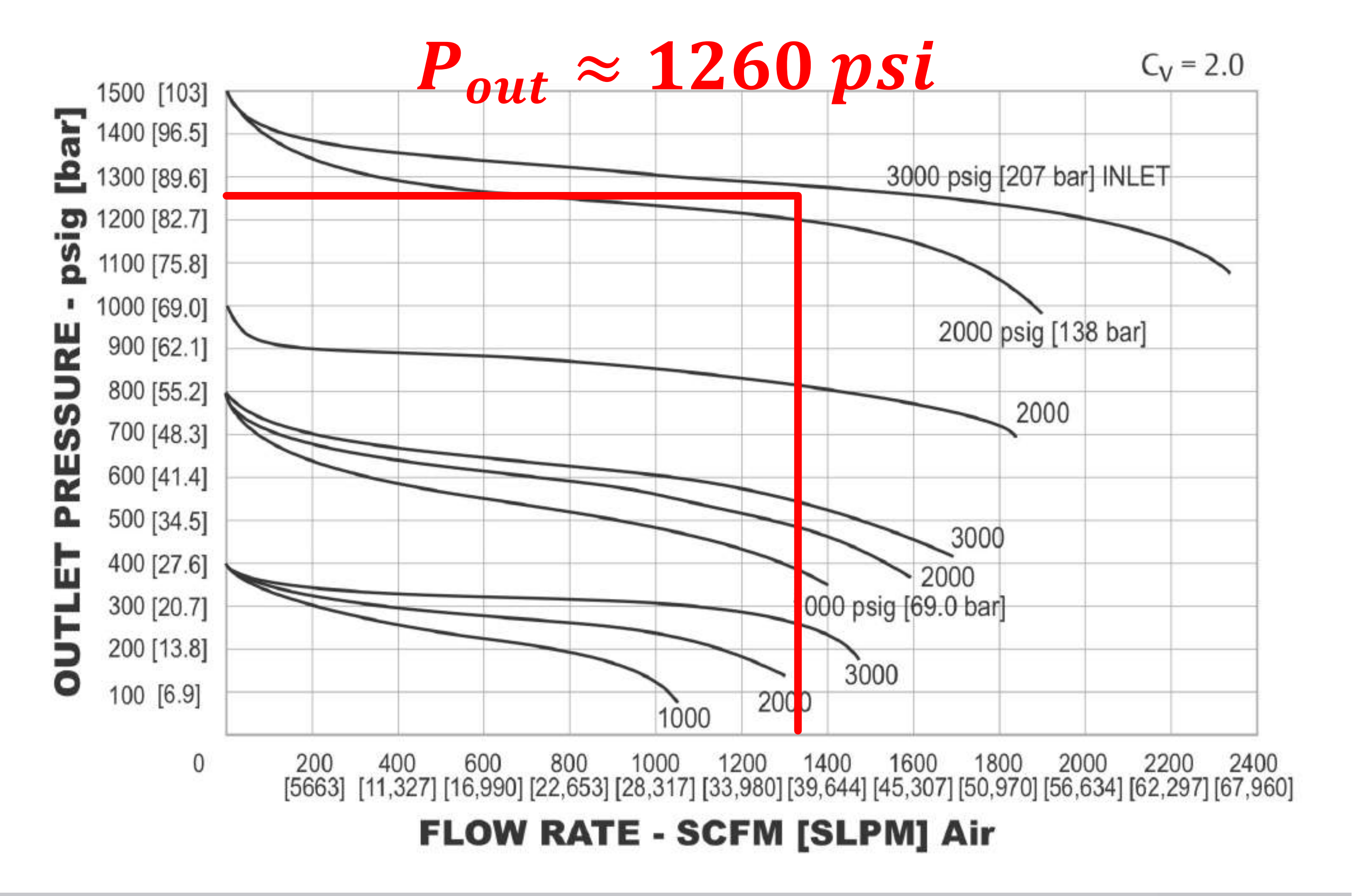
$$SCFM_{Air} = 1214\sqrt{\frac{1.1044}{1}}$$

$$SCFM_{Air} = 1276$$

Motivation & Introduction

Single Engine Oxygen Regulator Set Pressure

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

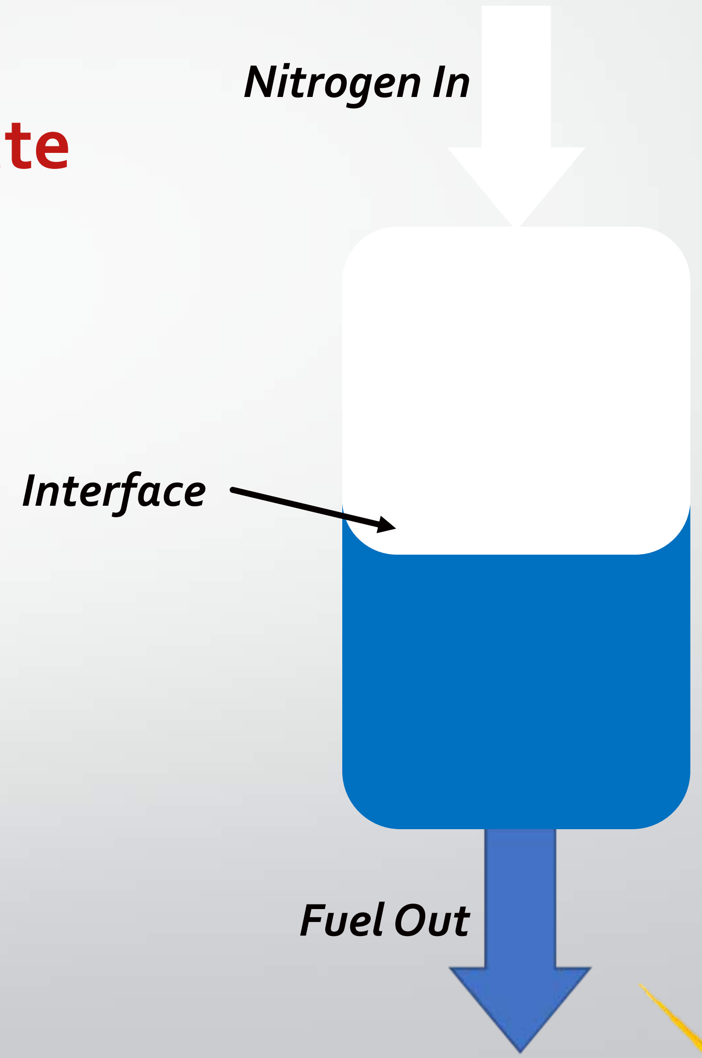
$$\boldsymbol{Volmetric\ Flow_{N,I} = Volumetric\ Flow_{F,I}}$$

$$Volmetric\ Flow = \dot{m}/\rho$$

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

$$\rho_{F=}810\ kg/m^3 \qquad P_{N,I} = \rho_{N,I} R_{N,I} T_{N,I}$$

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



Motivation & Introduction

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Single Engine Nitrogen Mass Flow Rate

$$\boldsymbol{Volmetric\ Flow_{N,I} = Volumetric\ Flow_{F,I}}$$

$$Volmetric\ Flow = \dot{m}/\rho$$

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

$$\rho_{F=}810\ kg/m^3 \qquad P_{N,I} = \rho_{N,I}R_{N,I}T_{N,I}$$

$$\dot{\boldsymbol{m}}_{\boldsymbol{N}} = \frac{\dot{\boldsymbol{m}}_{\boldsymbol{F}}\boldsymbol{P}_{\boldsymbol{N,I}}}{\boldsymbol{\rho}_{\boldsymbol{F,I}}\boldsymbol{R}_{\boldsymbol{N,I}}\boldsymbol{T}_{\boldsymbol{N,I}}}$$

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

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

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

$$\dot{\boldsymbol{m}}_{\boldsymbol{F}} = \boldsymbol{0.88}\ {}^{\boldsymbol{lbm}}/_{\boldsymbol{s}}\ (\boldsymbol{0.4}\ \frac{\boldsymbol{kg}}{\boldsymbol{s}})$$

$$\rho_{F=}810\ kg/m^3$$

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

$$T_{N,I} = 75°F\ (297\ K)$$

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

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

$$\dot{\boldsymbol{m}}_{\boldsymbol{N}} = \boldsymbol{0.123}\ {}^{\boldsymbol{lbm}}/_{\boldsymbol{s}}\ (\boldsymbol{0.056}\ {}^{\boldsymbol{kg}}/_{\boldsymbol{s}})$$

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Motivation & Introduction

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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 $T_{atm} = 298\ K \quad P_{atm} = 1.01\ \mathrm{E5\ Pa}$

Note: Don't forget about units!

(SCFM is in English units)

$$\dot{m}_N = 0.123\ {}^{lbm}/_{s}\ (0.056\ {}^{kg}/_{s})$$

$$0.049\left(\frac{m^3}{s}\right) = (0.056)\frac{kg}{s}(298)\mathrm{K}(296.8)\frac{J}{Kg-K}\left(\frac{1}{1.01E5}\right)\frac{1}{Pa}$$

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

$$\boldsymbol{SCFM_{N2} = 104}$$

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 F (277 K) → $\dot{m}_N$= 0.06 $\frac{kg}{s}$ → 111 $SCFM_{N2}$

T_{atm} = 100 F (311 K) → $\dot{m}_N$= 0.053 $\frac{kg}{s}$ → 98 $SCFM_{N2}$

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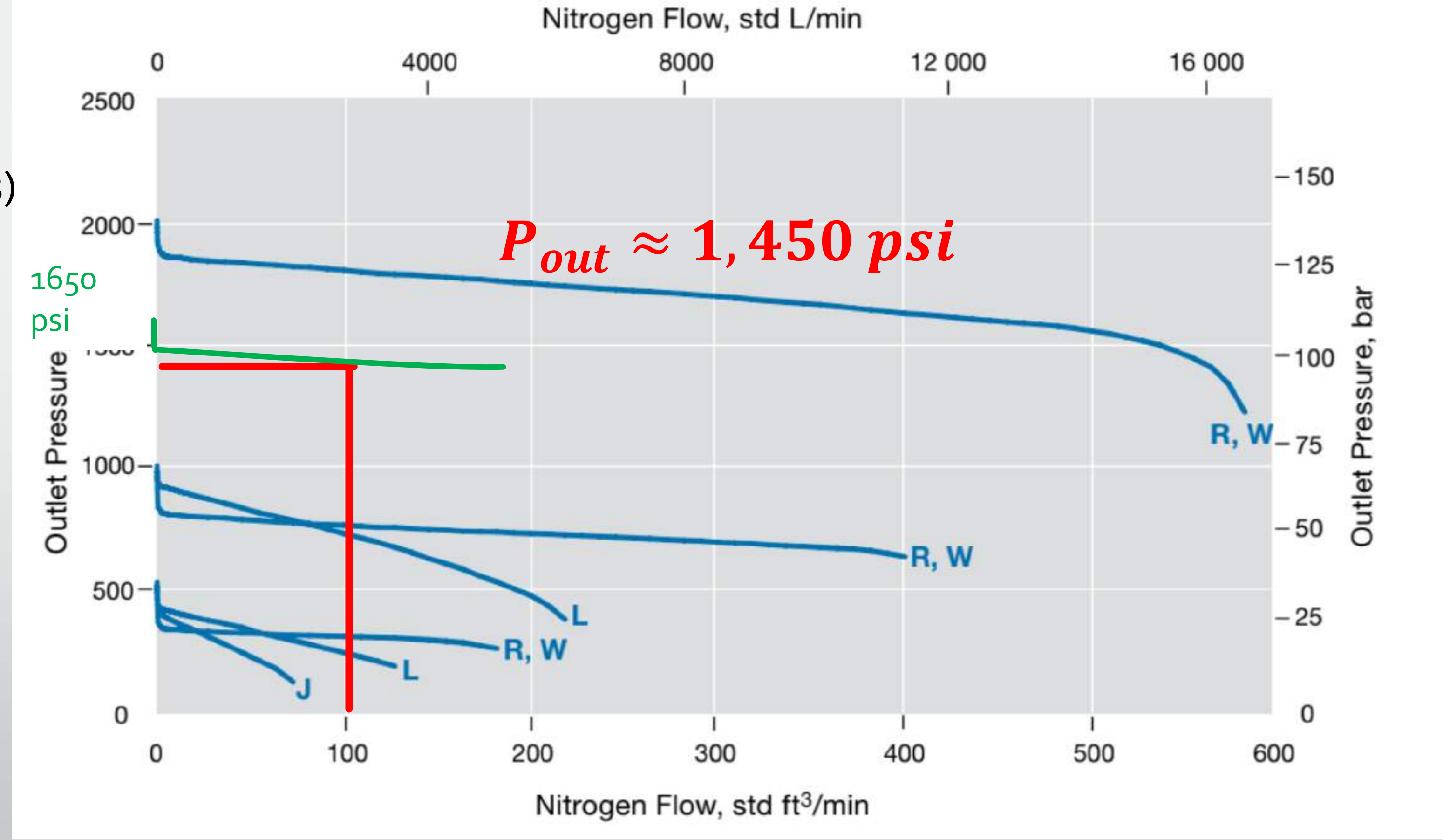
Motivation & Introduction

Single Engine Nitrogen Regulator Set Pressure

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 1,650psi.



Motivation & Introduction

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Jessie & James Operating Condition Summary

Single Engine Operating Conditions	
$\dot{M}_{TOT} = 1.15\ kg$	$OF = 1.875$
Fuel	OX
Injector $\%P_d = 40\ \%$	*Injector* $\%P_d = 20\ \%$
Cylinder Pressure = $2600\ psi$	*Cylinder Pressure* = $2600\ psi$
$P_{regulate} = 1650\ psi$	$P_{regulate} = 1500\ psi$
$P_{supply} = 1450\ psi$	$P_{supply} = 1260\ psi$
$P_{injector} = 1400\ psi$	$P_{injector} = 1200\ psi$
$P_{chamber} = 1000\ psi$	$P_{chamber} = 1000\ psi$

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Motivation & Introduction

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Dual Engine Oxygen Mass Flow Rate to SCFM

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

$$SCFM = \dot{m}\frac{T_{atm}\,R}{P_{atm}}$$

Note: Don't forget about units!

(SCFM is in English units)

$$\dot{m}_O = 1.65\ {}^{lbm}/_{s}\,(0.75\ {}^{kg}/_{s})$$

$$0.57\left(\frac{m^3}{s}\right) = (0.75)\frac{kg}{s}(298)K(259.8)\frac{J}{Kg-K}\left(\frac{1}{1.01E5}\right)\frac{1}{Pa}$$

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

$$\boldsymbol{SCFM_{O2} = 1214}$$

$$SCFM_{Air} = SCFM_{O2}\sqrt{\frac{SG_{O2}}{SG_{air}}}$$

$$SCFM_{Air} = 1214\sqrt{\frac{1.1044}{1}}$$

$$\boldsymbol{SCFM_{Air} = 1276}$$

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

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 F (277 K) → 1190** $SCFM_{Air}$

T_{atm} **= 100 F (311 K) → 1336** $SCFM_{Air}$

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Motivation & Introduction

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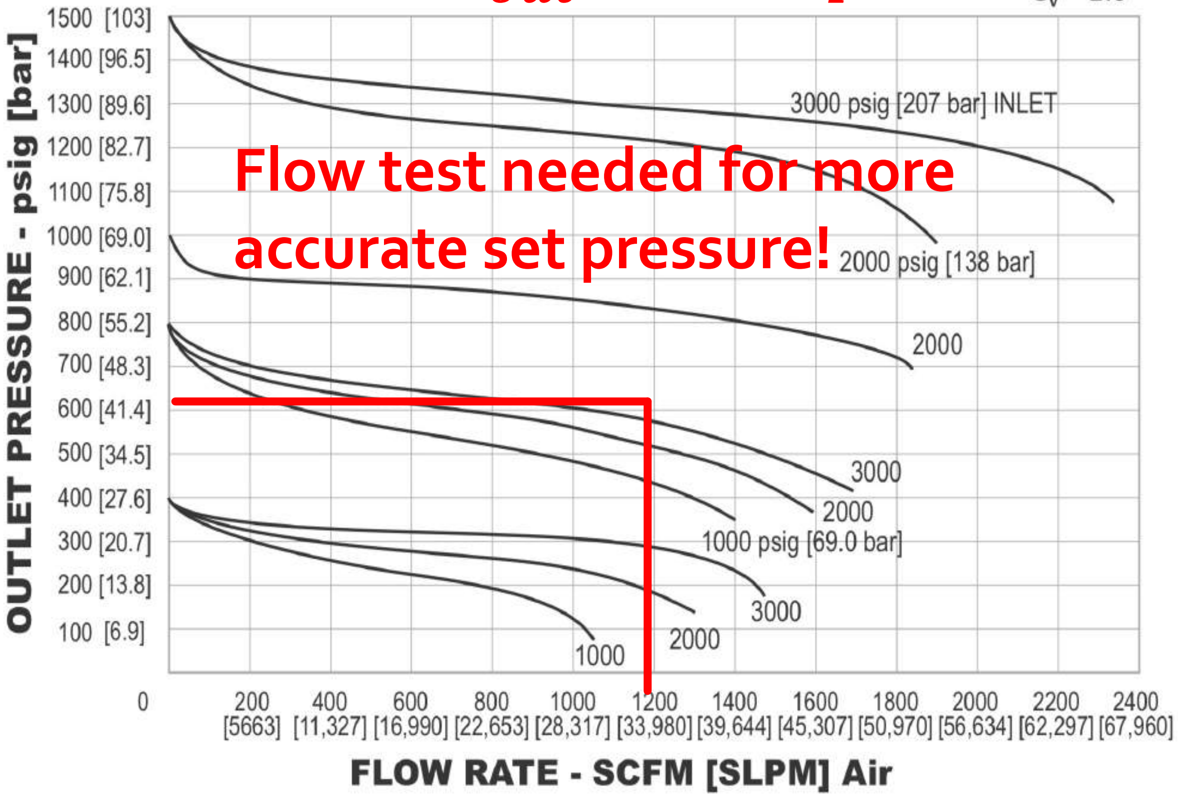
Dual Engine Oxygen Regulator Set Pressure

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 $SCFM_{air}$, ~ 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

$$P_{out} \approx 650\ psi$$



Motivation & Introduction

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Dual Engine Nitrogen Mass Flow Rate

$$\boldsymbol{Volmetric\ Flow_{N,I} = Volumetric\ Flow_{F,I}}$$

$$Volmetric\ Flow = \dot{m}/\rho$$

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

$$\rho_{F=}810\ kg/m^3 \qquad P_{N,I} = \rho_{N,I} R_{N,I} T_{N,I}$$

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

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

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

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

$$\boldsymbol{\dot{m}_F = 0.88\ ^{lbm}/_s\ (0.4\ \frac{kg}{s})}$$

$$\rho_{F=}810\ kg/m^3$$

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

$$T_{N,I} = 75°F\ (297\ K)$$

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

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

$$\boldsymbol{\dot{m}_N = 0.551\ ^{lbm}/_s\ (0.025\ ^{kg}/_s)}$$

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Motivation & Introduction

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Dual Engine Nitrogen Mass Flow Rate to SCFM

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

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

Note: Don't forget about units!

