Casper
Critical Design Review

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BU College of Engineering
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Meeting Record

- Meeting attendance, notes, questions, discussions, and action items are tracked on Phriction
- Location: https://phab.burpg.space/w/projects/ghost_series/casper/casper_cdr_notes/

Document Name	*Author*	*Date*	*Notes*
Spectre CoDR	Casper Team	11/16/2019	Design review notes
Single Stage Trade Study Results	Austin Briggs, Justin Fiaschetti	1/20/2020	Results write up
Spectre Workbook	Casper Team	4/19/2020	
Injector Test Articles Workbook	Justin Fiaschetti, Austin Briggs	4/17/2020	
Casper Workbook	Casper Team	5/16/2020	
Casper Structural Calculations	Austin Briggs, Casey Goodwin	5/17/2020	
Casper CDR	Casper Team	5/17/2020	Design review notes

Design Team

Austin Briggs
(ENG ME ‘21)
Project Lead;
Injector Design

Justin Fiaschetti
(ENG ME ‘21)
Injector Design

Adam Kotler
(ENG ME ‘21)
Thermals;
Chamber Design

Peter Ha
(ENG ME ‘22)
Chamber Design

Casey Goodwin
(ENG ME ‘23)
Chamber Design

Casper Methodology

- Casper was designed as a low-cost and low-risk test platform for BURPG's Spectre flight engine
- Spectre features a number of new technologies that require testing to fully understand and optimize
    - Coaxial-swirl injector design
        - Casper will be used to test combustion stability and efficiency of various injector element designs to be used on Spectre
    - Thermal modeling
        - Casper will aid in the findings of heat transfer coefficients present in the chamber for use in regenerative cooling analysis for Spectre
    - Chamber design
        - Casper has the capability of testing different chamber characteristic lengths for information pertinent to Spectre and future BURPG engine design
- Rapid design changes, configurability in the field, frequent testing, and low cost were the driving forces behind Casper

High-Level Requirements

- Casper must help determine the combustion performance and stability of the Spectre engine.
- Casper must be able to appropriately quantify the characteristic velocity (C*) and thrust coefficient (Cf) of the engine.
- Casper must feature on-site interchangeable injector elements.
- Casper must interface with Horizontal Test Stand with little to no modifications.

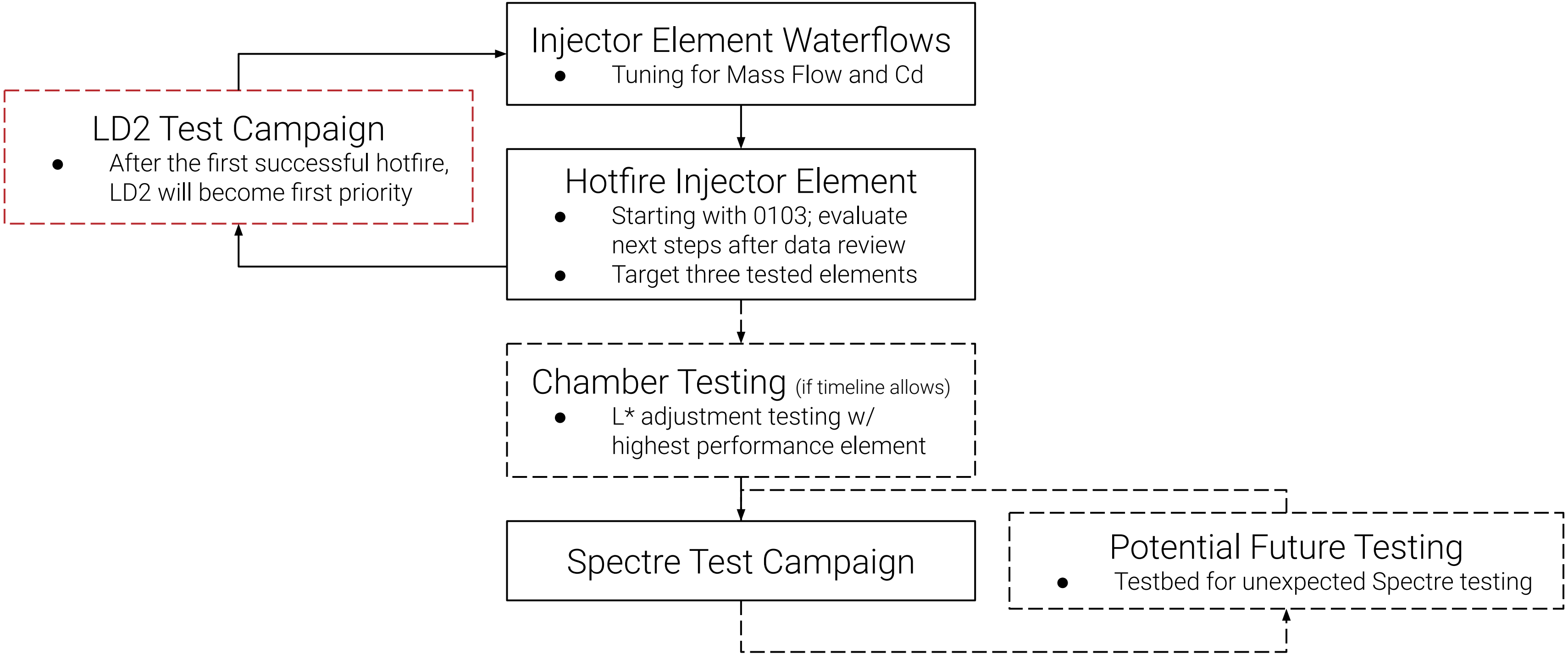
- Engine Body (Chamber & Injector Head) safety design requirements: NASA-STD-5005D
- Injector Elements safety design requirements: NASA-STD-5012B

- BURPG Requirements:
  - REQ-RPG-0003: Ambient design temperature is between 0°C to 38°C with a nominal ambient design temperature of 23°C.
  - REQ-RPG-0004: Minimum of two inter-propellant seals. All other sealing interfaces have a minimum of one seal.

Design Requirements

Requirement	*Value*	*Units*	*Type*	*Criticality*	*Source*
Injector Element Mechanical Loads Yield/ULT. FoS	1.1/1.5	--	Minimum	Critical	NASA-STD-5012D
Engine Body Mechanical Loads Yield/Ult. FoS	2/3	--	Minimum	Critical	NASA-STD-5005D
Fuel (Isopropanol) Mass Flow Rate	0.385	kg/s	Target	High Priority	Casper Workbook
Ox (Nitrous Oxide) Mass Flow Rate	1.640	kg/s	Target	High Priority	Casper Workbook
Design Thrust	1086	lbf	Minimum	High Priority	Spaceshot Trade Study Results
Characteristic Velocity Efficiency (ηC*)	90	%	Minimum	High Priority	Spaceshot Trade Study Results
Thrust Coefficient Efficiency (ηCf)	98	%	Minimum	High Priority	Lotus Target Numbers
Design Chamber Pressure	500	psig	Target	Med. Priority	Spaceshot Trade Study Results
Design Chamber OF Ratio	4.25	--	Target	Low Priority	Spaceshot Trade Study Results
Thermal Cycle Life	20	--	Minimum	Critical	Test Campaign + Uncertainty

Testing Timeline Overview



Test Campaign discussions will be held in a Casper TRR near the end of the summer

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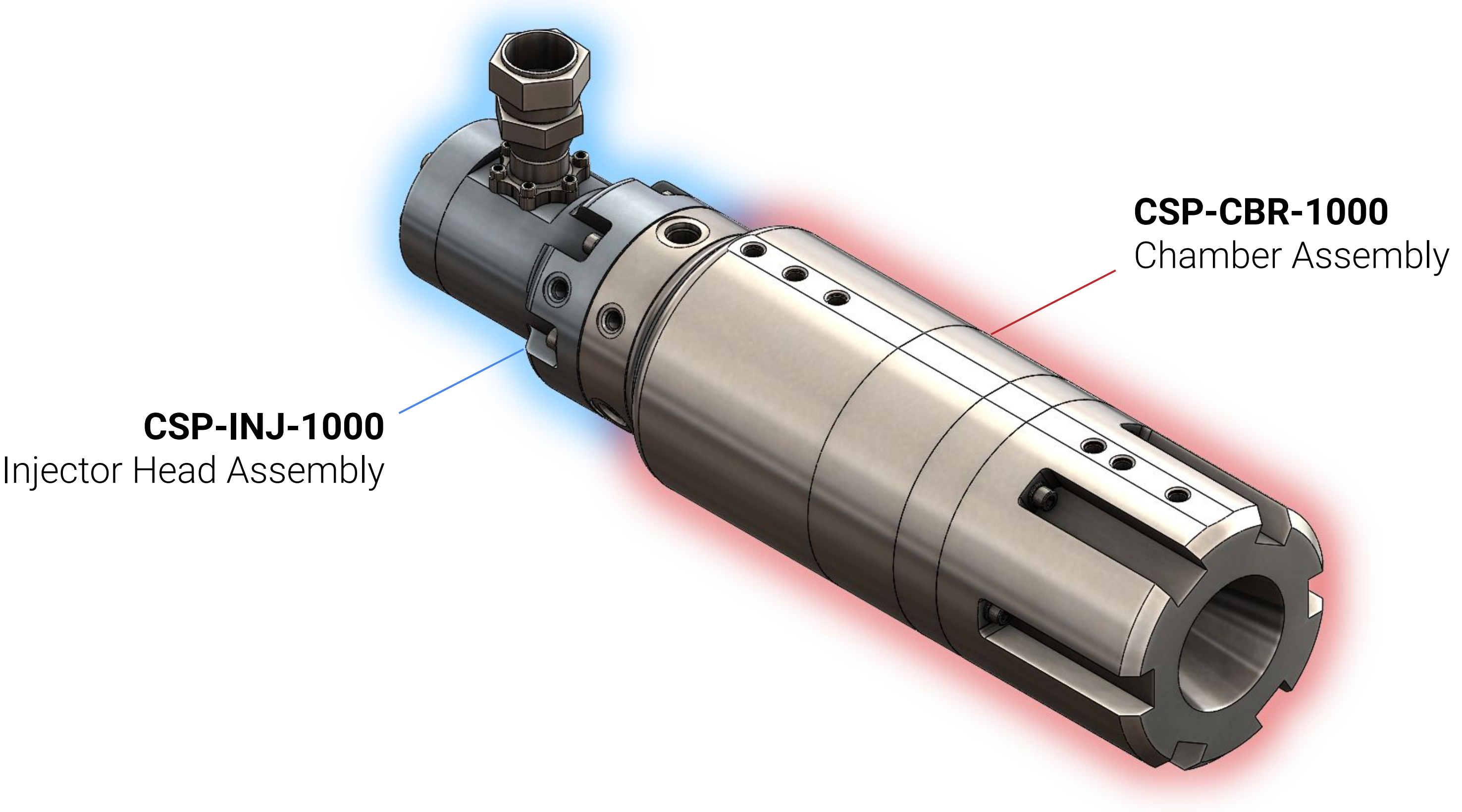
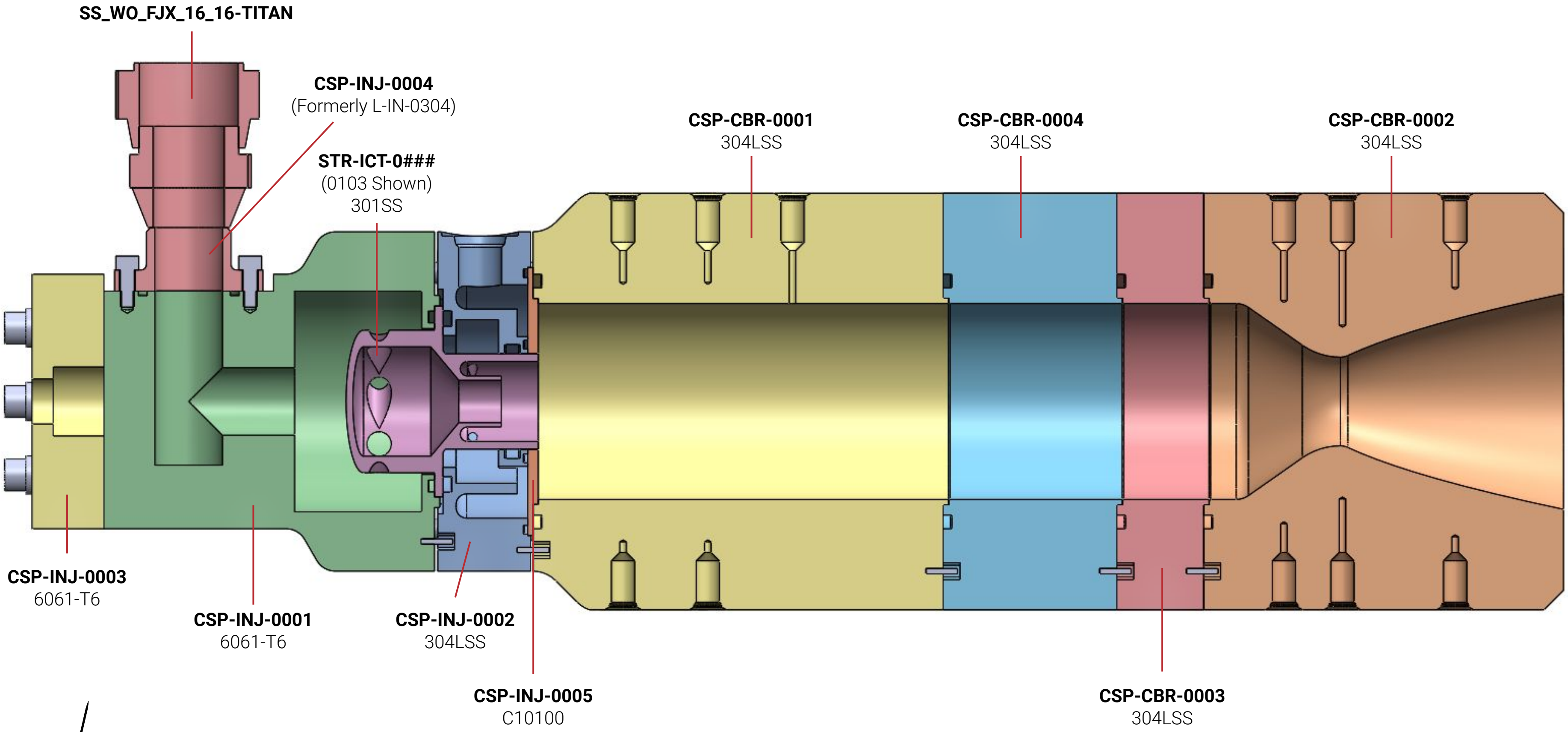
Design Overview

