

Epimetheus Engine Critical Design Review

Cesar Briones
Jan 27th, 2026

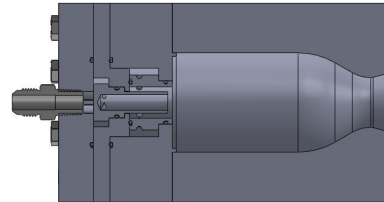
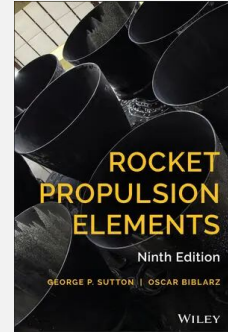
Agenda

1. Introduction and Purpose
2. Requirements
3. Engine Design
 - a. Propellant definition
 - b. Pressure definition
 - c. Chamber and nozzle sizing
4. Injector Design
 - a. Injector sizing and pressure drops
 - b. Coaxial swirl specific velocities
5. Engine Simulation
 - a. Thermal Analysis
 - b. Injector CFD Analysis
6. Manufacturing

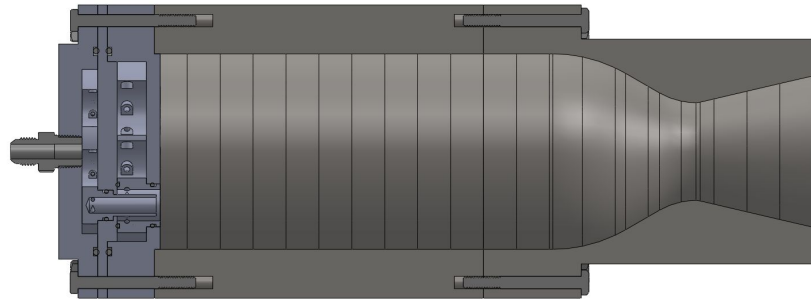
Purpose

This project started as a way to learn more about liquid propulsion.

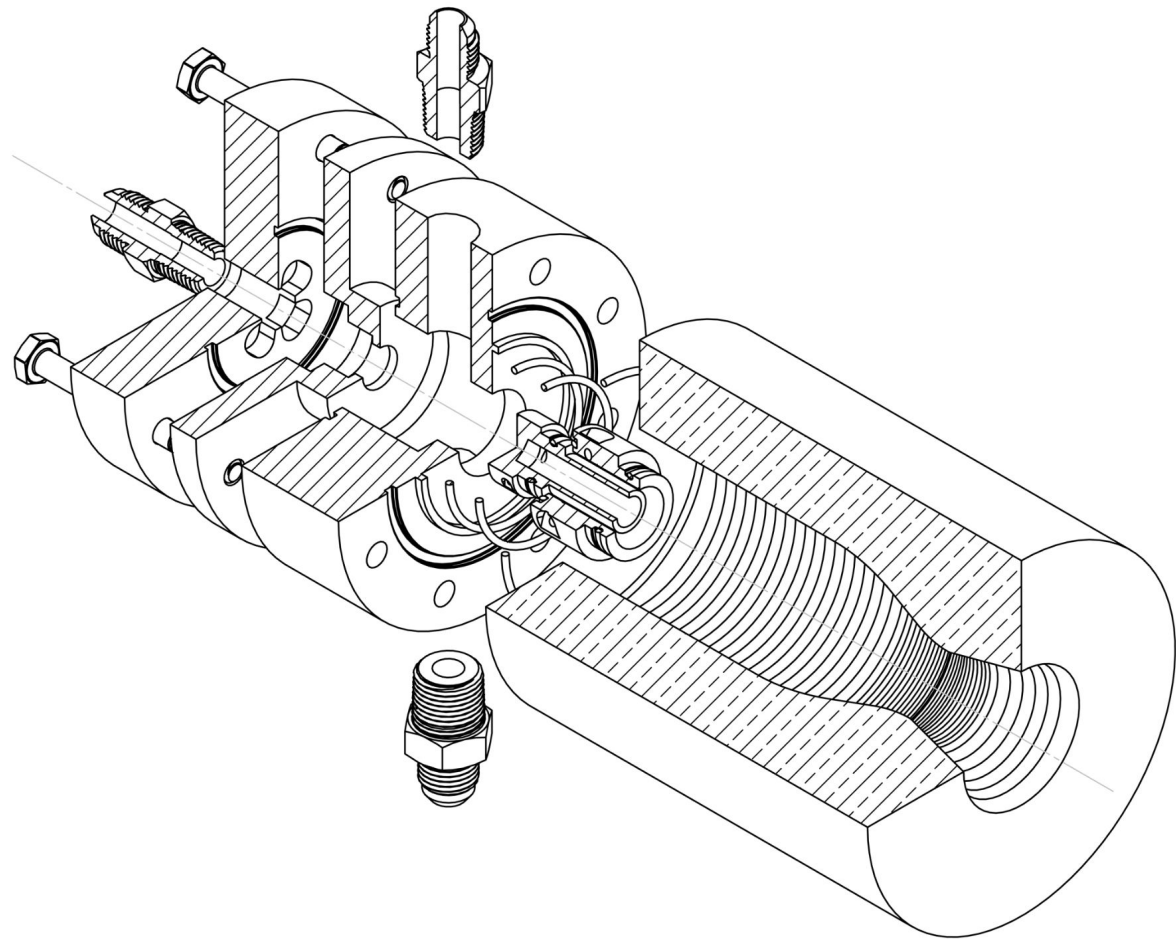
Now that the design is almost finished, I want to share the documentation so future generations can use this as a resource of knowledge.



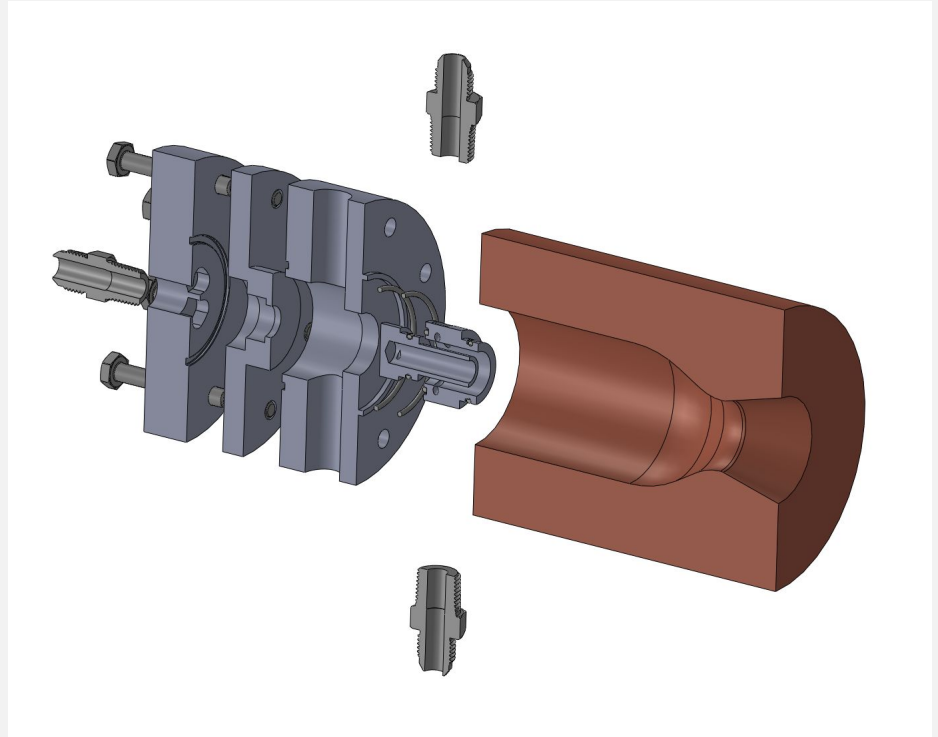
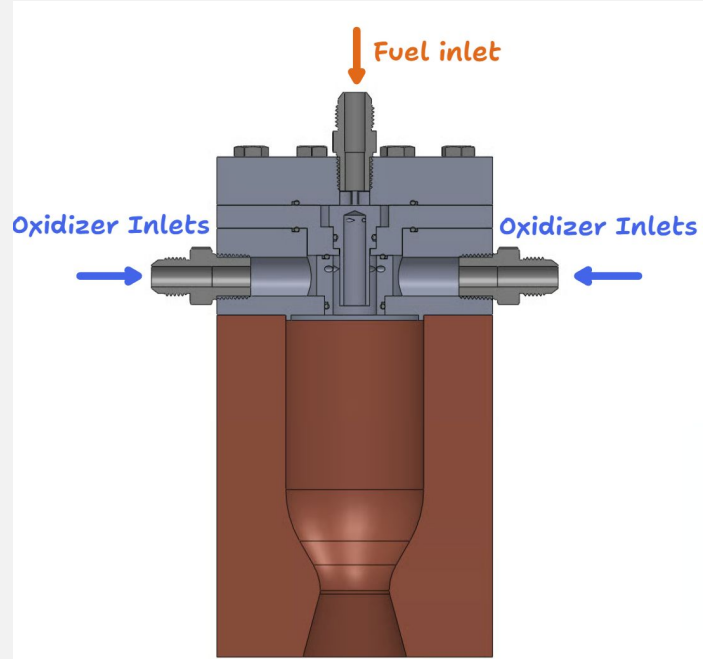
Current Engine Design