(SCFM is in English units)

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

$$0.0218(\frac{m^3}{s}) = (0.025)\frac{kg}{s}(298)K(296.8)\frac{J}{Kg-K}\left(\frac{1}{1.01E5}\right)\frac{1}{Pa}$$

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

$$SCFM_{N2} = 46$$

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) → $\dot{m}_N$= 0.027 $\frac{kg}{s}$ → 50 $SCFM_{N2}$

T_{atm} = 100 F (311 K) → $\dot{m}_N$= 0.024 $\frac{kg}{s}$ → 45 $SCFM_{N2}$

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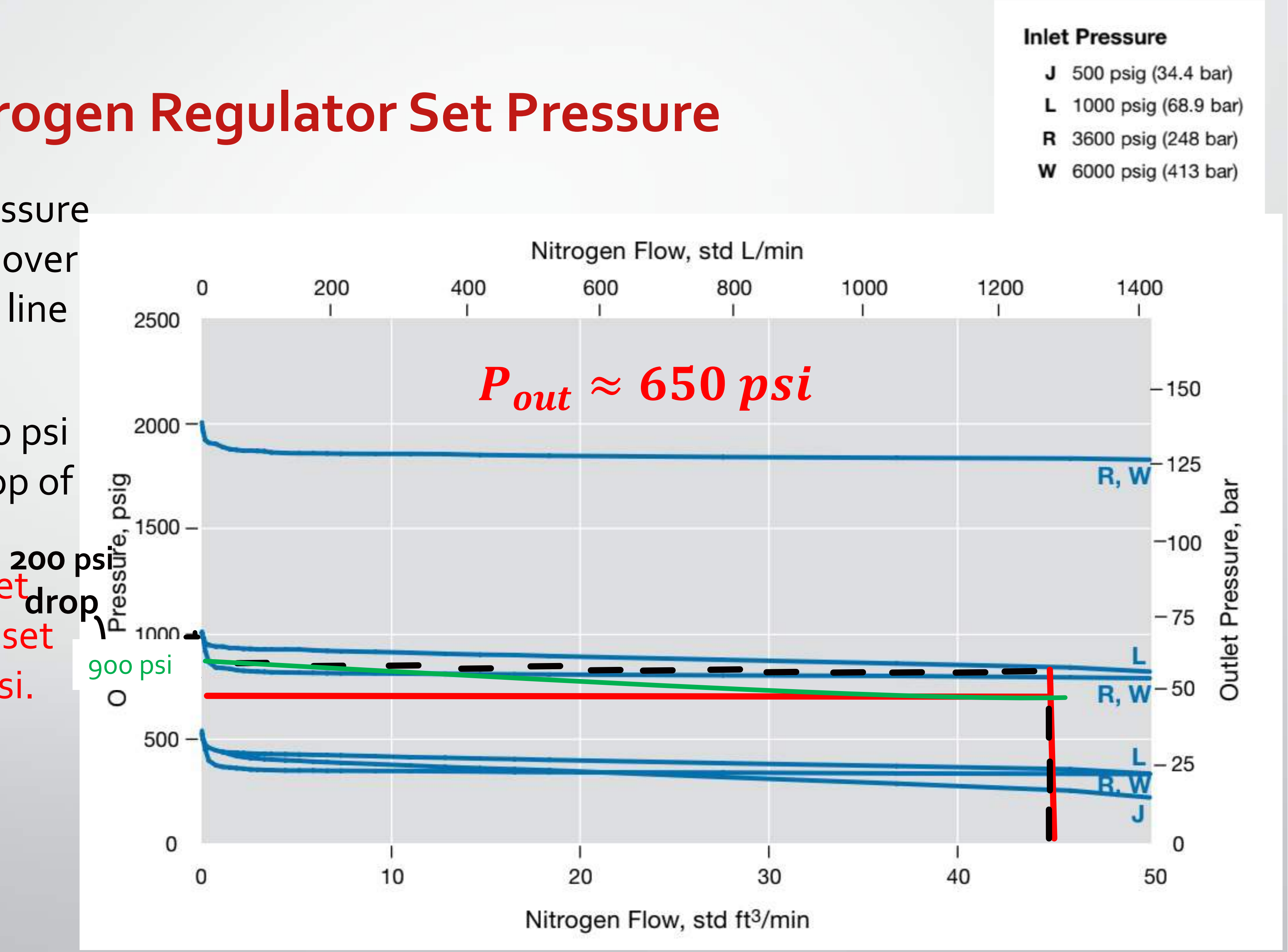
Motivation & Introduction

Dual Engine Nitrogen Regulator Set Pressure

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.



Motivation & Introduction

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Jessie & James Operating Condition Summary

Dual Engine Operating Conditions	
$\dot{M}_{TOT} = 0.575\ kg$	$OF = 1.875$
Fuel	OX
Injector $\%P_d = 20\ \%$	*Injector* $\%P_d = 20\ \%$
Cylinder Pressure = $2600\ psi$	*Cylinder Pressure* = $2600\ psi$
$P_{regulate} = 900\ psi$	$P_{regulate} = 900\ psi$
$P_{supply} = 650\ psi$	$P_{supply} = 650\ psi$
$P_{injector} = 600\ psi$	$P_{injector} = 600\ psi$
$P_{chamber} = 500\ psi$	$P_{chamber} = 500\ psi$

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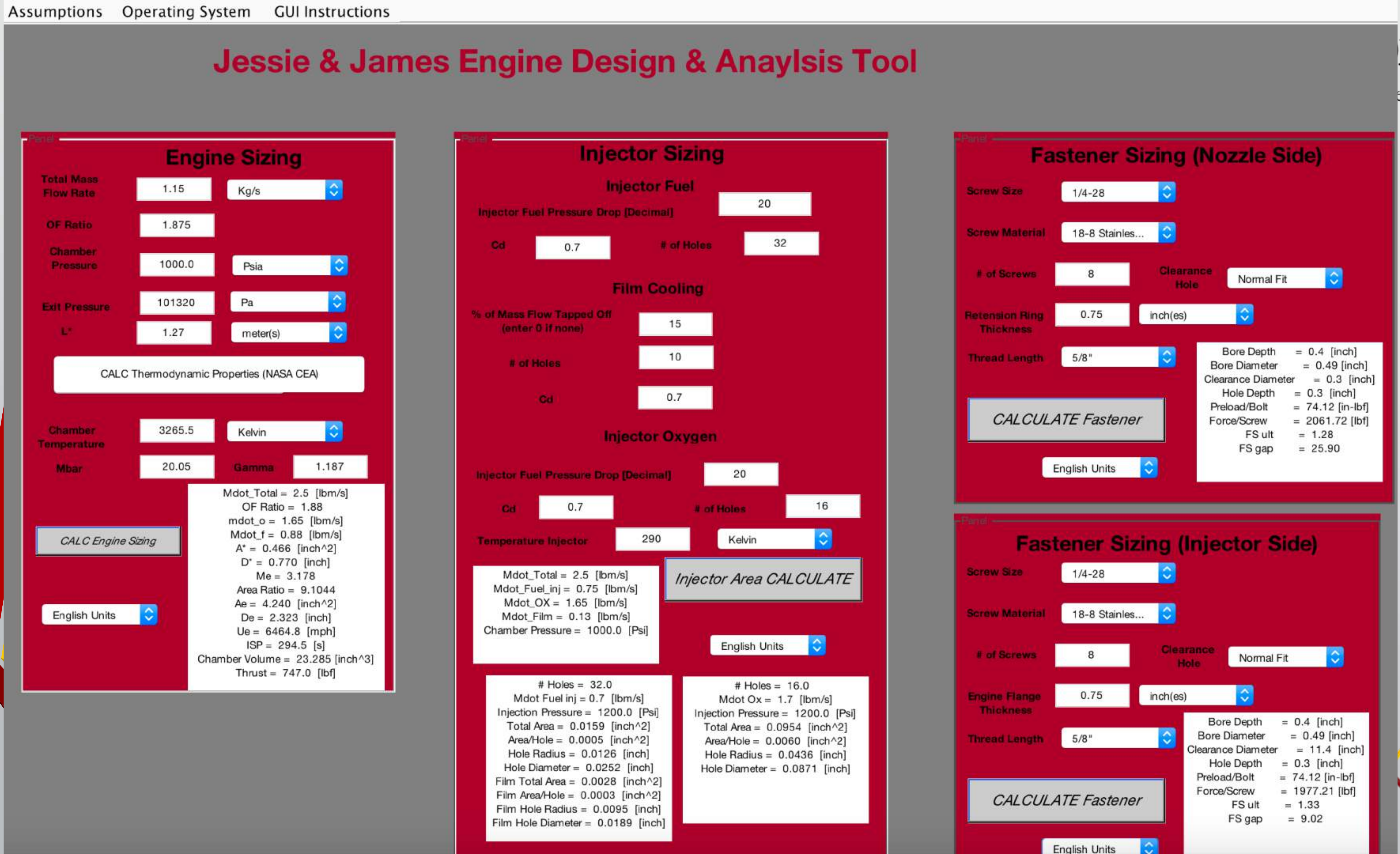
J&J DESIGN & Analysis

J&J DESIGN & Analysis
GUI Tool


Assumptions
Operating System
GUI Instructions
Jessie & James Engine Design & Anaylsis Tool
Engine Sizing
Total Mass Flow Rate
1.15
Kg/s
OF Ratio
1.875
Chamber Pressure
1000.0
Psia
Exit Pressure
101320
Pa
L*
1.27
meter(s)
CALC Thermodynamic Properties (NASA CEA)
Chamber Temperature
3265.5
Kelvin
Mbar
20.05
Gamma
1.187
CALC Engine Sizing
English Units
Mdot_Total = 2.5 [lbm/s]
OF Ratio = 1.88
mdot_o = 1.65 [lbm/s]
Mdot_f = 0.88 [lbm/s]
A* = 0.466 [inch^2]
D* = 0.770 [inch]
Me = 3.178
Area Ratio = 9.1044
Ae = 4.240 [inch^2]
De = 2.323 [inch]
Ue = 6464.8 [mph]
ISP = 294.5 [s]
Chamber Volume = 23.285 [inch^3]
Thrust = 747.0 [lbf]
Injector Sizing
Injector Fuel
Injector Fuel Pressure Drop [Decimal]
20
Cd
0.7
# of Holes
32
Film Cooling
% of Mass Flow Tapped Off (enter 0 if none)
15
# of Holes
10
Cd
0.7
Injector Oxygen
Injector Fuel Pressure Drop [Decimal]
20
Cd
0.7
# of Holes
16
Temperature Injector
290
Kelvin
Mdot_Total = 2.5 [lbm/s]
Mdot_Fuel_inj = 0.75 [lbm/s]
Mdot_OX = 1.65 [lbm/s]
Mdot_Film = 0.13 [lbm/s]
Chamber Pressure = 1000.0 [Psi]
Injector Area CALCULATE
English Units
Holes = 32.0
Mdot Fuel inj = 0.7 [lbm/s]
Injection Pressure = 1200.0 [Psi]
Total Area = 0.0159 [inch^2]
Area/Hole = 0.0005 [inch^2]
Hole Radius = 0.0126 [inch]
Hole Diameter = 0.0252 [inch]
Film Total Area = 0.0028 [inch^2]
Film Area/Hole = 0.0003 [inch^2]
Film Hole Radius = 0.0095 [inch]
Film Hole Diameter = 0.0189 [inch]
Holes = 16.0
Mdot Ox = 1.7 [lbm/s]
Injection Pressure = 1200.0 [Psi]
Total Area = 0.0954 [inch^2]
Area/Hole = 0.0060 [inch^2]
Hole Radius = 0.0436 [inch]
Hole Diameter = 0.0871 [inch]
Fastener Sizing (Nozzle Side)
Screw Size
1/4-28
Screw Material
18-8 Stainles...
# of Screws
8
Clearance Hole
Normal Fit
Retension Ring Thickness
0.75
inch(es)
Thread Length
5/8"
CALCULATE Fastener
English Units
Bore Depth = 0.4 [inch]
Bore Diameter = 0.49 [inch]
Clearance Diameter = 0.3 [inch]
Hole Depth = 0.3 [inch]
Preload/Bolt = 74.12 [in-lbf]
Force/Screw = 2061.72 [lbf]
FS ult = 1.28
FS gap = 25.90
Fastener Sizing (Injector Side)
Screw Size
1/4-28
Screw Material
18-8 Stainles...
# of Screws
8
Clearance Hole
Normal Fit
Engine Flange Thickness
0.75
inch(es)
Thread Length
5/8"
CALCULATE Fastener
English Units
Bore Depth = 0.4 [inch]
Bore Diameter = 0.49 [inch]
Clearance Diameter = 11.4 [inch]
Hole Depth = 0.3 [inch]
Preload/Bolt = 74.12 [in-lbf]
Force/Screw = 1977.21 [lbf]
FS ult = 1.33
FS gap = 9.02

J&J DESIGN & Analysis
Engine & Injector Sizing

J&J Design & Analysis

Engine & Injector Sizing

Single Engine Design Point

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

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Propellant Mass Flow Rates

$$\frac{\dot{m}_o}{\dot{m}_F} = 1.875$$

$$\dot{m}_o + \dot{m}_F = 1.15\ kg/s$$

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

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

$$\dot{\boldsymbol{m}}_{\boldsymbol{F}} = \mathbf{0.4\ kg/s}$$

$$\dot{\boldsymbol{m}}_{\boldsymbol{o}} = \mathbf{0.75\ kg/s}$$

Throat Area

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

$$A^{*} = \frac{1.15}{6.895\ MPa}\sqrt{\frac{(3265.5)(414.66)}{1.187}}(1 + \frac{1.187 - 1}{2})^{\frac{1.187+1}{2(1.187-1)}}$$

$$\boldsymbol{A^{*} = 300.4\ mm^2\ , (0.466\ inch^2)}$$

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Throat Diameter

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

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

$\boldsymbol{D^*}$ **= 0.0195 m (0.770 inch)**

Exit Mach Number

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

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

$$\boldsymbol{M_e = 3.178}$$

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Exit to Throat Area Ratio

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

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

$$\boldsymbol{\frac{A_e}{A^*} = 9.1041}$$

Exit Velocity

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

$$u_e = \sqrt{2\frac{(8314)\,(1.187)}{1.187-1}\frac{3265.5}{20.05}[1-(\frac{101352.9}{6.895\ MPa})^{\frac{1.187-1}{1.187}}]}$$

$$\boldsymbol{u_e = 2889.31\ m/s\,,\ (6464.8\ mph)}$$

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Specific Impulse

$$Isp = \frac{u_{eq}}{g}$$

$$Isp = \frac{2889.311}{9.8}$$

$$\boldsymbol{Isp = 294.5\ sec}$$

Thrust

$$F_T = \dot{m}u_e + A_e(p_e - p_a)$$

$$F_T = (1.15)(2889.31) + 0.0027(101352.9 - 6.895 * 10^6)$$

$$\boldsymbol{F_T} = \textbf{3.32 kN (747 lbf)}$$

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Chamber Volume

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

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

$$\mathbf{V_{ch} = 381.5\ cm^3, (23.28\ inch^3)}$$

Propellants	Characteristic Length (L^*)	
	Low (m)	High (m)
Liquid fluorine / hydrazine	0.61	0.71
Liquid fluorine / gaseous H_2	0.56	0.66
Liquid fluorine / liquid H_2	0.64	0.76
Nitric acid / hydrazine	0.76	0.89
N_2O_4 / hydrazine	0.60	0.89
Liquid O_2 / ammonia	0.76	1.02
Liquid O_2 / gaseous H_2	0.56	0.71
Liquid O_2 / liquid H_2	0.76	1.02
Liquid O_2 / RP-1	1.02	1.27
H_2O_2 / RP-1 (including catalyst)	1.52	1.78

How to determine characteristic length

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Chamber Length

$A_t = 3E - 4\ m^2$, $(0.466\ inch^2)$

$D_t = 1.96\ cm$, $(0.77\ inch)$

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

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

$$\frac{A_c}{A_t} = 6.59$$

$A_c = 0.002\ m^2, (3.10\ inch^2)$

$$L_C = \frac{V_c}{A_c}$$

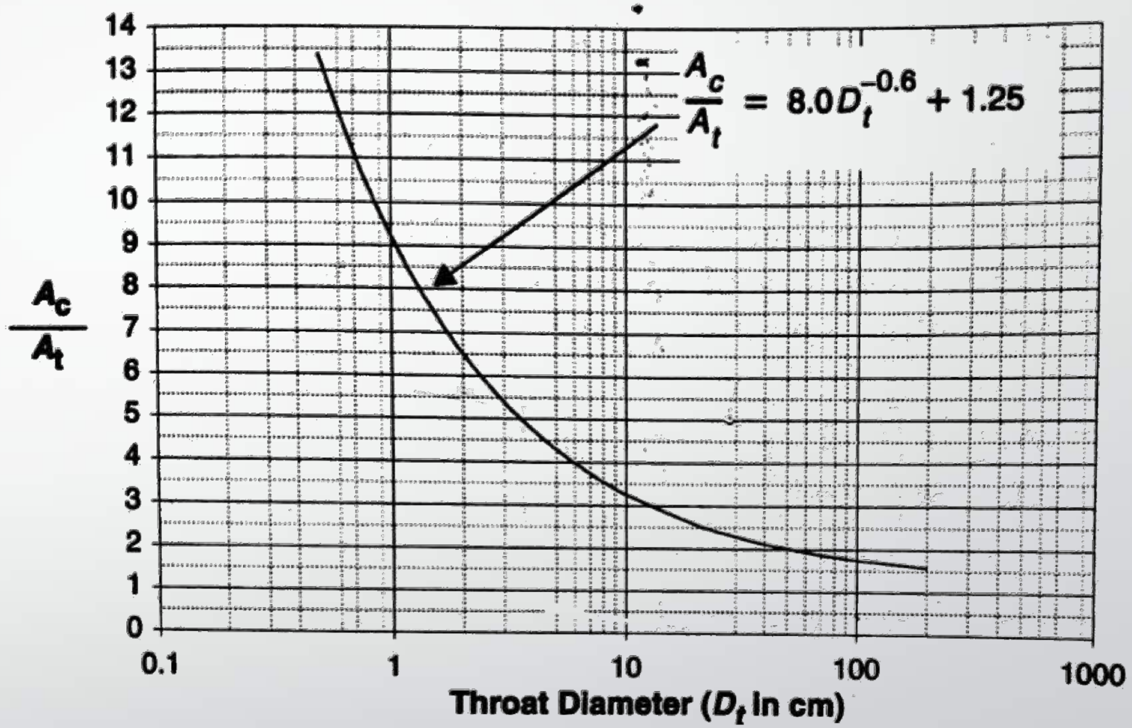
$$L_C = \frac{3.815\ E - 4\ m^3}{0.002\ m^2}$$

$L_C = 0.19\ m\ (7.51\ inch)$

Use as a starting point. Ended with:

$L_C = 0.17\ m\ (6.58\ inch)$

$D_C = 54\ mm\ (2.125\ inch)$



J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Nozzle Length (Conical)

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

Where L_n=conical nozzle length

D_t=nozzle throat diameter

θ_{cn}= nozzle cone half angle (15°)

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

$$\boldsymbol{L_n = 2.87\ in\ (72.8\ mm)}$$

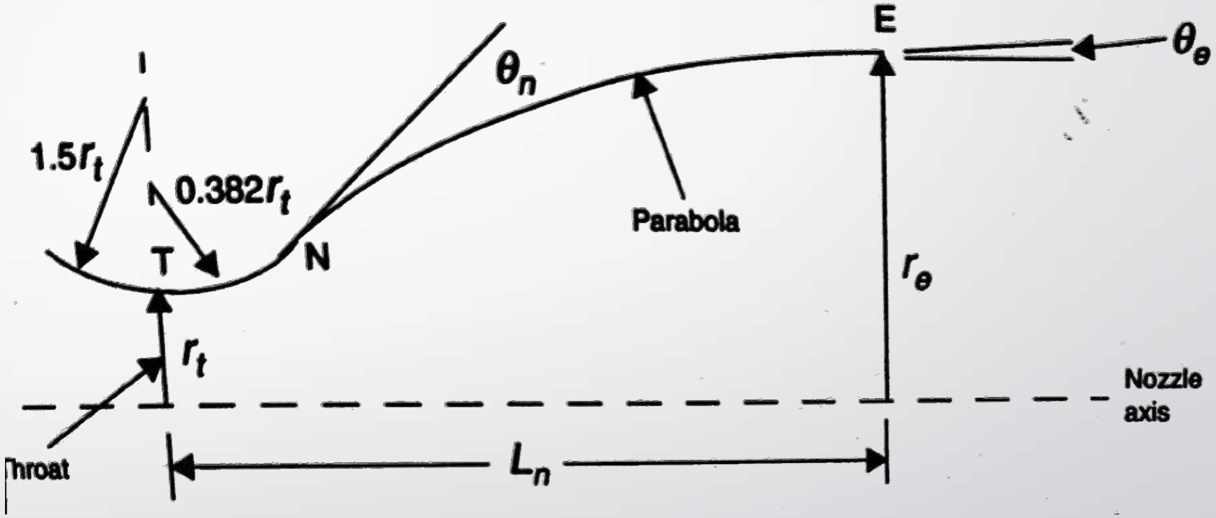


Diagram is for a parabola shaped nozzle. J&J used this diagram for sizing the converging & diverging part of the nozzle