Subassemblies



Part Numbers & Materials



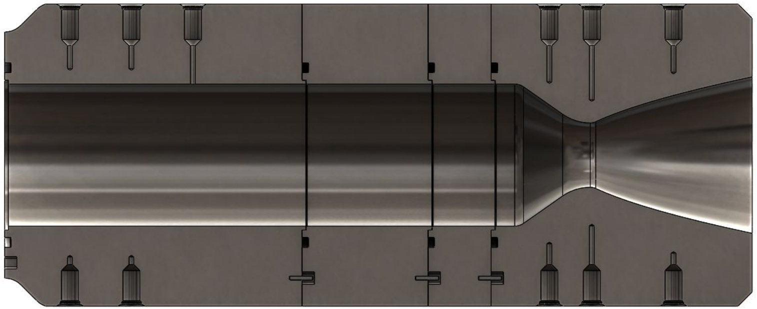
Chamber Design

Chamber and Nozzle Components

Chamber Metrics

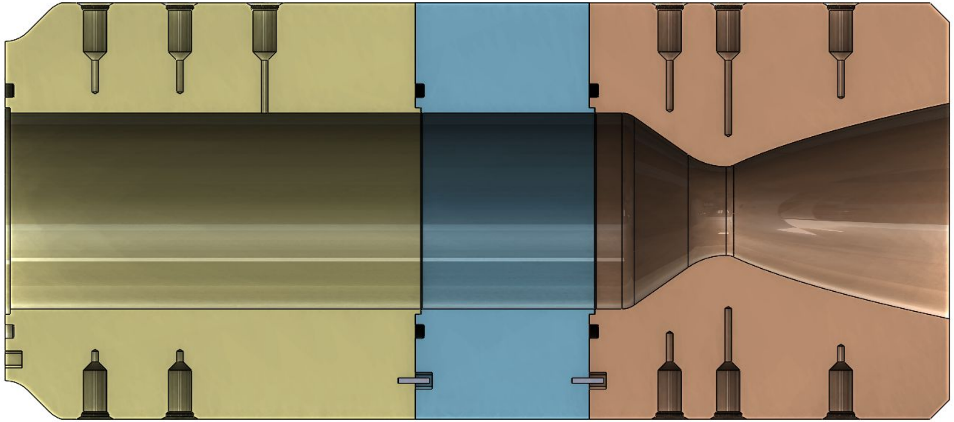
Parameter	*Imperial*	*Units*	*Metric*	*Units*
Thrust	1086	lbf	4831	N
O/F Ratio	4.25	--	4.25	--
Chamber Pressure	500	psig	3.447	MPa
Mass Flow Rate	4.466	lbm/s	2.026	kg/s
Expansion Ratio	7.221	--	7.221	--
Bell Length	80	%	80	%
Converging Angle	35	deg	35	deg
Initial Angle	25	deg	25	deg
Final Angle	11	deg	11	deg
Chamber Diameter	**2.310**	**in**	**5.867**	**cm**
Throat Diameter	**1.046**	**in**	**2.657**	**cm**
Exit Diameter	**2.54**	**in**	**6.452**	**cm**
Min Chamber Length	**9.086**	**in**	**23.08**	**cm**
Max Chamber Length	**12.16**	**in**	**30.89**	**cm**

Casper Workbook 5/16/2020



Main Thrust Chamber

- Components are made out of 304L SS for high temperature operation, high corrosion resistance (oxidation and intergranular[1]), and availability
- Designed to have an identical stay-time as Spectre
- Able to be rapidly assembled and disassembled on-site



Parameter	*Value*	*Units*
Spectre Stay-Time	0.0015	sec
Casper Stay-Time	0.0015	sec
Nominal Characteristic Length (L*)	40.0	in
Nominal Chamber Length	11.14	in

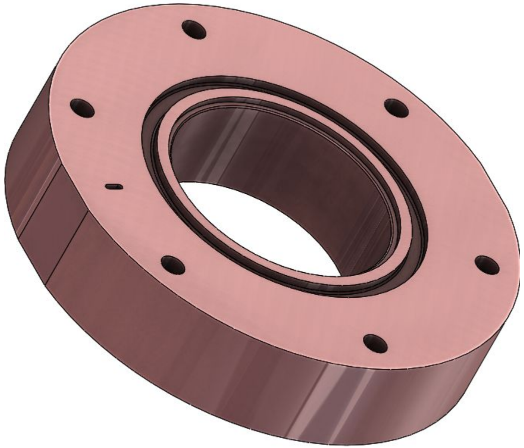
Spectre Workbook 5/15/2020
Casper Workbook 5/17/2020

- Nominally, the thrust chamber is comprised of three components
  - CSP-CBR-0001, CSP-CBR-0002, and CSP-CBR-0004

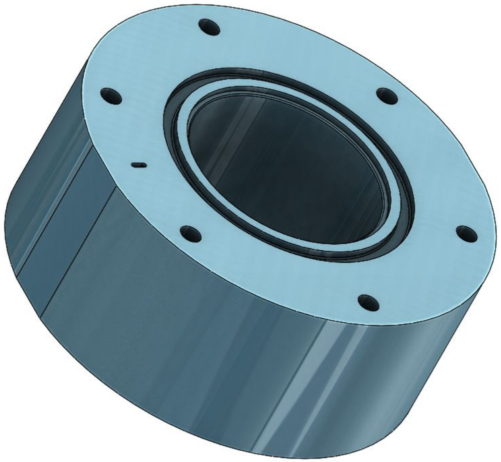
[1]Nonstabilized grades of austenitic stainless steels are susceptible to intergranular corrosion when exposed to temperatures between 700 and 1650°F (MIL-HDBK-5J)

Variable L* Rings

- Since L* data for isopropyl alcohol/nitrous oxide is difficult to find, Casper was designed to be able to obtain this data
- Swappable chamber extensions allow for adjustment of chamber L*
  - Thermal data from thermocouples will be collected during possible L* injector tests along with thrust data from HTS
  - Metrics of heat from thermocouples and thrust will be combined to determine the highest performing L*



CSP-CBR-0003 extends L* by 5 in



CSP-CBR-0004 extends L* by 10 in

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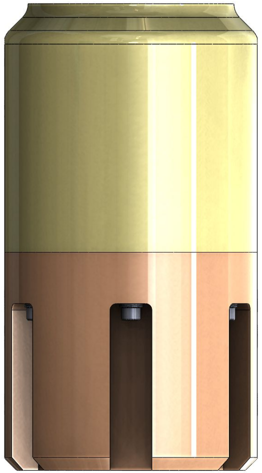
L* Configurations

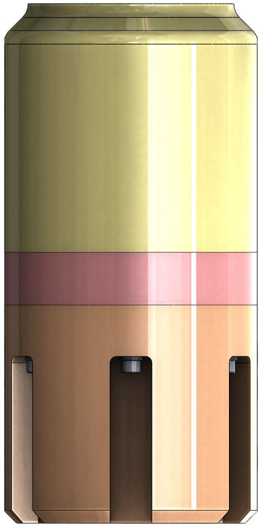
Shortened Configuration

Parameter	*Value*	*Units*
Characteristic Length (L*)	30	in
Stay-Time	0.00114	sec
Chamber Length	9.086	in



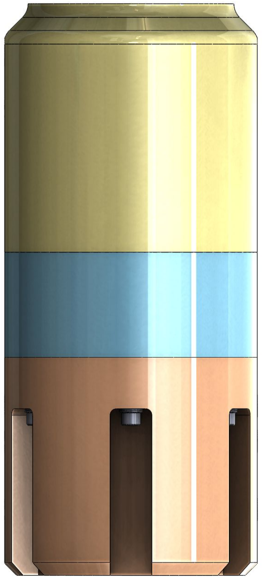
Semi-Shortened Configuration

Parameter	*Value*	*Units*
Characteristic Length (L*)	35	in
Stay-Time	0.00133	sec
Chamber Length	10.11	in



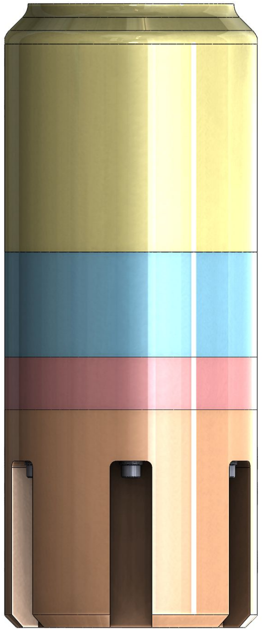
Nominal Configuration

Parameter	*Value*	*Units*
Characteristic Length (L*)	40	in
Stay-Time	0.00152	sec
Chamber Length	11.14	in



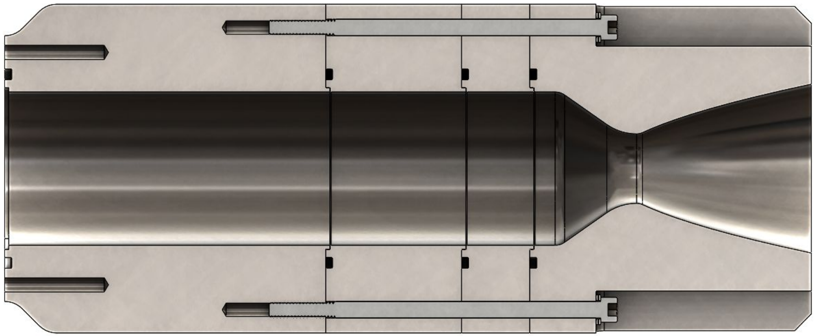
Extended Configuration

Parameter	*Value*	*Units*
Characteristic Length (L*)	45	in
Stay-Time	0.00171	sec
Chamber Length	12.16	in



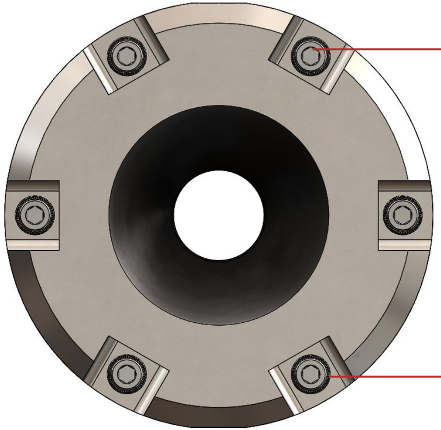
Attachment

- Axial attachment of the elements is facilitated by radial bolts from the nozzle section
  - Allows for flexibility in chamber length
  - On-site rapid chamber adjustment
- Vibration resistance is handled through Nord-Lock locking washers
- A required installation torque is given based on Nord-Lock torque guidelines



Parameter	*Value*	*Units*	*Source*
Number of Bolts	6	--	
Bolt Ultimate Tensile Strength	70,000	psi	McMaster 92196A561
Bolt Installation Torque	6.8±1.7	ft-lbf	Nord-Lock; NASA-RP-1228
Maximum Operational Load/ Bolt	59.749	lbf	Pressure Balance
Ultimate Margin	9.921	--	

Casper Structural Calculations 5/17/2020



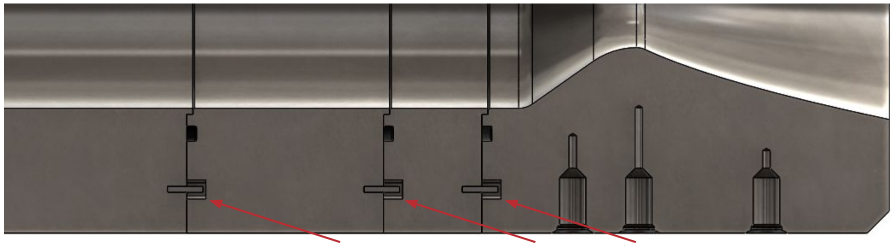
6x **92196A561** Socket Head Screw .2500-20 x 5.000 long, 18-8SS

6x **91812A229** Nord-Lock Washer .2500 Screw Size, 316SS

Concentricity & Clocking

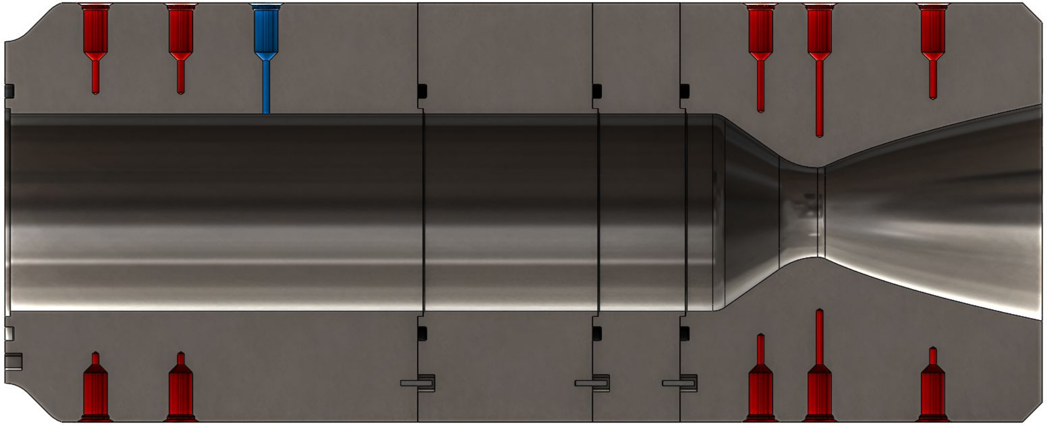
- Concentricity of the chamber elements are handled by toleranced lips on each component
  - Concentricity features are uniform across chamber components to allow for mix/match

- Rotational clocking of the component is accomplished by a press-fit dowel pin sliding into a clearance-fit dowel slot
  - Ease of manufacturing and ease of assembly



Instrumentation Ports

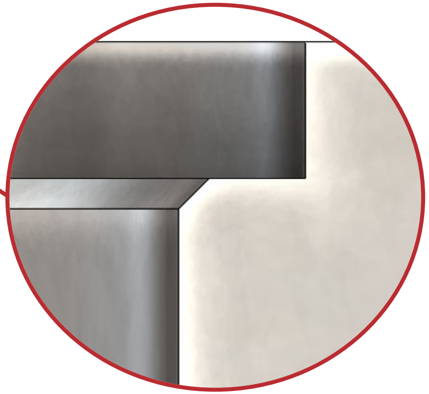
- Two milled flats house eleven total instrumentation ports
  - 10x Thermocouple ports for measuring heat flux (more info in Thermal Analysis section)
  - 1x Pressure Transducer port for measuring chamber pressure
- All instrumentation ports are AS5202-2 geometry and locations are independent of L* configuration



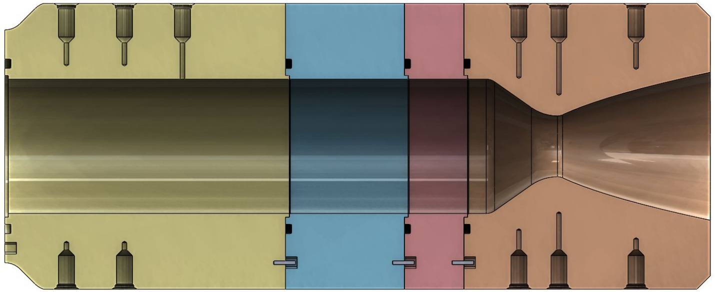
Sealing Geometry

- Buna-N70 O-rings are used to seal between the chamber rings and with the injector head
- Seal max temperature is not of concern for short firings
    - Melting is acceptable as seals are considered expendable and failure modes are benign
- Sealing geometries are consistent between rings, allowing for interchangeability