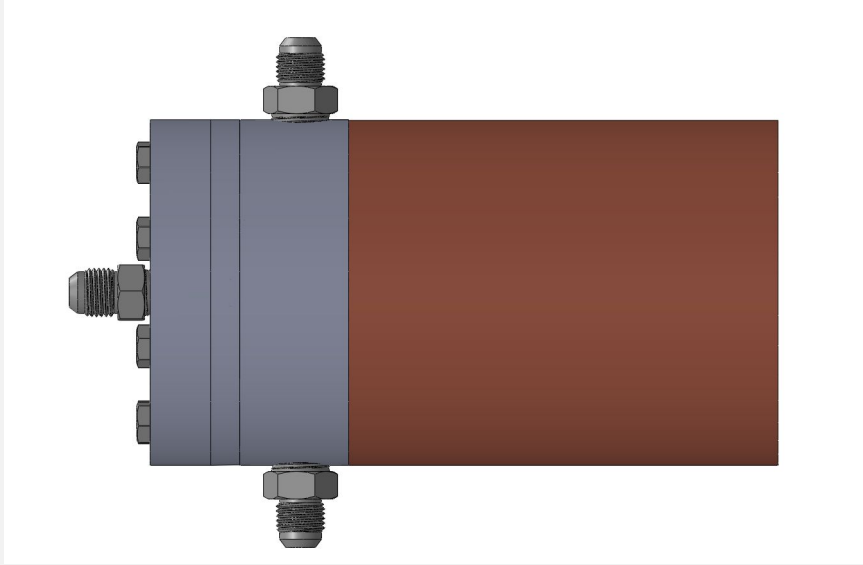
First Engine Design



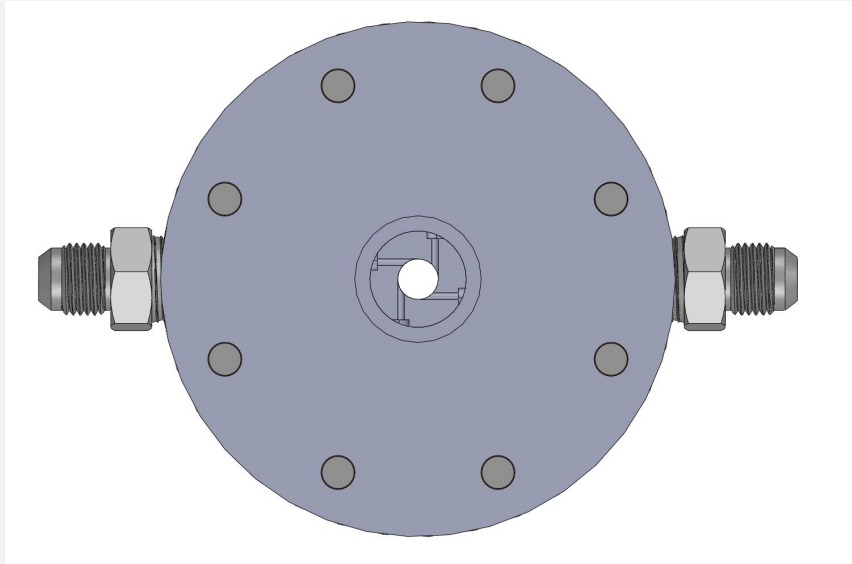
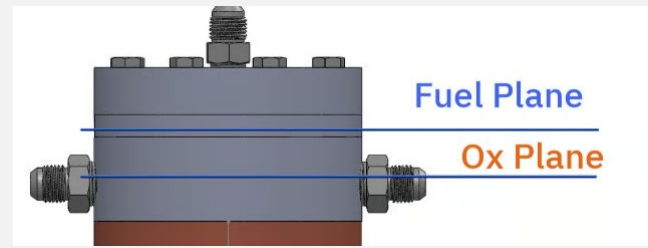
Introduction



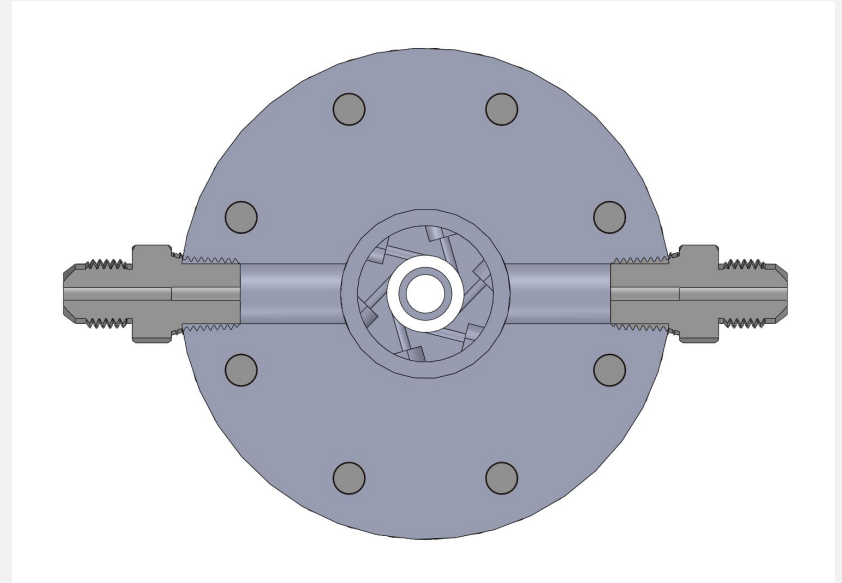
Introduction Cont.



Introduction Cont.



Fuel plane



Ox plane

Requirements

Req. ID	Requirement	Rationale
Req. 1	The engine shall hit at least 500 N of thrust	Setting a goal for the engine design
Req. 2	The engine shall use Nitrous Oxide and Ethanol	Constrain the propellant choices
Req. 3	The engine shall use a heat sink as a thermal mitigation method	Constrain the thermal mitigation methods
Req. 4	The engine shall be able to be integrated into the current test stand	Critical for testing
Req. 5	The engine shall burn for at least 5 seconds	Constrain for burn time

Engine Design - Propellant Definition

The chosen propellant are Nitrous Oxide and Ethanol 90%

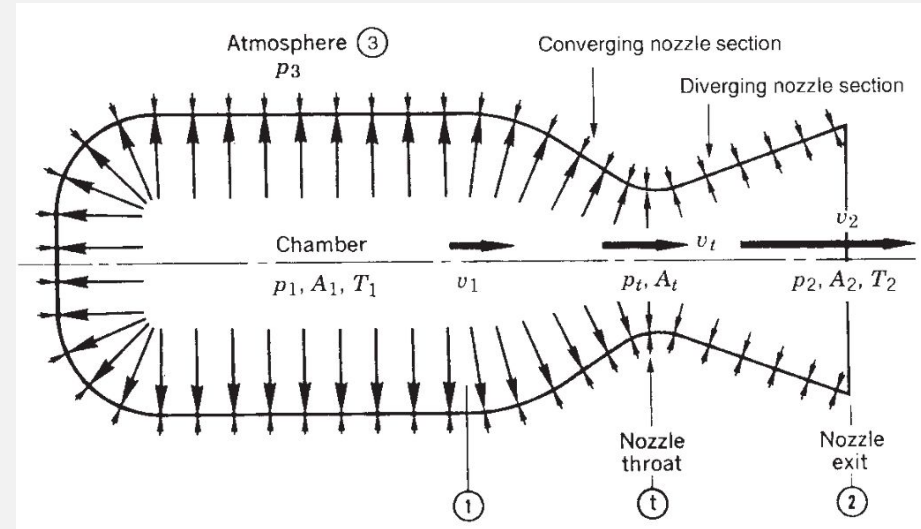
Propellant	Density (kg/m ³)
N ₂ O	1078
C ₂ H ₅ OH 90%	789

Density @ 9bar

Engine Design - Pressure Definition

P_1 was chosen to be 9 bar. It was chosen as a relatively low chamber pressure.