J&J Design & Analysis

Engine & Injector Sizing

Single Engine

Chamber Wall Thickness

$$t_w = \frac{FS p_c r_c}{\sigma_y}$$

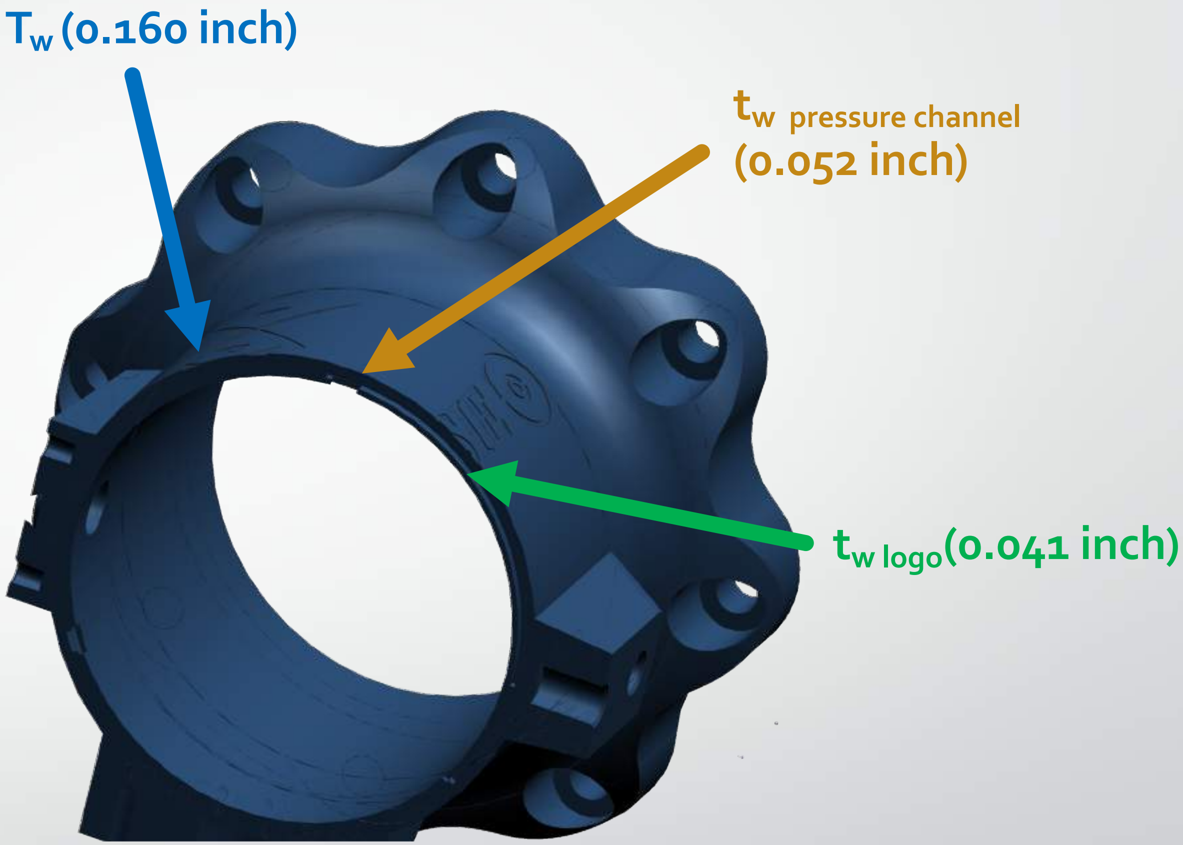
Where t_w = wall thickness

r_c = Chamber Radius 0.027 m(1.5 inch)

p_c = chamber pressure = 6.895 Mpa (1000 psi)

σ_y = Yield Strength = 1000 Mpa (145 ksi)

FS = Safety Factor



t_w = 4.06mm (0.160 inch) [@ chamber wall] FS = 15.5

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

$t_{w\ logo}$ = 1.04 mm (0.041inch) [on wall where chamber pressure channel crosses over logo] FS= 4

J&J Design & Analysis

Engine & Injector Sizing

Summary of Engine Specifications
Single Engine Static Fire

Propellant	Kerosene	Gaseous Oxygen
OF ratio	1.875	
$\dot{M}_{TOT}$	$1.15\ kg/s$	$2.5\ lbm/s$
P_c	$6.895\ MPa$	$1000\ psi$
P_e	$101352.9\ Pa$	$14.7\ psi$
L^*	$1.27\ m$	$50\ inches$
D^*	19.6 mm	0.770 inch
T_c	$3266\ K$	5418 °F
A^*	0.3004 mm^2	0.466 $inch^2$
A/A^*	9.1041	
Isp	$294.5\ s$	
F_T	3.32 kN	$750\ lbf$
V_{ch}	381.5 cm^3	$23.286\ inch^3$
L_c	$0.17\ m$	$6.58\ inch$
D_c	$54\ mm$	$2.125\ inch$
L_n	$72.8\ mm$	$2.87\ inch$
T_w	$3.81\ mm$	$0.15\ inch$

J&J Design & Analysis

Engine & Injector Sizing

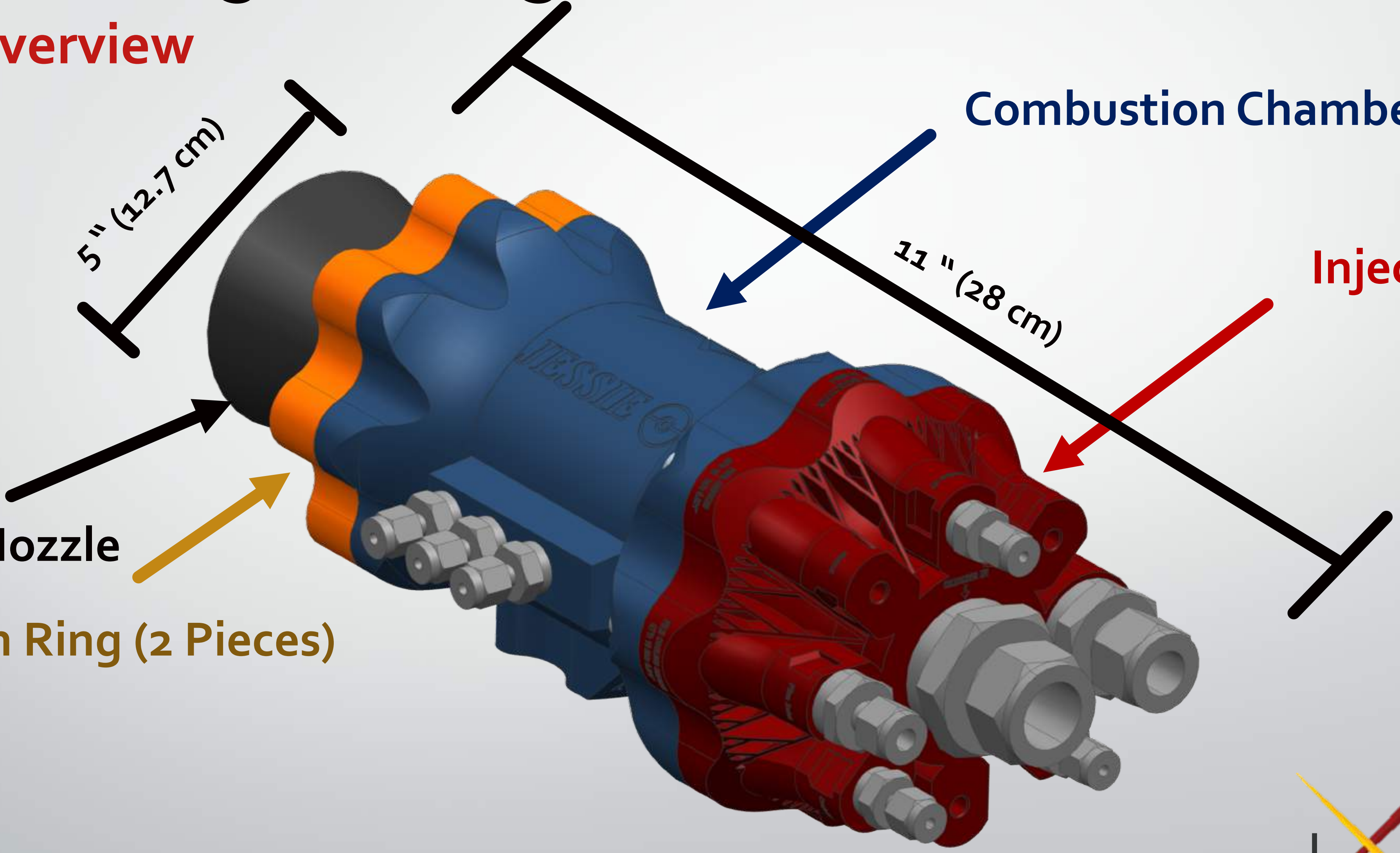
Summary of Engine Specifications
Dual Engine Static Fire

Propellant	Kerosene	Gaseous Oxygen
OF ratio	1.875	
$\dot{M}_{TOT}$	$0.575\ kg/s$	$1.3\ lbm/s$
P_c	$3.45\ MPa$	$500\ psi$
P_e	$101320\ Pa$	$14.7\ psi$
L^*	$1.27\ m$	$50\ inches$
A^*	$0.300\ mm^2$	$0.465\ \text{inch}^2$
D^*	19.6 mm	0.770 inch
T_c	$3222\ K$	5340 °F
A/A^*	5.4902	
Isp	$275.9\ s$	
F_T	$1.56\ kN$	$350\ lbf$
V_{ch}	$338.18\ cm^3$	$23.286\ inch^3$
L_c	$0.16\ m$	$6.283\ inch$
D_c	$54\ mm$	$2.125\ inch$
L_n	$49\ mm$	$1.93\ inch$
T_w	$3.81\ mm$	$0.15\ inch$

J&J DESIGN & Analysis
Top Level Engine Design

J&J Design & Analysis
Overall Engine Design

J&J Overview



J&J Design & Analysis
Overall Engine Design

USC Viterbi School of Engineering

J&J Overview

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

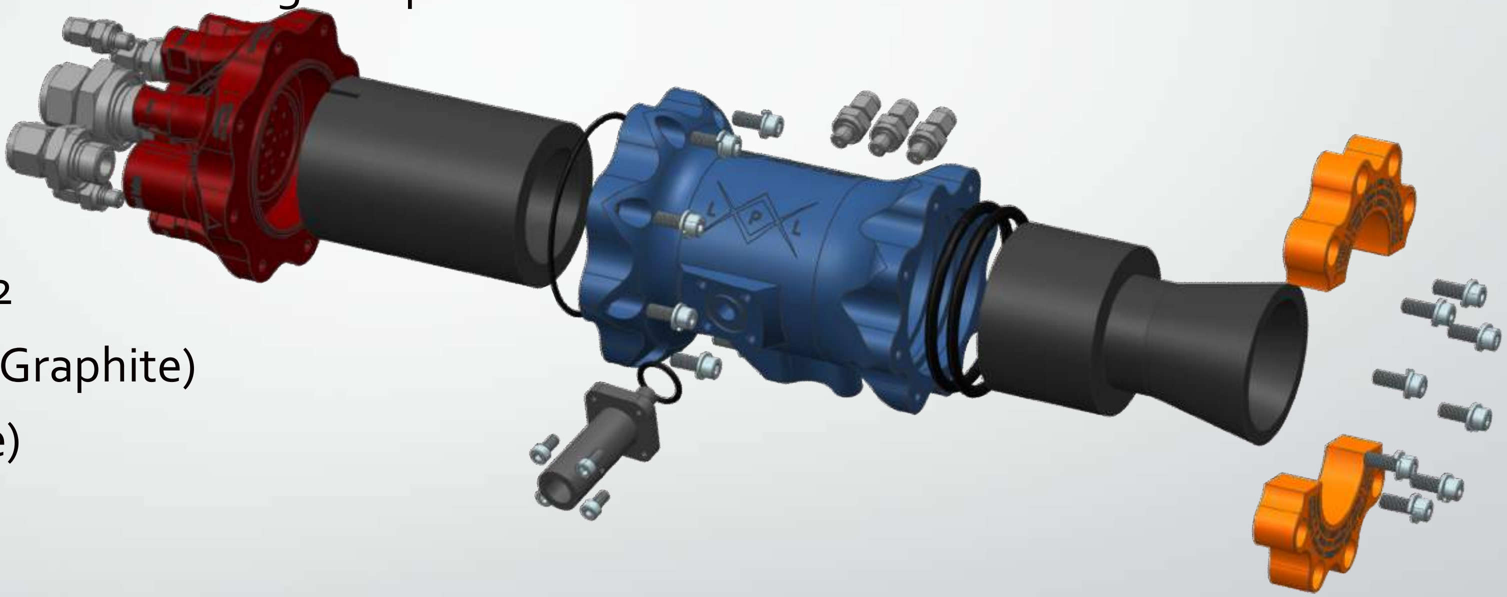
LPL

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



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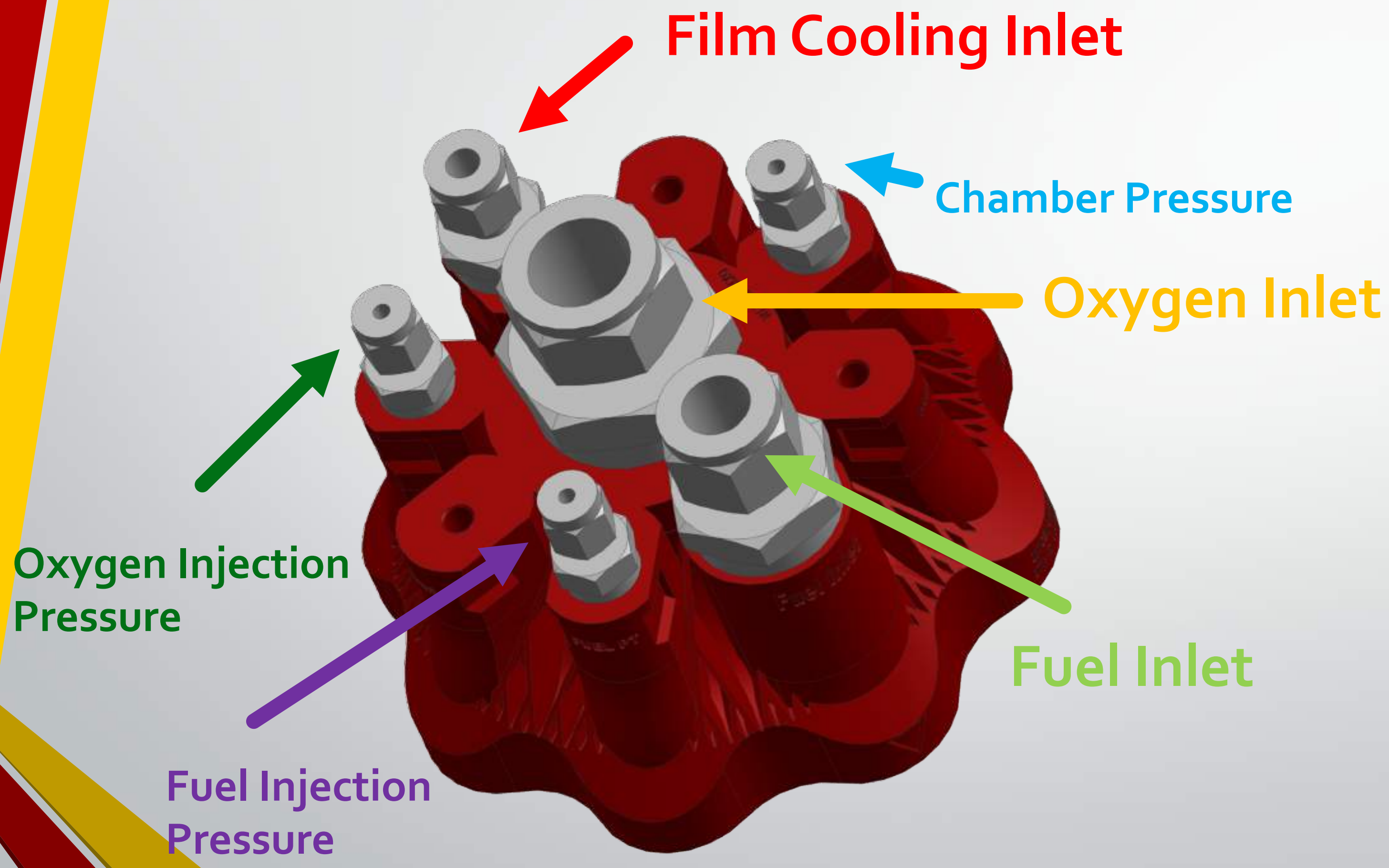
L P L

J&J Design & Analysis
Overall Engine Design

Jessie – Injector Ports



Oxygen Inlet - *SS-1210-1-OR*

¾" Tube OD X 1 1/16-12 Male-O-Seal SAE/MS Straight Thread

Fuel Inlet - *SS-810-1-OR*

½" Tube OD x ¾-16 Male O-Seal SAE/MS Straight Thread

Film Cooling Inlet- *SS-400-1-OR*

¼" Tube OD x 7/16-20 Male O-Seal SAE/MS Straight Thread

Sensor Ports - *SS-200-1-OR*

1/8" Tube OD x 5/16-24 Male O-Seal SAE/MS Straight Thread

J&J Design & Analysis
Overall Engine Design

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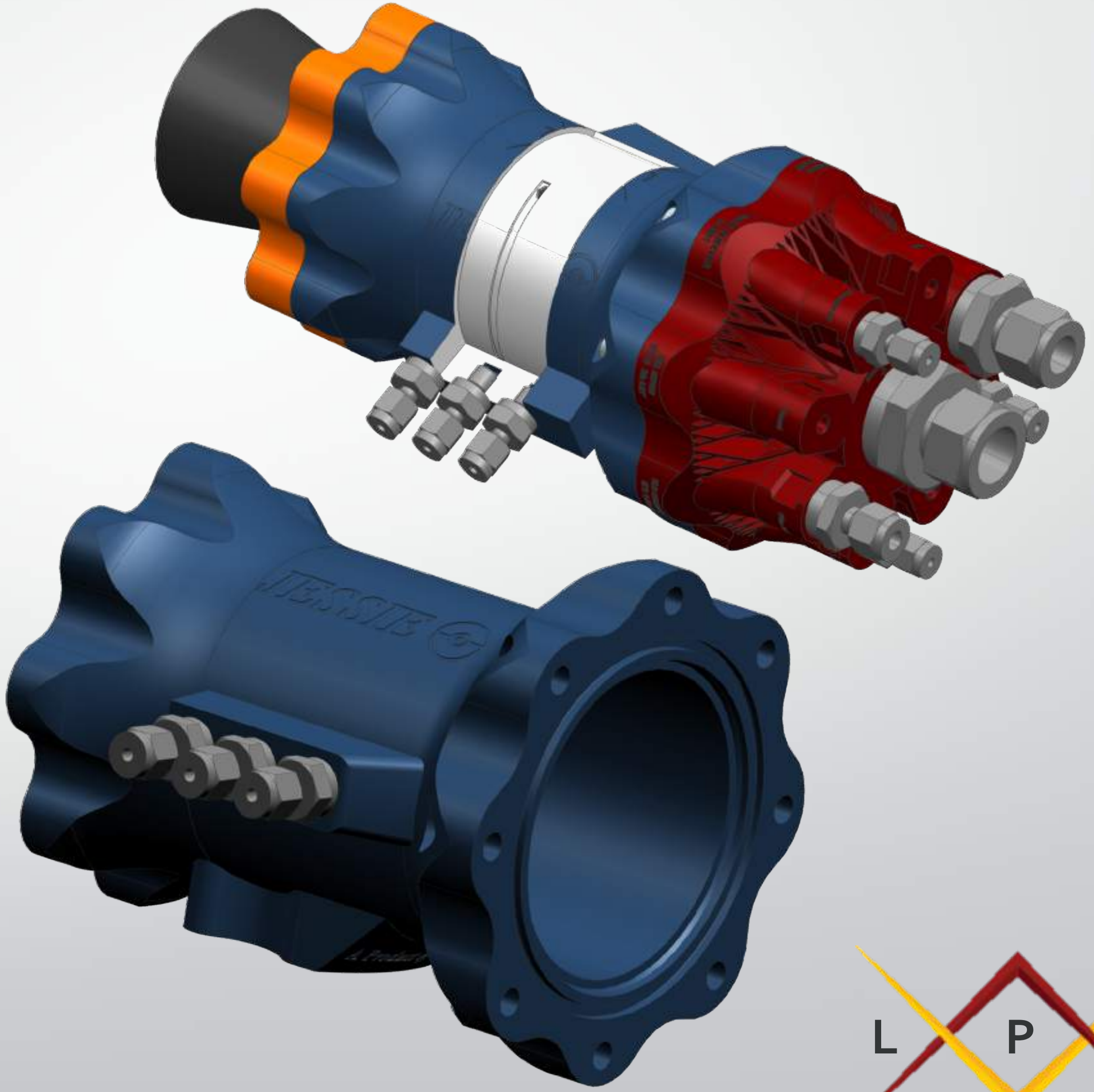
Chamber Pressure Sensors

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 senor block

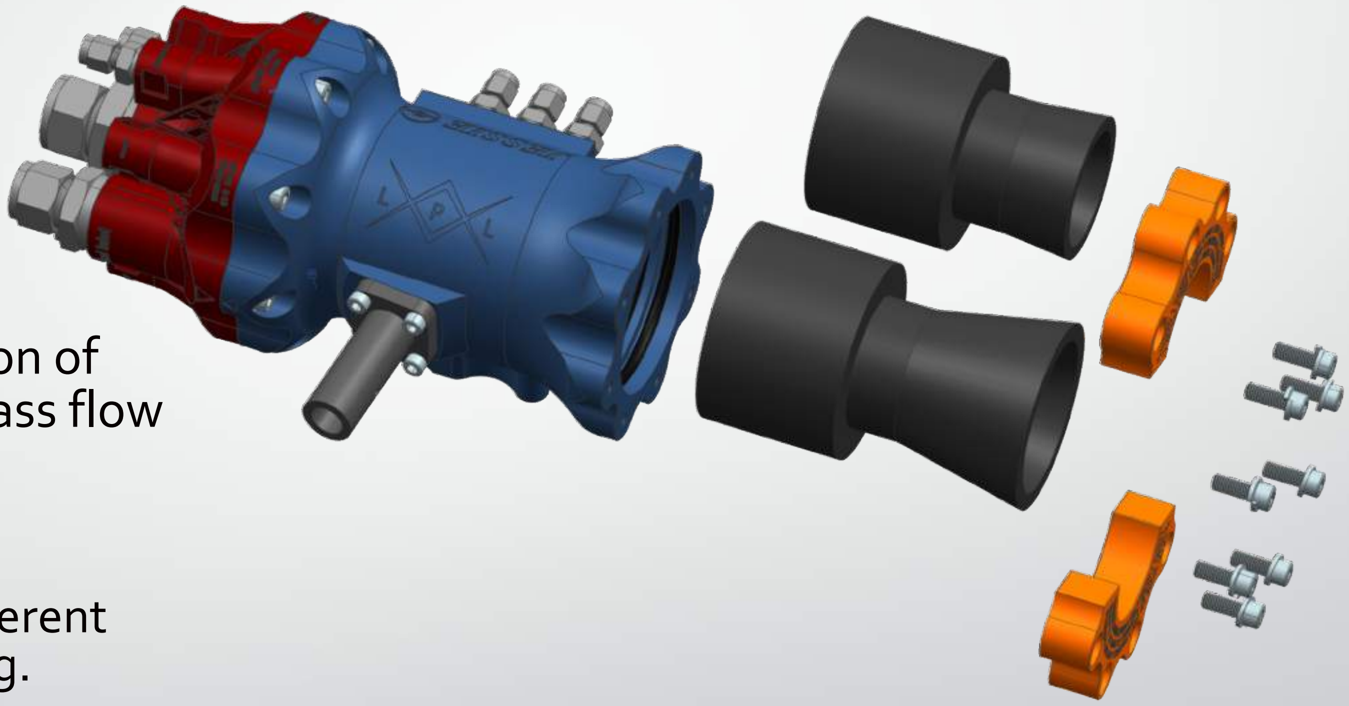
Sensor Ports - *SS-200-1-OR*
1/8" Tube OD x 5/16-24 Male O-Seal SAE/MS Straight Thread



L P L

J&J Design & Analysis
Overall Engine Design

Swap Nozzle for Different Operating Conditions



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.

