NATIONAL SPACE GRANT COLLEGE AND FELLOWSHIP PROGRAM

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OREGON TECH

Liquid Rocket Engine Development

8 November 2018

Oregon Tech Rocketry Project

Est. 2017

Introduction and Purpose

Who’s on team & roles

Julien MD - Chief Design Engineer
David M - Chief Analytical Engineer
Milo G - Water Coolant
Kierra S - Computational Fluid Dynamics

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Make a Liquid Rocket Engine for Use at Spaceport America Cup

Reach a 30,000 ft ± 300 ft target apogee
Carry a 4kg minimum payload to the apogee
Remain under 40,960 N-s (9,208 lb-s) of total impulse
Reliable
Cost Efficient

Goals

Design Goals:

- Develop lasting simulation tools.
- Full designs of injection system and regenerative/water cooled test engines.
- Validate designs using FEA

Manufacturing Goals:

- Manufacture injector test parts
- Machine final stainless steel parts for injector.
- Manufacture steel engine chamber and nozzle
- Manufacture water cooling jacket.

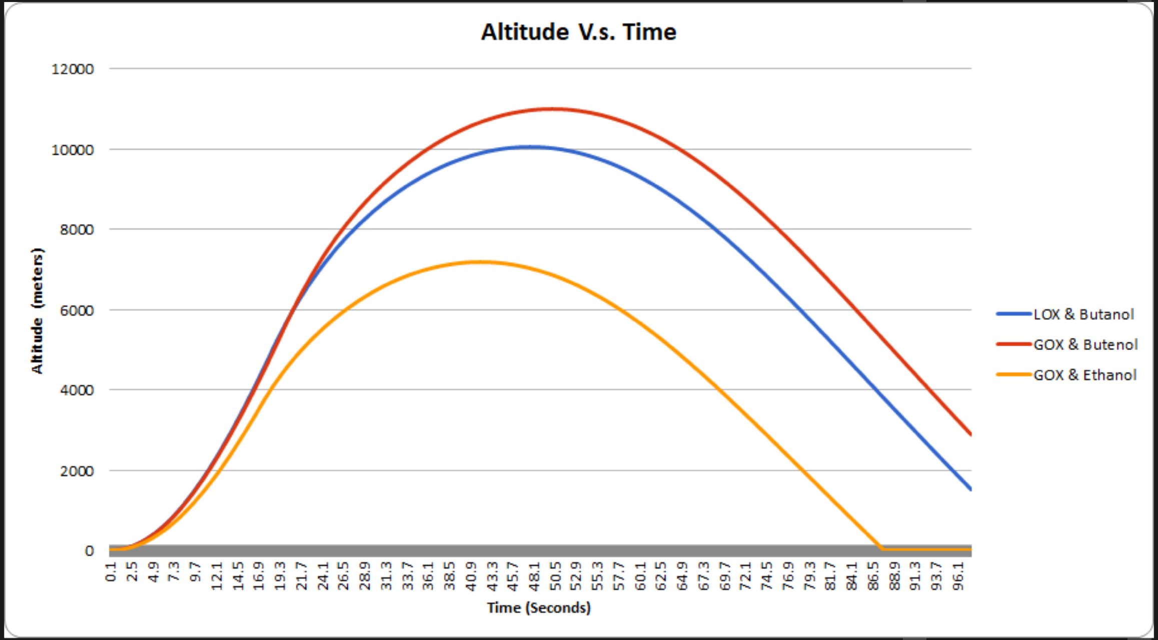
Testing Goals:

- Flow characterization testing of injector
- Cold flow testing of completed engine
- Hot fire testing of engine

Determination of Specifications/Flight Analysis Tool

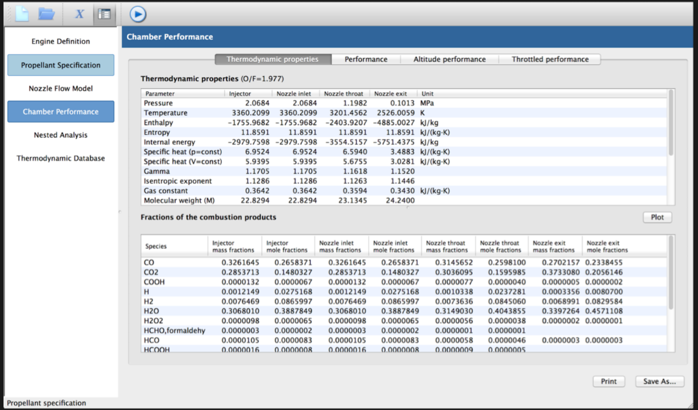
In-house developed engine parameter selection and max apogee tool

- Altitude atmosphere simulation
- Appropriate handling of supersonic drag
- Automated Configuration parsing



Propellant Selection

Performance and thermodynamic characteristics of propellants with Rocket Propulsion Analysis (RPA) software.



Thermodynamic properties (O/F=1.977)

Parameter	Injector	Nozzle inlet	Nozzle throat	Nozzle exit	Unit
Pressure	2.0684	2.0684	1.1982	0.1013	MPa
Temperature	3360.2099	3360.2099	3201.4562	2526.0059	K
Enthalpy	-1755.9682	-1755.9682	-2403.9207	-4885.0027	kJ/kg
Entropy	11.8591	11.8591	11.8591	11.8591	kJ/(kg·K)
Internal energy	-2979.7598	-2979.7598	-3554.5157	-5751.4375	kJ/kg
Specific heat (p=const)	6.9524	6.9524	6.5940	3.4883	kJ/(kg·K)
Specific heat (V=const)	5.9395	5.9395	5.6755	3.0281	kJ/(kg·K)
Gamma	1.1705	1.1705	1.1618	1.1520	
Isentropic exponent	1.1286	1.1286	1.1263	1.1446	
Gas constant	0.3642	0.3642	0.3594	0.3430	kJ/(kg·K)
Molecular weight (M)	22.8294	22.8294	23.1345	24.2400	

Fractions of the combustion products

Species	Injector mass fractions	Injector mole fractions	Nozzle inlet mass fractions	Nozzle inlet mole fractions	Nozzle throat mass fractions	Nozzle throat mole fractions	Nozzle exit mass fractions	Nozzle exit mole fractions
CO	0.3261645	0.2658371	0.3261645	0.2658371	0.3145652	0.2598100	0.2702157	0.2338455
CO2	0.2853713	0.1480327	0.2853713	0.1480327	0.3036095	0.1595985	0.3733080	0.2056146
COOH	0.0000132	0.0000067	0.0000132	0.0000067	0.0000077	0.0000040	0.0000005	0.0000002
H	0.0012149	0.0275168	0.0012149	0.0275168	0.0010338	0.0237281	0.0003356	0.0080700
H2	0.0076469	0.0865997	0.0076469	0.0865997	0.0073636	0.0845060	0.0068991	0.0829584
H2O	0.3068010	0.3887849	0.3068010	0.3887849	0.3149030	0.4043855	0.3397264	0.4571108
H2O2	0.0000098	0.0000065	0.0000098	0.0000065	0.0000056	0.0000038	0.0000002	0.0000001
HCHO,formaldehy	0.0000003	0.0000002	0.0000003	0.0000002	0.0000001	0.0000001		
HCO	0.0000105	0.0000083	0.0000105	0.0000083	0.0000058	0.0000046	0.0000003	0.0000003
HCOOH	0.0000016	0.0000008	0.0000016	0.0000008	0.0000009	0.0000005		

Sample Page from RPA Simulation

Isp Performance:

- Combustion Temperature
- Combustion Pressure
- Ratio of Specific Heats

Practical Performance:

- High Impulse Density
- Lack of Corrosive Effects
- Ease of Ignition
- Stable Combustion
- ***Safety***

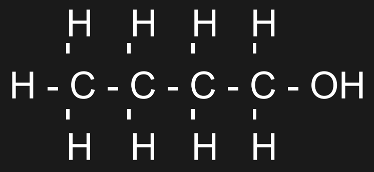
Cooling:

- High Specific Heats
- High Thermal Conductivity
- High Critical Temperature

Propellant Selection

Why we chose Butanol

- Cleaner/Cooler than Kerosene
- Better thrust/cooling than ethanol
- Renewable Biofuel