P_3 was chosen to be 0.9 bar (1000 m altitude), for slight chance to see mach diamonds at hot fire test.



Engine Design - Chamber Sizing

Chamber diameter was chosen to be 2 in.

Reasons influencing this choice are budget, test stand integration, and safety

Engine Design - Nozzle Sizing

The chamber to throat area ratio dictates how small your throat is in relation to the chamber. As this number approaches infinity, assuming an infinitely small throat, there will be no losses.

The team chose a value of 4, meaning that the diameter of the throat would be half of the chamber

Chamber-to-Throat Area Ratio	Throat Pressure (%)	Thrust Reduction (%)	Specific Impulse Reduction (%)
∞	100	0	0
3.5	99	1.5	0.31
2.0	96	5.0	0.55
1.0	81	19.5	1.34

Engine Sizing - Diverging Nozzle Section

In order to know the exit diameter of the nozzle, we need to know the exit mach velocity.

$$p_0 = p \left[1 + \frac{1}{2} (k - 1) M^2 \right]^{k/(k-1)}$$

$$900000 = 91192.5 \left[1 + \frac{1}{2} (1.157 - 1) M^2 \right]^{1.157/(1.157-1)}$$

$$M = 2.154$$

$k = 1.157 = C_p/C_v$ of mix propellant

Engine Sizing - Diverging Nozzle Section Cont.

The relationship between the mach number and area is known through the following equation.

$$\frac{A_y}{A_x} = \frac{M_x}{M_y} \sqrt{\left\{ \frac{1 + [(k-1)/2]M_y^2}{1 + [(k-1)/2]M_x^2} \right\}^{(k+1)/(k-1)}}$$

Y = @nozzle exit
X = @nozzle throat

$$\frac{A_2}{A_t} = \frac{1}{2.154} \sqrt{\left\{ \frac{1 + [(1.157-1)/2]2.154_y^2}{1 + [(1.157-1)/2]1_x^2} \right\}^{(1.157+1)/(1.157-1)}}$$

$$\frac{A_2}{A_t} = 2.33, r_2 = 0.752 \text{ in}$$

Velocity at throat is Mach 1!!

k = 1.157 = Cp/Cv of mix propellant

Engine Sizing Diverging Nozzle Section Cont.

We can approximate ideal thrust by knowing this value!

Mach number = 2.154

Nozzle exit density = 0.1327 kg/m^3


Nozzle exit sonic velocity = 913.31 m/s

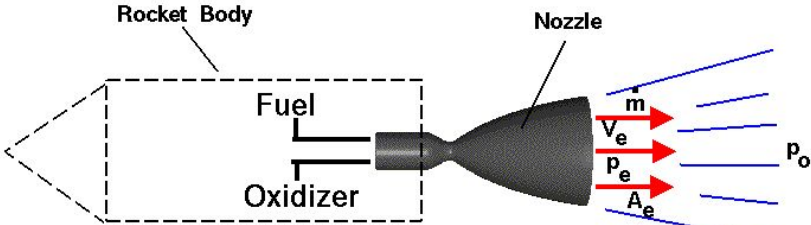
$p_e = 0.9 \text{ atm}$

$p_0 = 1 \text{ atm}$

$A_e = \pi * 0.752^2 \text{ in}^2$

$$F = 580 \text{ N}$$

 **Rocket Thrust Equation** Glenn
Research
Center

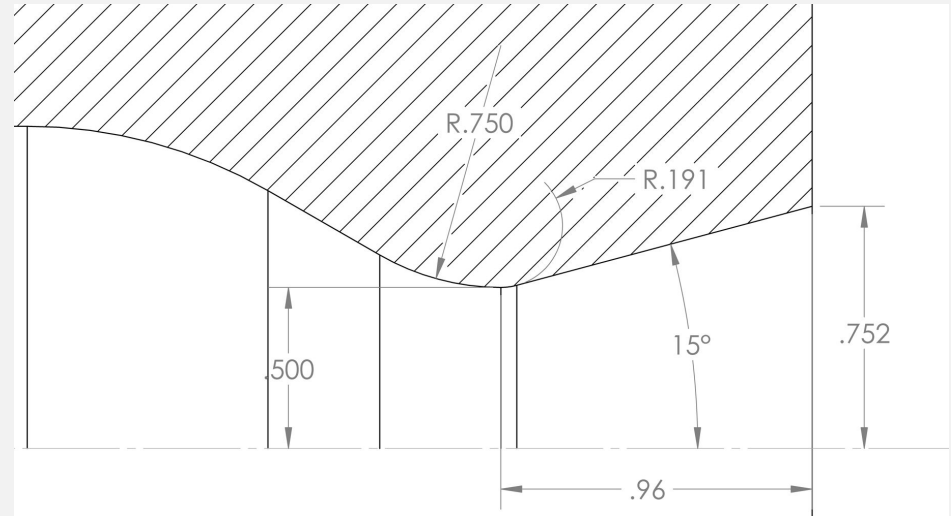
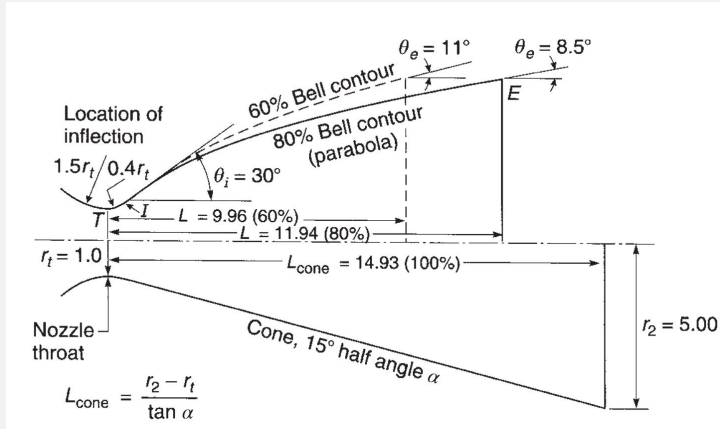


\dot{m} = mass flow rate
 p = pressure
 V = Velocity
 A = Area

Thrust = $F = \dot{m} V_e + (p_e - p_0) A_e$

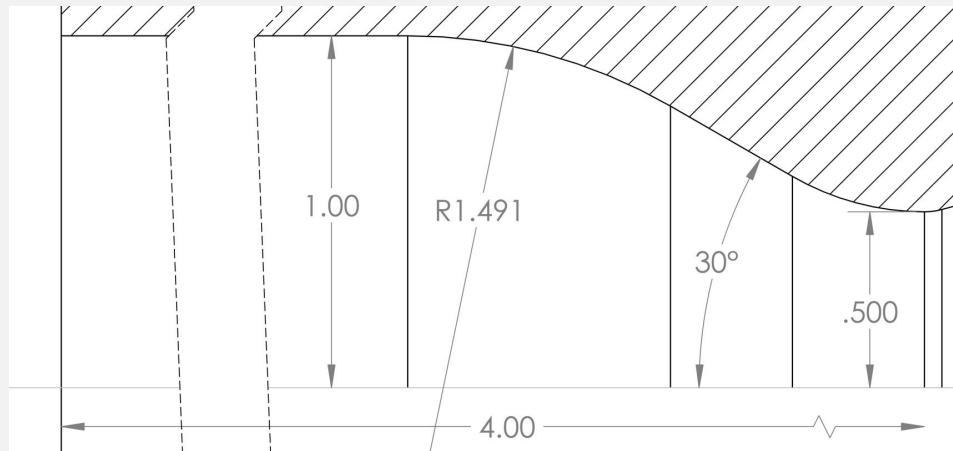
Engine Sizing - Diverging Nozzle Section Cont.

By following the cone, 15° half angle, the following nozzle can be constructed



Engine Sizing - Converging Nozzle Section

As described in RPE, the converging nozzle section shape does not significantly affect nozzle performance. "Its subsonic flow can easily be turned with very low pressure drops and almost any given radius, cone angle, wall contour curve, or nozzle inlet shape satisfactory."