J&J Design & Analysis
Overall Engine Design

Material data sheet EOS Maraging Steel MS1

Mechanical properties of parts at 20 ℃ (68 °F) As Built	
Tensile strength - in horizontal direction (XY) - in vertical direction (Z)	typ. 1100 ± 100 MPa (160 ± 15 ksi) typ. 1100 ± 100 MPa (160 ± 15 ksi)
Yield strength (Rp 0.2 %) - in horizontal direction (XY) - in vertical direction (Z)	typ. 1050 ± 100 MPa (typ. 152 ± 15 ksi) typ. 1000 ± 100 MPa (145 ± 15 ksi)
Modulus of elasticity - in horizontal direction (XY) - in vertical direction (Z)	typ. 160 ± 25 GPa (23 ± 4 Msi) typ. 150 ± 20 GPa (22 ± 3 Msi)
Coefficient of thermal expansion	typ. 15 ± 0.8 W/m°C (104 ± 6 Btu in/(h ftÇ °F)

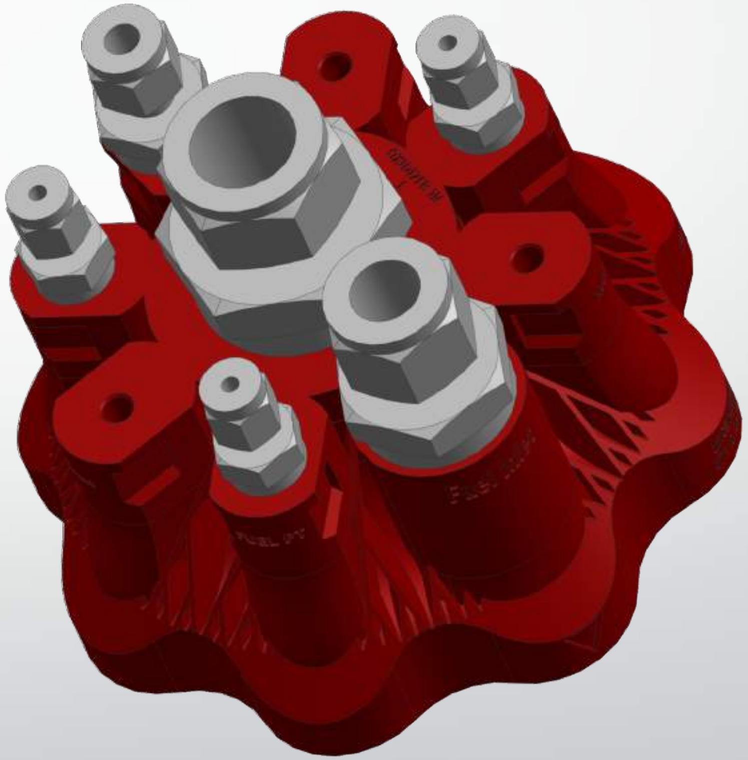
J&J DESIGN & Analysis
Injector Design

J&J Design & Analysis

Engine & Injector Sizing

Injector

- 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%

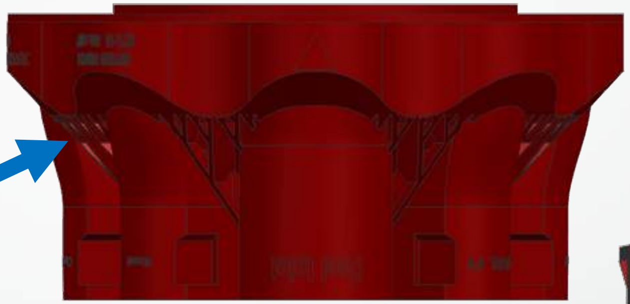


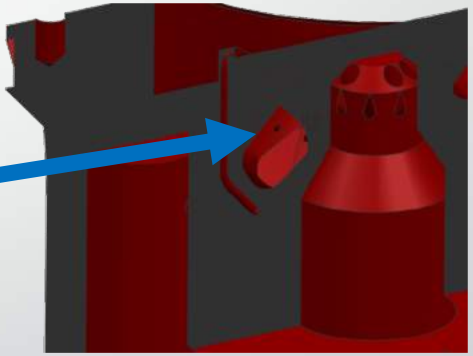
J&J Design & Analysis

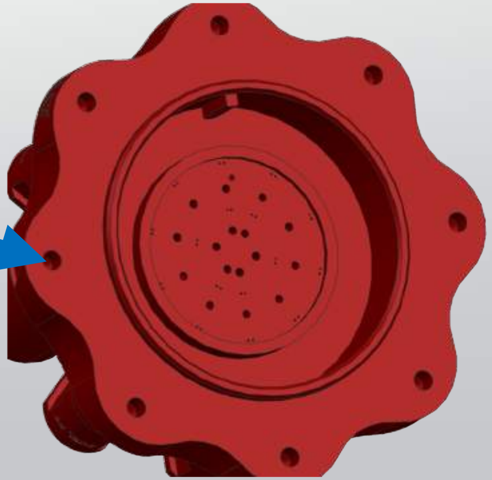
Engine & Injector Sizing

Injector

3D printing Considerations





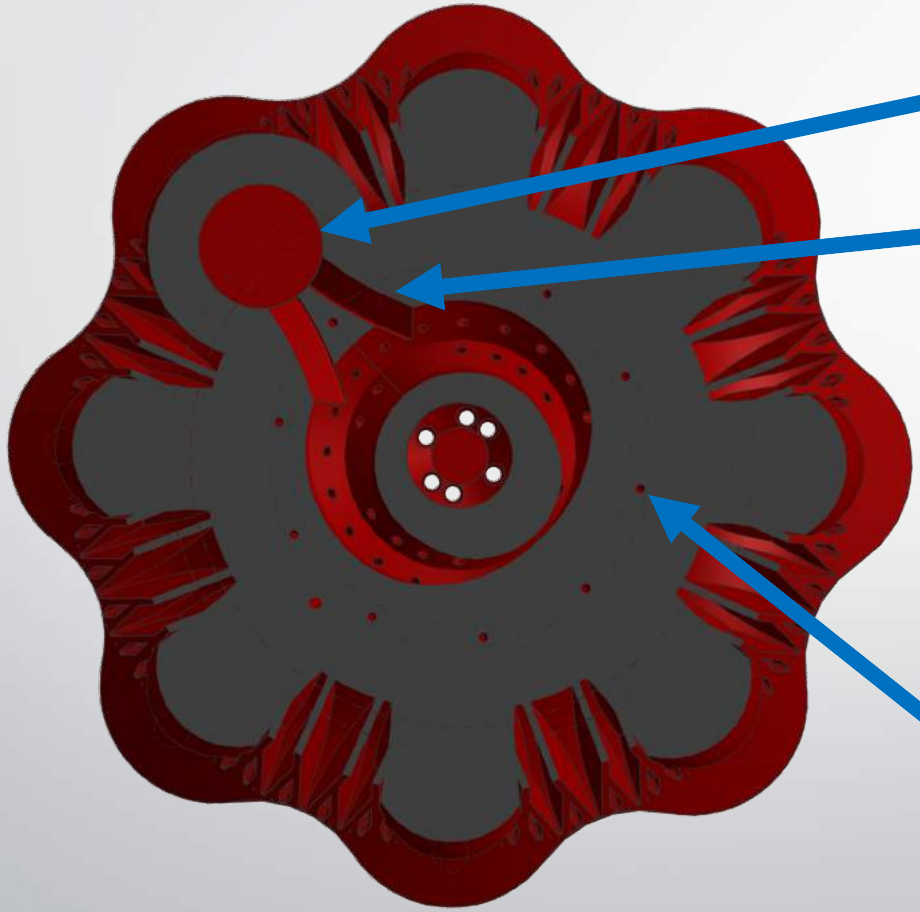


- Since this injector will be 3D printed, any overhangs more than ~45 degrees require a support structure of some sort. This can be designed in, or formed in the pre-3D printing software. In this case, a support "tree" has been designed in to reduce the mass of the printed part.
- Other overhangs are 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)

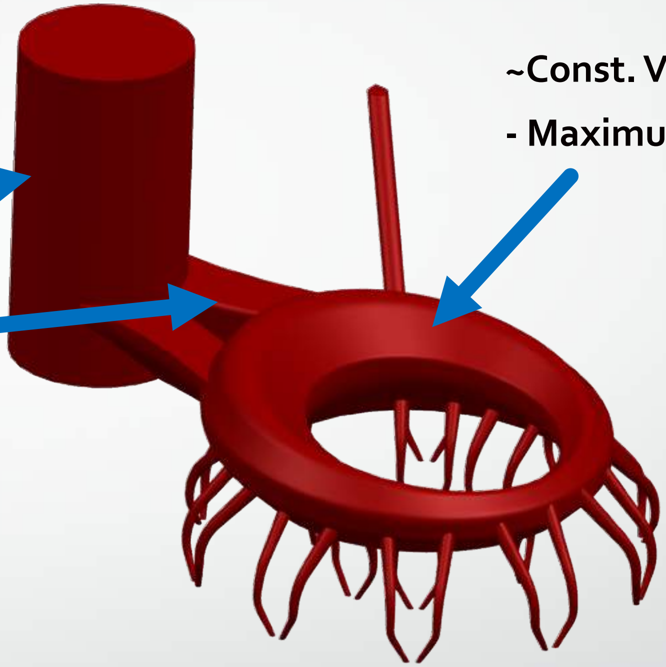
J&J Design & Analysis

Engine & Injector Sizing

Injector



Top View Slice through Fuel Manifold



~Const. Velocity Manifold

- Maximum area $> 4A_f$

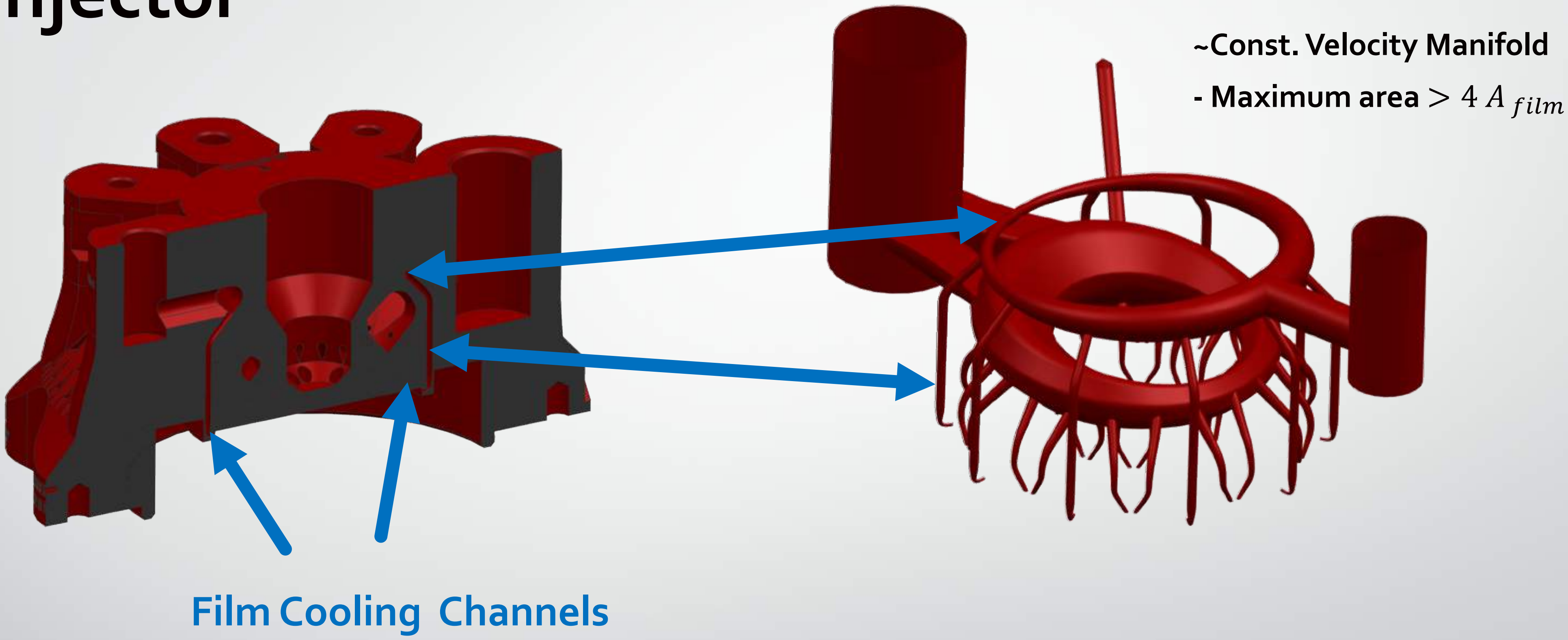
Fuel Fluid Flow Volume

Film Cooling Channels

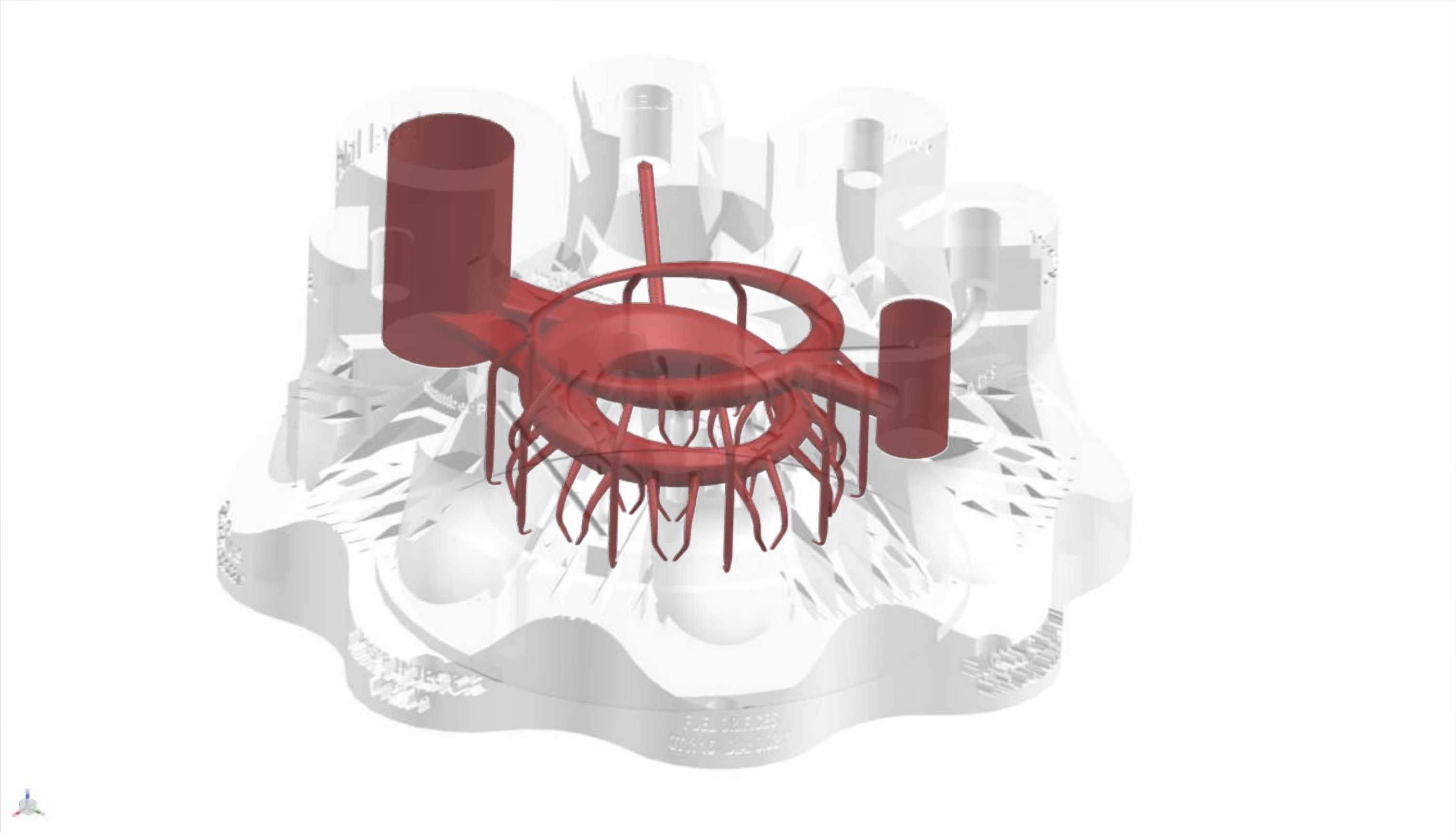
J&J Design & Analysis

Engine & Injector Sizing

Injector



J&J Design & Analysis
Engine & Injector Sizing
Injector

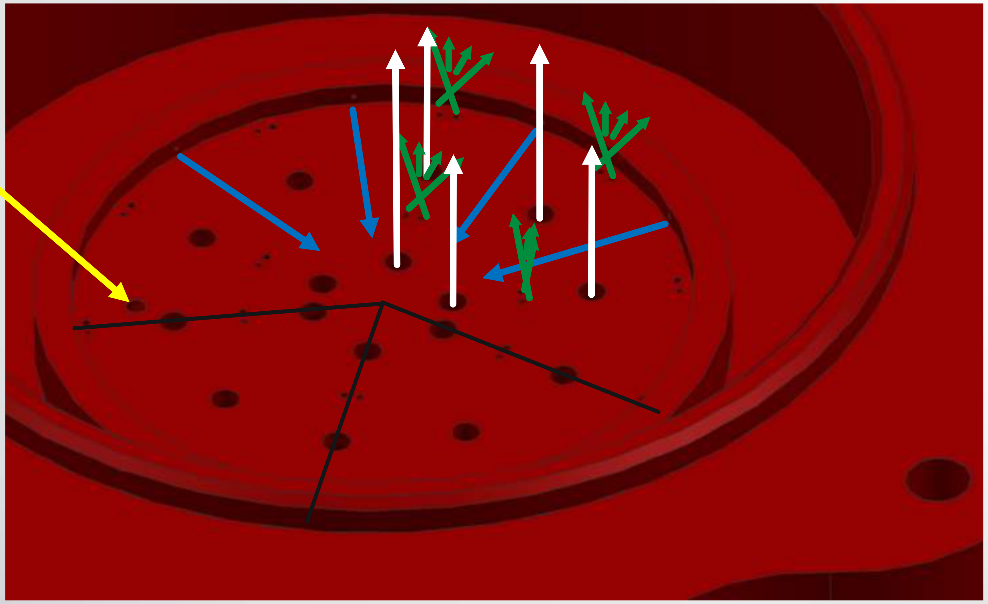


J&J Design & Analysis

Engine & Injector Sizing

Injector

Chamber PT channel



Orifice Arrangement

Film Cooling
Oxygen
Fuel

- 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.