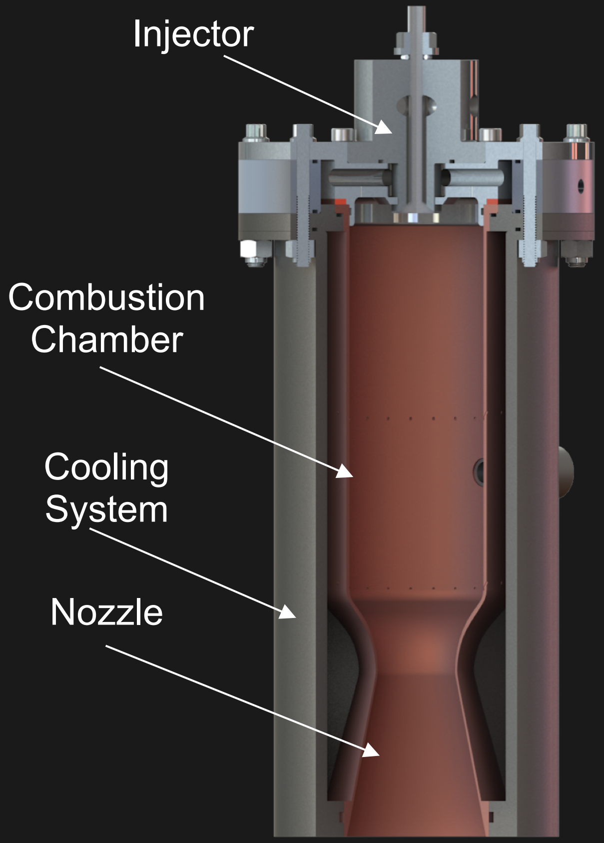
Why We chose liquid oxygen

- Cheaper than N2O
- Safer than N2O
- Lighter tanks

Fuel	LOX & Butanol	LOX & Kerosene	LOX & Ethanol
Chamber Pressure psi	300	300	300
C. Pressure kPa	2068.428	2068.428	2068.428
Isp (sec) (1 atm)	255.09	259.44	250.86
Mixture Ratio (O/F) (Optimal)	1.977	2.454	1.661
K Inlet Temp	3360.99	3464.3717	3265.7661
K Throat Temp	3201.4562	3295.4425	3113.1011
K Exit Temp	2526.0059	2583.2677	2452.1124
P Inlet kPa	2068.4	2068.4	2068.4
Gamma Chamber	1.1705	1.1797	1.1627
Exit Velocity (Ideal)	2501.6133	2544.2516	2460.127
Thrust Coefficient (Ideal)	1.4337	1.4321	1.4341
Boiling Point (C) (Fuel)	117.7	150	78.37
Fuel Cost (Per Gallon)	$4.00	$3.60	$1.31

Design

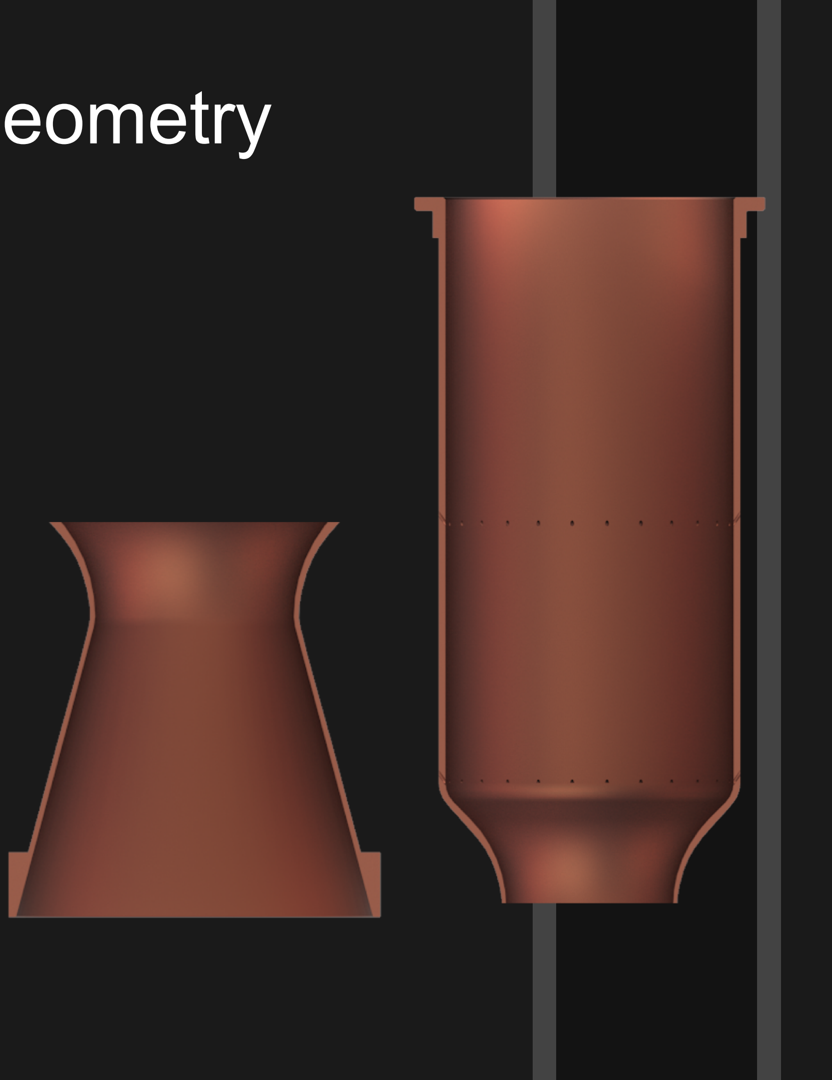
Propellant:	Butanol & Liquid Oxygen
Combustion Pressure:	1380 kpa | 200 psi
Combustion Temperature:	3000 ℃ | 5480 ℉
Thrust:	2.22 kN | 500 lbf
Specific Impulse (sea level):	255s
Burn Time Capability:	20 Seconds



Thrust Chamber and Nozzle Geometry

Thrust chamber and nozzle designed for manufacturing simplicity & optimized for selected materials.

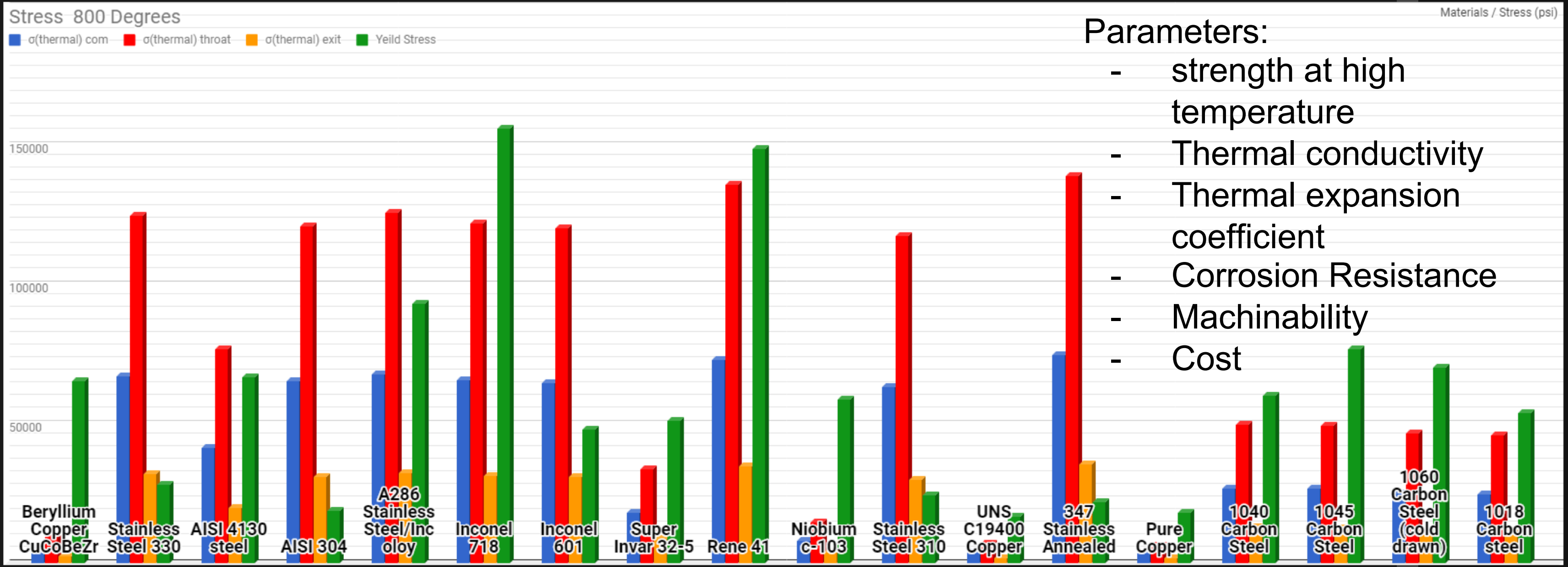
- Areas determined from propellant properties, pressures, compressible flow, and desired thrust
- Nozzle is a conical shape. Easy to manufacture with a <2% efficiency compromise.
- Combustion Chamber geometry based on empirical references.