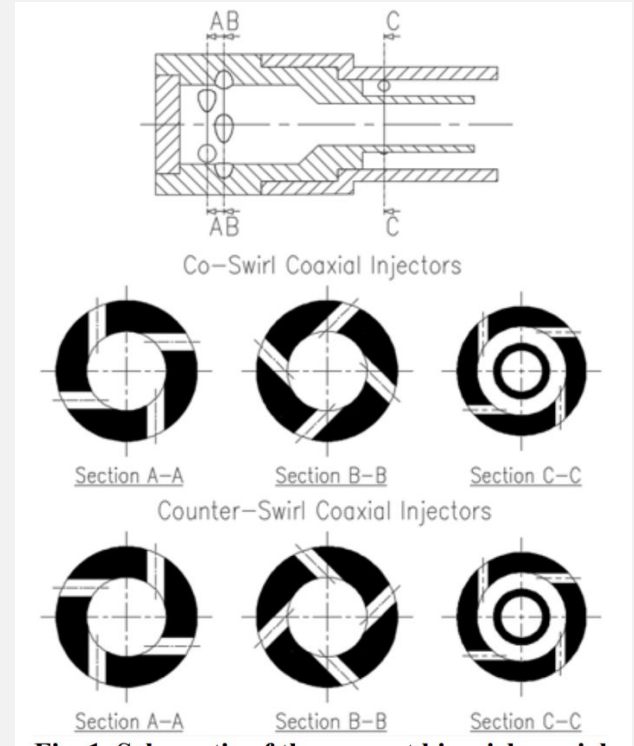
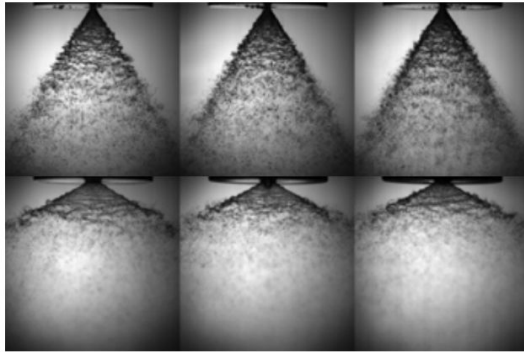
Questions?

Next: Injector

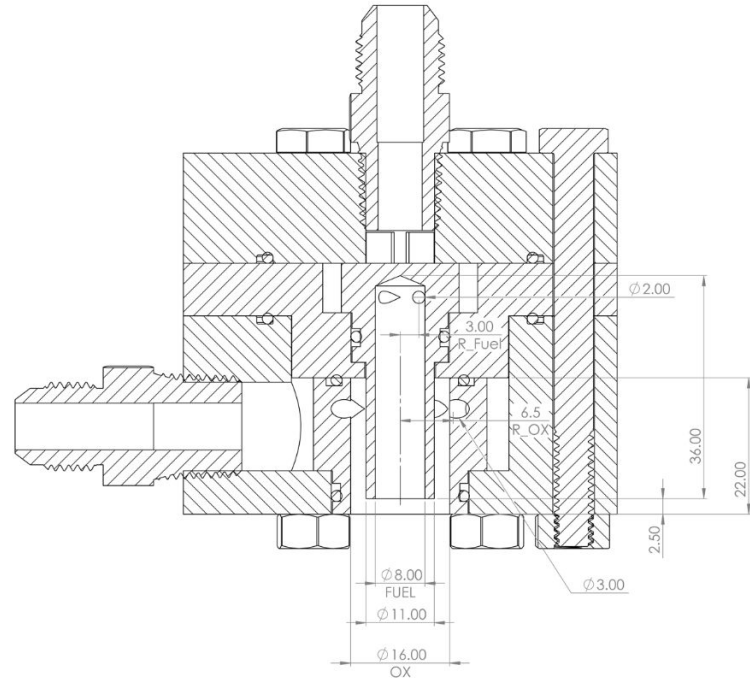
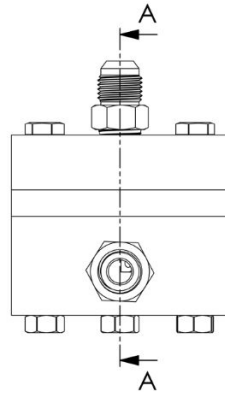
Injector Overview

Coaxial Swirl injector

- Inject fluid tangentially into a cylinder.
- Modular design
- Conical flow and atomization



Injector Overview Cont.



Injector Design

In order to generate velocity for the propellants to mix, it is necessary to have a pressure drop across the injector. Literature suggests a range between 15% and 25%.

Combustion chamber is 9 bar. Therefore, according to this recommendations, we would need a pressure drop between 1.58 bar to 3 bar

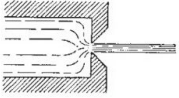
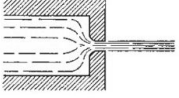
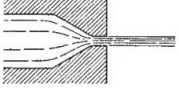
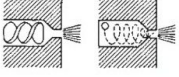
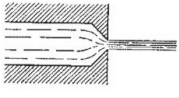
However, after consulting with different individuals, I have received the consensus to aim for the higher end of the pressure drop percent.

Injector Design - Estimated Discharge Coeff

From RPE, a coaxial swirl injector is estimated to have a Cd in between 0.2 and 0.55

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

For safety reasons and nature of a not flying engine, the higher Cd is chosen

Orifice Type	Diagram	Diameter (mm)	Discharge Coefficient
Sharp-edged orifice		Above 2.5	0.61
		Below 2.5	0.65 approx
Short tube with rounded entrance $L/D > 3.0$		1.00	0.88
		1.57	0.90
		1.00 (with $L/D \sim 1.0$)	0.70
Short tube with conical entrance		0.50	0.7
		1.00	0.82
		1.57	0.76
		2.54	0.84-0.80
		3.18	0.84-0.78
Short tube with spiral effect		1.0-6.4	0.2-0.55
Sharp-edged cone		1.00	0.70-0.69
		1.57	0.72

Injector Sizing - Pressure drop

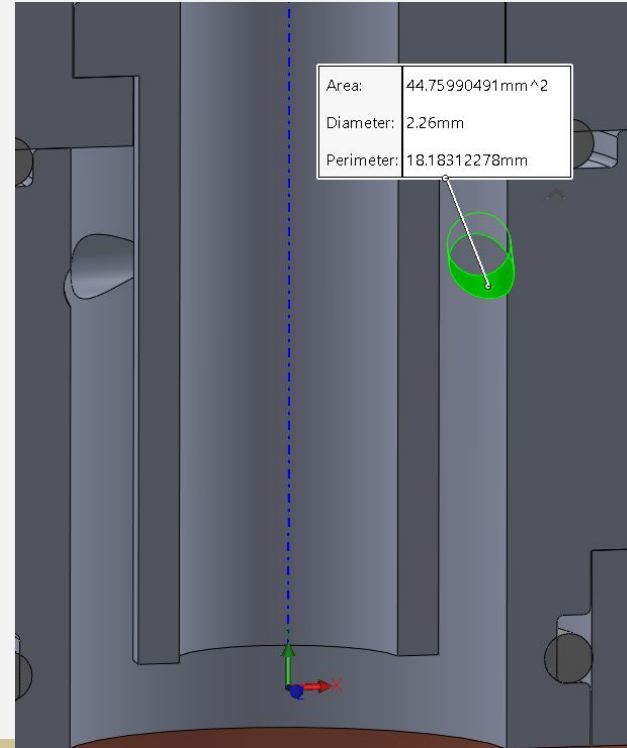
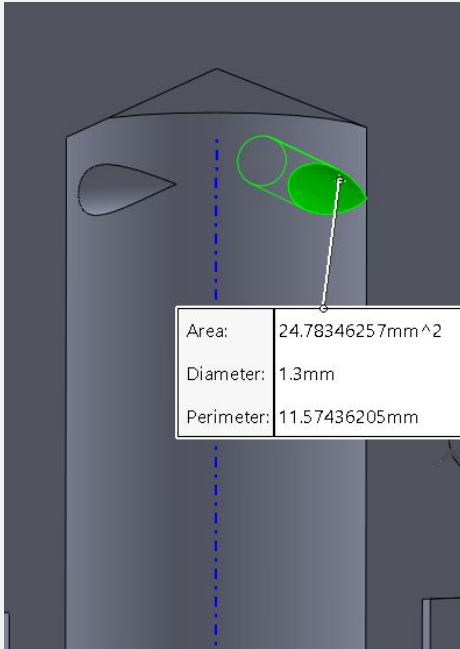
We know the mass flowrate, estimate Cd range, and Area of the injector