J&J Design & Analysis

Engine & Injector Sizing

USC Viterbi School of Engineering

Fuel Injector Sizing (Based on Dual Engine Conditions)

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

Where

$\rho = 810\ \frac{kg}{m^3}$

$c_d = 0.7$ (square edge orifice)

$A_f = injector\ orifice\ total\ area$

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

Pressure Drop 20%

$P_{inj,f} = 4.137E6\ (600\ psi)$

$\dot{m}_f = 0.17\ \frac{kg}{s}$ (15% tapped off for $\dot{m}_{film}$)

$\#\ of\ holes$ = 32

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

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

$$A_{i,f} = \frac{A_f}{\#\ of\ holes}$$

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

$$A_{i,f} = 2.27E - 7m^2$$

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

$\boldsymbol{D_f = 0.538\ mm}$ **(0.021 inch)**

LPL

J&J Design & Analysis

Engine & Injector Sizing

Film Orifice Sizing (Based on Dual Engine Conditions)

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

Where

$\rho = 810\ \frac{kg}{m^3}$

$c_d = 0.7$ (square edge orifice)

$A_{film} = injector\ orifice\ total\ area$

$P_c = 3.447\text{E}6$ Pa (500 psi)

Pressure Drop 20%

$P_{inj,film} = 4.137E6\ (600\ psi)$

$\dot{m}_{film} = 0.03\ \frac{kg}{s}$ (15% tapped off from $\dot{m}_f$)

$\#\ of\ holes$ = 10

$$A_{\ film} = \left(\frac{0.03}{0.7}\right)\sqrt{\left(\frac{1}{2(810)}\right)\frac{1}{(4.137E6 - 3.447E6)}}$$

$$A_{film} = 1.28\text{E} - 6\ m^2$$

$$A_{i,film} = \frac{A_f}{\#\ of\ holes}$$

$$A_{i,film} = \frac{1.28E - 6}{10}$$

$$A_{i,film} = 1.28E - 7m^2$$

$$D_{film} = 2\left(\frac{1.28E - 7}{\pi}\right)^{0.5}$$

$\boldsymbol{D_{film} = 0.404\ mm}$ **(0.0159 inch)**

J&J Design & Analysis
Engine & Injector Sizing

USC Viterbi School of Engineering

Oxygen Injector Sizing (Based on Dual Engine Conditions)

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

Where

$R_0 = 259.8 \frac{J}{Kg-K}$

$T_0 = 290\ K$

$c_d = 0.7$ (square edge orifice)

$A_o = injector\ orifice\ total\ area$

$P_c = 3.447\text{E}6$ Pa (500 psi)

Pressure Drop 20%

$P_{inj,o} = 4.137E6\ (600\ psi)$

$\dot{m}_o = 0.375 \frac{kg}{s}$

$\#\ of\ holes = 16$

$$A_o = \left(\frac{0.375}{0.7}\right)\sqrt{\frac{(259.8)(290)}{2(4.137E6)(4.137E6 - 3.447E6)}}$$

$$A_o = 6.155\text{E} - 5\ m^2$$

$$A_{i,o} = \frac{A_o}{\#\ of\ holes}$$

$$A_{i,o} = \frac{6.155E - 5}{16}$$

$$A_{i,o} = 3.85E - 6m^2$$

$$D_o = 2\left(\frac{3.85E - 6}{\pi}\right)^{0.5}$$

$\boldsymbol{D_o = 2.21\ mm}$ **(0.087 inch)**

LPL

J&J DESIGN & Analysis
Thermal Control

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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 then phenolic (nozzle material for nozzle Blue Steel 2.0)
- 15% of the full will be tapped off to cool the injector

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Graphite Chamber Liner & Nozzle

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

L P L

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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

Jessie Graphite Parts
1 - Chamber Liner
1 - 1000 psi optimum expansion nozzle
1 – 500 psi optimum expansion nozzle

James Graphite Parts
1 - Chamber Liner
1 - 1000 psi optimum expansion nozzle
1 – 500 psi optimum expansion nozzle

J&J Design & Analysis
Overall Engine Design

Material data Isomolded Graphite

Property	SI Units	English
Young's modulus *	*7~8 GPa*	*1.015Mpsi ~1.16Mpsi*
Compressive strength *	*8963 Pa*	*13000 psi**
Density	$0.065\ lb/in^3$	*1.81* gr/cm^3
Flexural Strength	*7250 psi*	*50 MPa*
Thermal Conductivity	*85 W/*$(m^2.K/m)$	*49 BTU/*$(h.ft^2{}^\circ F/ft)$
CTE	*4.6 Microns/m*°C	*2.6 in/in*$^\circ F\times10^{-6}$

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

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Insulation Thickness

$t_{insul} = t_{exp}\dot{e}f_s$

Where t_{insul}= insulation thickness (m)

t_{exp}= insulation exposure time (s)

$\dot{e}$= insulation erosion rate (m/s)

f_s= safety factor

$t_{insul} = (25)s(0.10)\dfrac{mm}{s}(4)$

t_{insul} = 10 mm (0.39 inch)

$\mathbf{t_{chamber\ liner} = 11.11\ mm\ (0.4375\ inch)}$

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

Material	ρ kg/m^3	c_p cal/gm·K	κ W/m·K	F_{tu} MPa	$\dot{e}$* mm/s
Pyrolytic Graphite	2200	0.50	0.059	103	0.05
Polycrystalline Graphite	1700	0.60	26.0	48	0.10
2-D Carbon/Carbon	1400	0.54	13.8	110	-
3-D Carbon/Carbon	1900	0.50	31.5	186	0.10
Carbon/Phenolic	1400	0.36	1.00	72.4	0.18
Graphite/Phenolic	1400	0.39	1.59	52.4	0.28
Silica/Phenolic	1700	0.30	0.55	52.4	1.3
Glass/Phenolic	1900	0.22	0.028	414	1.5
Paper/Phenolic	1200	0.37	0.40	152	1.9

ρ = Material density
c_p = Material specific heat
κ = Material thermal conductivity
F_{tu} = Ultimate tensile strength
$\dot{e}$ = erosion rate

*Reference data:
p_c = chamber pressure = 6.9 MPa
D_t = throat diameter = 0.3 m
T_c = combustion temperature = 3030 K
Note that values are scaled using correlations for convective heat transfer (see Heister [1990]).

This provides enough confidence to fire for a short duration & use test results to estimate a more accurate erosion rate

L P L

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Ablative Cooling Energy Conservation

$$(\dot{Q}_{rad} + \dot{Q}_{con}) = \dot{m}_{ablative}\, h_{ablative}$$

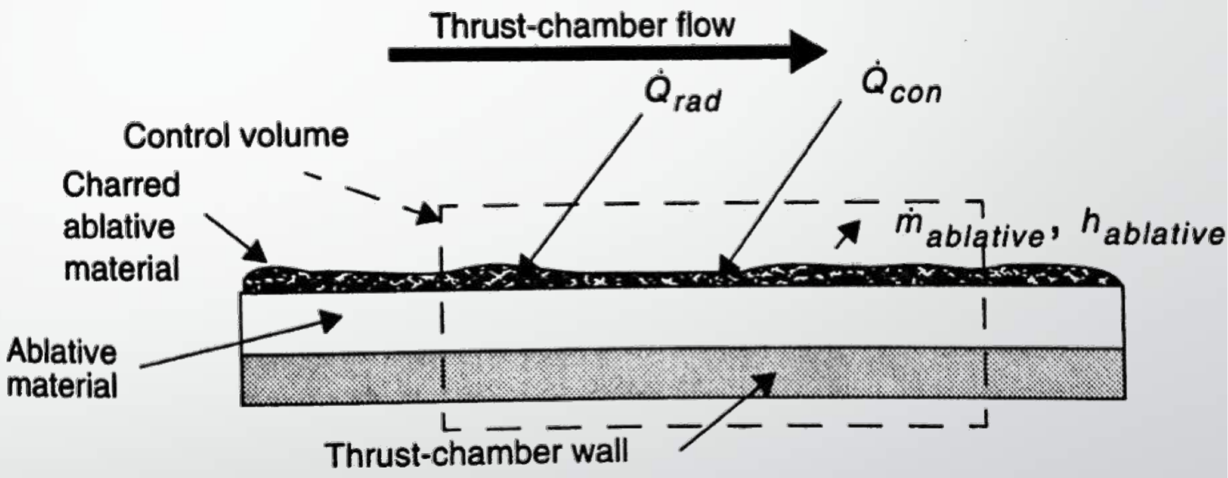
Where:

$\dot{Q}_{rad}$ = heat addition due to radiation (W)

$\dot{Q}_{con}$ = heat addition due to convection (W)

$\dot{m}_{ablative}$ = the mass flow of the ablative material (kg/s)

$h_{ablative}$ = enthalpy of material ablation (J/kg)



Note: Need to know ε_{flame} & $h_{ablative}$. Looking into this. Can estimate $h_{ablative}$ after a static fire by measuring the amount of material that has ablated.

LPL

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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)

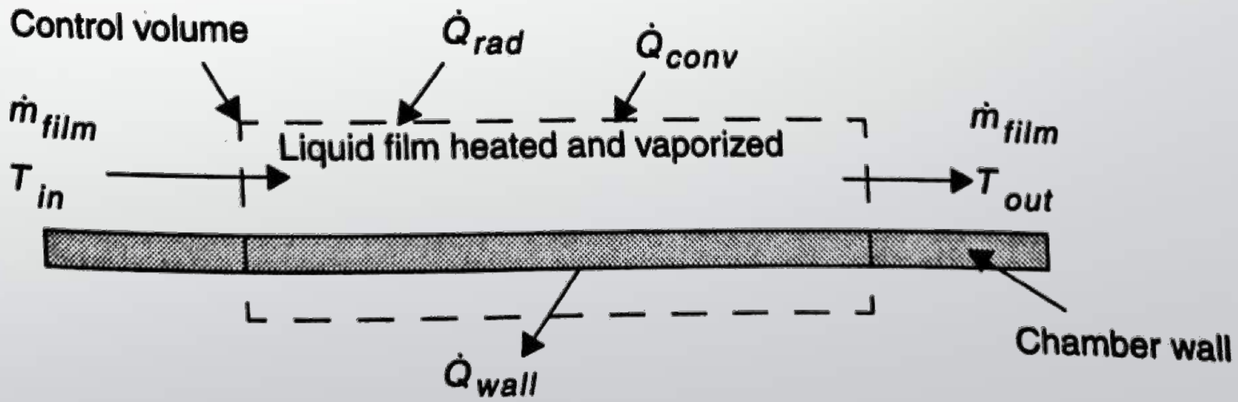
h_{fg}= heat of vaporization of the fluid (J/kg)

$\dot{Q}_{wall}$= 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

L P L

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Engine Interfaces

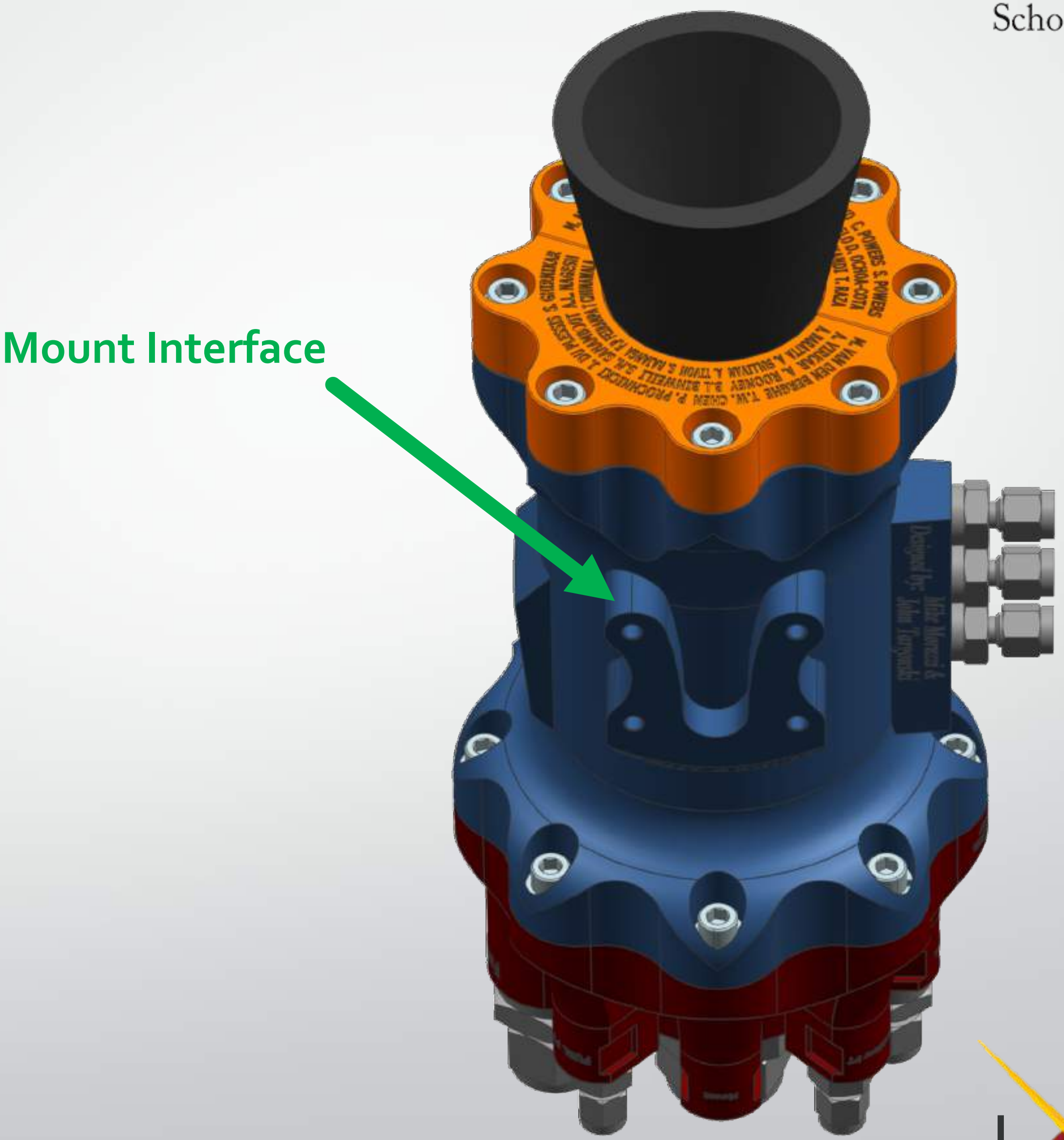
J&J Design & Analysis
Engine Interfaces

Mount Interface

Mount Interface:

4

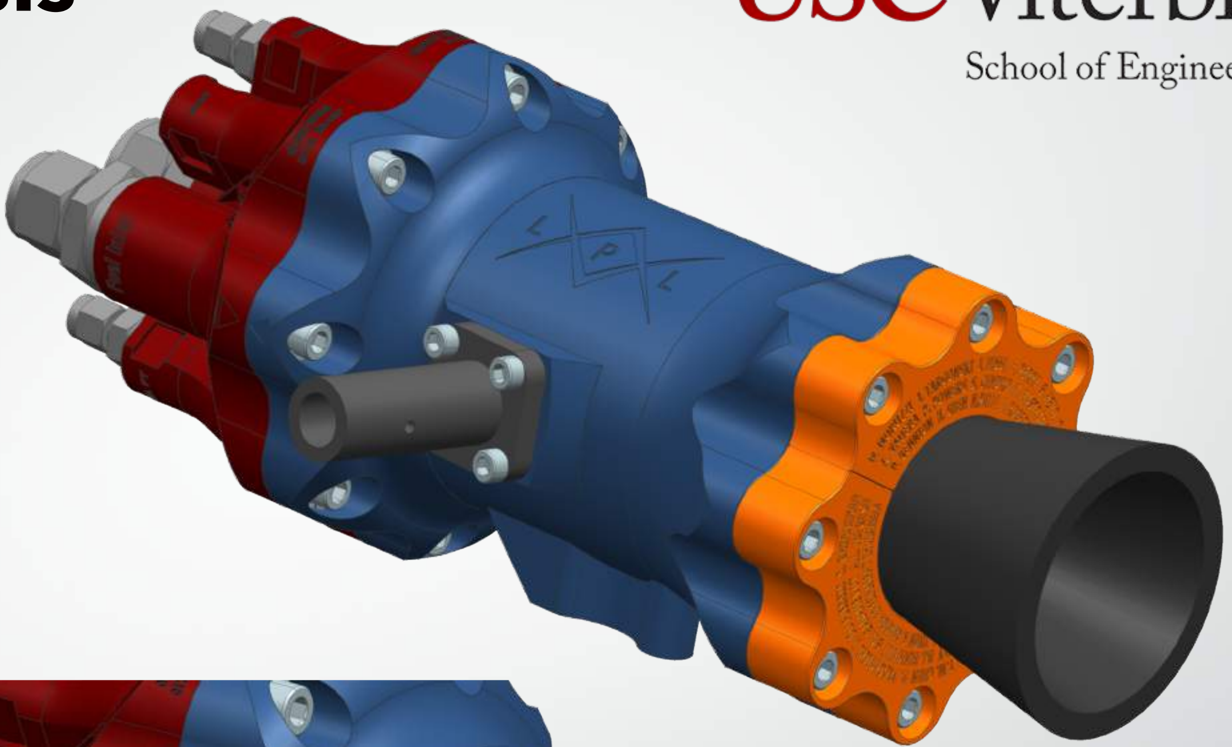
This is mount the engine to the slide rail featured on Hydra



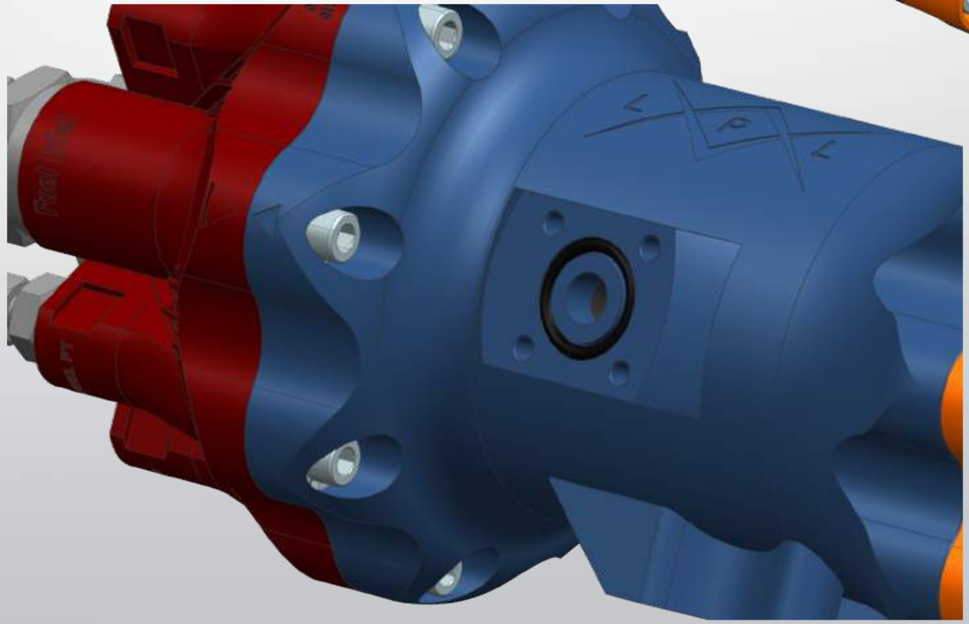
J&J Design & Analysis
Engine Interfaces

Ignitor Interface

4



The ignitor interface will secure and seal the ignitor onto the engine

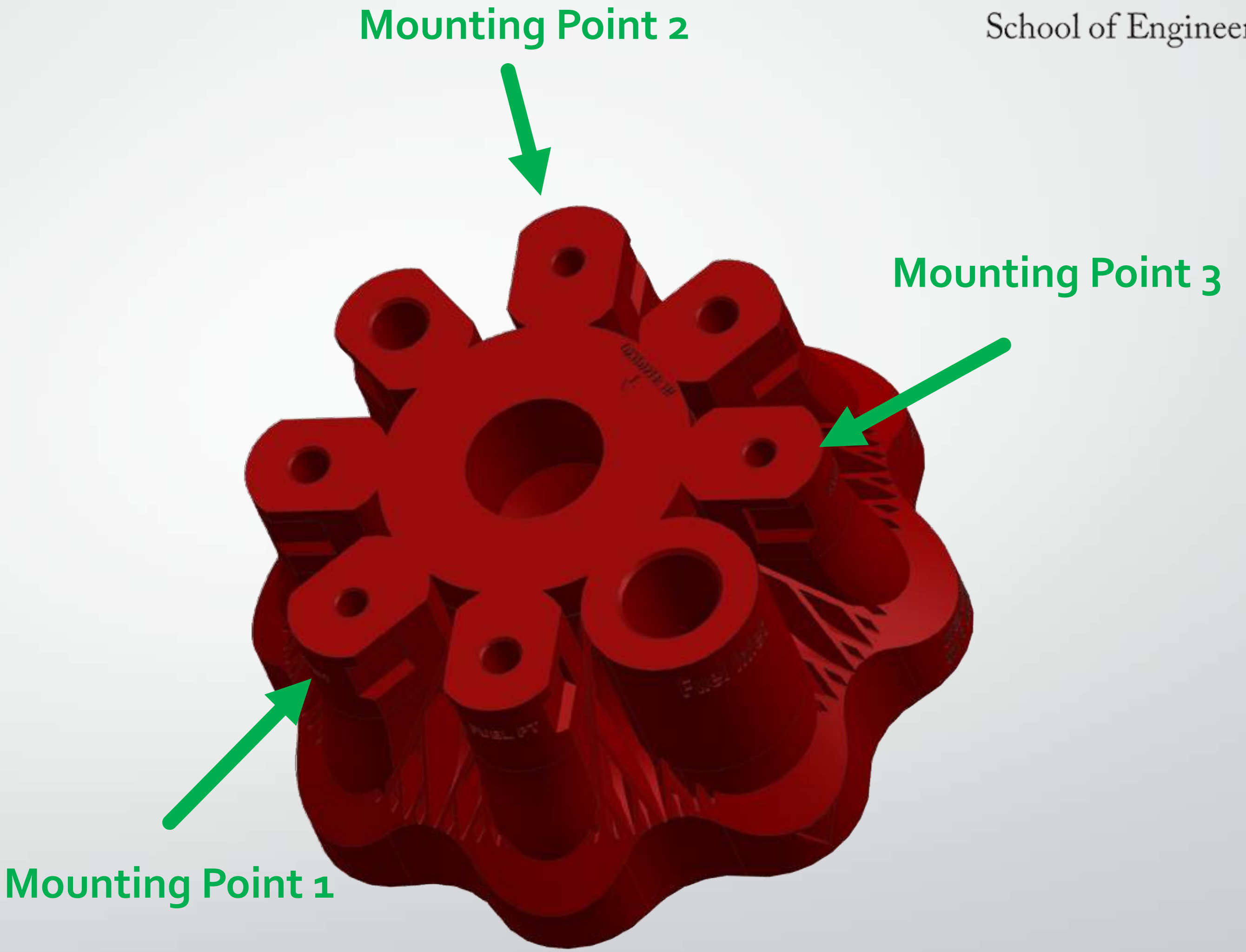


J&J Design & Analysis
Engine Interfaces

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 DESIGN & Analysis
Fasteners & Sealing