Materials Analysis

Compared >25 promising materials at range of temperatures from 800F-2000F *(showing 18)*

- Copper & Steel Alloys showed promising results
- Beryllium Copper shows best results.



Parameters:

- strength at high temperature
- Thermal conductivity
- Thermal expansion coefficient
- Corrosion Resistance
- Machinability
- Cost

Materials Analysis

Selected Materials:

- Low Carbon Steel
  - Cheap manufacturing of components
  - Corrosion may limit life span of combustion chamber in high oxidation environment

- Pure Copper
  - More expensive than steel
  - Better corrosion resistance
  - Superior thermal conductivity

- Haynes 282
  - High performance at extreme temperatures
  - Allows us to experiment with using advanced manufacturing methods
  - Low thermal conductivity

Cooling Design

Alternatives

Regen:

- No wasted fuel.
- Performance affected by flow rate, wall material and thickness.

Film:

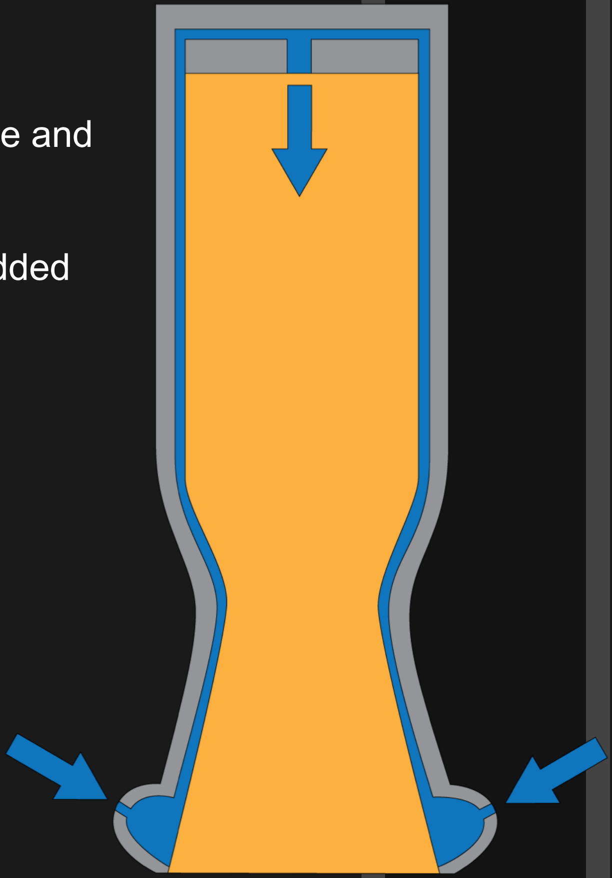
- Excess fuel along walls forms barrier.
- Some wasted fuel, reduced performance

Ablative:

- inexpensive but limits engine reuse

Selected regen for performance and reusability.

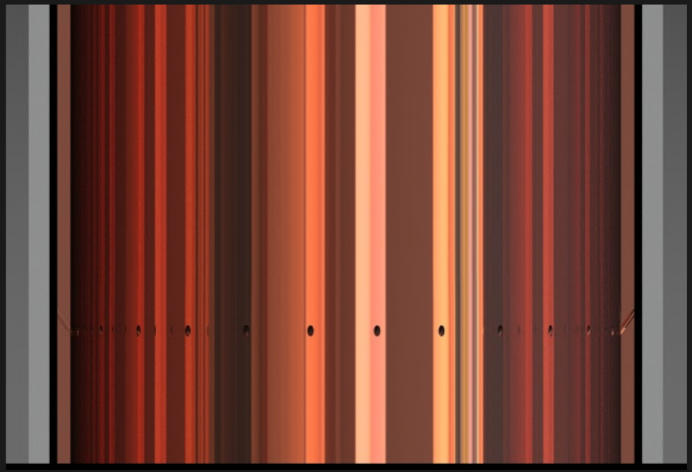
Incorporated film cooling for added safety factor.



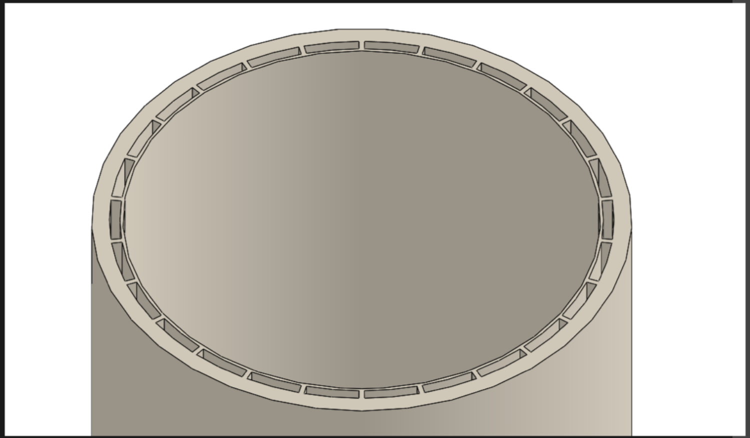
Cooling Design

- Coaxial Shell
  - Works well for our requirements
  - Easier to manufacture

- Channel Wall
  - Higher Strength
  - Hard to Manufacture



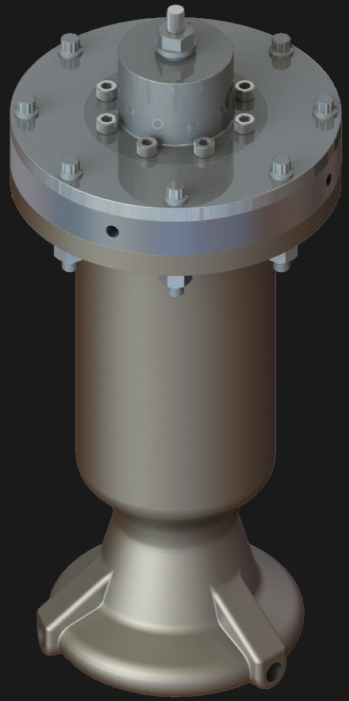
Coaxial Shell



Channel Wall (low aspect ratio)

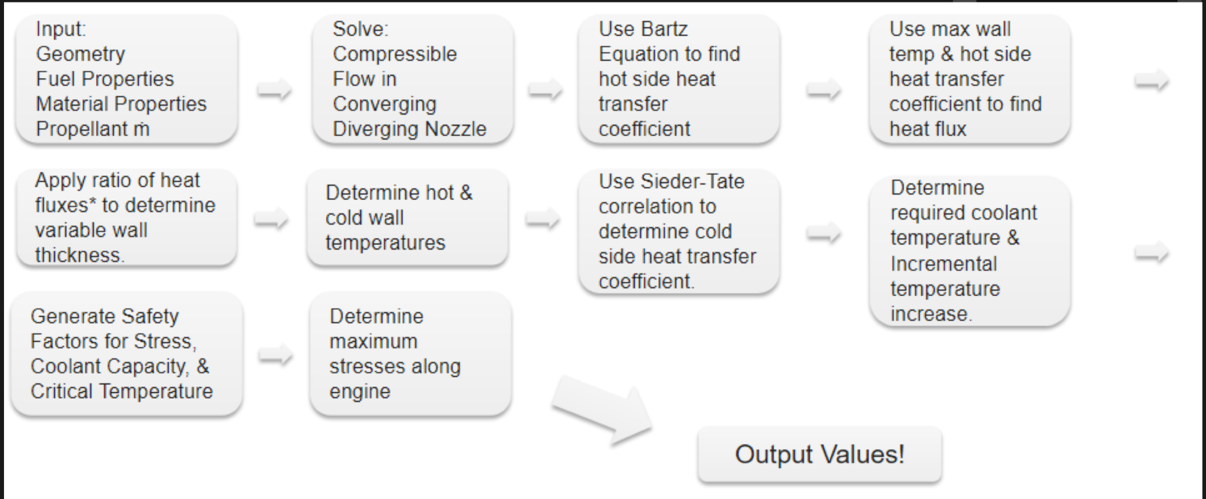
3D Printed Engine

- Channel-wall cooling channel design for extra strength.
- Designed for DMLS.
- Made from Haynes 282
- Allows comparison of heavily simplified manufacturing of regenerative cooling jacket.