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

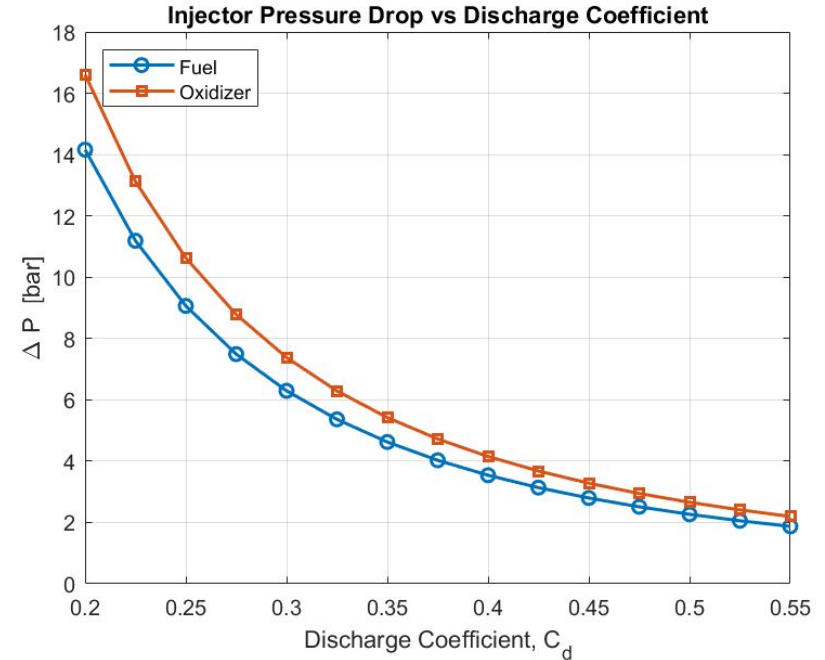
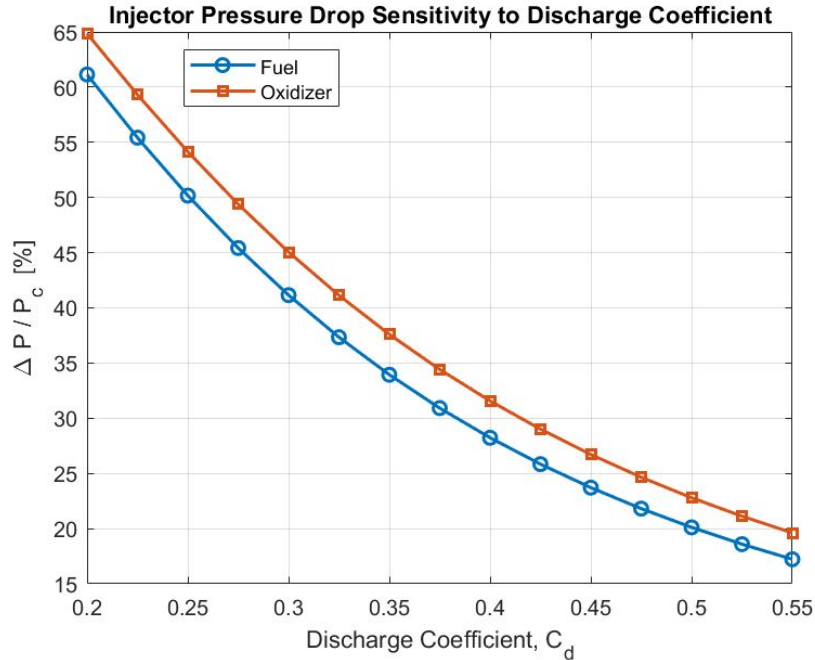
$$\Delta p = \frac{1}{2\rho} \left(\frac{\dot{m}}{C_d A} \right)^2$$

Parameter	Fuel	Oxidizer
Density	1,078.00	789.00
M_rate	0.0587	0.2464
r_h	6.50E-04	1.13E-03
n	4.00	6.00
r_nw	4.00E-03	8.00E-03
R	3.35E-03	6.87E-03

Injector Sizing - Pressure drop Cont.



Injector Sizing - Pressure drop Cont.



Injector - Coaxial Swirl Parameters

All the formulas used in this section were obtained from “Experimental and Theoretical Study on Spray Angles of Bi-Swirl Coaxial Injectors” by W. Yoon and K. Ahn. The values in the table below will be used in this chapter.

Experimental and Theoretical Study on Spray Angles of Bi-Swirl Coaxial Injectors

W. Yoon and K. Ahn[†]

[†] School of Mechanical Engineering, Chungbuk National University, Chungdae-ro 1, Seowon-gu, Cheongju, Chungbuk 28644, Korea

$$r_{ma,ne} = \sqrt{\frac{r_{gc,ne}^2 + r_{nw}^2}{2}} = r_{nw} \sqrt{\frac{2 - \varphi_n}{2}}$$

$$RV_h = r_{nw}V_{nw} = r_{gc,n}V_{gc,n} = r_{ma,n}V_{ma,n} = r_{ma,ne}V_{ma,ne}$$

$$K = \frac{A_{nw}R}{A_h r_{nw}} = \frac{r_{nw}R}{nr_h^2} \frac{\sqrt{2}(1-\varphi_n)}{\varphi_n^{3/2}} = K$$

$$\varphi_{ne} = \frac{\varphi_n}{\sqrt{3-2\varphi_n}} \quad V_h = \frac{m}{\rho n \pi r_h^2}$$

$$m = \rho U_n \varphi_n A_n = \rho U_{ne} \varphi_{ne} A_n$$

$$(m_i + m_o)U_{t,em} = m_i U_{i,ine} + m_o U_{o,one}$$

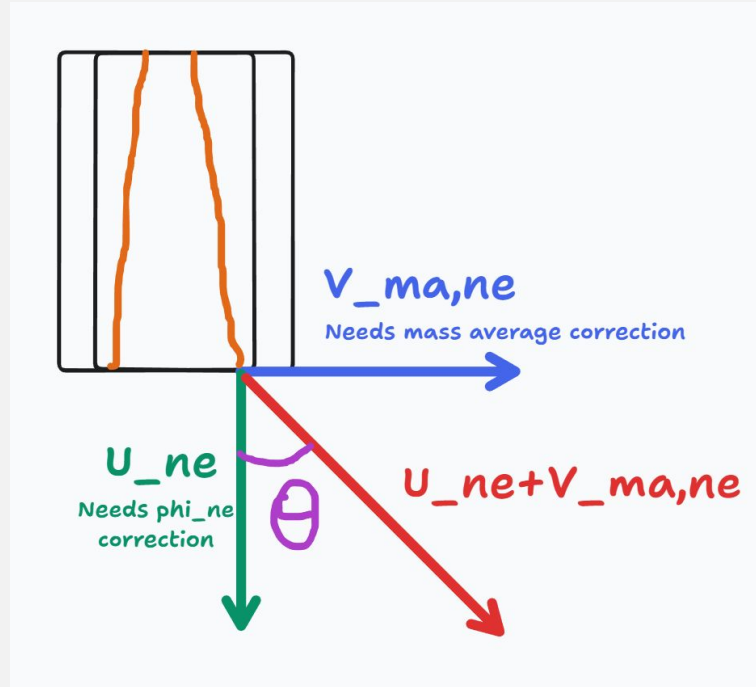
$$(m_i + m_o)V_{t,em} = m_i V_{i,ma,ine} + m_o V_{o,ma,one}$$

$$\theta_{t,em} = \tan^{-1}\left(\frac{V_{t,em}}{U_{t,em}}\right)$$

Injector - Coaxial Swirl Parameters Cont.

$$m = \rho U_n \phi_n A_n = \rho U_{ne} \phi_{ne} A_n$$

Whole nozzle diameter



$$V_h = \frac{m}{\rho n \pi r_h^2}$$

Small tangential holes

Injector - Coaxial Swirl Parameters Cont.

Propellant	ϕ	K	ϕ_{ne}	U_{ne} (m/s)	V_h (m/s)	$V_{ma,ne}$ (m/s)
Fuel	0.26	7.93	0.16	6.58	10.26	8.97
Ox	0.27	7.17	0.17	8.89	12.97	11.66

$U_{t,ne}$ (m/s)	$V_{t,ne}$ (m/s)	θ (°)	2θ (°)
8.44	11.14	52.85	105.71

Questions?