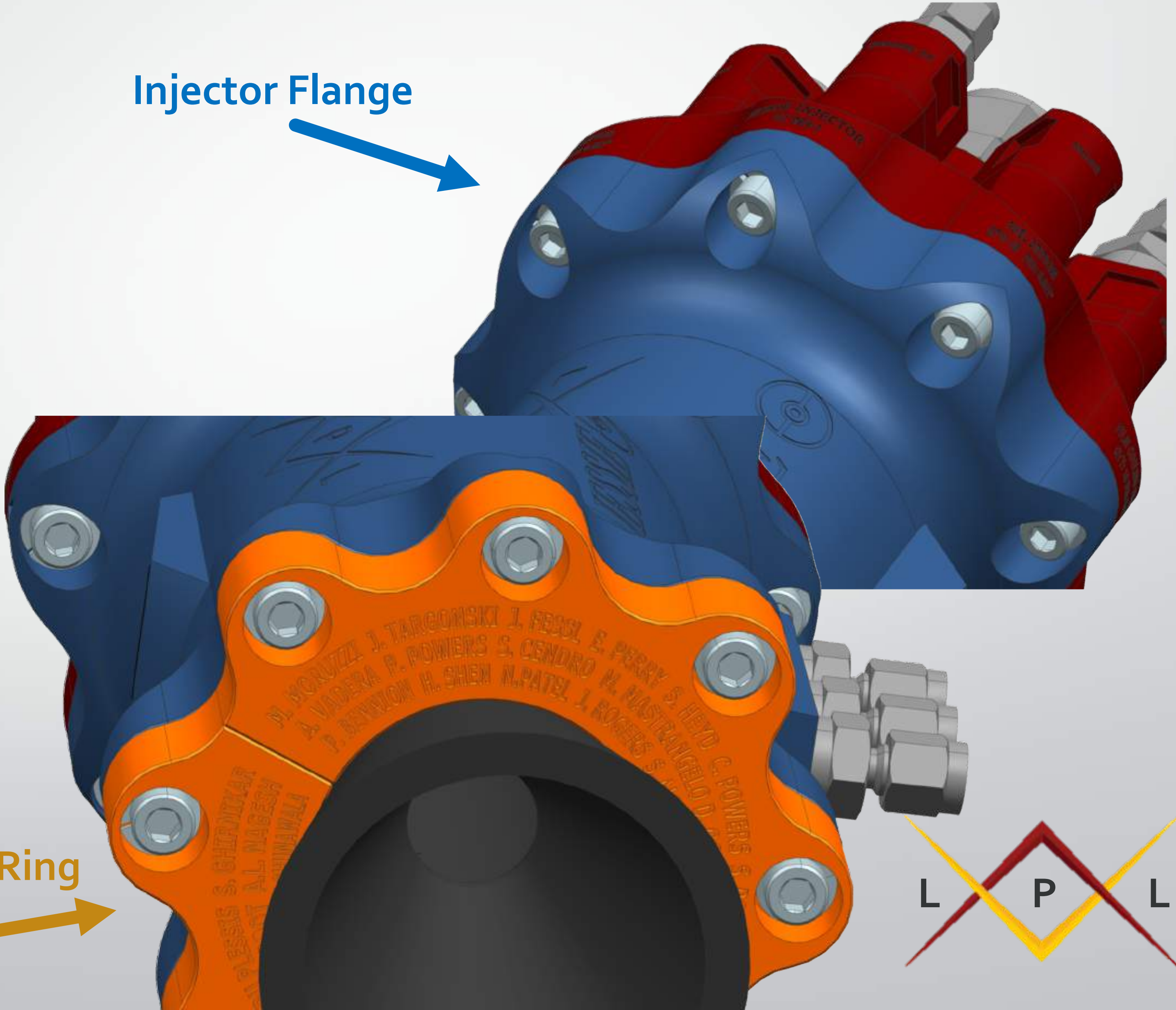
J&J Design & Analysis

Fasteners & Sealing

J&J Fasteners

J&J will feature a total of 16 ¼-28 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.



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J&J Fasteners & Washer Material Properties

Screws

Used for both retention ring and injector side

Type: ¼-28

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

LPL

J&J Design & Analysis

Fasteners & Sealing

J&J Fasteners & Retention Ring Material Properties

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)

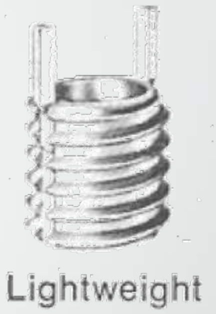
Internal Thread Class 3B ¼-28

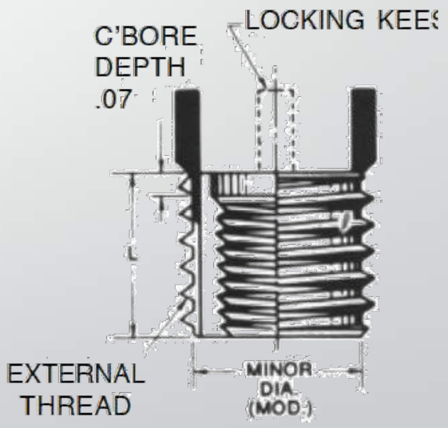
Material: 303 CRES (passivated)

External Thread: 3/8 – 16

Shear Engagement: 0.2371"

L: 0.37"





J&J Design & Analysis
Fasteners & Sealing

Screw Preload Force

$$Preload\ Force = 0.75\ (\sigma_{proof})A_t$$

Where $A_t = Tensile\ Area$

(0.75 is coefficient used for reusable screws)

$$Preload\ Force = 0.75\ (80\ ksi)0.0364in^2$$

$$\boldsymbol{Preload\ Force = 2184\ lbf\ (9.610\ kN)}$$

Screw Torque Equation

$$\mathrm{T = K_t F_i D}$$

Where : T= torque (in-lb, ft-lb, or N-m)

$\mathrm{K_t}$= torque coefficient (**0.15 lubed**)

$\mathrm{F_i}$= Initial preload Force in the bolt

D= nominal diameter of bolt

$$\mathrm{T} = (0.15)(2184)lbf\,(0.25)\mathrm{in}$$

Torque Preload = 81.9 in-lbf (9.25 N-m)

For screws on both the injector and nozzle side

J&J Design & Analysis
Fasteners & Sealing

Screw Stiffness

$K_{screw} = \frac{A_t E_{screw}}{L_{joint}}$ (Fully Threaded screw)

E_{bolt} = 28500 ksi

L_{joint} = 0.35 inch

$A_t = 0.0364 in^2$

$K_{screw} = \frac{0.0364 in^2 \, 28500 \text{ ksi}}{0.35 \text{ inch}}$

$\boldsymbol{K_{screw}}$ **= 2.964 Msi**

Joint Stiffness

$$K_{joint} = \frac{\pi E_{joint} d_{shank}}{2 ln\left(5\left(\frac{L_{joint} + 0.5 d_{shank}}{L_{joint} + 2.5 d_{shank}}\right)\right)}$$

E_{joint} = 22000 ksi (entirely marging steel)

$d_{shank} = 0.281$ inch

$$K_{joint} = \frac{\pi(22000E3)(0.281)}{2 ln\left(5\left(\frac{0.35 + (0.5)(0.281)}{0.35 + (2.5)(0.281)}\right)\right)}$$

$\boldsymbol{K_{joint}}$ **= 11.5 Msi**

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Fasteners & Sealing

Joint coefficient of screw-load factor, C

$$C = \frac{k_{screw}}{k_{screw} + k_{joint}}$$

$$C = \frac{2.964\ Msi}{2.964\ \text{Msi} + 11.5\ Msi}$$

$$\boldsymbol{C} = \mathbf{0.20}$$

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…

J&J Design & Analysis
Fasteners & Sealing

Fastening - Retention Ring Side

Determining Load on Fasteners

$$P_{Retention\ Ring} = (P_0)(A_c - A_t)$$

$$P_{Retention\ Ring} = (1000\ psi)(3.55in^2 - 0.466in^2)$$

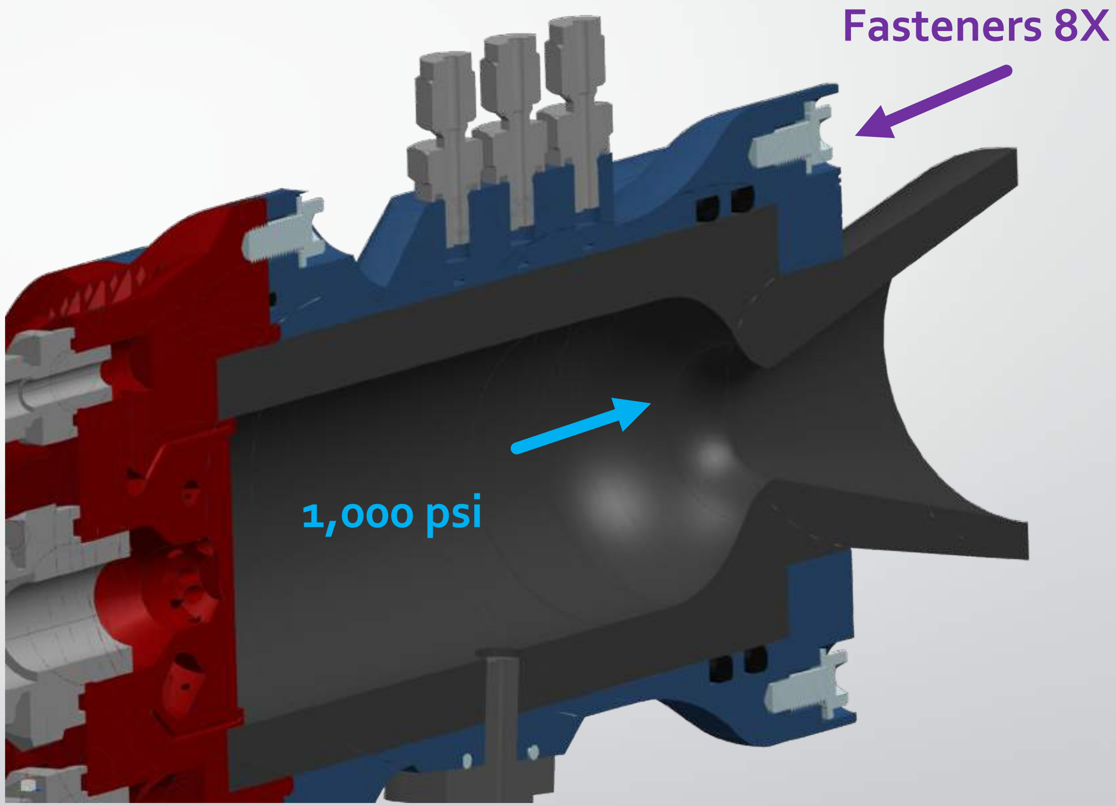
$$\boldsymbol{P_{Retention\ Ring}} = 3084\ \text{lbf}$$

$$P_{screw} = \frac{P_{Retention\ Ring}}{\#\ of\ Screws}$$

$$\#\ of\ Screws = 8$$

$$P_{screw} = \frac{3084\ \text{lbf}}{8}$$

$$\boldsymbol{P_{screw} = 385.5\ lbf}$$



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Fasteners & Sealing

Fastening - Retention Ring Side

$$\sigma_{screw} = \frac{P_{screw}}{Tensile\ Area}$$

$$\sigma_{screw} = \frac{385.5\ lbf}{0.0364 in^2}$$

$\boldsymbol{\sigma_{screw}}$ **= 10.6 ksi**

$$FS = \frac{\sigma_{ult}}{\sigma_{screw}}$$

$$FS = \frac{80\ ksi}{10.6\ ksi}$$

$$\boldsymbol{FS = 7.55}$$

Failure in tension is NOT predicted!

The required minimum preload to prevent gapping is then

$F_{i,min} = P(1 - C)$ = 385.5 lbf (1-0.20)

$F_{i,min}$ = 308 lbf

$\boldsymbol{Preload\ Force = 2184\ lbf}$ ✓

Factor of Safety against gapping

$$FS_{gap} = \frac{F_i}{P(1-C)} = \frac{2184\ lbf}{385.5\ lbf\,(1-0.20)}$$

$\boldsymbol{FS_{gap}}$ **= 7.08**

Gapping is NOT predicted!

J&J Design & Analysis
Fasteners & Sealing
Fastening - Injector Side

Determining Load on Fasteners

$$P_{Injector} = (P_0)(A_c)$$

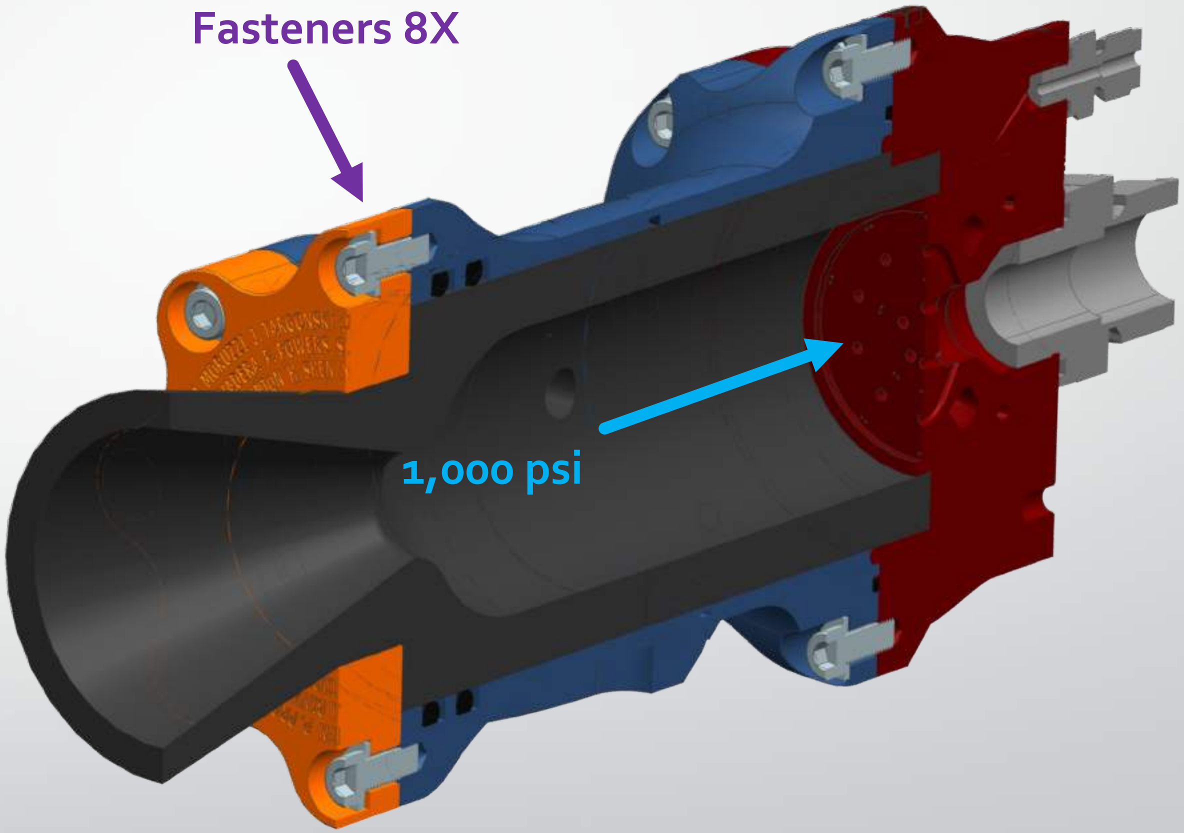
$$P_{Injector} = (1000\ psi)(3.55in^2)$$

$$\boldsymbol{P_{Injector}} = 3550\ \text{lbf}$$

$$\#\ of\ Screws = 8$$

$$P_{screw} = \frac{3550\ \text{lbf}}{8}$$

$$\boldsymbol{P_{screw} = 444\ lbf}$$



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Fasteners & Sealing

Fastening – Injector Side

$$\sigma_{screw} = \frac{P_{screw}}{Tensile\ Area}$$

$$\sigma_{screw} = \frac{444\ lbf}{0.0364 in^2}$$

$\boldsymbol{\sigma_{screw}}$ **= 12.2 ksi**

$$FS = \frac{80\ ksi}{12.2\ ksi}$$

$$\boldsymbol{FS = 6.56}$$

Failure in tension is NOT predicted!

The required minimum preload to prevent gapping is then

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

$F_{i,min} =$ 355 lbf

$\boldsymbol{Preload\ Force = 2184\ lbf}$ ✓

Factor of Safety against gapping

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

$\boldsymbol{FS_{gap}}$ **= 6.15**

Gapping is NOT predicted!

J&J Design & Analysis
Fasteners & Sealing

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

Minimum Screw Length of Engagement

$$L_{e,min} = \frac{(2)A_t}{K_n \max \pi \left(\frac{1}{2} + 0.5775n(E_s min - K_n \max\right)}$$

$$L_{e,min} = \frac{2(0.0364)}{(0.1857)\pi(\frac{1}{2} + 0.5775(28)(0.1904 - 0.1857)}$$

$\boldsymbol{L_{e,min}}$ **= 0.217 inch**

Since different materials need to get the J value

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

A_s = Shear area of external thread (screw)
A_n = Shear area of internal thread (hole)

If $J > 1$ then the minimum length of engagement needs to be extended to:

$$L_{e,min\ new} = J \ x \ L_{e,min\ org}$$

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

$k_n \max$ = *Maximum minor diameter of internal thread*

$E_s \min$ = *Minimum pitch diameter of external thread*

n = *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 in²*

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

$E_n \max$ = *Maximum pitch diameter of internal thread*

$D_s \min$ = *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 inch²*

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Fasteners & Sealing

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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

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

$J = 0.34$

Since J < 1:

$L_{e,min} = 0.217$ inch

Our length of Engagement On Retention Ring Side:

Length of Thread Engagment

$$L_e = L_{screw} - (t_{retention_{ring}} - d_{counter\ bore}) - t_{washer}$$

$$L_e = 0.75" - (0.75" - 0.4") - 0.062"$$

$$L_e = 0.338"$$

On retention ring side both internal and external threads are NOT predicted to fail!

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J&J Design & Analysis
Fasteners & Sealing

Using Keenserts on Injector Side

Insert Internal Thread Failure Check

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

Where $A_s = Thread\ Shear\ Area$

$L_e = Length\ of\ Thread\ Engagment$

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

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

$$A_s = 0.30\ in^2$$

Insert Internal Thread Failure Check

$P_{ult} = 12370\ lb$ (MS51830E-202L)

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

For Injector Side

$$FS_{shear\ thread\ failure} = \frac{12370\ lbf}{444\ \ lbf}$$

$FS_{shear\ thread\ failure}$ =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

$P_{ult} = 8630\ lb$ (MS51830E-202L)

$A_s = 0.30\ in^2$

For injector side

$$FS_{shear\ thread\ failure} = \frac{8630\ lbf}{444\ \ lbf}$$

$FS_{shear\ thread\ failure}$ =19.4

Insert External Thread Failure is NOT predicted!