-232 Buna-N70 O-Ring Groove
per Parker O-Ring Handbook



Chamfered downstream edges prevent hotspots
and gas direction to the o-rings



Thermal Analysis

Chamber, Nozzle

Purpose of Thermal Analysis

- Aids in setting up hot-fire campaign
  - Determine maximum burn-time based on combustion chamber operating conditions
  - Delineates expected temperatures seen throughout engine
- Select/incorporate instrumentation to aid in determining heat-flux load imposed on chamber walls due to unique engine parameters
- Required for thorough structural analysis
- Establish a rough idea of Spectre thermal loading

Thermal Model

Transient analysis model used to predict determine inner and outer wall temperature transients, convection coefficients, initial flux

Correlations Used	*Parameter(s) Calculated*
Bartz Correlation	h_g, Hot-Gas convection coef.
Carslaw & Jaeger[1]	Inner, Outer Wall Temperature Transients
RPE, 7th Ed, Eq. 3-14	Nozzle Mach Number
RPE, 7th Ed, Eq. 3-7	Hot-Gas Temperature Distribution

Modes/Assumptions	*Inputs*	*Outputs*
Transient	Combustion Chamber Geometry	Transient Inner Wall Temperature
Internal Forced Convection	CEA Hot-Gas Data	Transient Outer Wall Temperature
Conduction	Material Properties	Axial Convection Coefficients
1-D Cylindrical		Hot-Gas Mach Number
Constant Thermal Conductivity		
Applied Internal Wall Temperature		

[1]Chapter 7-8, *Conduction of Heat in Solids*, H.S Carslaw, J.C Jaeger, *References->Heat Transfer*

Hot-Gas & Material Properties

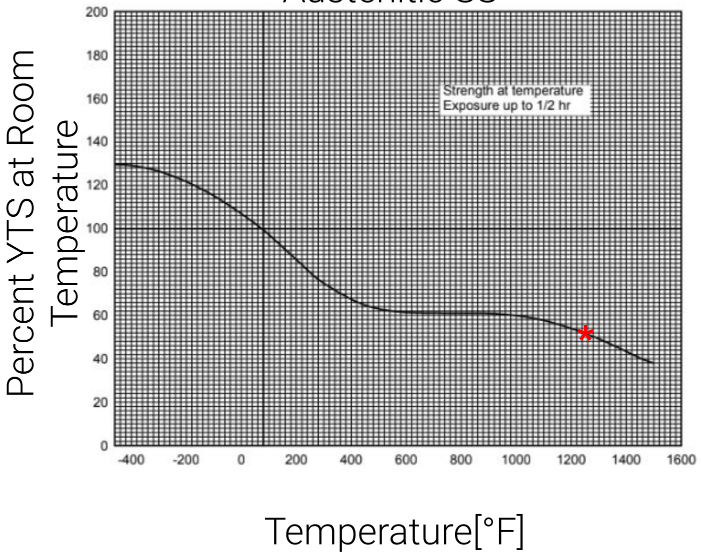
Hot-Gas Data[1]

Property	*Metric*	*Units*
OF Ratio	4.25	--
Chamber Pressure	500	psig
Max Gas Temperature	3120	°K
Characteristic Velocity	1600	m/s
Specific Heat Ratio	1.192	--
Molecular Weight	41.1	g/mol

304LSS Material Properties[2]

Property	*Metric*	*Units*
Thermal Conductivity	17	W/mK
Mass Density	.291	kg/m^3
Specific Heat Capacity	490	J/kgK

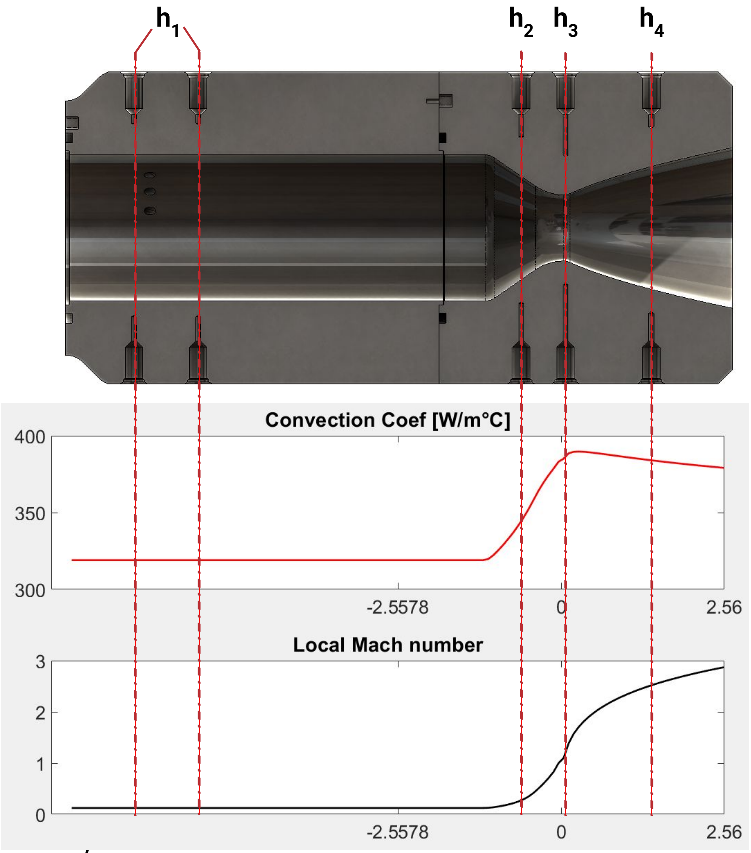
Strength vs. Temperature for Austenitic SS



- Design hot-fire campaign such that none 304LSS chamber components ever reach 50% mechanical strength
- 50% mechanical strength at ~660°C(1220°F)

[1]NASA Chemical Equilibrium with Applications(CEA)
[2]MIL-HDBK-5J

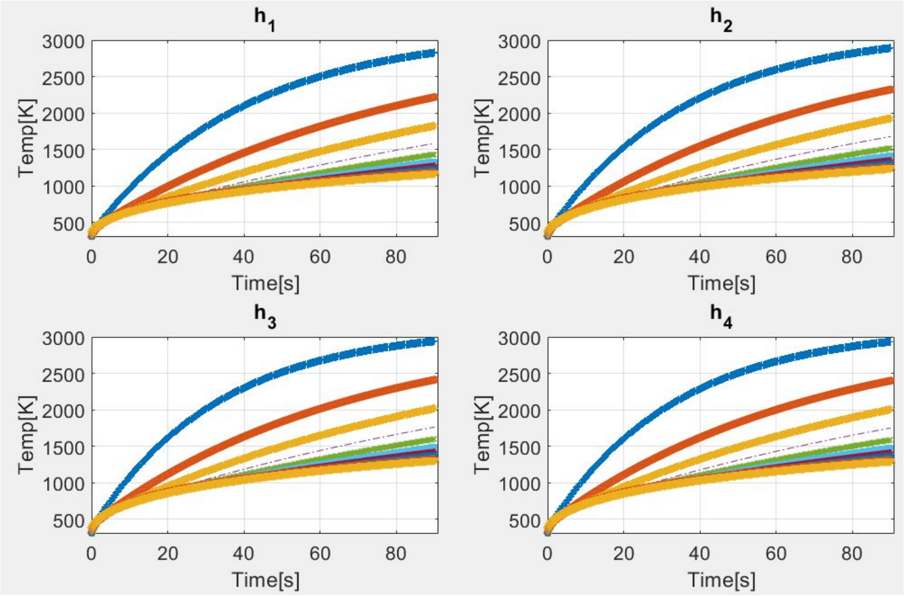
Thermocouple Locations



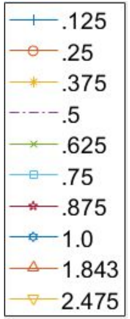
- Four locations with unique flux selected for thermocouple placement
  - Straight section
  - Convergent midpoint
  - Throat
  - Divergent midpoint
- Thermal flux to walls from hot-gas determined from thermocouple data
- Two thermocouples are used in the straight portion for fault tolerance and to capture unknown thermal layer progression

Transient Analysis Results - Inner Wall Temp

Hot-Gas Wall Temperature



Wall Thickness[in]



~Min Thickness

~Max Thickness

Min OD

Max OD

Convection Coefficients [W/mK]

h_1	319
h_2	354
h_3	390
h_4	384

Time[s] to 660°C

Thickness	*Convection Coefficient[W/mK]*			
	h_1	h_2	h_3	h_4
.125	9.25	8.25	7.50 [MIN]	7.75
.25	17.5	15.5	14.0	14.25
.375	24.5	21.5	19.0	19.25
.5	30.0	26.0	22.5	23.0
.625	34.0	29.0	24.75	25.25
.75	36.75	30.75	25.75	26.5
.875	38.25	31.50	26.25	27.0
1.0	39.0	31.75	26.25	27.0
1.843	39.25	32.0	27.5	27.5
2.475	39.5 [MAX]	33.0	28.25	27.75

General Trends

h ↑	time ↓
wall thickness ↑	time ↑

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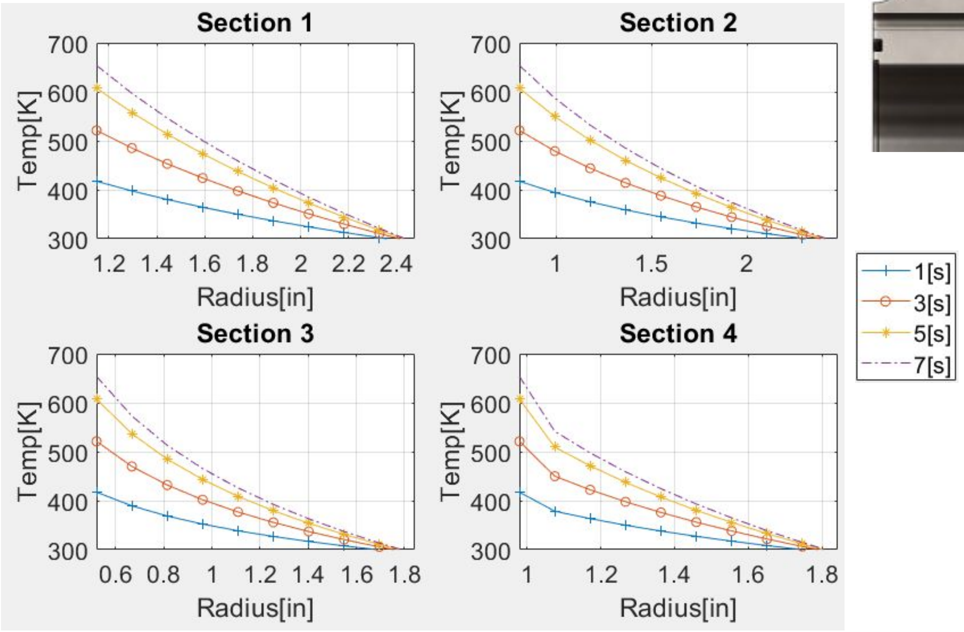
Transient Analysis - Profile Through Wall

Temperature Profile Across Section Radius(Wall Thickness)



Plot 'radius' is measured with respect to origin at chamber central axis

- Temperature profile mapped across engine wall between period of 1-7[s].
- Profiles allow us to predict range of temperatures expected through wall during hotfire campaigns
  - 3[s] max firing duration, tentative
- Profiles allow us to down-select suitable thermocouple types

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Thermocouple Locations (cont.)

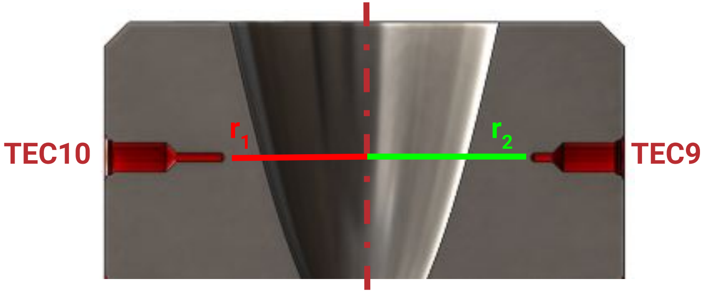
Probe Distance to Inner Wall

TEC1	.5	TEC3	.25	TEC5	.625	TEC7	.625	TEC9	.375
TEC2	.5	TEC4	.25	TEC6	.625	TEC8	.375	TEC10	.375

- Ten thermocouples to be implemented during initial campaign
- Name-order precedence given to thermocouples upstream of flow
- Further TC additions begin at #11, regardless of location. Ease in CAD
- Naming convention complies with BURPG Official Fluid Naming Structure
- Extra space available on machined flats for additional thermocouples TBD during test campaign

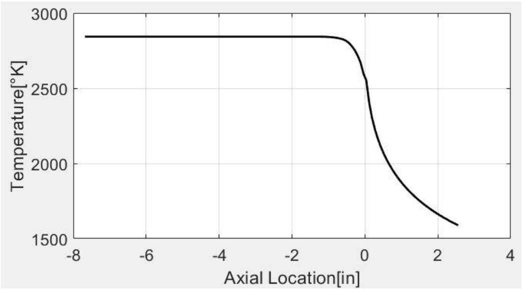
Flux Calculation

- Paired thermocouple data at axial location used to calculate heat flux across a section
- Heat flux[W/m^2] is equivalent across any two radial points at some axial location
- Heat flux decreases over time

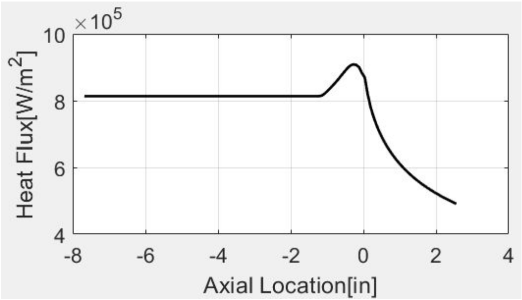


$$q = \frac{k}{ln(\frac{r_9}{r_{10}})}(T_{10} - T_9) \begin{cases} k, \ thermal \ conductivity \\ T_9, \ TEC9 \ measurement \\ T_{10}, \ TEC10 \ measurement \end{cases}$$

Hot-Gas Temperature Profile



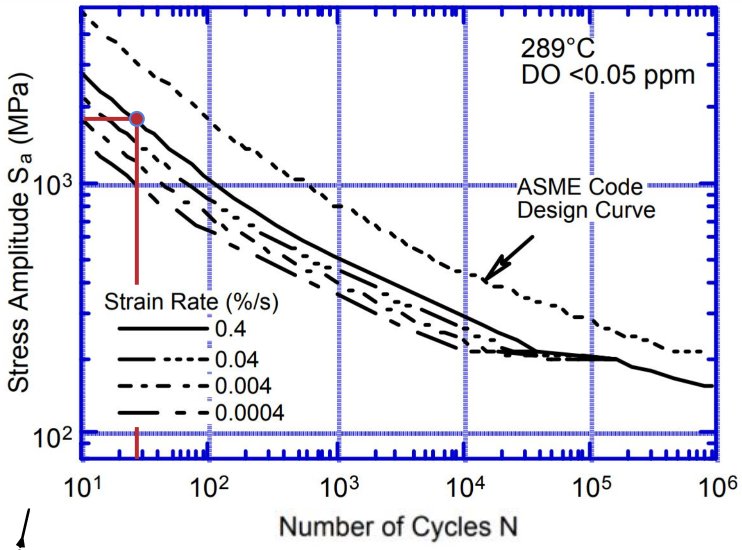
Initial Flux Prediction, time = 0



$$q = h(T_g - T_{amb}) \begin{cases} h, \ convection \ coefficient \\ T_g, \ hot-gas \ temperature \\ T_{amb}, \ Ambient \ temperature \end{cases}$$