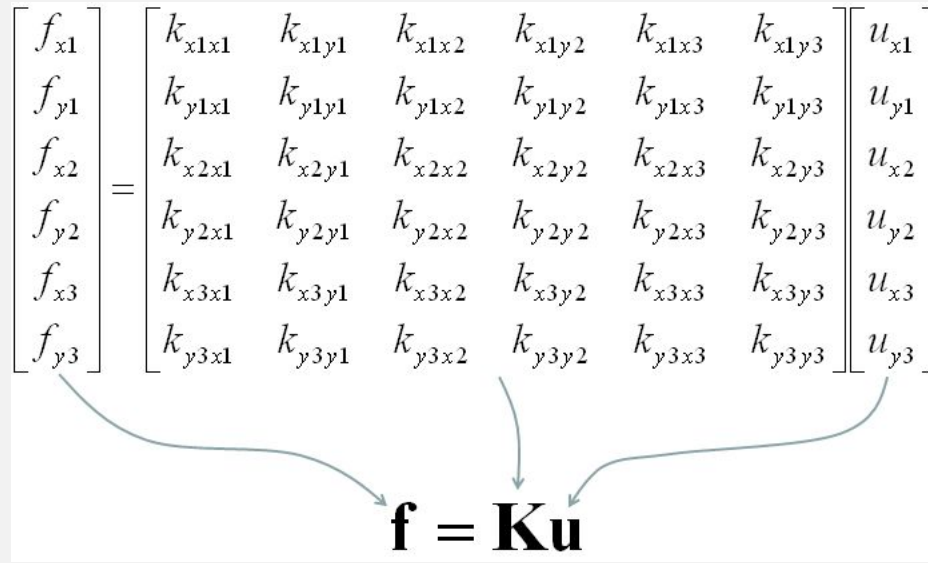
Next: Simulation

Engine Simulation

Simulate engine parameters via thermal FEA and CFD

$$\begin{bmatrix} f_{x1} \\ f_{y1} \\ f_{x2} \\ f_{y2} \\ f_{x3} \\ f_{y3} \end{bmatrix} = \begin{bmatrix} k_{x1x1} & k_{x1y1} & k_{x1x2} & k_{x1y2} & k_{x1x3} & k_{x1y3} \\ k_{y1x1} & k_{y1y1} & k_{y1x2} & k_{y1y2} & k_{y1x3} & k_{y1y3} \\ k_{x2x1} & k_{x2y1} & k_{x2x2} & k_{x2y2} & k_{x2x3} & k_{x2y3} \\ k_{y2x1} & k_{y2y1} & k_{y2x2} & k_{y2y2} & k_{y2x3} & k_{y2y3} \\ k_{x3x1} & k_{x3y1} & k_{x3x2} & k_{x3y2} & k_{x3x3} & k_{x3y3} \\ k_{y3x1} & k_{y3y1} & k_{y3x2} & k_{y3y2} & k_{y3x3} & k_{y3y3} \end{bmatrix} \begin{bmatrix} u_{x1} \\ u_{y1} \\ u_{x2} \\ u_{y2} \\ u_{x3} \\ u_{y3} \end{bmatrix}$$

f = Ku



Why Copper

High heat transfer to other parts of the walls

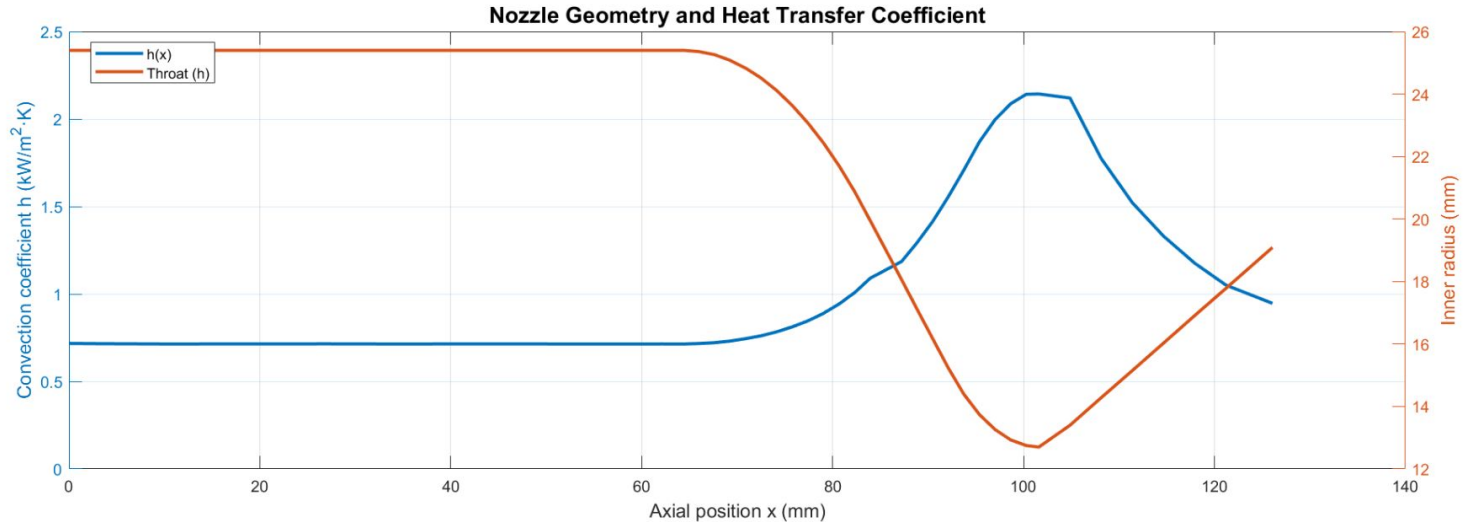
Remove heat from nozzle and store it in the walls

Already used by other teams like GSP



Combustion Chamber Thermal FEA

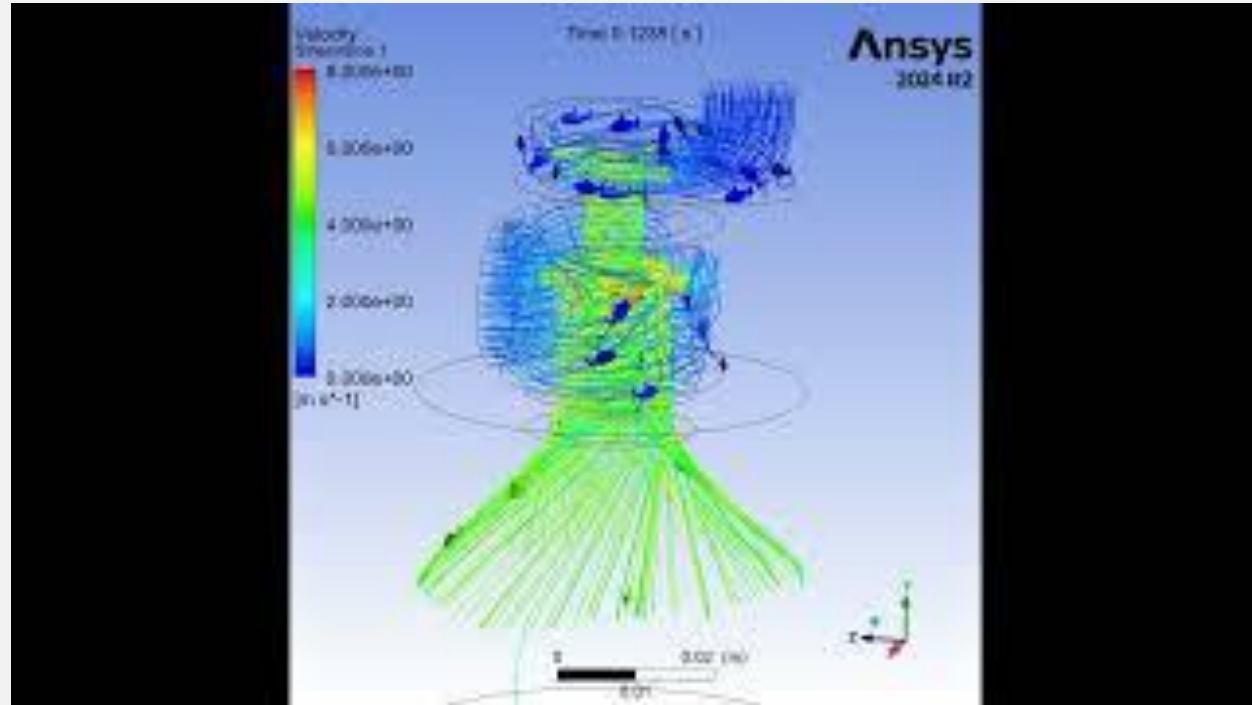
Convection heat coefficient increases around the nozzle