Insert Parent Material Thread Failure Check

$P_{ult} = (\mathbf{0.103\ in^2})(\mathbf{145ksi})$

$P_{ult} =$ 14,935 lbf

For injector side

$$FS_{shear\ thread\ failure} = \frac{14935\ lbf}{444\ \ lbf}$$

$FS_{shear\ thread\ failure}$ =33.6

Insert Parent Material Thread Failure is NOT predicted!

J&J Design & Analysis
Fasteners & Sealing

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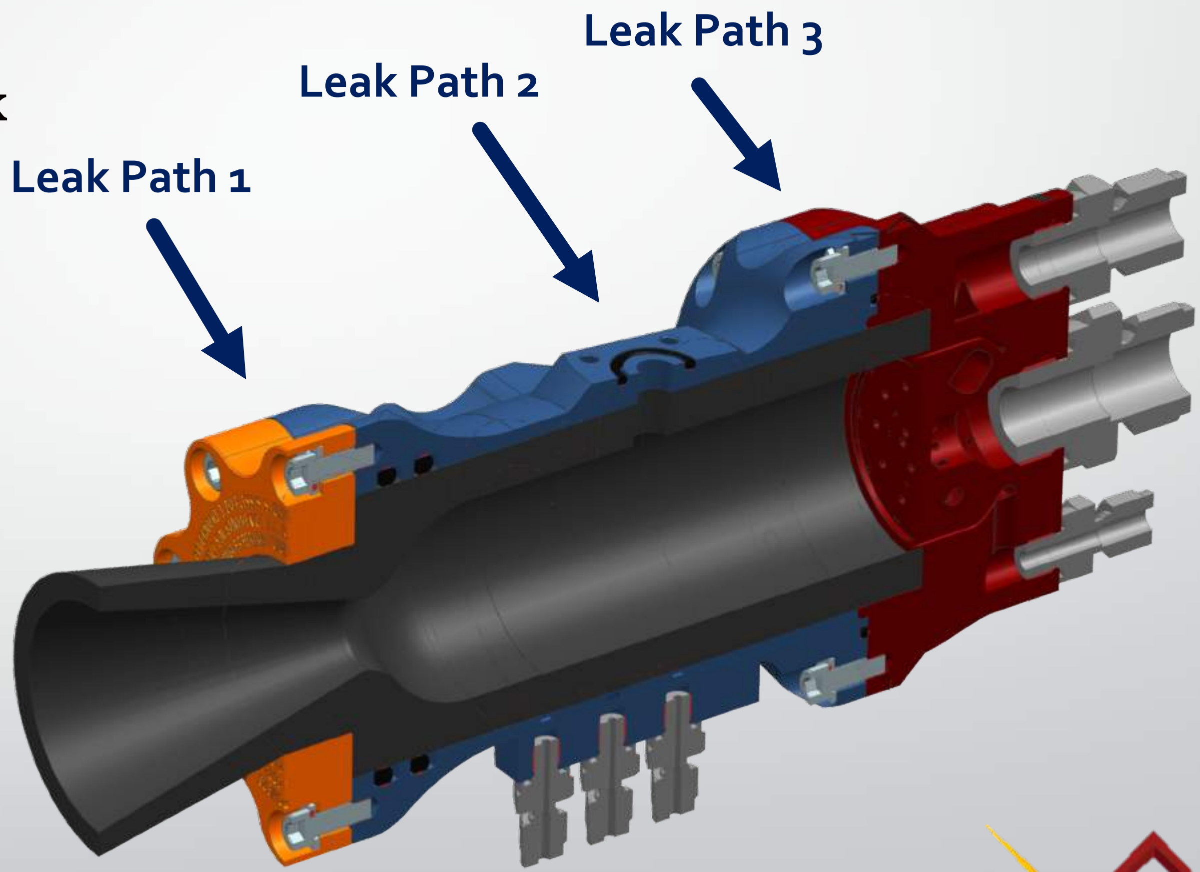
Sealing Features

Jessie & James each have 3 potential leak paths

1. *Nozzle & Chamber interface*
2. *Ignitor & Chamber interface*
3. *Injector & Chamber interface*



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J&J Design & Analysis

Fasteners & Sealing

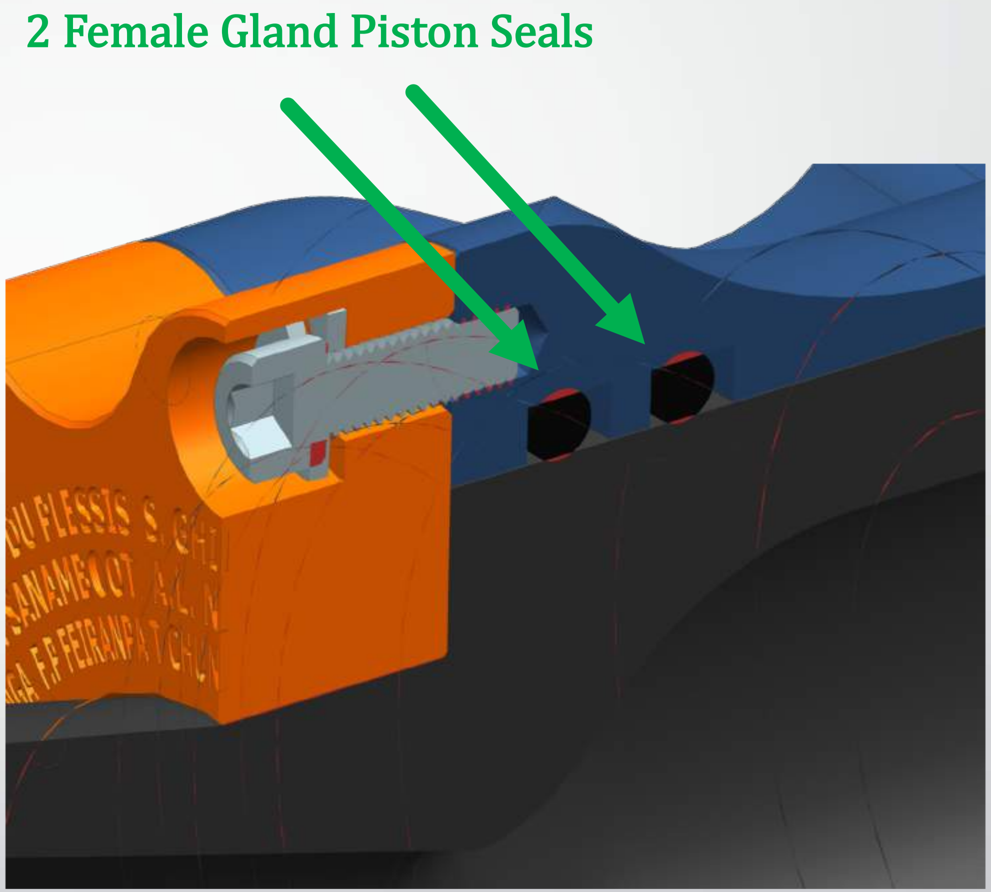
Sealing Features

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)



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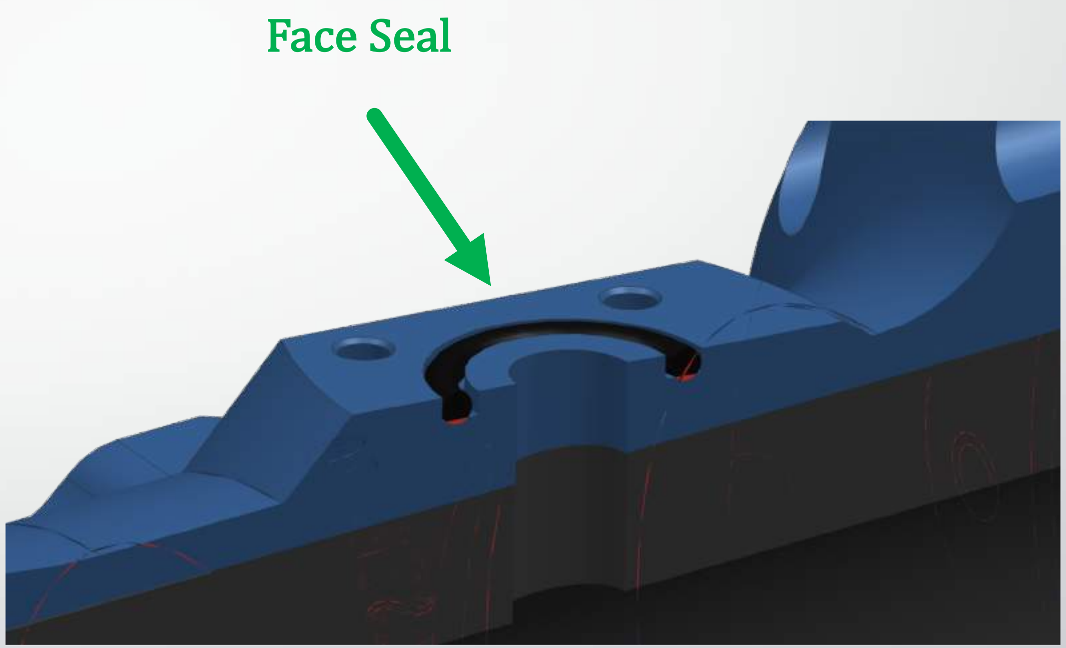
Fasteners & Sealing

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)



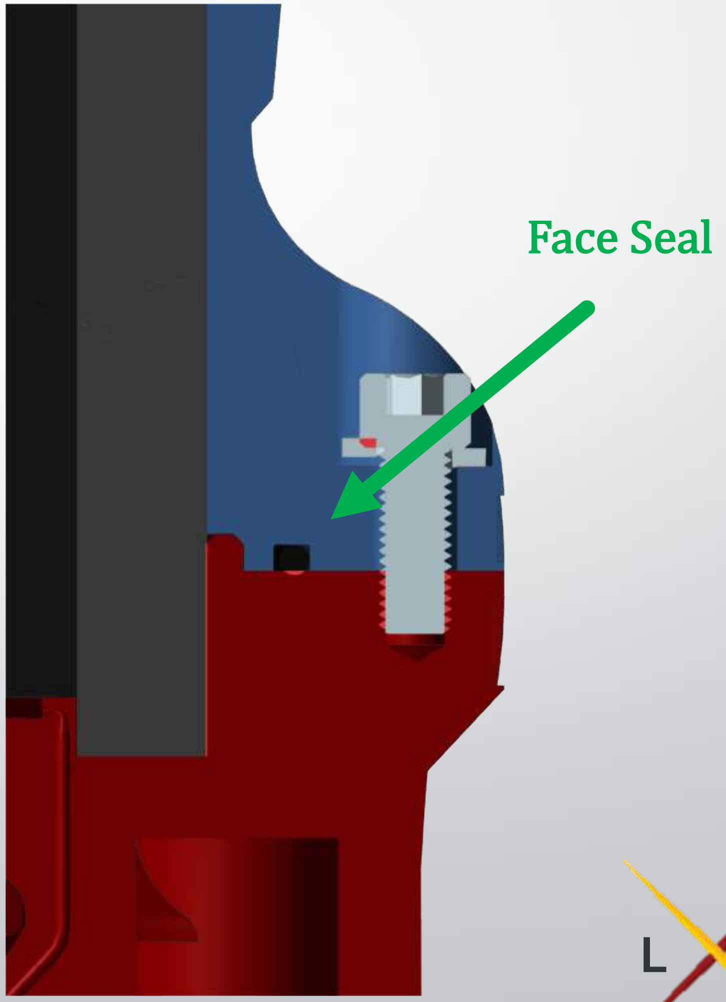
J&J Design & Analysis
Fasteners & Sealing

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)



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Fasteners & Sealing

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

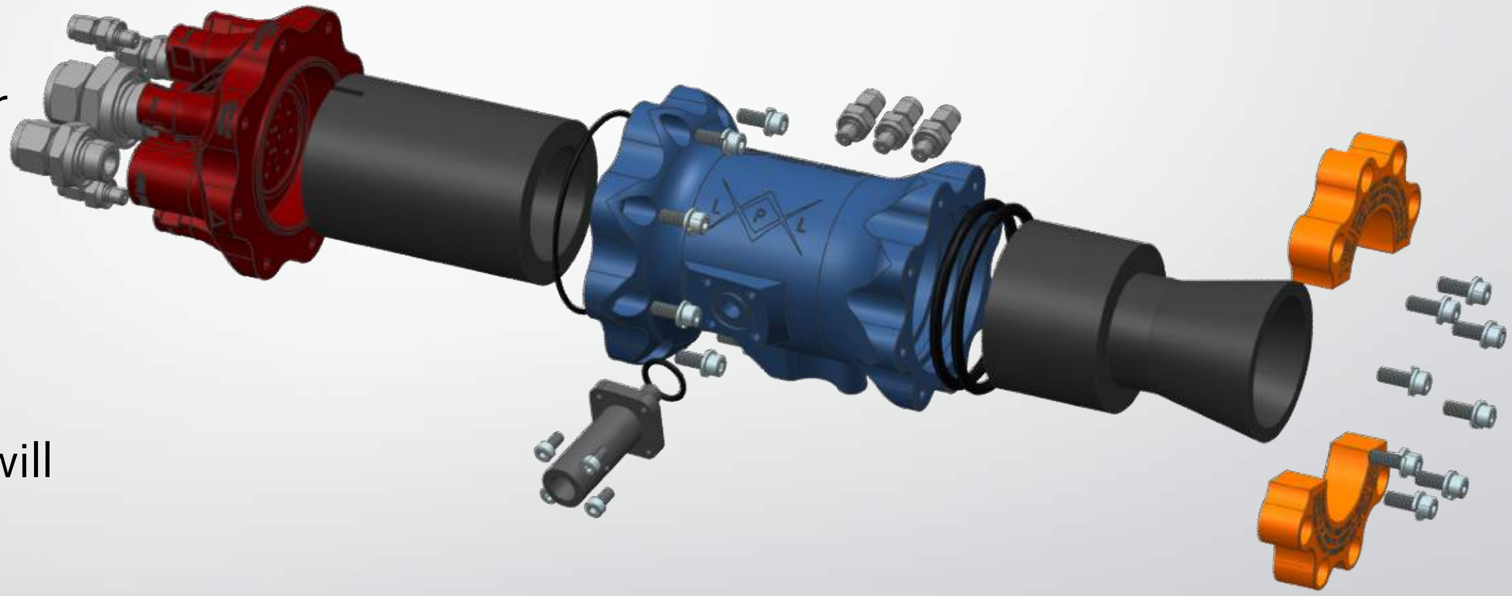
J&J Build & Test
Fabrication & Assembly

Installing the Chamber insert

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



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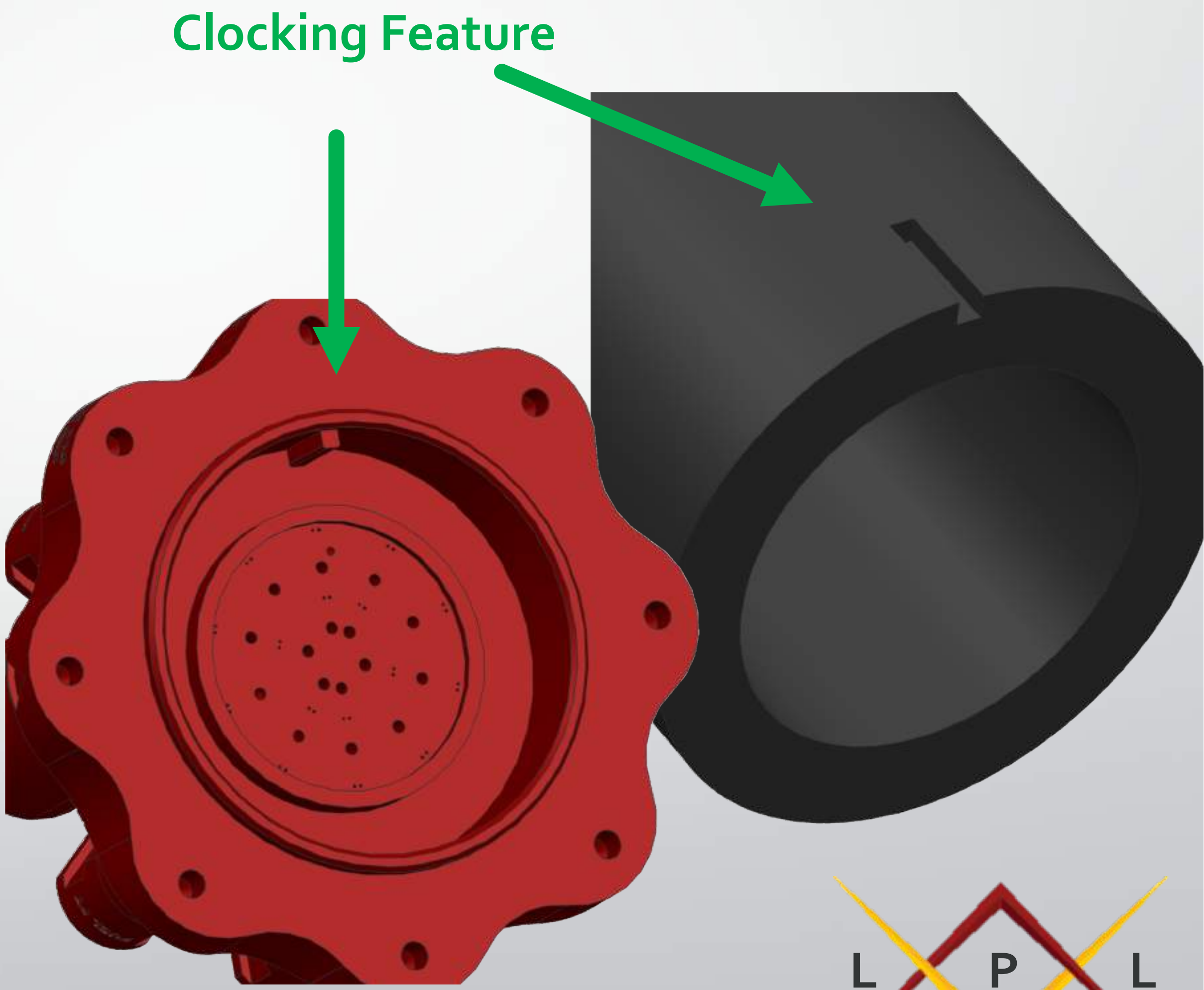
Fabrication & Assembly

Installing the Chamber insert

The axial length of the insert will be sized to be slightly larger then the engines 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



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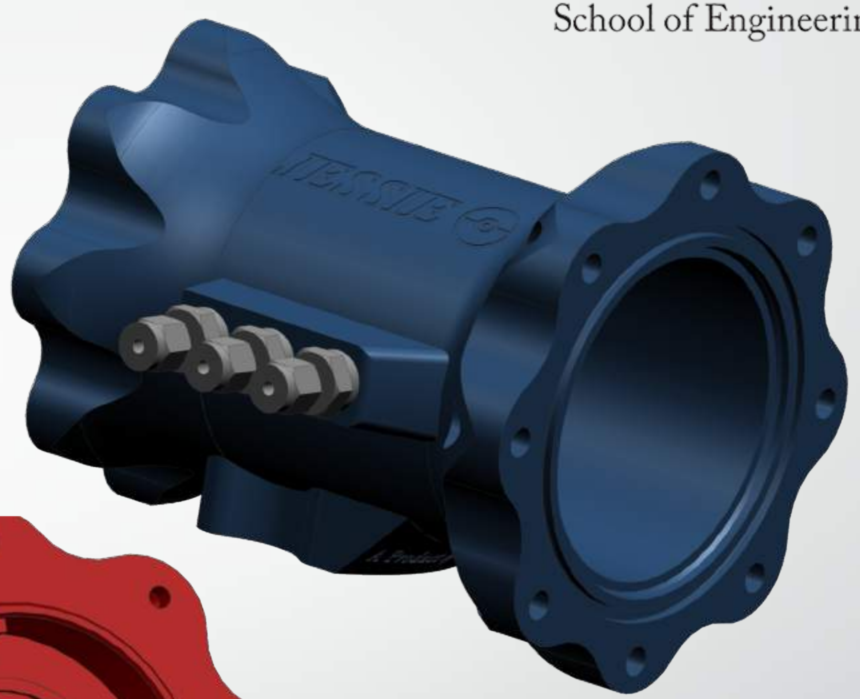
Fabrication & Assembly