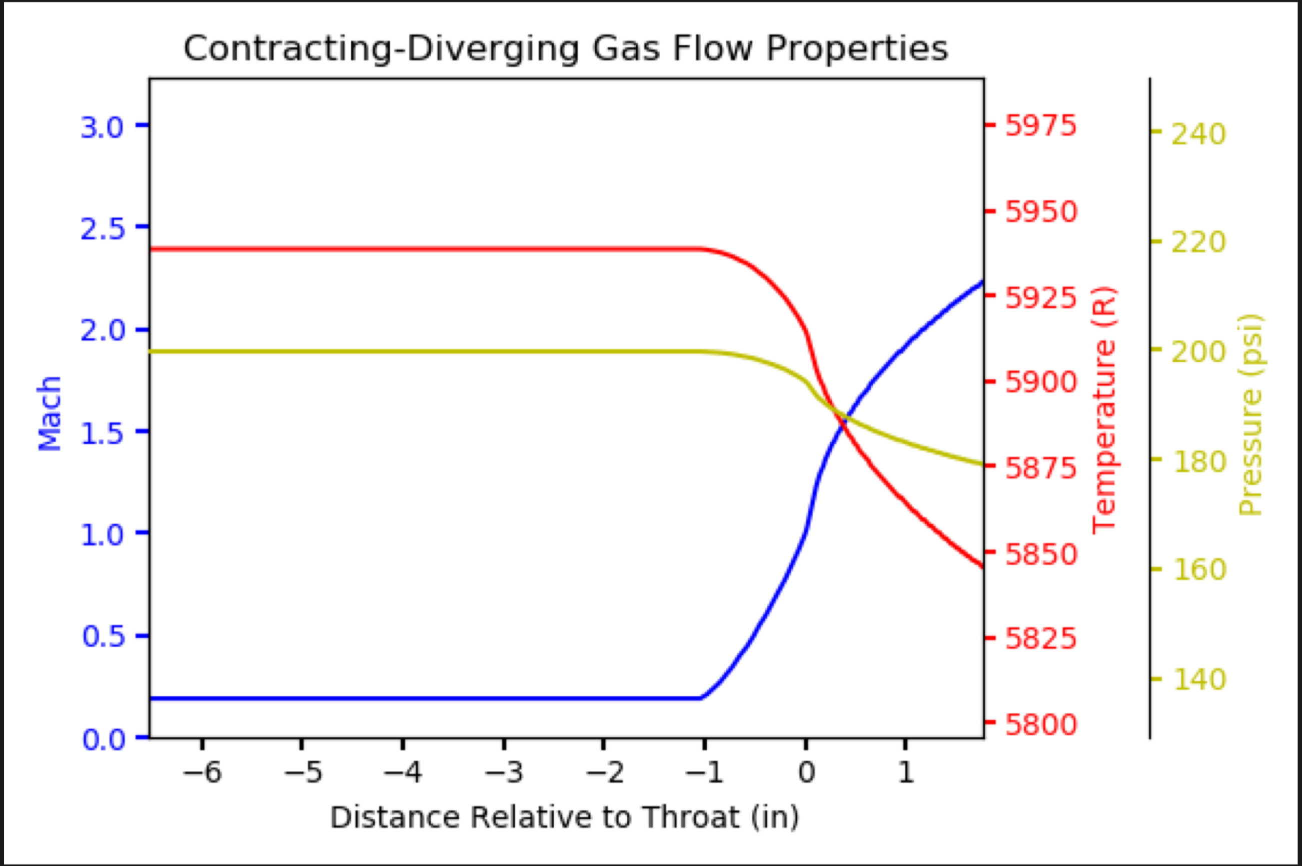


Regenerative Cooling Analysis

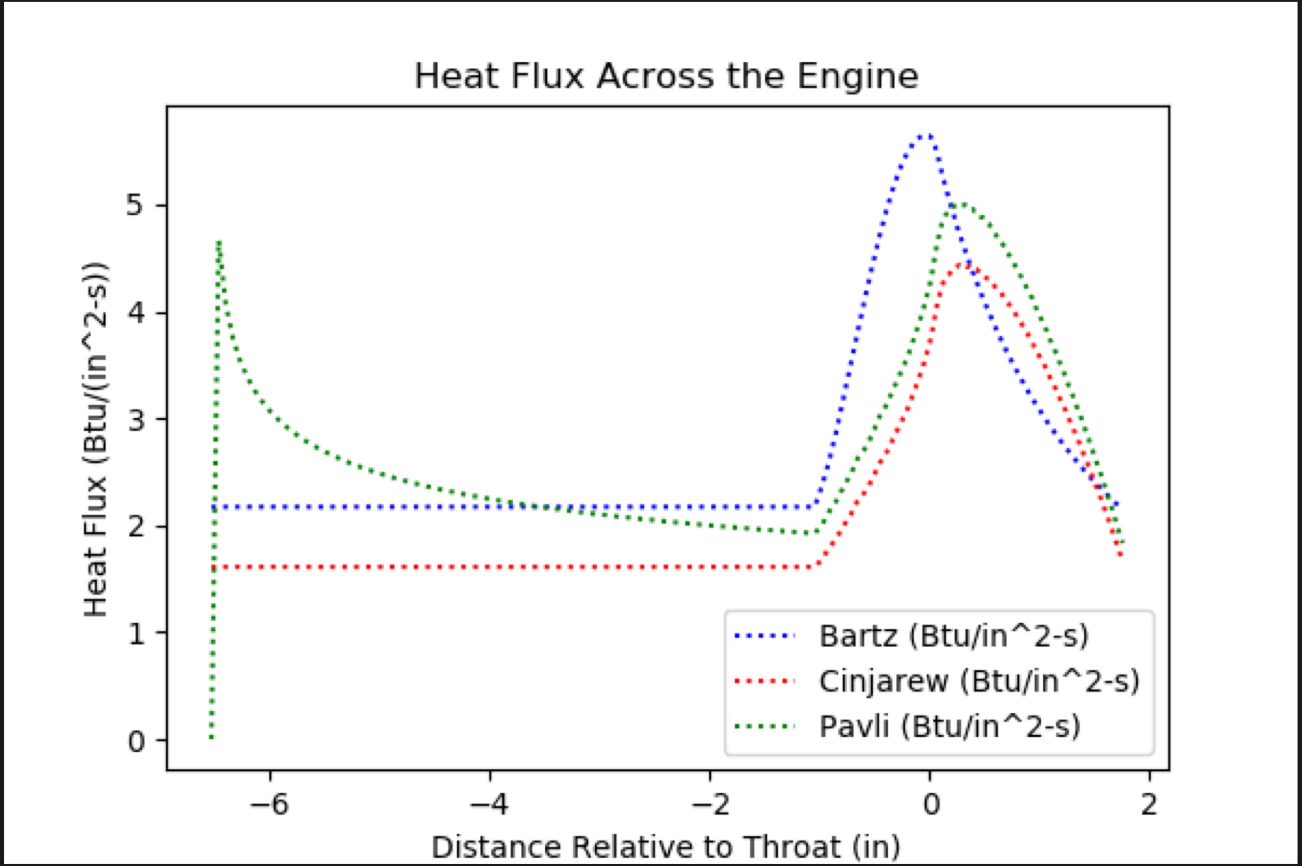
- 1D Steady State Axisymmetric Analysis
- Compressible Flow Modeled
- Used for all material types (shown is for Haynes 282)
- Heat fluxes Compared to allowable stresses