Injector CFD

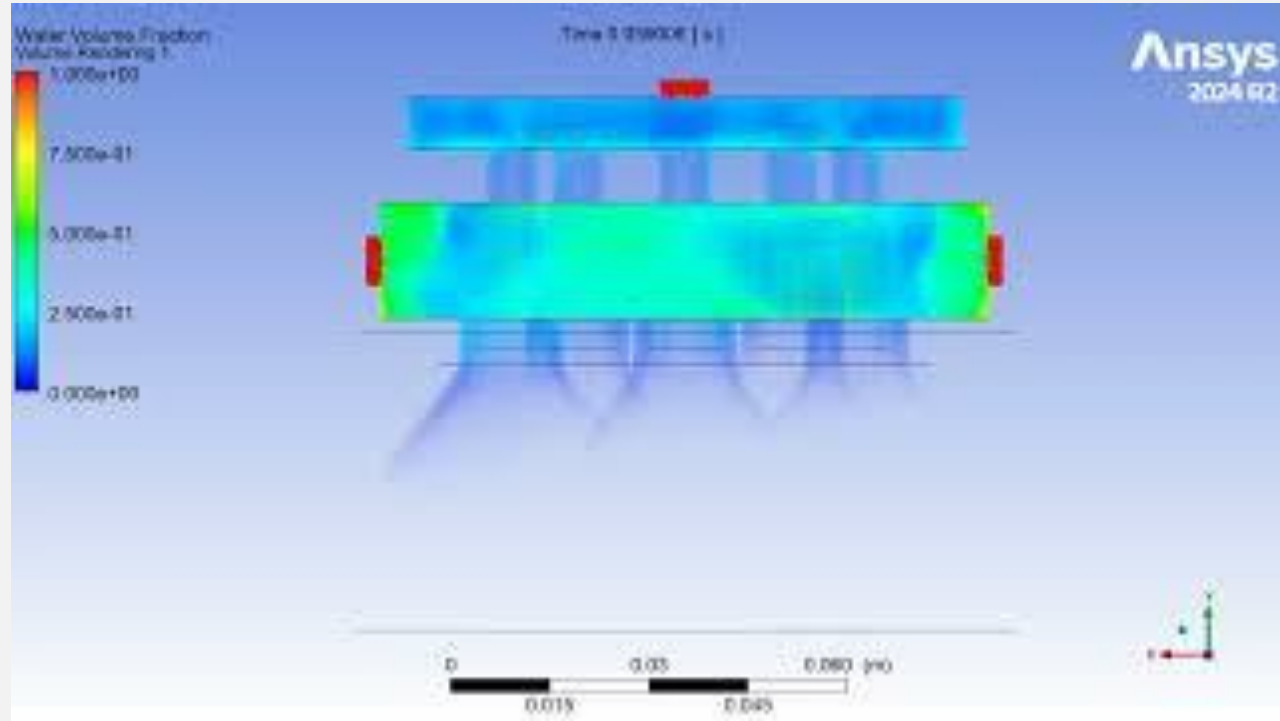
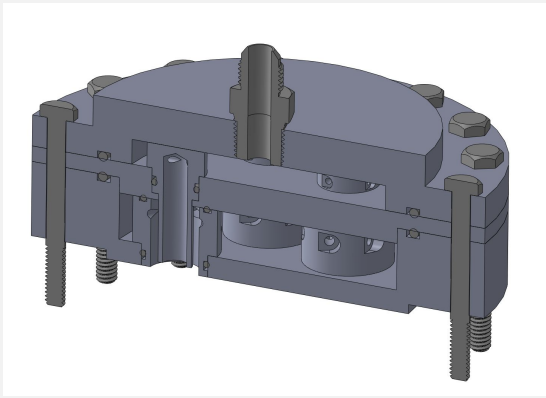
Volume of Fluid Simulation on Single Element Injector to verify fluid behavior

No significant conclusions were drawn from this simulation as data was lost quickly after simulation conclusion.



Injector CFD Cont.

Similar case for 5 element injector



Questions?

Next: Manufacturing and Tolerancing

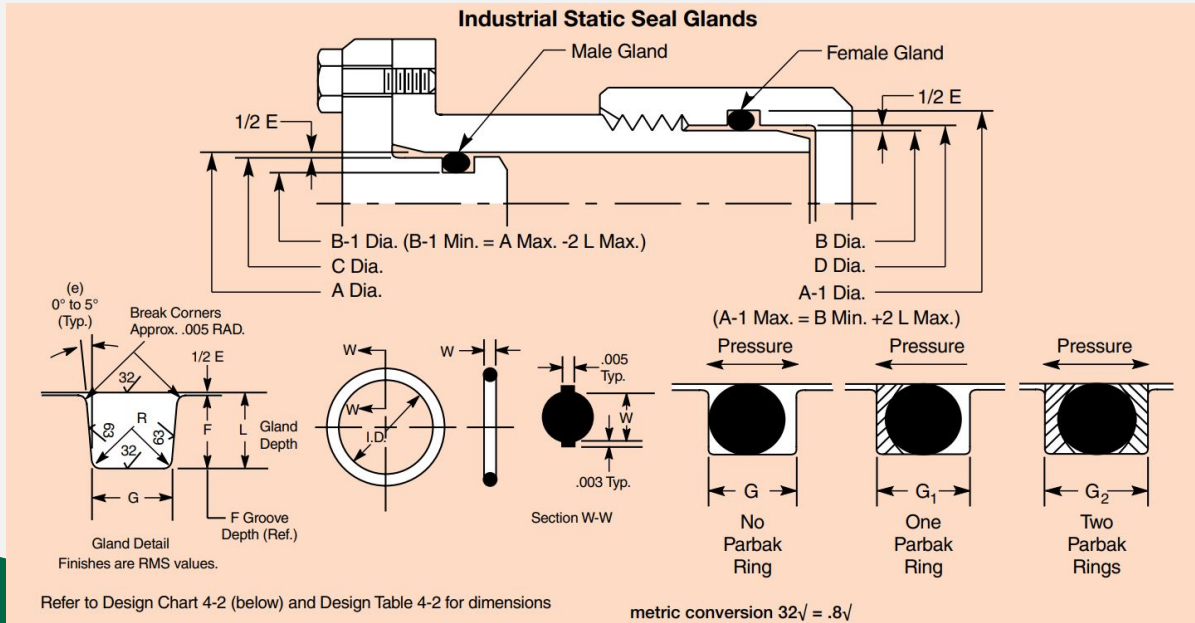
Manufacturing

Given that we don't have the capabilities to machine the injector. It will be sent to a third party manufacturing business.



Injector Tolerancing - Gland Case

Name	Dash Number	Crosssection	ID	mcmaster link	A	A_min	B-1	C	C_min	E_min	E_max
ox-ring static gland	18.00	0.07	0.739	https://www.mcmaster.com/9452K72/	0.877	0.875	0.775	0.873	0.872	0.002	0.005
fuel ring static gland	14.00	0.07	0.489	https://www.mcmaster.com/9452K58/	0.627	0.625	0.525	0.623	0.622	0.002	0.005



E(a) Diametral Clearance
.002 to .005

Injector Tolerancing - Hole size case

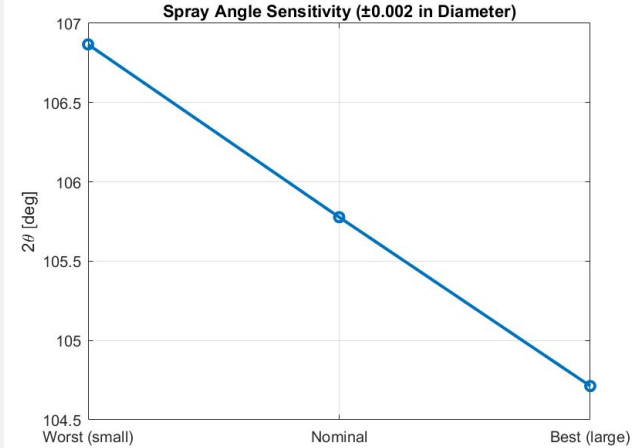
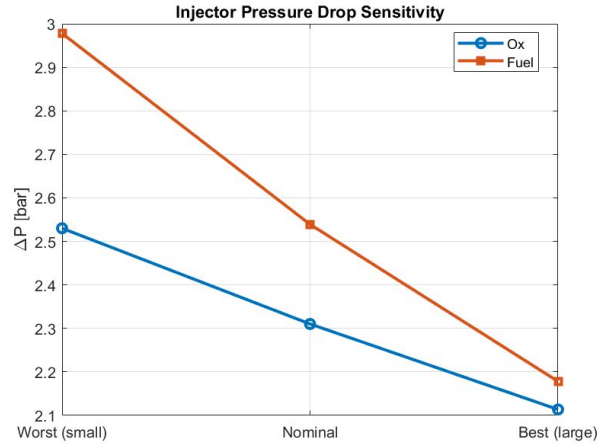
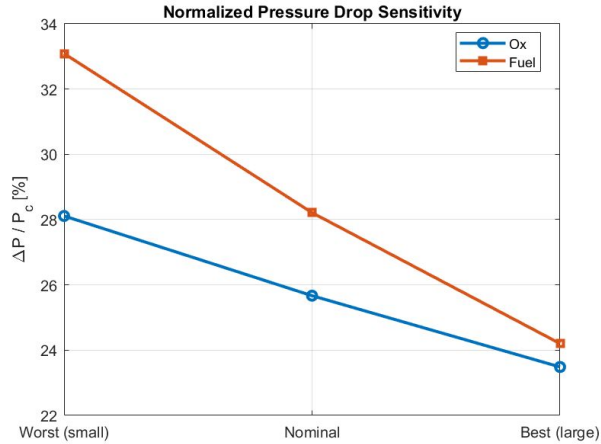
By applying a tolerancing of ± 0.002 in (0.051mm) on the injector holes, the pressure drop and angle is expected to change. The previous calculations were re-done assuming a change in size of these holes. Results below. Assuming 0.55 Cd