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

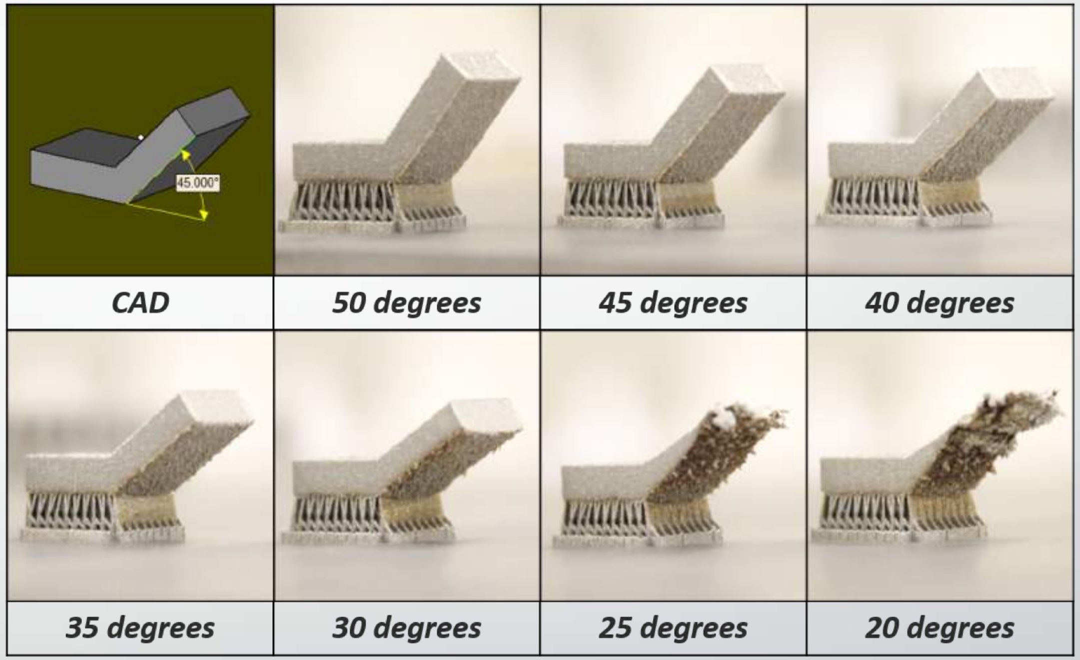
Printer: EOS M290

Design Constraints:

Max Print Height: 325 mm (12.8 inch)

Must avoid 45° overhangs

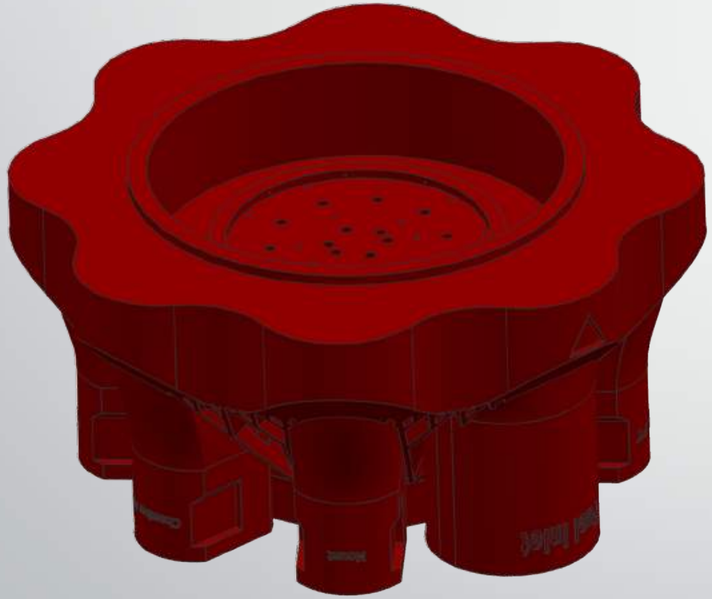
Features should be above 150 μm (0.006 inch)

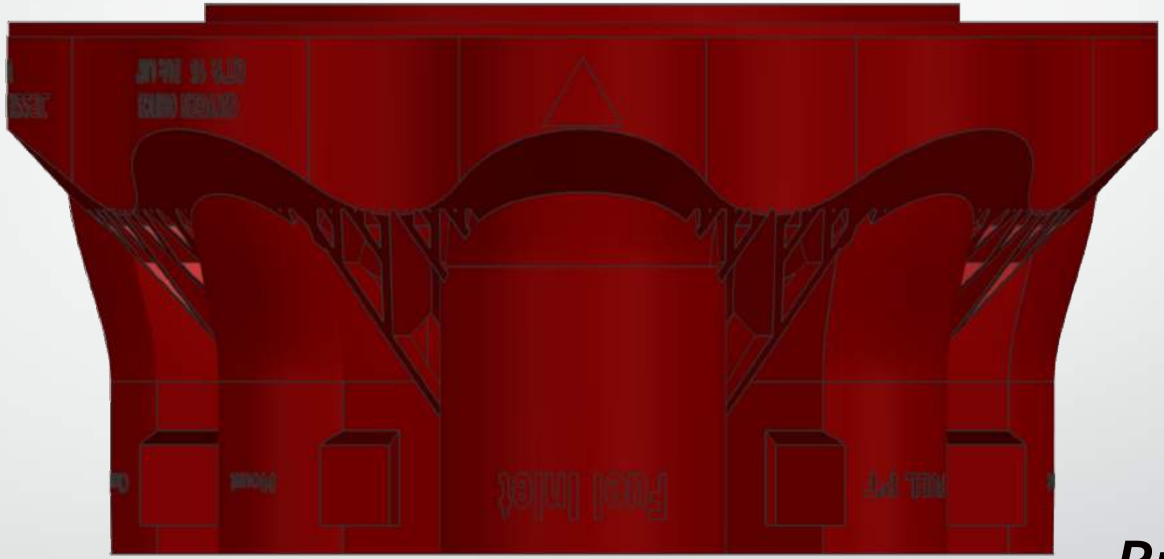


J&J Build & Test
Fabrication & Assembly

USC Viterbi School of Engineering

Injector Print Direction





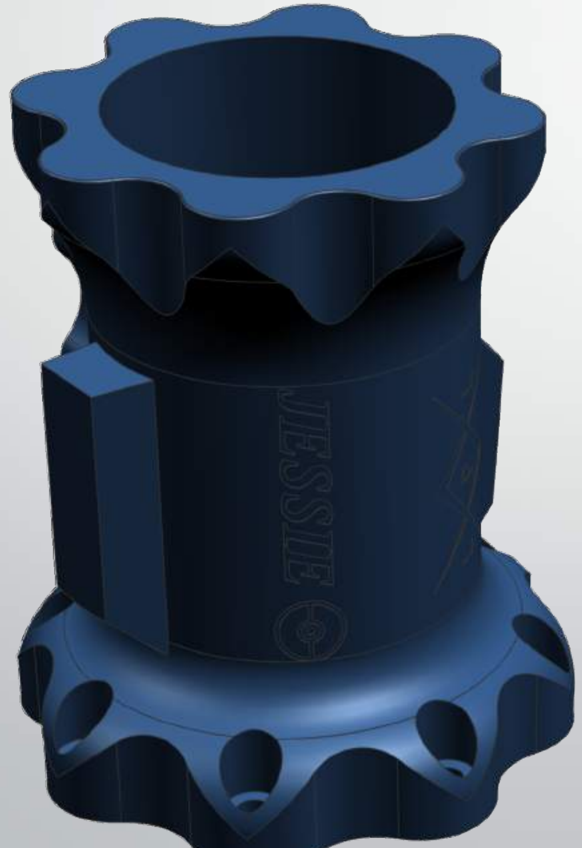
Print Direction

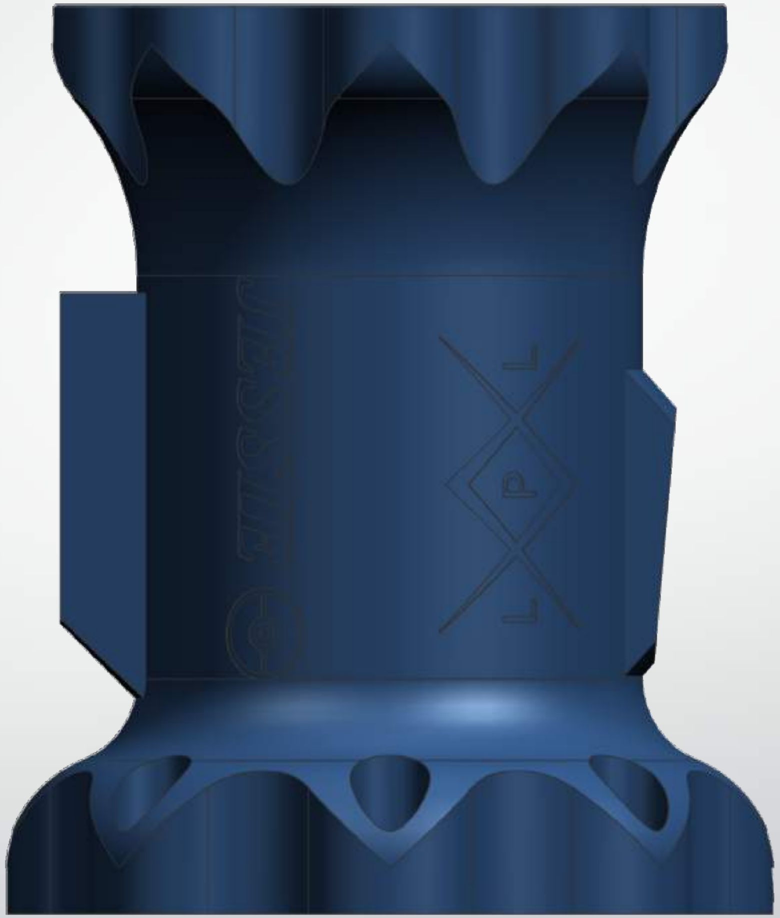
L P L

J&J Build & Test

Fabrication & Assembly

Chamber Print Direction





Print Direction

J&J Build & Test

Fabrication & Assembly

Retention Ring Print Direction

Print Direction

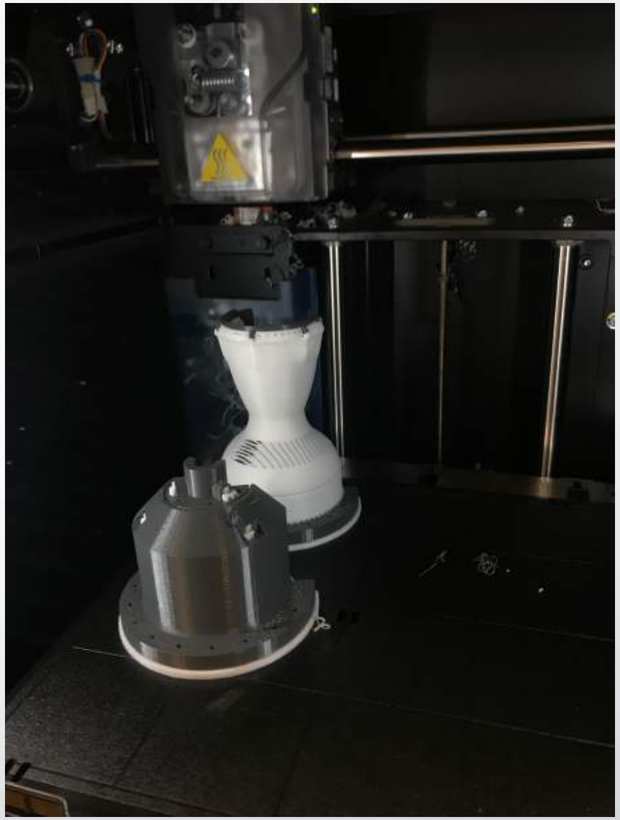
J&J Build & Test
Fabrication & Assembly

Additive Manufacturers

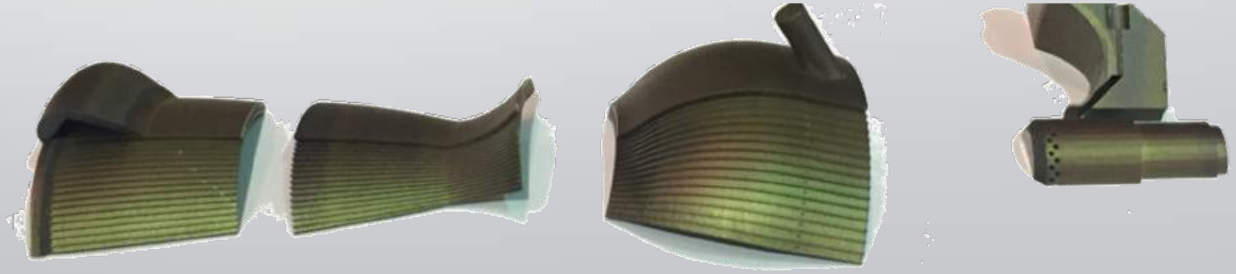
Will be using USC's Center for Advance Manufacturing (CAM) to print Jessie & James

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



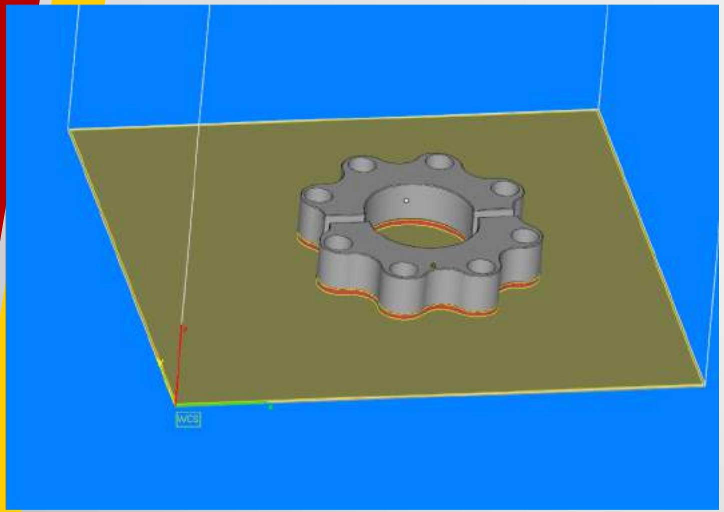
3/8" Scale of our Balerion Engine printed at CAM



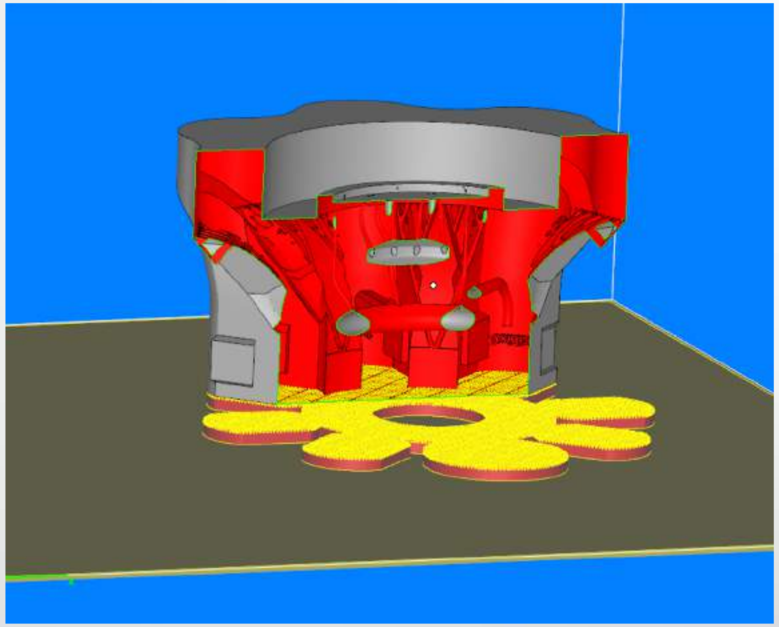
1/8" Slice of our Balerion Engine printed at CAM

J&J Build & Test
Fabrication & Assembly

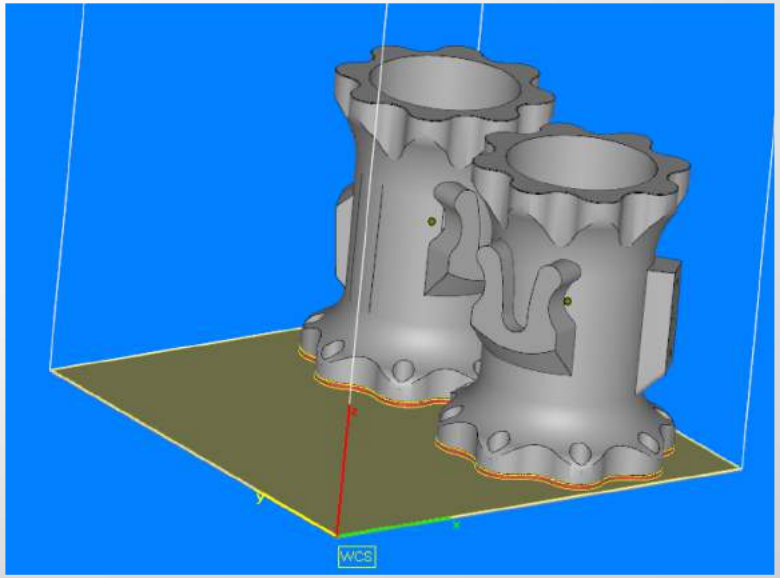
J&J Engine Parts on Build Plates



Retention Ring on build plate



Injector on Build Plate



Both Chambers on Build Plate

No Support Structure Required!

J&J Build & Test
Fabrication & Assembly

USC Viterbi
School of Engineering

Additive Manufacturers

Jessie & James Printing Cost Estimate

Print Hours

2 Combustion Chambers ~ 66 hours

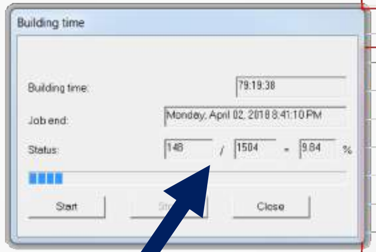
2 injectors & 4 (1/2) retention rings ~ 80 hours

Total weight of printed parts 5.72 kgs (12.6lbs)

Printing Time Cost: $1,022

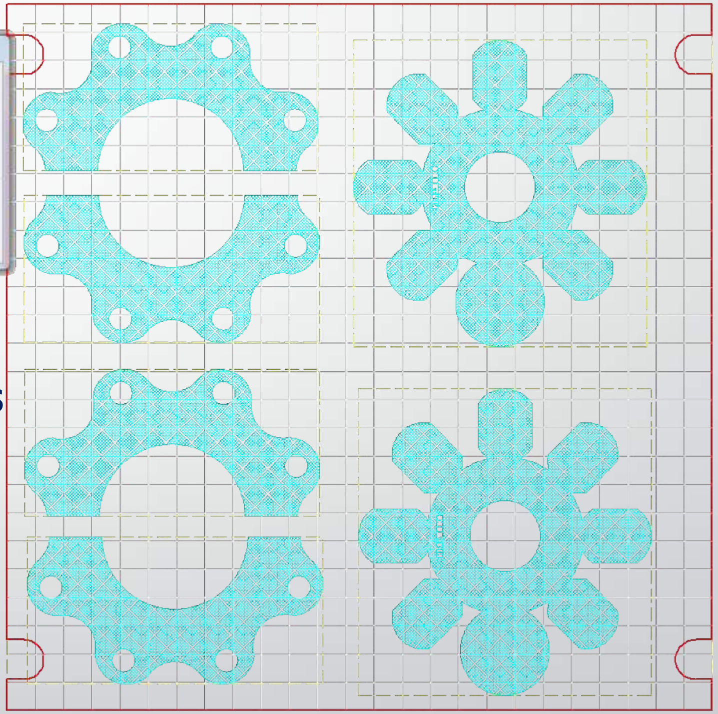
Material Cost: $1,716

Estimated Total Cost: $2,738



Estimated 80 hours build time

Jessie & James Injector & Retention Ring on build plate



L P L

J&J Build & Test
Tolerance Stack-ups

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:

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

$$\varepsilon_{max} = \frac{\sigma_{ult}}{E} = \frac{50\ MPA}{7\ GPA} = 0.007 \qquad , \quad \varepsilon = \frac{\Delta L}{L_0}$$

$$\Delta L = \varepsilon_{max} L_0 = (0.007)(0.11)m$$

$$\Delta L = 7.7E - 4\ m\ (0.030\ inch)$$

$$\boldsymbol{L_0 = 0.11\ m\ (4.375\ inch)}$$

Can Axial or Radially Compress ~0.030 inch before failure

Questions?

Future Modifications
Hydra

Future Modifications

Jessie & James

USC Viterbi School of Engineering

L P L

Supplementary Material

Master Equipment List (MEL)

Supplementary Material

Master Equipment List (MEL)

Supplementary Material

Cost

Supplementary Material

Cost

Supplementary Material

Schedule

J&J Design & Analysis
Overall Engine Design

James

Combustion Chamber

Injector

Isomolded Graphite Nozzle

Retention Ring (2 Pieces)

The only difference in design is the injector & pressure transducer ports are rotated by 180°

Supplementary Material
Schedule

Supplementary Material
Future Slide

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Radiation Heat Addition

Convection Heat Addition

Radiation heat transfer coefficient

$$h_{rad} = \varepsilon\sigma\left(T_c{}^2 + T_\infty{}^2\right)(T_c + T_\infty)$$

Where $\varepsilon = emissivity\ (flame)$

$\sigma = Stefan - Boltzmann\ constant = 5.67\times10^{-8}\left(\frac{W}{m^2K^4}\right)$

$T_c = chamber\ temperature$

$T_\infty = ambient\ temperature$

LPL

Motivation & Introduction

Constraints for Jessie & James

Hydra

- Bottle Pressure (limits 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

$$a = \sqrt{\gamma R T}$$

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