Thermal Cycle Life

- In order to ensure that Casper can handle an extensive testing campaign, its thermal cycle life must be evaluated
  - 14 required hot fires + 6 uncertainty = 20 requirement
- Due to high thermal and mechanical stresses during operation, fatigue can set in quickly
- S/N curves for 304LSS are from an austenitic stainless steel fatigue Argonne National Laboratory paper[1]
  - Strain Rate is assumed to be the highest interval due to the fast rate of thermal accumulation



Parameter	*Value*	*Units*	*Source*
Max Temp on Chamber Wall	660	°C	Thermal Analysis
Equivalent Thermal Stress	1883.21	MPa	Properties from MIL-HDBK-5J
Mechanical Stress	3.447	MPa	(Radial) Chamber Pressure
Total Stress	1886.66	MPa	
Number of Cycles	~28	--	
Margin	0.4	--	

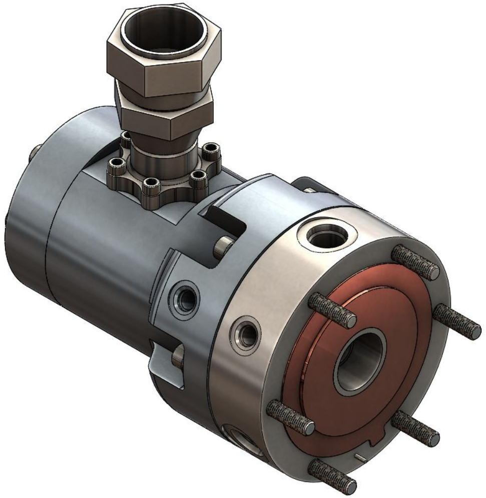
Casper Structural Calculations 5/17/2020

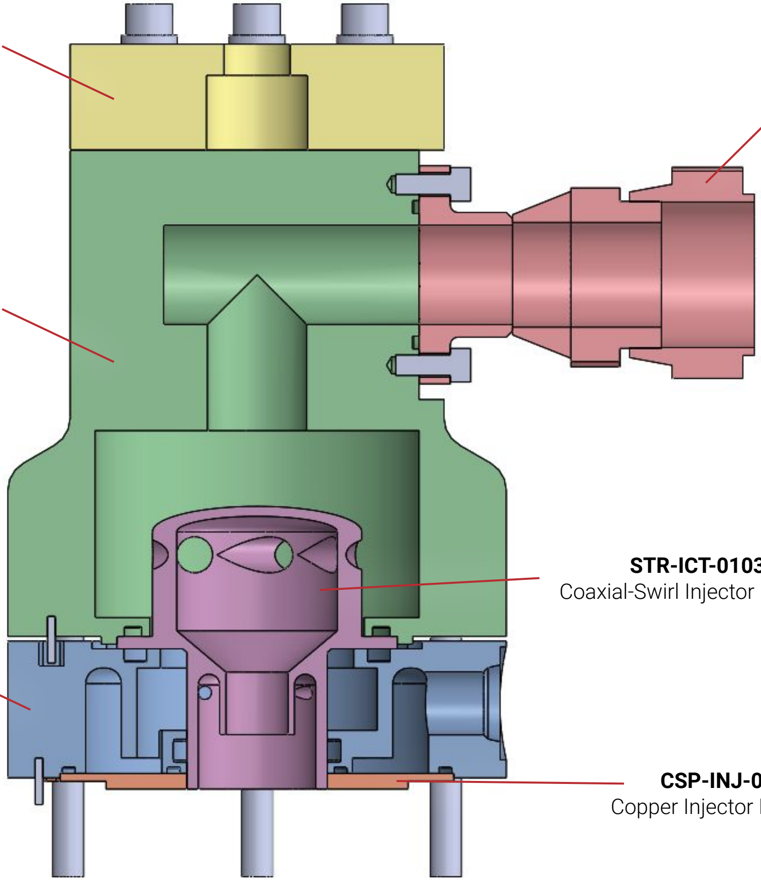
[1]Development of Fatigue Design Curve for Austenitic Stainless Steels in LWR Environments: A Review by Chopra [Argonne National Laboratory]

Injector Head Design

Injector dome and head

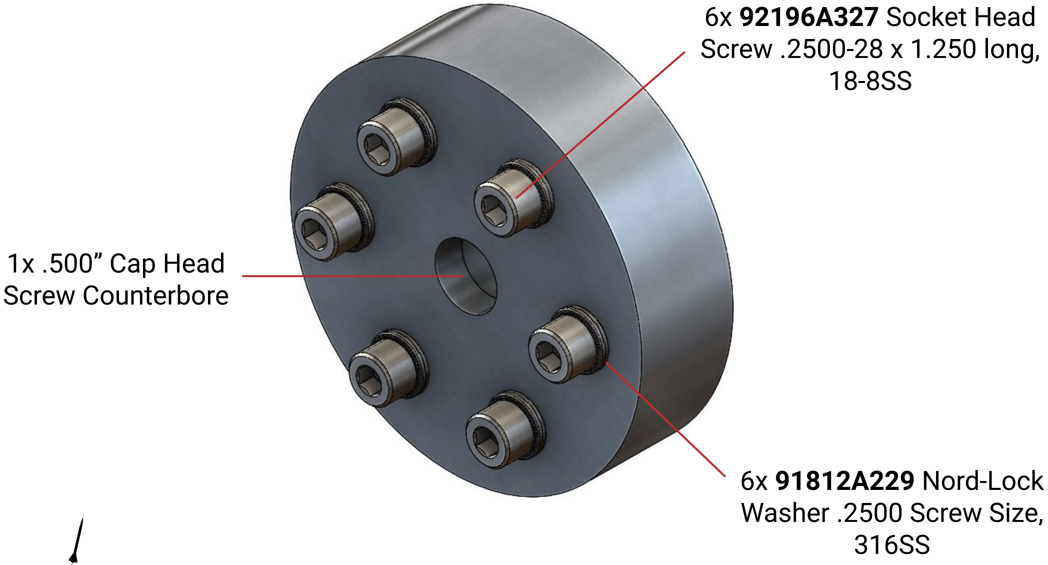
Injector Head Design Overview

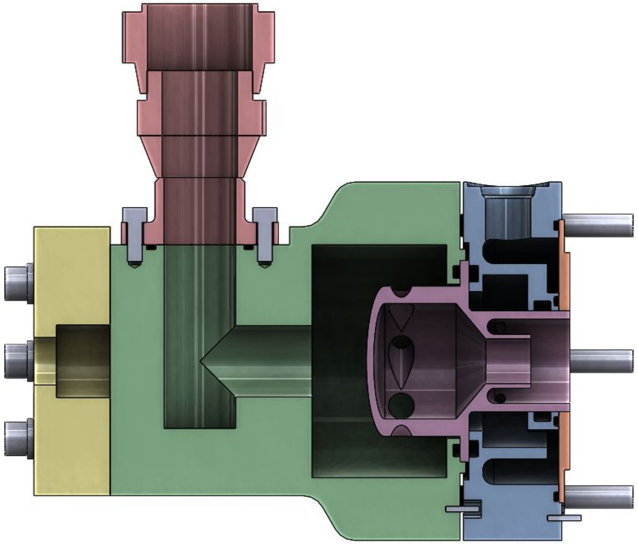




HTS Mounting Block

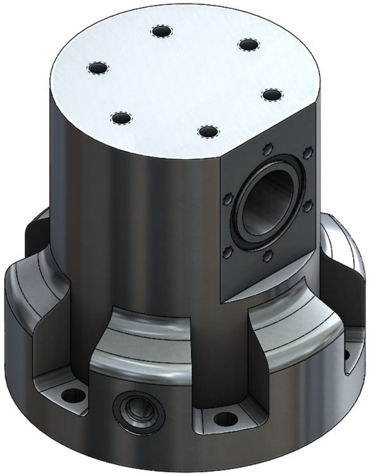
- Capable of directly mounting to HTS' 10,000 lbf load cell
- Casper is capable of being removed from the stand without the need to rotate the entire engine (like Iron Lotus)
- Allows for the entire engine assembly and removal to happen in the field with six screws
- Compression loading through back of the oxidizer plenum

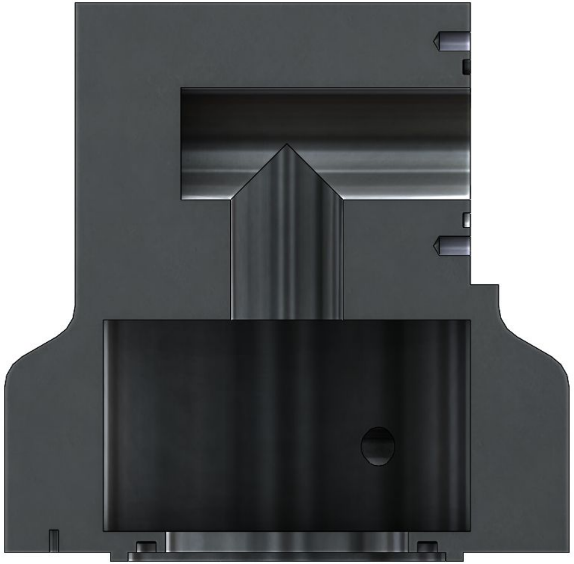


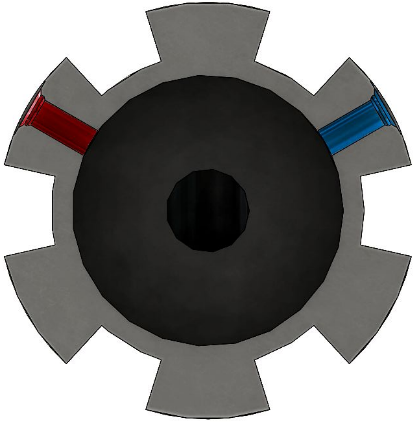


Oxidizer Plenum

- Goal is to effectively and evenly distribute oxidizer into the S1 inlet of the injector element
- Large plenum size and axial plenum inlet allow for even distribution
- Fed via a 1.000” flange fitting currently fitted to Iron Lotus
- AS5202-2 instrumentation ports read ox plenum pressure and plenum temperature





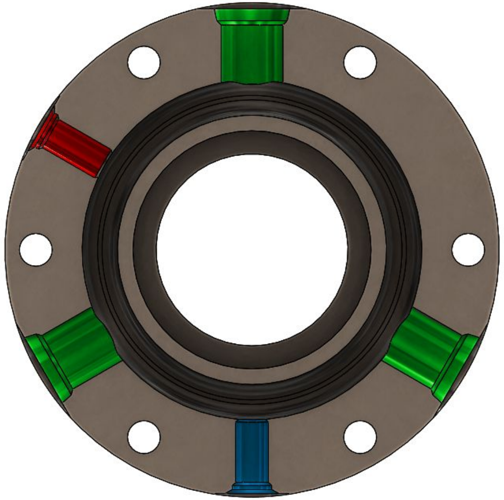


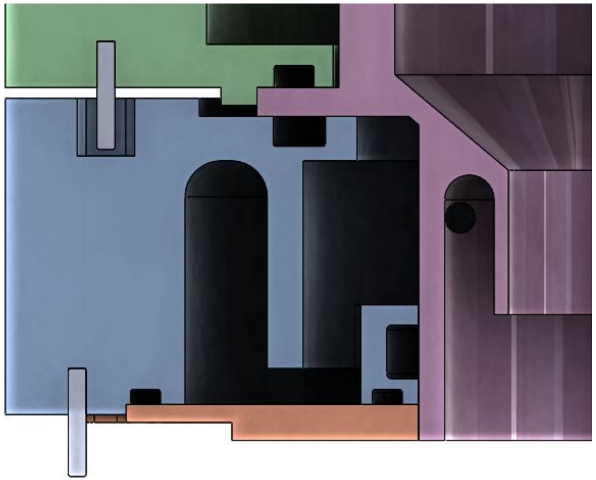
Section A-A

Fuel Plenum

- Fuel Plenum Goals
  1. Effectively and evenly distribute fuel into the S2 inlet of the injector element
  2. Provide passive cooling to the injector faceplate and polymer o-rings

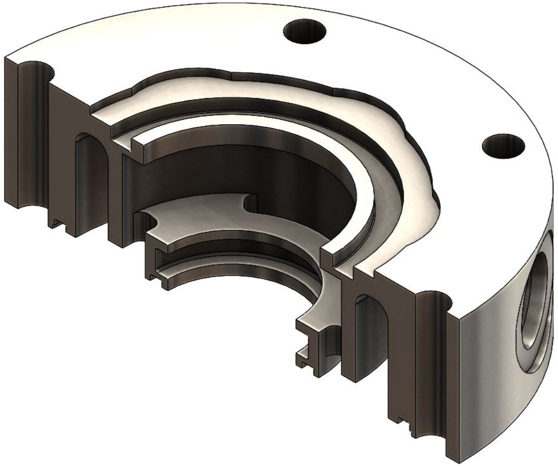
- Indirect plenum feed causes fuel to flow along the injector faceplate and seals, cooling them
- Made of 304L SS due to proximity to high temperatures
- Fed via three SAE J1926-6 ports coming from a distribution manifold
- Two AS5202-2 instrumentation ports read fuel plenum pressure and plenum temperature

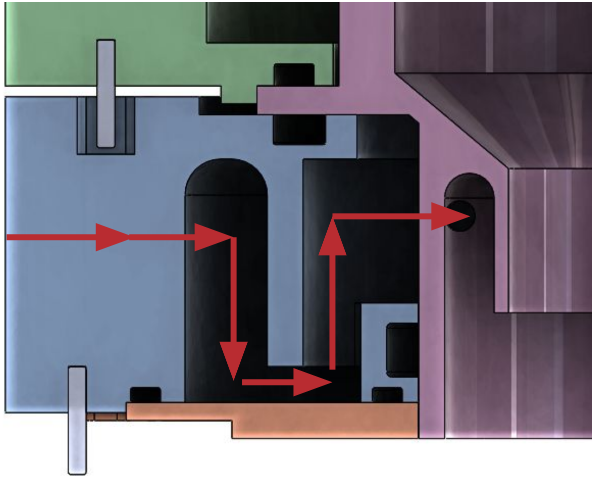




Fuel Plenum (cont.)