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===== TOLERANCE SENSITIVITY SUMMARY =====
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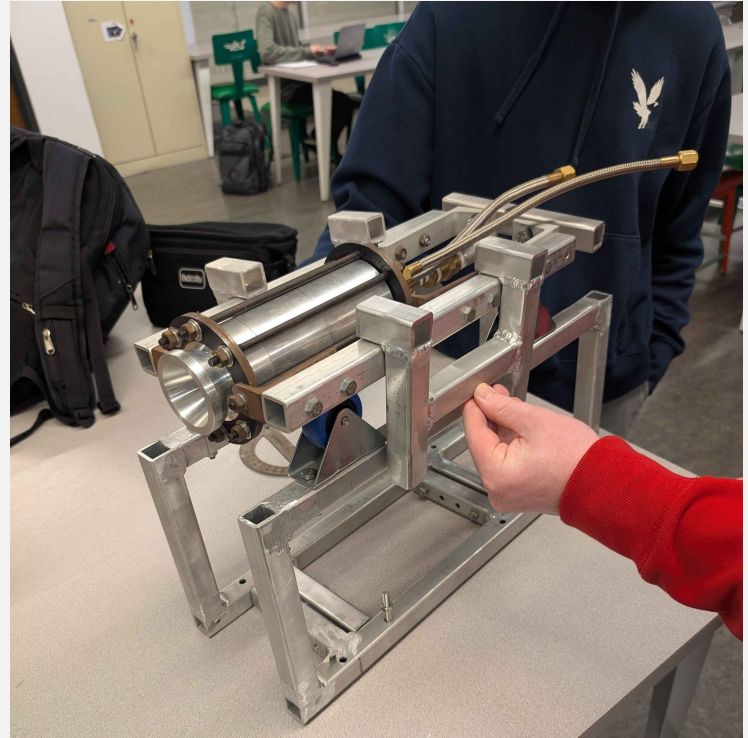
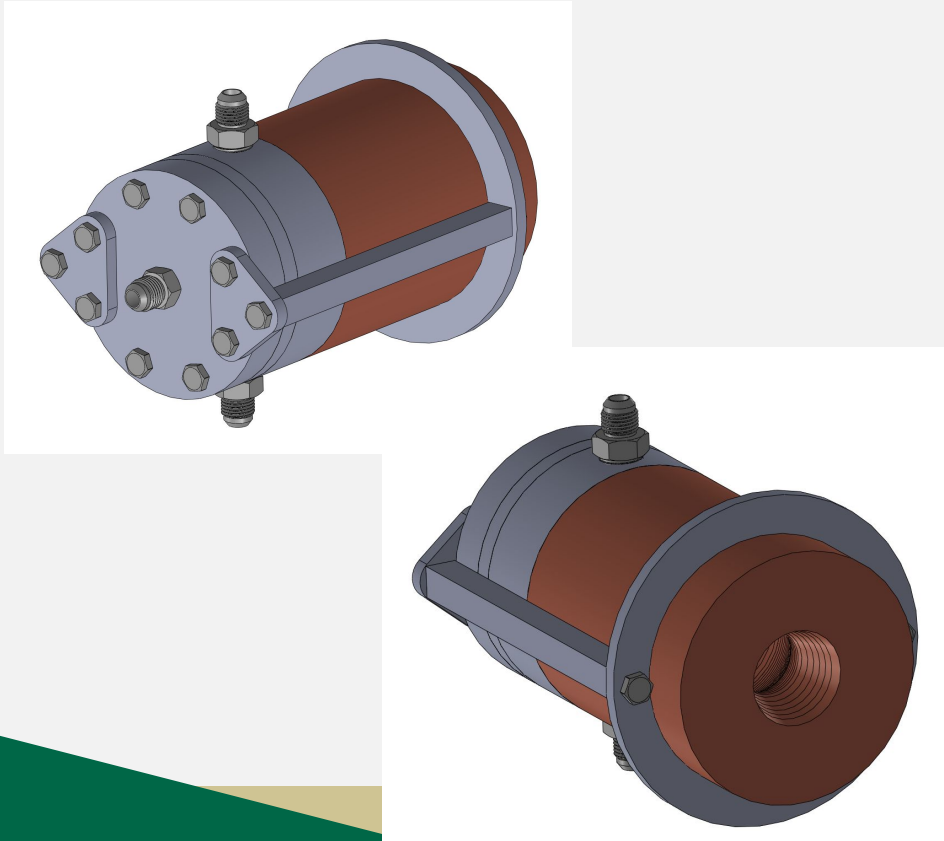
Case	d_ox [mm]	d_fuel [mm]	2 θ [deg]	ΔP_{ox} [%]	ΔP_{fuel} [%]
Worst (small)	2.209	1.249	106.87	28.11	33.09
Nominal	2.260	1.300	105.78	25.67	28.21
Best (large)	2.311	1.351	104.71	23.48	24.20

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Injector Tolerancing - Hole size case



Torito Test Stand Integration



Questions?

Next: RPA Parameters

Engine RPA Parameters

Parameter		Engine	Chamber
Thrust	sea level	0.5430	0.5430 kN
	opt exp	0.5546	0.5546 kN
	vacuum	0.6589	0.6589 kN
Specific Impulse	sea level	1780.0962	1780.0962 N·s/kg
	opt exp	1818.1183	1818.1183 N·s/kg
	vacuun	2160.3177	2160.3177 N·s/kg
Mass flow rate	total	0.3050	0.3050 kg/s
	oxidizer	0.2464	0.2464 kg/s
	fuel	0.0587	0.0587 kg/s

Engine RPA Parameters Cont.

Table 2. Combustion Properties

Parameter	Injector	Nozzle inlet	Nozzle throat	Nozzle exit Unit
Pressure	0.9000	0.8772	0.5105	0.0912 MPa
Temperature	2929.5158	2924.5450	2755.7265	2161.3967 K
Enthalpy	-3872.1607	-4188.6154	-17072.0414	-52920.4881 J/mol
	-151.8961	-164.2828	-663.3296	-2024.0227 kJ/kg
Entropy	268.7960	268.9458	271.4828	275.8003 J/(mol-K)
	10.5443	10.5484	10.5484	10.5484 kJ/(kg-K)
Internal energy	-28229.5378	-28504.6631	-39984.4521	-70891.3601 J/mol
	-1107.3812	-1117.9889	-1553.5852	-2711.3454 kJ/kg
Specific heat (p=const)	3.9781	3.9743	3.4688	1.8656 kJ/(kg-K)
Specific heat (V=const)	3.4327	3.4297	2.9913	1.5363 kJ/(kg-K)
Gamma	1.1589	1.1588	1.1596	1.2143
Isoentropic exponent	1.1434	1.1434	1.1490	1.2136
Gas constant	0.3262	0.3261	0.3231	0.3180 kJ/(kg-K)
Molecular weight	25.4922	25.4964	25.7369	26.1462
Density	0.9419	0.9198	0.5734	0.1327 kg/m ³
Sonic velocity	1045.2261	1044.2383	1011.3677	913.3169 m/s
Mach number	0.0000	0.1507	1.0000	2.1187
Area ratio	4.0000	4.0000	1.0000	2.2589 A/At
Mass flux	144.7705	144.7705	579.9299	256.7311 kg/(m ² -s)
Viscosity	0.9335	0.9324	0.8962	0.7595 x10 ⁻⁴ kg/(m-s)
Conductivity, frozen	0.2399	0.2395	0.2269	0.1819 W/(m-K)
Specific heat (p=const), frozen	1.7406	1.7403	1.7307	1.6798 kJ/(kg-K)
Prandtl number, frozen	0.6773	0.6774	0.6835	0.7015
Conductivity, effective	0.7049	0.7032	0.5657	0.2216 W/(m-K)
Specific heat (p=const), effective	3.9781	3.9743	3.4688	1.8659 kJ/(kg-K)
Prandtl number, effective	0.5268	0.5270	0.5496	0.6394

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Questions?

THANK YOU