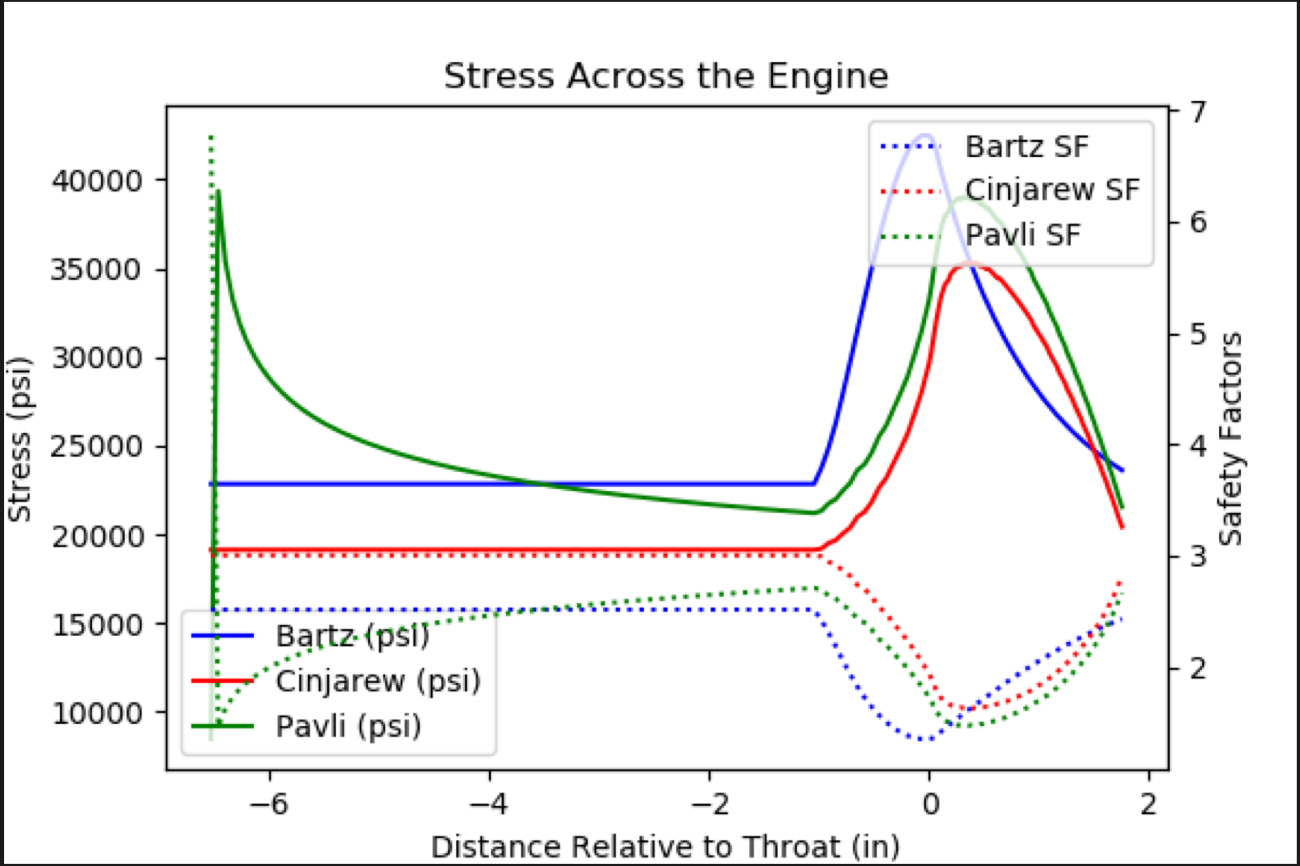
Regenerative Cooling Analysis



Regenerative Cooling Analysis

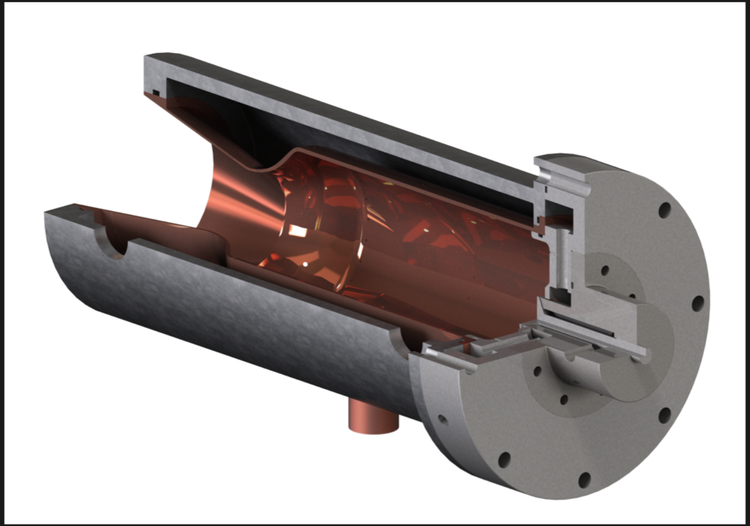


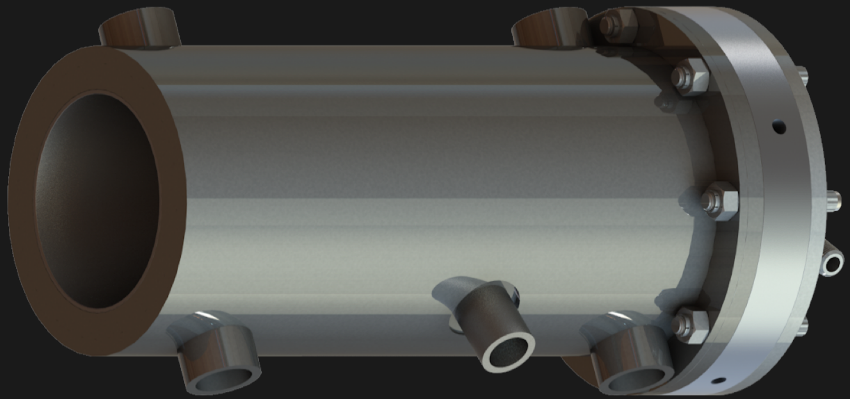
Regenerative Cooling Analysis



Water Cooled System

- For initial testing and validation of engine.
- Excessively cooled with water. Large pipe for easy manufacturing and instrumentation.
- Instrumentation support for pressure, temperature, thrust, and natural combustion frequency.





Injector Design

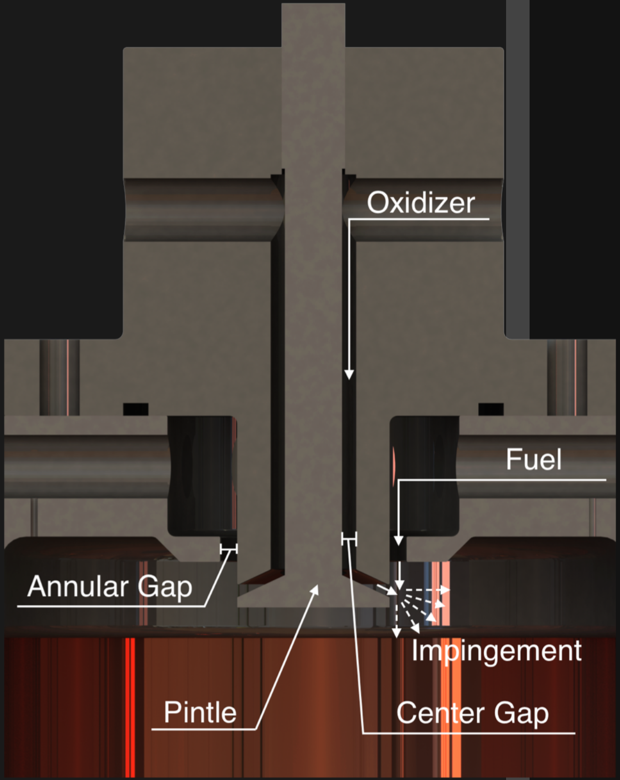
Flat plate ("showerhead") vs pintle:

- Flat plate (doublet, coaxial, etc.) - better performance/mixing

- Pintle - better combustion stability, easier to manufacture, easier to adjust or throttle

Pintle Injector Elements:

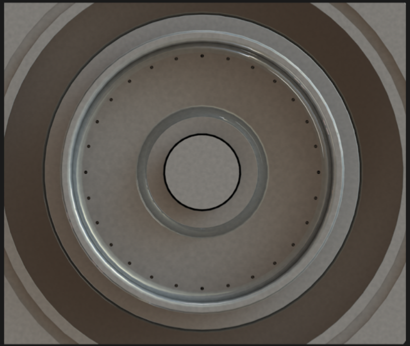
- Outer annulus
- Inner Annulus
- Pintle