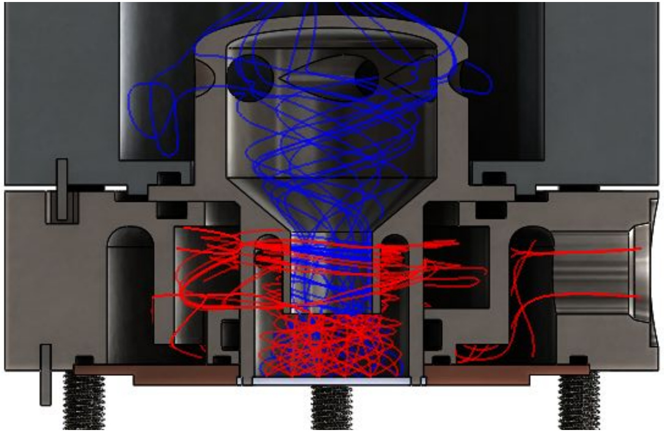
- Using a central bridged design, the center gland seal is able to be supported with fuel flow around it
- The indirect flow path of the fuel cools the faceplate and seals touching the hot gas

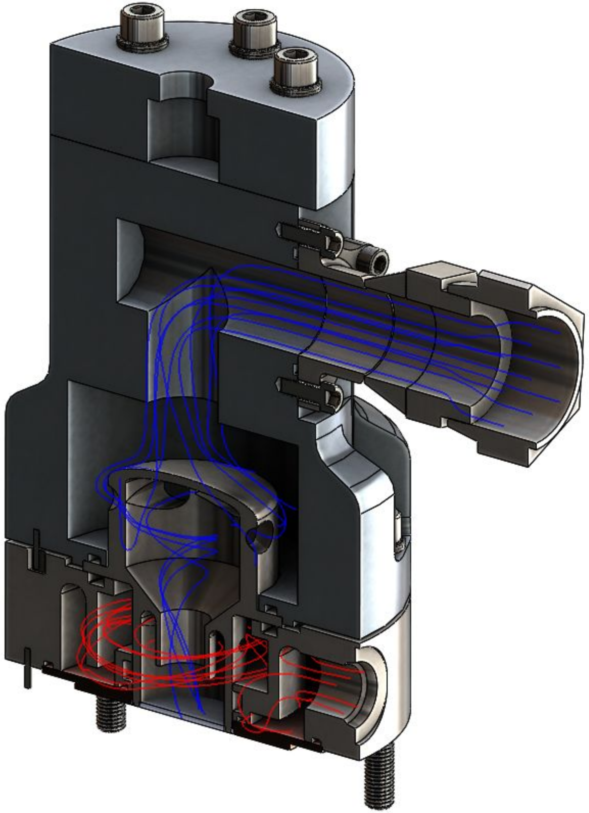




Flow Paths

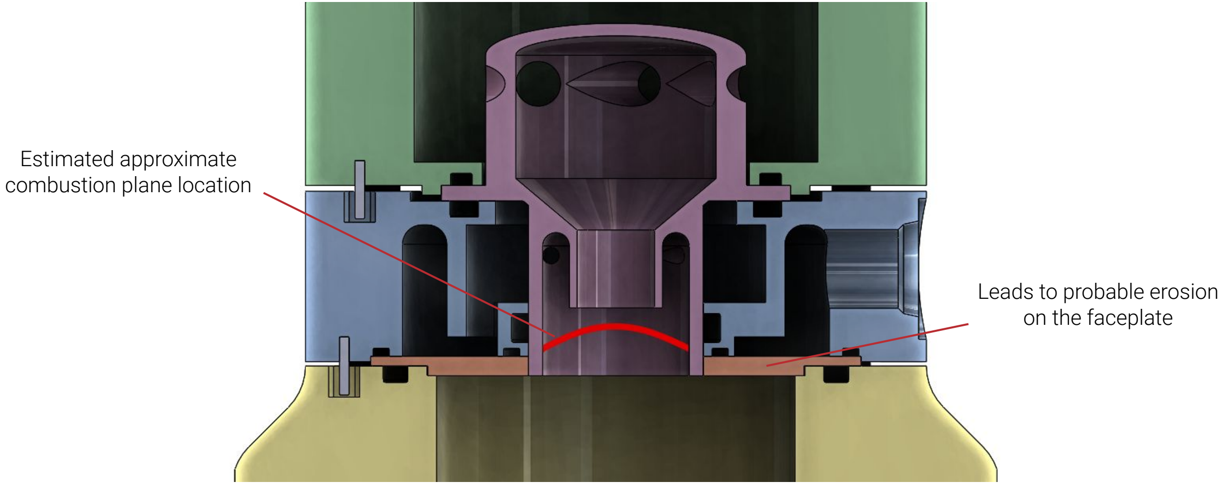
Images to demonstrate the approximate flow path of the fuel and oxidizer into the element





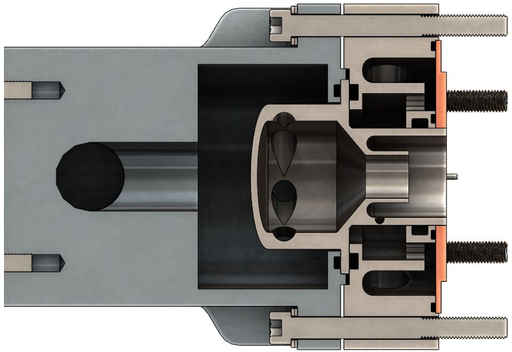
Copper Injector Faceplate

- One of the biggest concerns with coaxial-swirl injectors is element and faceplate erosion due to high combustion planes
- To ensure that faceplate corrosion won't be an issue for Spectre, Casper has the capability of changeable faceplates that can be swapped out and changed based on findings from testing
  - Erosion can be visually determined & measured by tools in EPIC (Engineering Product Innovation Center)
  - Actively cooled by the IPA in the plenum. Can include cooling channels in the future if necessary
- Made of C110 copper for maximum heat transfer capability (material going to be used on Spectre)



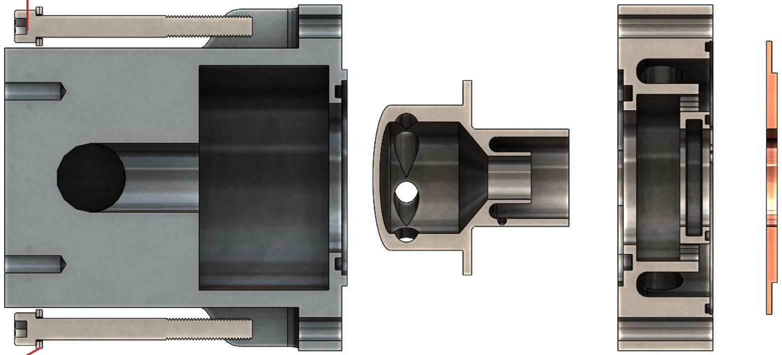
Attachment

- Six radial bolts hold the injector assembly to the chamber assembly
  - On-site swappable injector elements
  - Separate from chamber extension bolts, minimizes disassembly of the entire engine
- Vibration resistance is handled through Nord-Lock locking washers
- A required installation torque is given based on Nord-Lock installation torques. Maintains positive margin



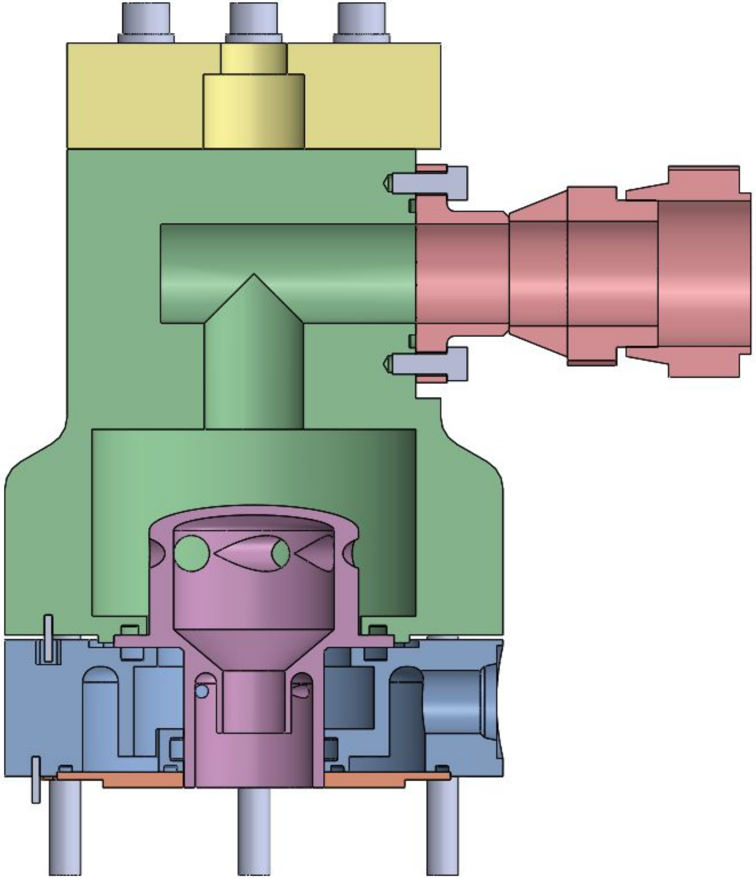
Parameter	*Value*	*Units*	*Source*
Number of Bolts	6	--	
Bolt Ultimate Tensile Strength	70,000	psi	McMaster 92196A332
Bolt Installation Torque	6.8±1.7	ft-lbf	Nord-Lock; NASA-RP-1228
Maximum Operational Load/Bolt	285.021	lbf	Pressure Balance
Margin	0.757	--	

Casper Structural Calculations 5/17/2020



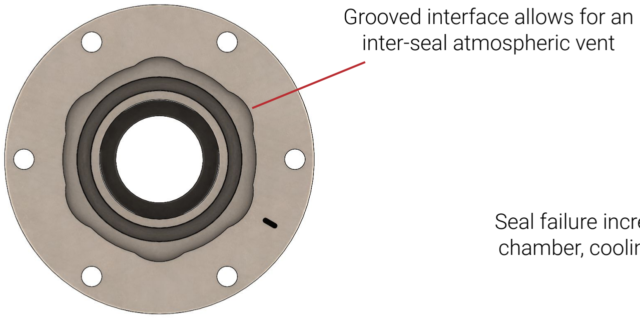
Concentricity & Clocking

- Concentricity of components are handled through toleranced, circular lips and grooves on each of the components
  - Consistent method with Chamber concentricity
- Clocking is primarily handled through a press-fit dowel pin sliding into a clearance-fit dowel slot
  - Ease of manufacturing and ease of assembly
  - Consistent method with Chamber clocking
- Faceplate clocking is handled through an offset machined tab and slot

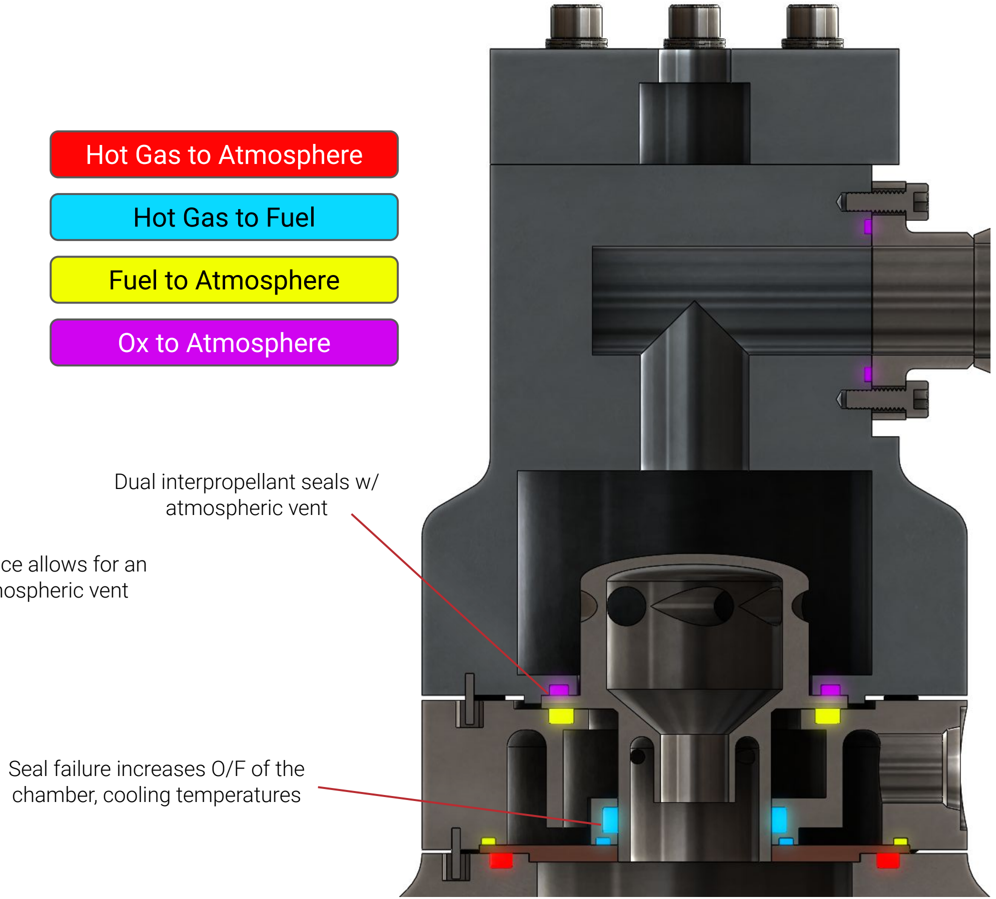


Sealing

- Buna-N70 o-rings are used for compatibility and cost
- Melting is acceptable
    - Hot Gas to Atmosphere failure is benign
    - Hot Gas to Fuel failure is failsafe (decrease O/F ratio)
- Double interpropellant seals are incorporated with atmospheric vents for added safety



CSP-INJ-0002



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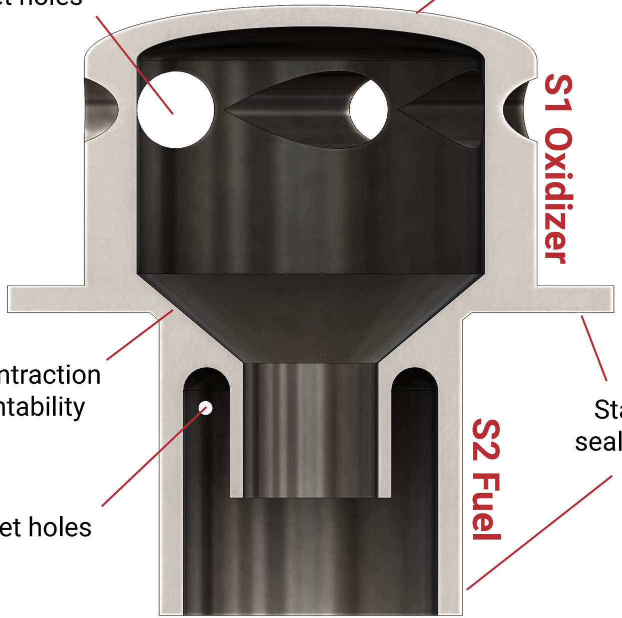
Injector Element Design

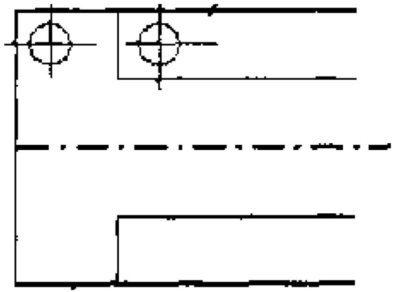
Design Overview

- Casper and Spectre will feature a Coaxial-Swirl Injector type
  - Driven by high efficiency requirements for Spectre
  - Lower manufacturing cost than similarly performing impinging jet injectors (IL, LD2)
- Elements will be additively manufactured out of 301SS on the GE Mlab DMLS printer in EPIC
- Casper will feature a single element to Spectre's three
- Common sealing surfaces allow for interchangeable elements

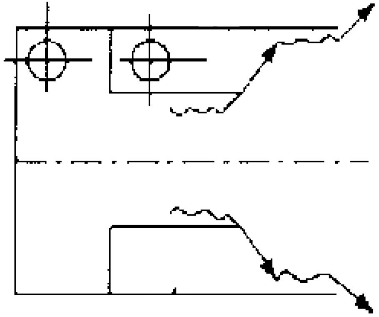


Coaxial-Swirl Basics

- Made up of two “stages”
  - S1: central hole
  - S2: outer annulus
- Coaxial-Swirl injectors utilize a tangential component of velocity to the fuel and oxidizer to give them a swirling motion
- Swirling results in a conical exit to the fuel/oxidizer
  - How these cones interact determines the type of injector
  - Casper utilizes an internal mixing configuration meaning S1 (oxidizer) mixes with S2 (fuel) before exiting the element
    - Superior mixing, combustion efficiencies, and stable combustion



External Mixing

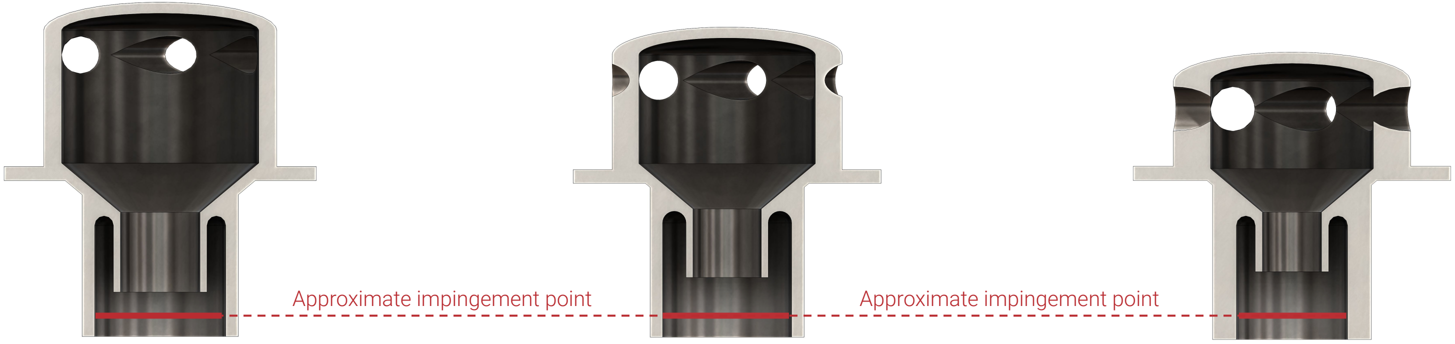


Internal Mixing

Design and Dynamics of Jet and Swirl Injectors by Bazarov, Yang, Puri [Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis, and Design]

Testing Path

Aggressive Impingement | **Nominal Impingement** | **Softer Impingement**



STR-ICT-0004
S1: 80°
S2: ??
Combined: ??

STR-ICT-0003
S1: 70°
S2: ?? (163°)
Combined: ?? (123°)

STR-ICT-0005
S1: 60°
S2: ??
Combined: ??

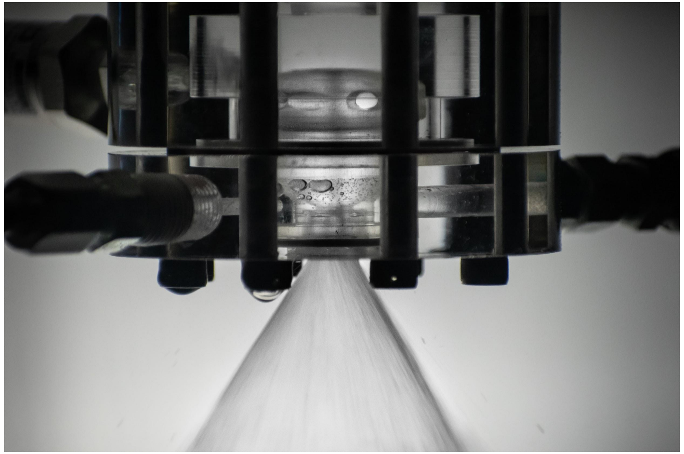
- Coaxial-Swirl injectors are tough to design for due to a large number of variables and effects [Appendix]
- Ultimately, cone angle is the easiest and most encompassing. Adjusting other variables just change cone angles
- With newfound discharge coefficient data, S1 cone angles can be calculated. S2 and combined cone angles are harder to define and can only be estimated
- Will be testing at least three configurations: nominal impingement, soft impingement, aggressive impingement

Injector Element Parameters

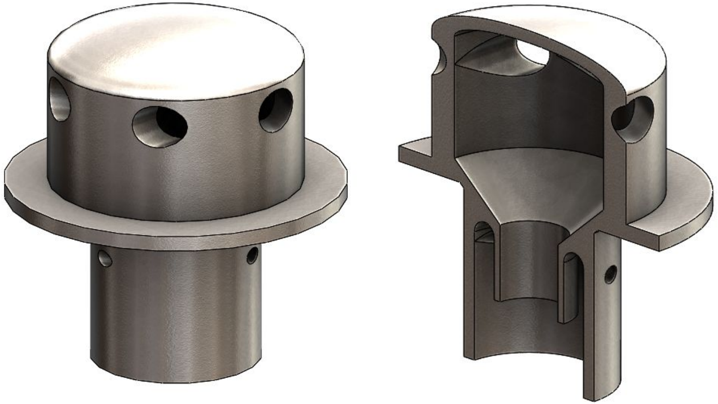
Value	*0103*	*0104*	*0105*	*Units*
Cone Angle S1/S2/Combined	70°/??/??	80°/??/??	60°/??/??	deg
Geometric Characteristic Parameter (Abramovich #) S1/S2	1/23.66	1.5/23.66	0.6/15.53	--
Coefficient of Discharge S1/S2	0.363/0.0248	0.275/0.0248	0.513/0.0357	--
Mixing Residence Time	0.000532	0.000502	0.0005	sec
Inlet Hole Quantity S1/S2	6/3	6/3	6/3	--
Inlet Hole Diameter S1/S2	0.288/0.106	0.276/0.106	0.314/0.108	in
Coefficient of Fullness S1/S2	81.5/27.75	74/13.5	91/18.6	% Full

Testing Path (cont.)

- Low pressure waterflows of SLA printed elements on a homebuilt stand
- Elements will be tuned to match required mass flow rates and correlations between cone angles and geometric parameters are recorded
- Final selected waterflow articles will be retested with DMLS before being hotfired
- Testing for combustion stability, combustion efficiencies, and thermal data as discussed



S1 initial waterflow test conducted on November 16, 2019



Further Test Campaign discussions will be held in a Casper TRR near the end of the summer

Logistics

Procurement & Manufacturing

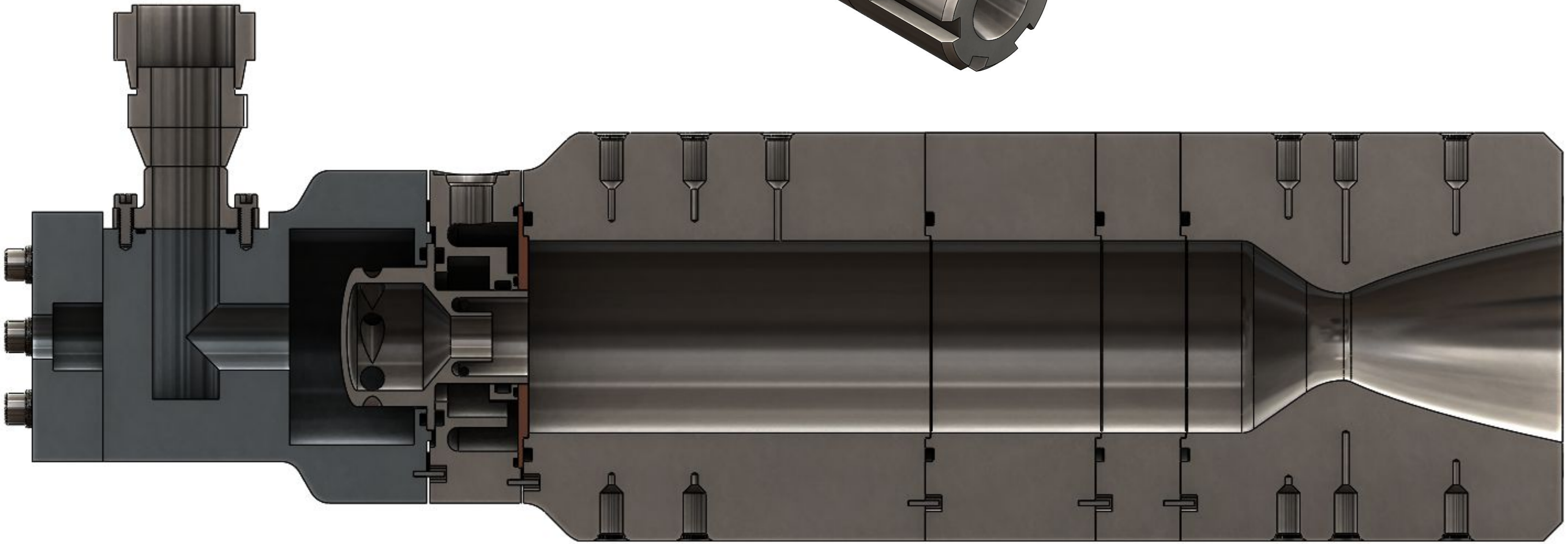
- Manufacturing will be completed in EPIC (Engineering Product Innovation Center)
- Casper was designed to decrease as much cost as possible

Item	*Source*	*Unit Cost*	*Units*	*Total*
304L Stainless Steel Rod [Ø5.000 x 19.500 Long]	Yarde Metals	$234.87	1	$234.87
6061-T6511 Aluminum Rod [Ø4.750 x 19.576 Long]	Yarde Metals	$72.44	1	$72.44
32009631 C110 Copper Sheet [12.000 x 12.000 x .125 Thick]	MSC Direct	$85.83	1	$85.83
92196A561 Socket Head Screw, 18-8SS [.250-20 UNC-3A x 5.000 Long]	McMaster-Carr	$2.71	6	$16.26
92196A332 Socket Head Screw, 18-8SS [.250-28 UNF-3A x 2.500 Long]	McMaster-Carr	$5.86	1	$5.86
92196A327 Socket Head Screw, 18-8SS [.250-28 UNF-3A x 1.250 Long]	McMaster-Carr	$8.04	1	$8.04
91812A229 Nord-Lock Washer, 316SS [.250 Screw Size]	McMaster-Carr	$9.28	5	$46.40
90145A417 Dowel Pin, 18-8SS [Ø.0625 x .375 Long]	McMaster-Carr	$9.67	1	$9.67
9452K161 [-232] Buna-N 70A O-Ring	McMaster-Carr	$10.69	1	$10.69
9452K96 [-225] Buna-N 70A O-Ring	McMaster-Carr	$14.37	1	$14.37
9452K36 [-216] Buna-N 70A O-Ring	McMaster-Carr	$9.05	1	$9.05
9452K141 [-135] Buna-N 70A O-Ring	McMaster-Carr	$11.86	1	$11.86
9452K114 [-027] Buna-N 70A O-Ring	McMaster-Carr	$8.90	1	$8.90
9452K77 [-023] Buna-N 70A O-Ring	McMaster-Carr	$6.54	1	$6.54

Total: **$540.78**

Path Forward

1. Implement feedback from industry on this review
2. Develop ANSYS Structural models to check stresses in an internal review
3. Begin work on preliminary Spectre design
4. Test Readiness Review near the end of summer (industry)
5. Manufacture
6. Waterflow test articles
7. Hot Fire
8. Repeat



Appendix

Appendix Contents

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BURPG Overview

The Boston University Rocket Propulsion Group or BURPG is a student-led and organized group that develops industry-level rockets and liquid rocket engines with the goal of creating a liquid engine to fly a rocket to the Karman Line--the international recognized edge of the atmosphere and start of space.

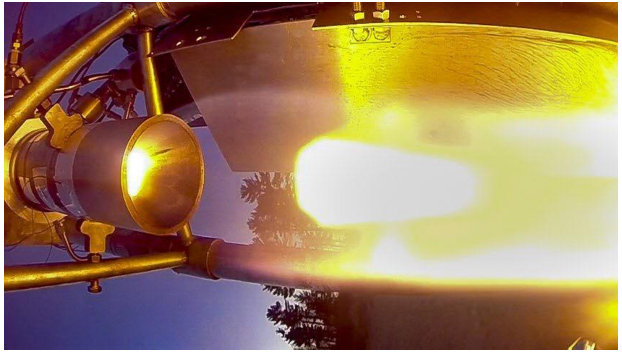
In the process, our unique team-based learning approach consistently creates some of the top aerospace engineering graduates ready to take on the future space industry.

BURPG History

We have over twenty years of technical history. Starting in 2002, the BU Rocket Team began developing custom solid rocket motors and large high-powered rockets at a time when university rocketry programs didn't exist.

In 2013, we rebranded as the BU Rocket Propulsion Group and began chasing our goal of reaching space. Developing custom hybrid rockets, we developed the most powerful hybrid engine ever tested by a university. A record that still holds to this day.

In an effort to develop top-tier engineers, BURPG now develops liquid engines--the most complex engine type--and rockets to fly them on. In Spring 2017, BURPG tested Iron Lotus, the most powerful liquid engine tested by undergraduates.



BURPG Legacy

Since BURPG was founded, we have continued to produce some of the industry's top engineers through BURPG's team-based, goal-driven engineering process that reflects how industry operates.

Our team has gone on to work and intern for some of the world's most cutting-edge companies. We train our team to not only be able to work for these top companies but also be successful in them.