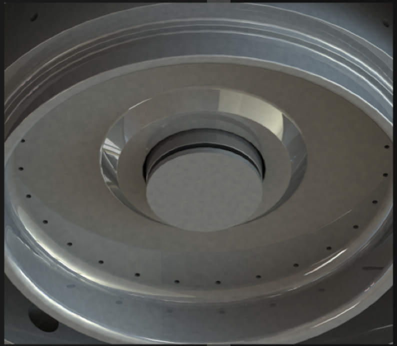


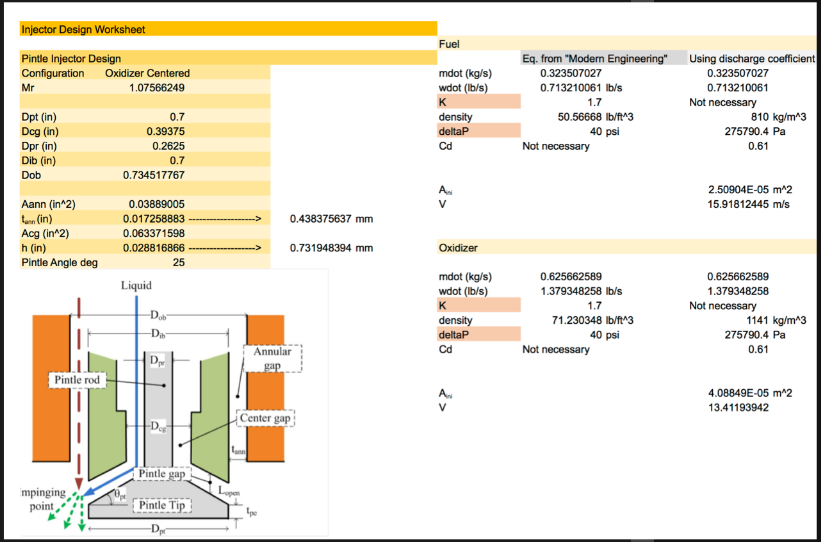
Pintle Injector Anatomy

Pintle Injector Design

- Geometry based on required flow rate, pressure drop, and momentum ratio (radial to axial).
- Pintle screw to adjust flow rates on the fly for testing
- Chose oxidizer centered to increase ease of flow rate adjustment, engine survivability.







Injector Design Worksheet

Pintle Injector Design		
Configuration	Oxidizer Centered	
Mr	1.07566249	
Dpt (in)	0.7	
Dcg (in)	0.39375	
Dpr (in)	0.2625	
Dib (in)	0.7	
Dob	0.734517767	
Aann (in^2)	0.03889005	
t_{ann} (in)	0.017258883 ----------------->	0.438375637 mm
Acg (in^2)	0.063371598	
h (in)	0.028816866 ----------------->	0.731948394 mm
Pintle Angle deg	25	

Fuel	Eq. from "Modern Engineering"	Using discharge coefficient
mdot (kg/s)	0.323507027	0.323507027
wdot (lb/s)	0.713210061 lb/s	0.713210061
K	1.7	Not necessary
density	50.56668 lb/ft^3	810 kg/m^3
deltaP	40 psi	275790.4 Pa
Cd	Not necessary	0.61
A_{ni}		2.50904E-05 m^2
V		15.91812445 m/s

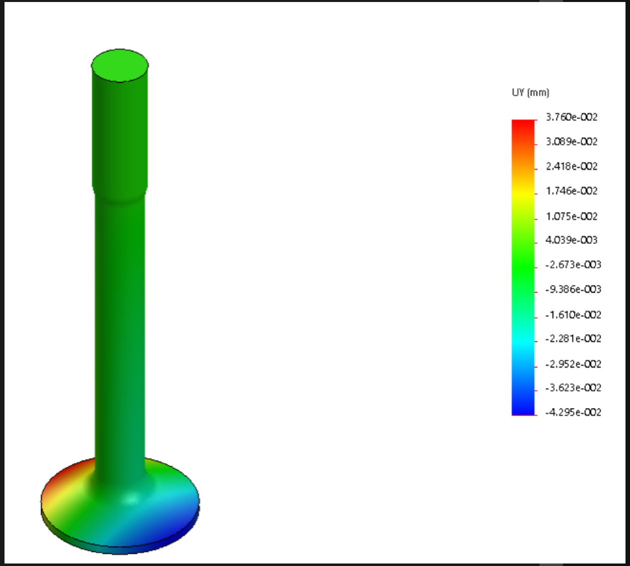
Oxidizer	Eq. from "Modern Engineering"	Using discharge coefficient
mdot (kg/s)	0.625662589	0.625662589
wdot (lb/s)	1.379348258 lb/s	1.379348258
K	1.7	Not necessary
density	71.230348 lb/ft^3	1141 kg/m^3
deltaP	40 psi	275790.4 Pa
Cd	Not necessary	0.61
A_{ni}		4.08849E-05 m^2
V		13.41193942

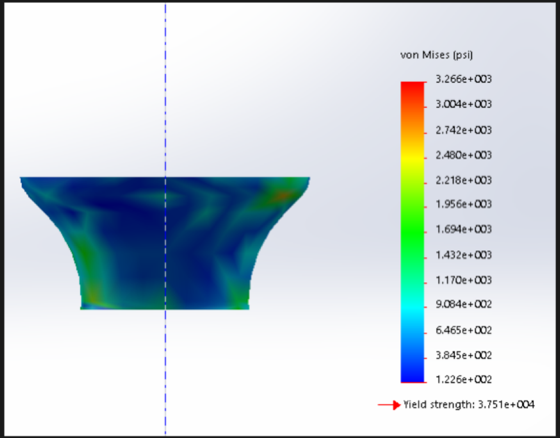
Injector Geometry Tool

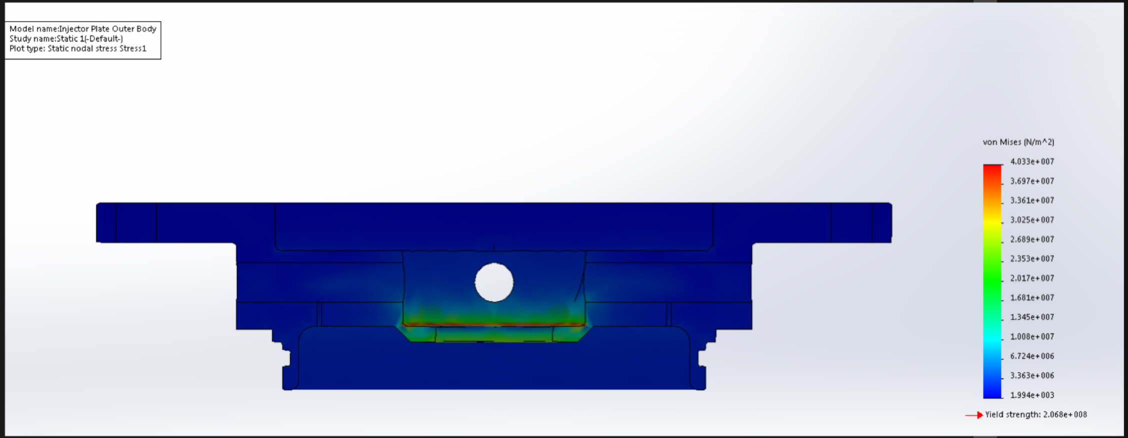
FEA Stress Validation

Injector:

- Worst Case Loadings
- Primary stress from pressure

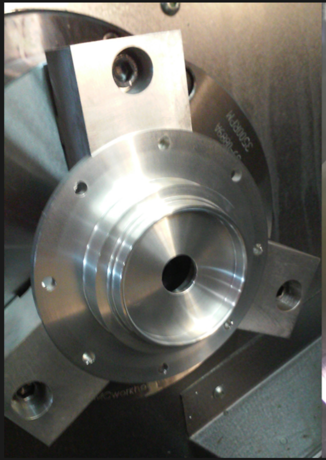


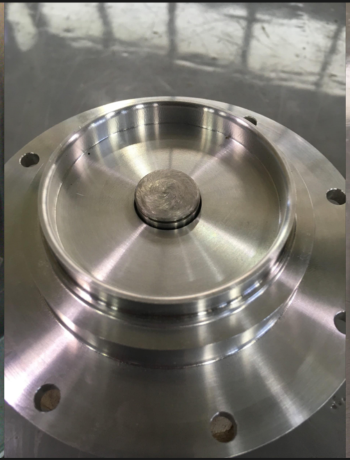


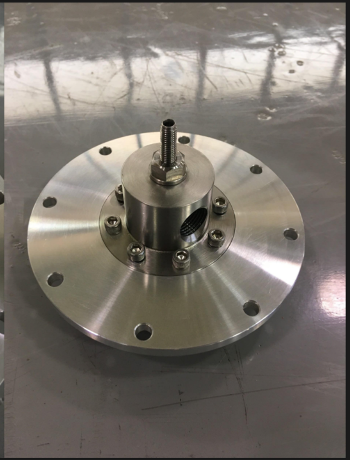


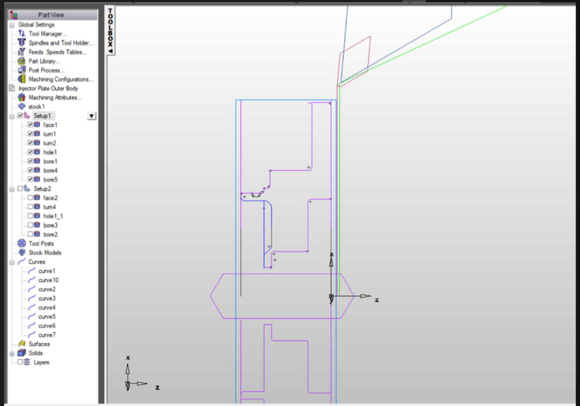
Manufacturing

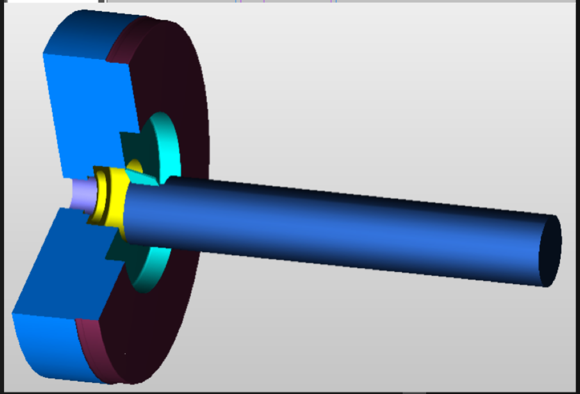
- Aluminum and Steel test pieces
- CNC of most complicated injector pieces
- Pintle and other delicate or simple pieces machined by hand





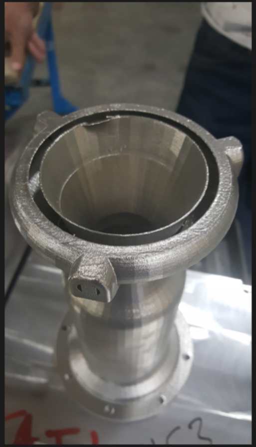


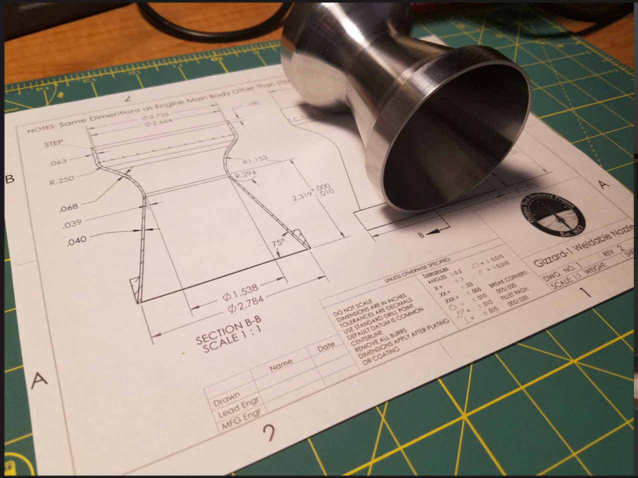




Manufacturing

- Collaborated with Quality Machined Products to make engine in two parts.
- Welding done with assistance of OIT/KCC welding instructors and class.
- Post weld heat treating





Manufacturing

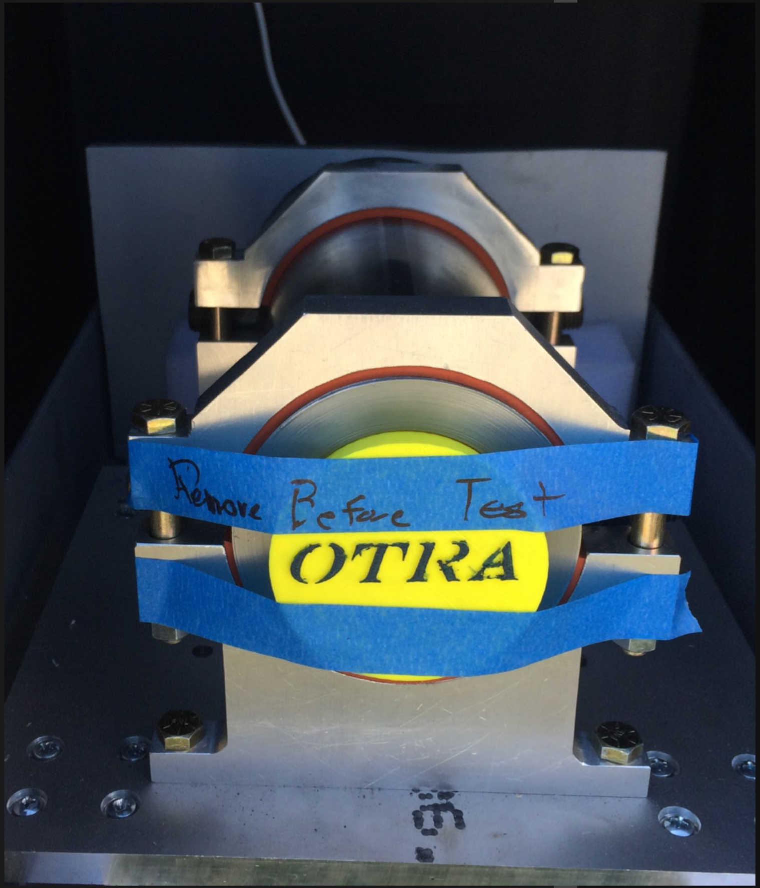
Testing

Spray pattern characterization pre-testing with low pressure water

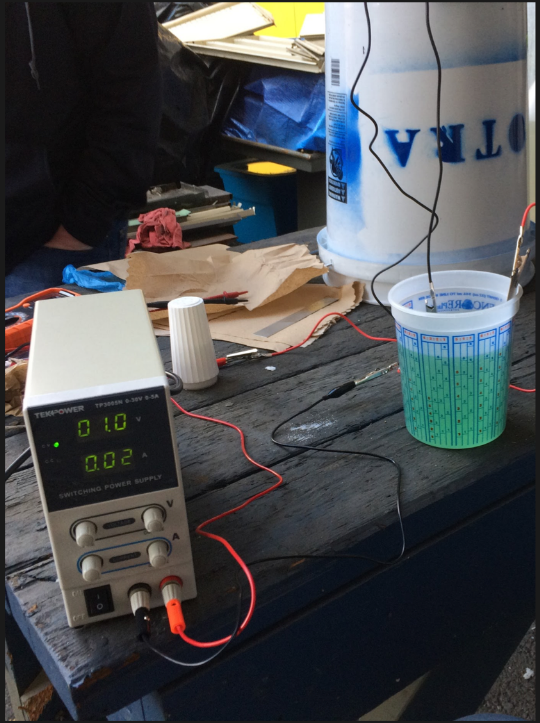
- Measurement of spray angles
- Uniformity
- Mixing (colored water)