Check out some of the places our team has worked:

BURPG Terms & Phrases

- Mk.I - Mk.V
  - Our hybrid rocket engines developed up to 2016
- Starscraper
  - Our previous spaceshot rocket attempt. Now retired
- Lotus Dev 1 (LD1)
  - Our first liquid engine developed and fired in 2016
- Iron Lotus (IL)
  - A 2,500 lbf thrust heatsink test-bed engine for our LD2 engine
  - Most powerful liquid engine hotfired by a university (2017)
- Lotus Dev 2 (LD2)
  - Our 2,500 lbf thrust flight optimized, regen-cooled engine
  - Will be flying on the Pursuit launch vehicle
- Low Altitude Demonstrator (LAD)
  - A large solid rocket to test spaceshot technologies
- Horizontal Test Stand (HTS)
  - Our 10,000 lbf thrust liquid engine test stand
- Citadel
  - Our 1,500 lbf thrust gaseous engine test stand
- Mortise
  - Our 450 lbf thrust gaseous methane, gaseous oxygen engine
- ASTRo
  - A High-Powered Rocket with active aerodynamic controls
  - A test platform for controls systems of Starscraper and Pursuit
- Pursuit
  - The first liquid rocket for the team
  - Flying to over 60km and powered by LD2
  - The most complex vehicle developed by a university
- Spectre
  - The most powerful engine developed by BURPG
  - Over 3,000 lbf of thrust
  - To power our future space shot rocket
- Casper
  - A 1,000 lbf heatsink test-bed engine for our Spectre engine

Spaceshot Trade Study Revision

- A reflection on how the team was sizing its upcoming spaceshot realized there was a need for a higher accuracy model of sizing vehicles and simulating them.
- Previous flight dynamics methods and trade studies resulted in high runtime, high error, and no way of predicting the mass of a vehicle.
- Two tools were developed:
  - Spaceshot Sizing Worksheet (Excel)
    - Takes in system level inputs (SL Thrust, Chamber Pressure, Diameter, etc.) and outputs mass and length values.
    - Features full pressure drop, pressurant system, and tank sizing calculators.
    - A 1.5x factor (based off of Starscraper design vs. actual) is applied to an optimized configuration resulting in an achievable construction mass.
  - Sparrow (MATLAB)
    - Highly accurate 1DOF simulation utilizing ODE solvers for fast runtime and accurate results.
    - Outputs performance such as apogee, time to burnout, max velocity, etc.
- Git repository: https://phab.burpg.space/source/Talon/

Spaceshot Trade Study Results

- Hundreds of results were run and compiled on the Drive.
- Single-stage and two-stage vehicles were tested at varying input parameters.
- Selected spaceshot configuration:

Sea Level Thrust	6,000	lbf
Chamber Pressure	500	psia
ηC*	90	%
ηCf	98	%
OF Ratio	4.25	
Tank Diameter	14	in
Length Ox Tank	15	ft
Pressurant Temperature	300	°F

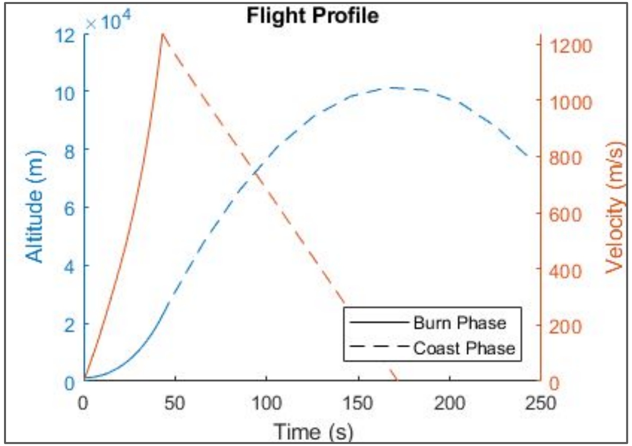


Figure 1: Flight profile of the chosen spaceshot configuration

- A full writeup on the process of the trade study is on phab including a fallback design: https://phab.burpg.space/w/projects/ghost_series/spectre/trade_study/

BURPG

Chamber Equation-Driven CAD

"d1"= "d2" * 2.209'ft

"d2"= 39.3701* 2 * ("A2" / (3.14159)) ^ 0.5'ft

"D3@Sketch 1" = "d2" * 1.5 * 0.5

"D4@Sketch 1" = "d2" * 0.5 * 0.4

"d3"= 39.3701 * 2 * ("A2" * "AreaRatio" / (3.14159)) ^ 0.5'ft

"ChamberLength" = 8.603'in

"ConvergenceAngle" = 35'degrees

"D9@Sketch 1" = "ConvergenceAngle"

"BellRatio"= 0.8

"Mdot"= 2.026'kg/s

"P1"= 3447378.647'N/m^2

"k"= 1.1773

"R"= 201.958'N*m/kg*K

"T1"= 3120.25'K

"A2"= ("Mdot" * "V2") / "SonicVelocity"'m^2

"D10@Sketch 1" = "d1"

"AreaRatio"= 7.2214

"D2@Sketch 1" = "d2"

"ConeLength"= ("d3" - "d2") / (2 * tan (15))'in

"D12@Sketch 1" = "ChamberLength" * "LstarRatio"+ 0.3521

"V2"= 0.295133'm^3/kg

"SonicVelocity"= 1079.4'm/s

"D13@Sketch 1" = 1 / 4

"LstarRatio"= 0.75

"D5@Sketch 1" = "ConeLength"

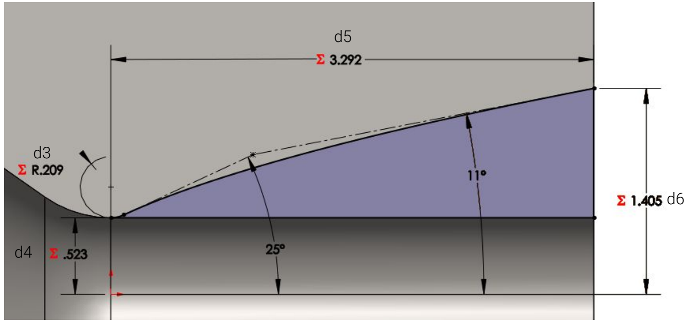
"D3@Sketch4"=0.4*"d2"/2

"D4@Sketch4"="d2"/2

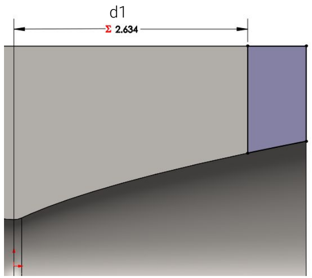
"D5@Sketch4"="ConeLength"

"D6@Sketch4"="d3"/2

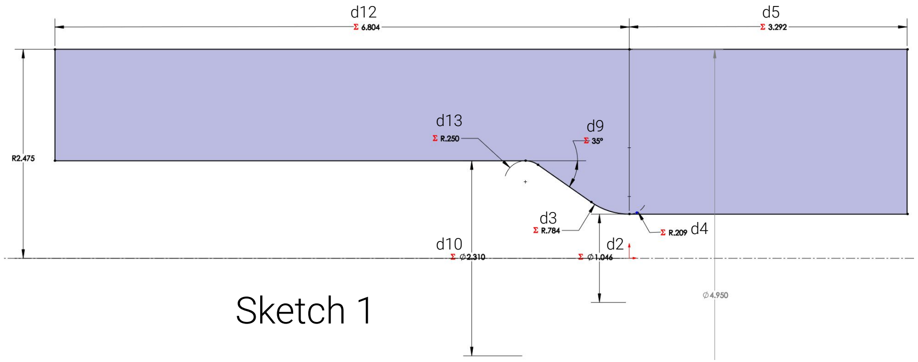
"D1@Sketch19"="BellRatio"*"ConeLength"



Sketch 4



Sketch 19



Sketch 1

Chamber Bolt Calculations

- Pulled from the Casper Structural Calculations spreadsheet
- Utilizes the clamping force and torque equations from NASA-RP-1228
- Factors of Safety and maximum preload percentage found in NASA-STD-5005D

$T = KFd$, where T denotes torque, F denotes axial load, d denotes bolt diameter, and K(torque coefficient) is a calculated value from the formula:

$$K = \left(\frac{d_m}{2d}\right) \frac{\tan \psi + \mu \sec \alpha}{1 - \mu \tan \psi \sec \alpha} + 0.625\mu_c$$

as given in reference 14 (p. 378) where

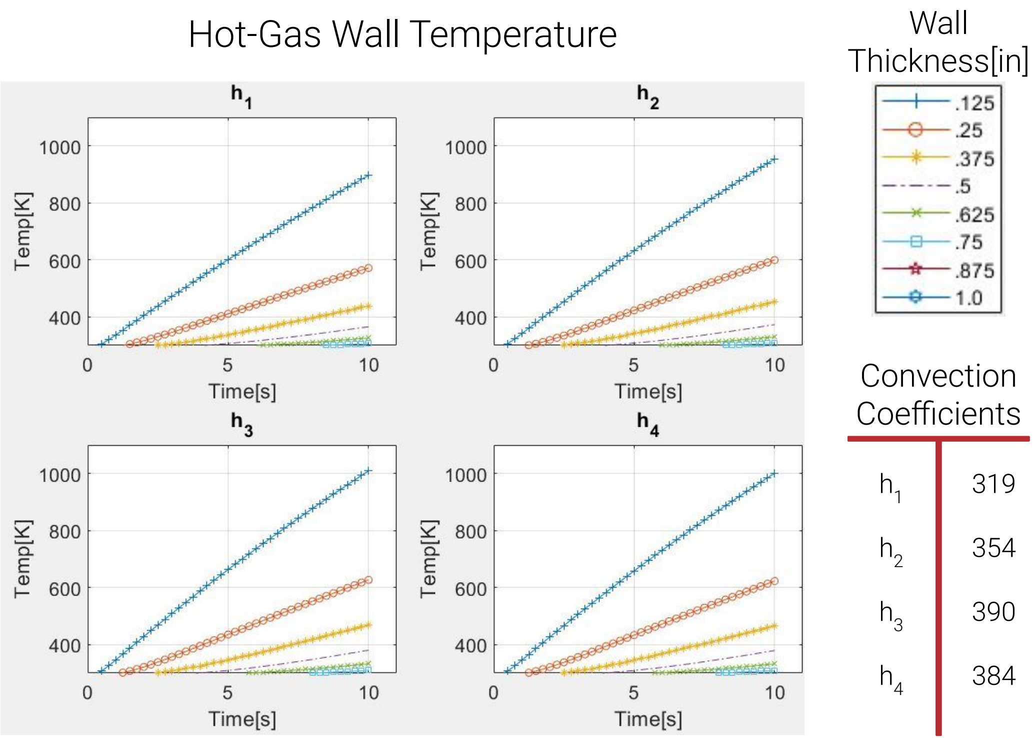
d_m	thread mean diameter
ψ	thread helix angle
μ	friction coefficient between threads
α	thread angle
μ_c	friction coefficient between bolthead (or nut) and clamping surface

Chamber Bolt Calculations

Parameter	Variable	Metric Value		Imperial Value		Source	Notes
Ultimate Factor of Safety		3	--	3	--	NASA-STD-5005D	
Yield Factor of Safety		2	--	2	--	NASA-STD-5005D	
Bolt Tensile Ultimate Strength		4.83E+08	Pa	70000	psi	McMaster 92196A561	
Bolt Tensile Yield Strength		2.07E+08	Pa	30000	psi	http://www.tatoolsonline.c	
Maximum Allowable Preload Stress		1.45E+08	Pa	21000	psi	NASA-STD-5005D	
Bolt Minor Diameter	*d*	0.00479	m	0.1887	in	https://www.engineersedg	.250-20-3A Minor Diameter
Bolt Effective Cross Section		1.80E-05	m^2	0.02797	in^2		
Maximum Allowable Clamping Force	*F*	2612.398	N	587.291	lbf		
Bolt Thread Mean Diameter	*dm*	0.00545	m	0.2147	in	https://www.engineersedg	.250-20-3A Min Pitch Diamete
Thread Helix Angle	*ψ*	3.400	deg	3.400	deg	US Department of Comm	
Friction Coefficient Between Threads	*μStSt*	0.740	--	0.740	--	NASA-RP-1228	
Thread Angle	*α*	60	deg	60	deg	UNC Standard	
Friction Coefficient Between Bolthead and Surface	*μAlSt*	0.740	--	0.740	--	NASA-RP-1228	
Maximum Allowable Torque	*T*	17.814	N*m	13.139	ft*lbf	NASA-RP-1228	
Nord-Lock Installation Torque		6.915	N*m	5.1	ft*lbf	Nord-Lock Torque Guide	316SS Nord-Lock Installation
Torque Installation Tolerance		25	%	25	%	NASA-RP-1228	Torque Wrench Tolerance
Torque Specification		**9.220**	**N*m**	**6.800**	**ft*lbf**		
(±)		**2.305**	**N*m**	**1.700**	**ft*lbf**		
Minimum Clamping Force		1014.044	N	227.966	lbf		
Number of Bolts		6	--	6	--		
Chamber Pressure		3.45E+06	Pa	500	psi	Casper Workbook 5/16/2	
(Chamber - Throat) Cross Sectional Area		2.15E-03	m^2	3.332	in^2		
Chamber Apparent Force		7410.737	N	1666	lbf		
Diverging Nozzle Apparent Force		2921.147	N	656.7	lbf	Casper Workbook 5/16/2	
Total Maximum Load		4489.590	N	1009.300	lbf		
Maximum Load to Withstand		748.2650127	N	168.217	lbf		
Maximum Operational Load		**265.779**	**N**	**59.749**	**lbf**		
Maximum Stress in Each Bolt		1.47E+07	Pa	2136.486	psi		
Yield Margin		**6.021**	--	**6.021**	--		
Ultimate Margin		**9.921**	--	**9.921**	--		

Transient Analysis - Outer Wall Temp

Hot-Gas Wall Temperature



Convection Coefficients

h_1	319
h_2	354
h_3	390
h_4	384

BURPG

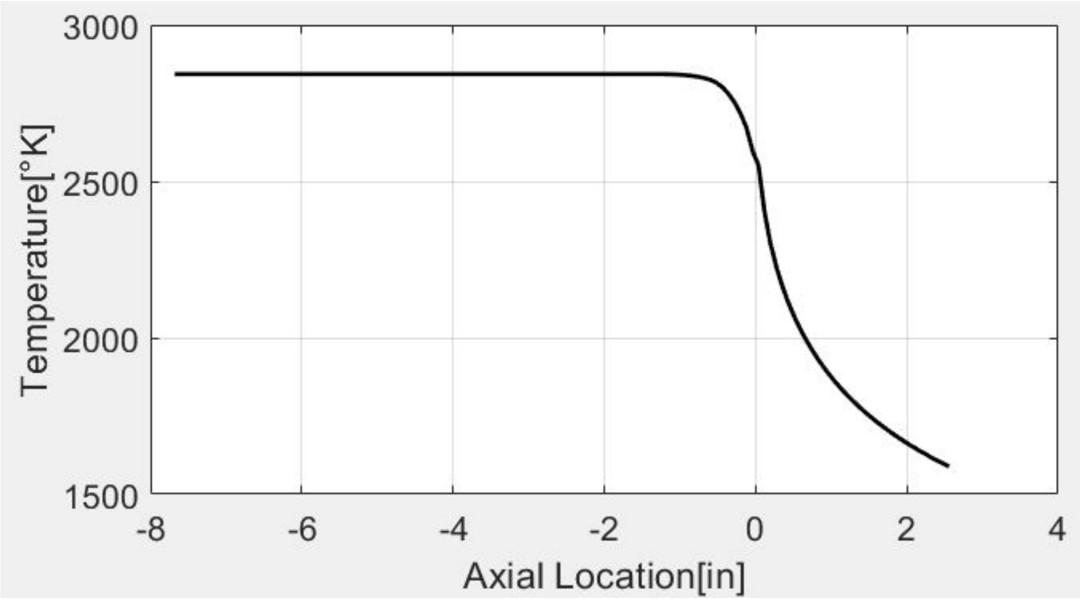
Transient Analysis - Bartz Correlation

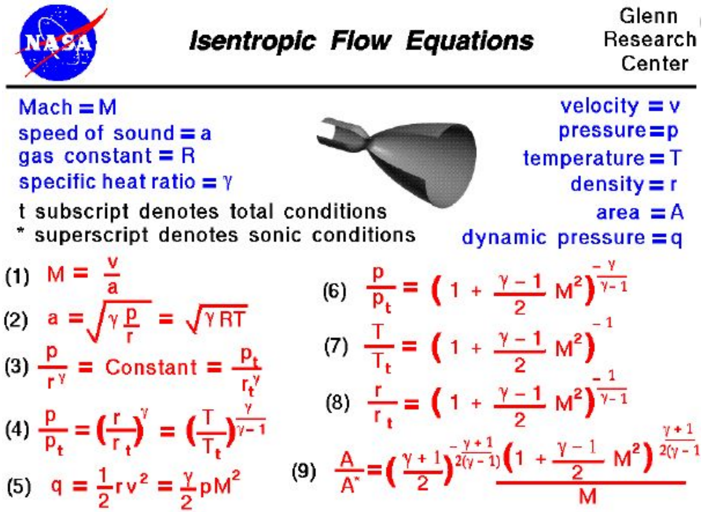
Bartz - Convective HT Coefficient

- Solves combustion flow convective HT coefficient at inner combustor wall
- Inputs: chamber geometry, flow conditions, and fluid properties

$$h_g = [\frac{0.026}{D_t^{\frac{1}{5}}}(\frac{mu^{\frac{1}{5}}C_p}{Pr^{\frac{3}{5}}})_{ns}(\frac{(p_c)_{ns}g}{c*})^{\frac{4}{5}}(\frac{D_t}{R})^{\frac{1}{10}}](\frac{A_t}{A})^{\frac{9}{10}}\sigma$$