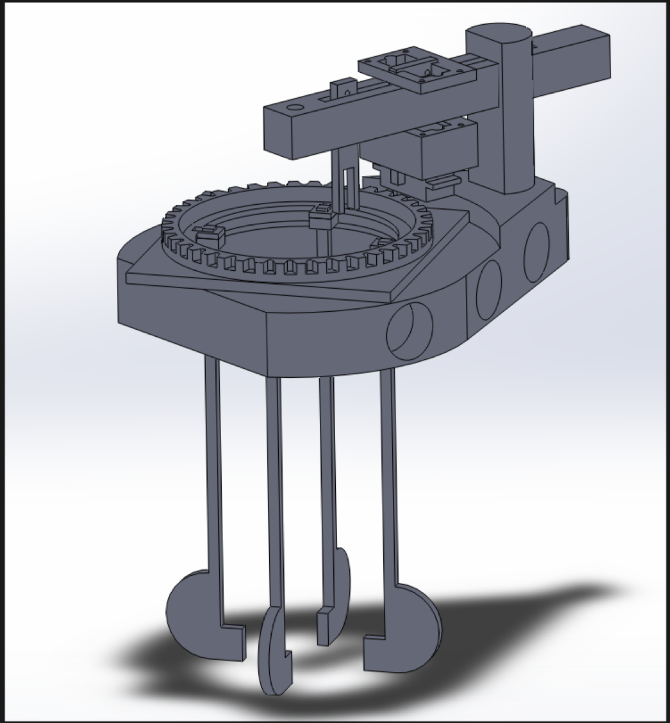
What's Happening Now

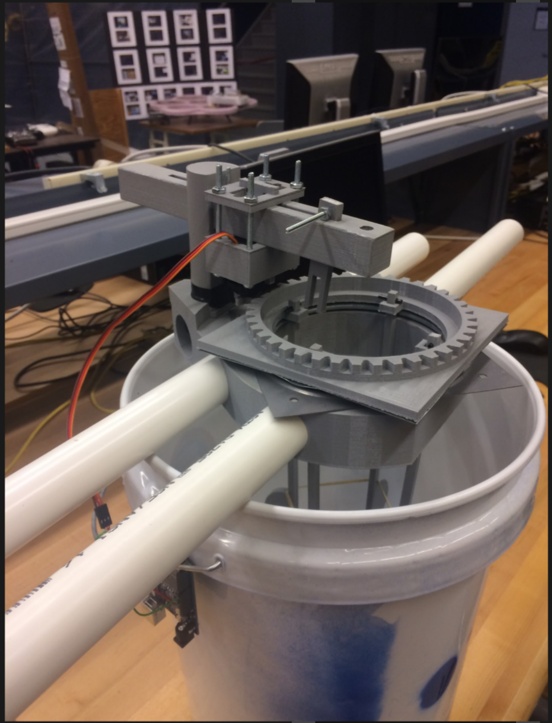
- Insurance
- High ΔP mixture & cold flow testing (water and liquid nitrogen)
- Manufacturing of spares and copper engine
- Further preparations for Hot-Fire



What’s Happening Now

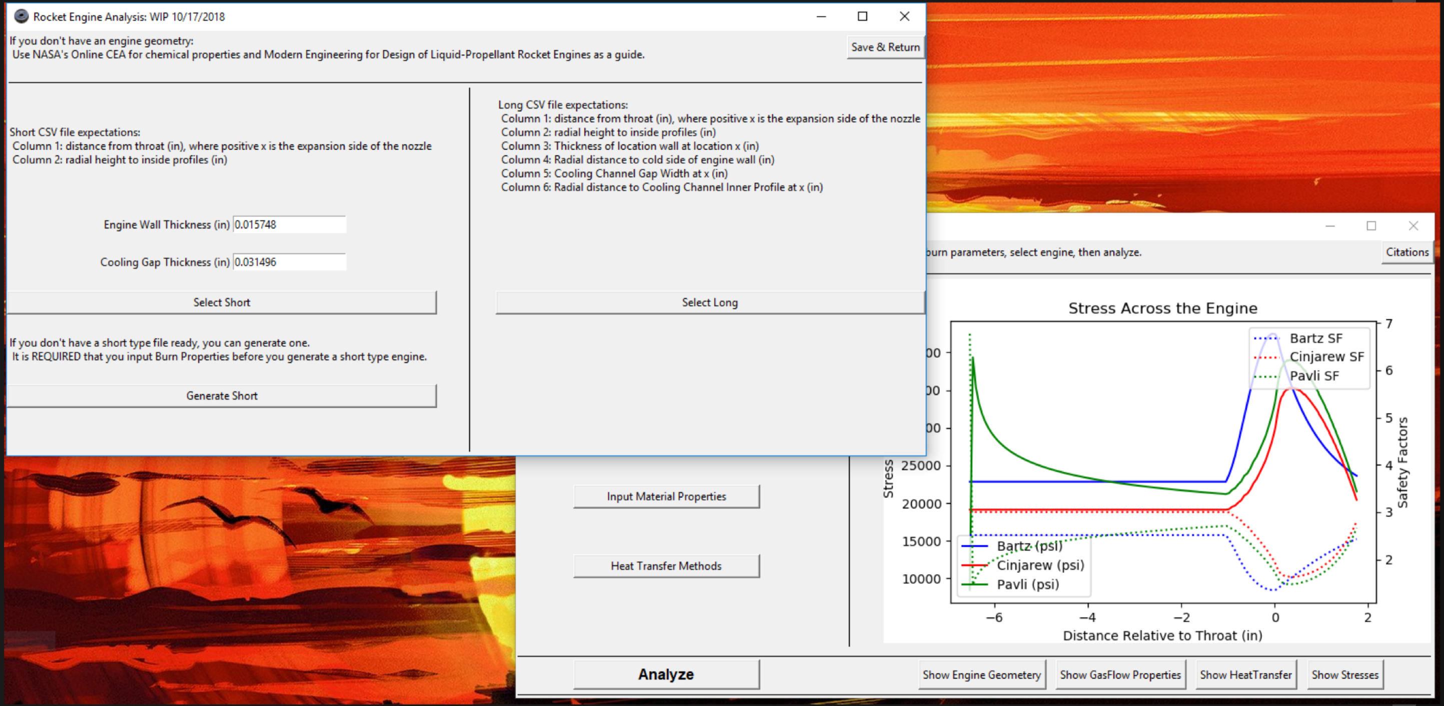






Development of chemical electroplating device and process for cost effective engine development

What's Happening Now



Simplification and improvement of inhouse design & analysis tools.

What’s Happening Now

Teaching new OTRA members what we have learned

Questions?

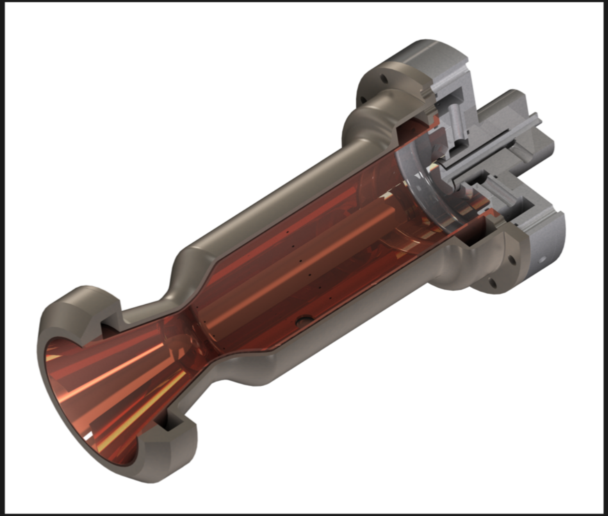
Regenerative Cooling Jacket

Engine cooled by fuel on route to injector.

Thin channels for high flow velocities.

Jacket made from nickel plated steel rather than aluminum to limit galvanic corrosion with the copper while maintaining low cost and easy machinability.

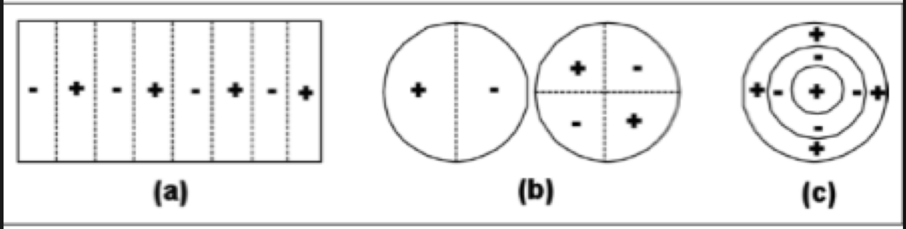
Jacket made in two halves. Early test article bolted together to allow disassembly for inspection. Final engines welded.



Acoustic Analysis

Longitudinal vs tangential vs radial mode severity

Potential approaches for addressing instabilities: injector mixing, modifying natural frequencies - acoustic absorbers, internal baffles to break wave propagation.



Modes or Natural Frequencies of Combustion Chamber				
	Lambda	LOX & Butanol	GOX & Butanol	GOX & Ethanol
c (m/s)		1171.443	1171.443	1171.443
1-Longitudinal	0	4203.998467	4773.399044	4763.922451
2-Longitudinal	0	8407.996934	9546.798088	9527.844901
3-Longitudinal	0	12611.9954	14320.19713	14291.76735
1-Tangential	1.8412	10147.88511	12826.63207	12779.1242
2-Tangential	3.0542	16833.40794	21276.93877	21198.13227
1-Radial	3.8317	21118.64619	26693.35548	26594.4874
2-Radial	7.0156	38666.90351	48873.84312	48692.82194

Lessons Learned

- Engineering: A rocket engine from A to B
  - Challenges with Design Tools
  - Manufacturing
  - Testing

- Administrative
  - Manufacturing
  - Insurance