Chamber Temperature Profile

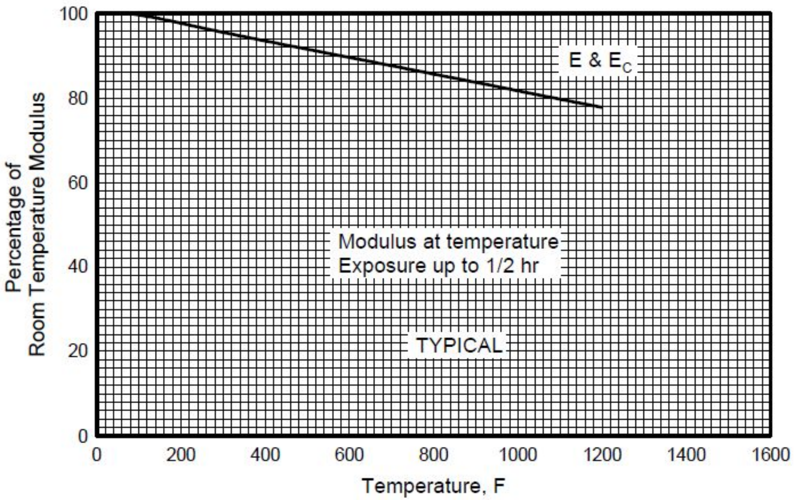


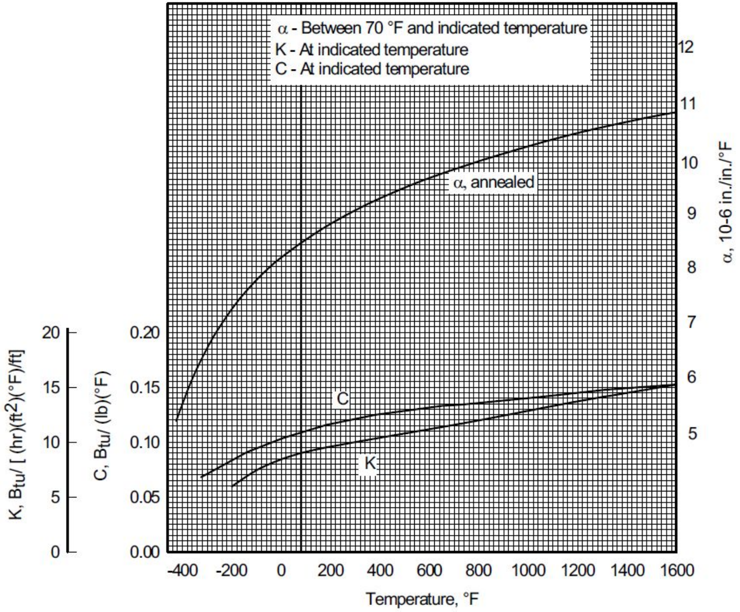


Thermal Cycle Calculations

- Pulled from the Casper Structural Calculations spreadsheet
- Utilizes material property data from MIL-HDBK-5J for austenitic stainless steel
- Utilizes S/N curve from an austenitic stainless steel fatigue Argonne National Laboratory paper

Thermal Cycle Calculations							
Parameter	Variable	Metric Value		Imperial Value		Source	Notes
Max Temperature on Chamber Wall		660	degC	1220	degF	Where 304LSS i	
Young's Modulus [@1220°F]	*E*	1.56E+11	Pa	22620000	psi	MIL-HDBK-5J [F	
Thermal Expansion Coefficient [@1220°F]	*α*		m/m/°C	0.0000105	in/in/°F	MIL-HDBK-5J [F	
Equivalent Thermal Stress	*σ*	1883.210	MPa	273136.5	psi		
Chamber Pressure		3.447	MPa	500	psi		
Total Stress		1886.657	MPa	273636.5	psi		





Injector Head Bolt Calculations

- Pulled from the Casper Structural Calculations spreadsheet
- Utilizes the clamping force and torque equations from NASA-RP-1228
- Factors of Safety and maximum preload percentage found in NASA-STD-5005D

$T = KFd$, where T denotes torque, F denotes axial load, d denotes bolt diameter, and K(torque coefficient) is a calculated value from the formula:

$$K = \left(\frac{d_m}{2d}\right) \frac{\tan\psi + \mu \sec\alpha}{1 - \mu \tan\psi \sec\alpha} + 0.625\mu_c$$

as given in reference 14 (p. 378) where

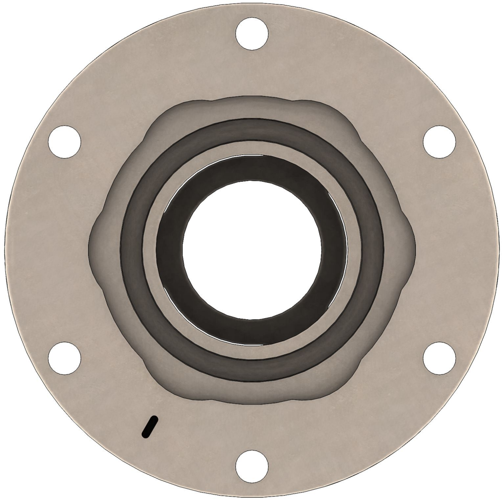
d_m	thread mean diameter
ψ	thread helix angle
μ	friction coefficient between threads
α	thread angle
μ_c	friction coefficient between bolthead (or nut) and clamping surface

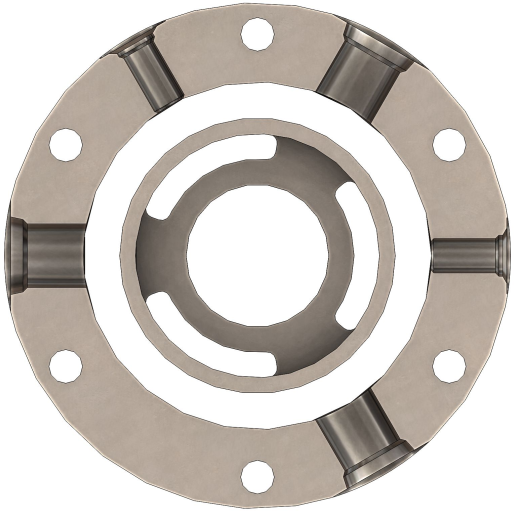
Injector Head Bolt Calculations							
Parameter	Variable	Metric Value		Imperial Value		Source	Notes
Ultimate Factor of Safety		3	--	3	--	NASA-STD-5005	
Yield Factor of Safety		2	--	2	--	NASA-STD-5005	
Bolt Tensile Ultimate Strength		4.83E+08	Pa	70000	psi	McMaster 92196	
Bolt Tensile Yield Strength		2.07E+08	Pa	30000	psi	http://www.tatool	
Maximum Allowable Preload Stress		1.45E+08	Pa	21000	psi	NASA-STD-5005	
Bolt Minor Diameter	*d*	1.01E+08	m	0.2062	in	https://www.engi	.250-28-3A Minor Diameter
Bolt Effective Cross Section		2.15E-05	m^2	0.03339	in^2		
Maximum Allowable Clamping Force	*F*	3119.412	N	701.272	lbf		
Bolt Thread Mean Diameter	*dm*	2183.588	m	0.2243	in	https://www.engi	.250-28-3A Min Pitch Diameter
Thread Helix Angle	*ψ*	2.300	deg	2.300	deg	US Department o	
Friction Coefficient Between Threads	*μStSt*	0.740	--	0.740	--	NASA-RP-1228	
Thread Angle	*α*	60	deg	60	deg	UNF Standard	
Friction Coefficient Between Bolthead and Surface	*μAlSt*	0.610	--	0.610	--	NASA-RP-1228	
Maximum Allowable Torque	*T*	20.591	N*m	15.187	ft*lbf	NASA-RP-1228	
Nord-Lock Installation Torque		6.915	N*m	5.1	ft*lbf	Nord-Lock Torqu	316SS Nord-Lock Installation Torqu
Torque Installation Tolerance		25	%	25	%	NASA-RP-1228	Torque Wrench Tolerance
Torque Specification		**9.220**	**N*m**	**6.800**	**ft*lbf**		
(±)		**2.305**	**N*m**	**1.700**	**ft*lbf**		
Minimum Clamping Force		1367.631	N	307.456	lbf		
Number of Bolts		6	--	6	--		
Oxidizer Plenum Pressure		4.06E+06	Pa	588.235	psi	Casper Workboo	
Oxidizer Plenum Projected Area		3.43E-03	m^2	5.309	in^2		
Oxidizer Plenum Apparent Force		13892.318	N	3123.111	lbf		
Fuel Plenum Pressure		4.06E+06	Pa	588.235	psi	Casper Workboo	
Fuel Plenum Projected Area		2.24E-03	m^2	3.477	in^2		
Fuel Plenum Apparent Force		9098.851	N	2045.499	lbf		
Chamber Pressure		3.45E+06	Pa	500	psi	Casper Workboo	
Chamber Cross Sectional Area		2.70E-03	m^2	4.191	in^2		
Chamber Apparent Force		9321.248	N	2095.5	lbf		
Total Engine Thrust		4830.769	N	1086	lbf	Casper Workboo	
Nozzle Apparent Force		-4490.480	N	-1009.5	lbf		
Oxidizer Cold Flow Force		13892.318	N	3123.111	lbf		
Fuel Cold Flow Force		9098.851	N	2045.499	lbf		
Dual Propellant Cold Flow Force		13892.318	N	3123.111	lbf		
Hot Fire Force		9061.550	N	2037.111	lbf		
Maximum Force to Withstand		2315.388	N	520.519	lbf		
Maximum Operational Load		**947.755**	**N**	**213.063**	**lbf**		
Maximum Stress in Each Bolt		4.40E+07	Pa	6380.291	psi		
Yield Margin		**0.175**	--	**0.175**	--		
Ultimate Margin		**0.219**	--	**0.219**	--		

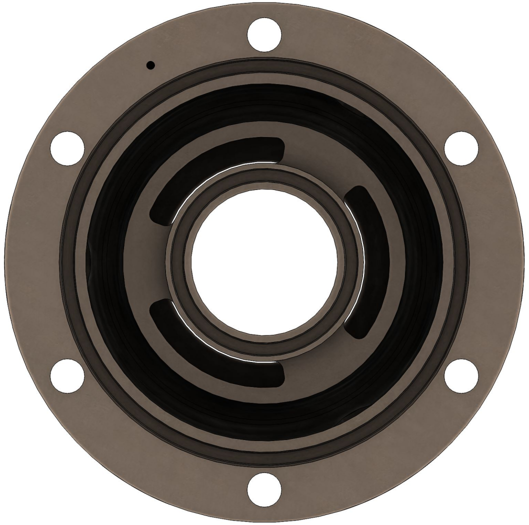
Thermocouple Acquisition

- Thermocouples to be used for Casper will be acquired through Thermocouple Technology, LLC.

Fuel Plenum More Views







Injector Element Design Process

- Design process followed the process outlined in:

  Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis, and Design: Design and Dynamics of Jet and Swirl Injectors by Bazarov, Yang, Puri

- Discharge coefficients pulled from:

  Atomization and Sprays: A Study on Discharge Coefficients of Open-Type/Closed-Type Swirl Injectors for a Liquid Rocket Engine by Ahn, Choi

Types of Coaxial-Swirl Injectors

This reference slide was pulled from the Spectre CoDR

Coaxial-Swirl injectors can be characterized by the shape of their swirl chambers

An open stage doesn't contain a distinct change in diameter between the nozzle and swirl chamber

A closed stage has a larger diameter swirl chamber with a contraction zone

- Open-Open
  - Simplest, smallest element. Mainly done with gas-gas
- Open-Closed
  - Lower circumferential velocity at nozzle of open inner stages causes $\alpha_1 < \alpha_2$
  - No mixing in $R_r \leq 1$
  - Longer recess length need for $R_r > 1$
- Closed-Closed
  - Up to $\eta c^* = 98\%$ for internal mixing
  - Open Stage 2 leads to prohibitively large element size
- Closed-Open
  - Up to $\eta c^* = 97.5\%$ for internal mixing
  - Open Stage 2 fits well

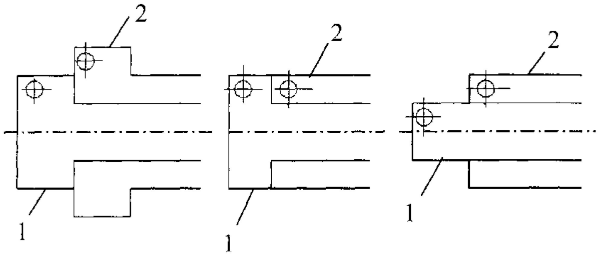
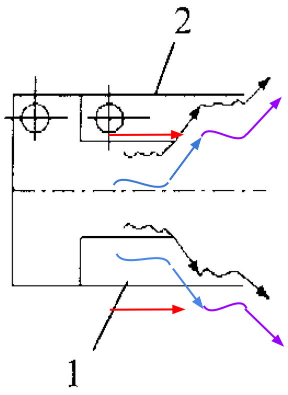


Diagram describing a closed-closed, closed-open, and open-open design (left to right)

Internal vs. External Mixing Overview

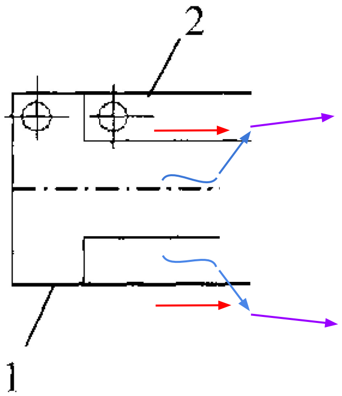
Internal Mixing

- $R_r > 1$
- Impinges inside of nozzle
- Stay time in nozzle controls internal mixing
- Shorter mixing distance in chamber
- Used contact with Stage 2 nozzle wall to help with mixing as well as gas-liquid interaction in the combustion chamber



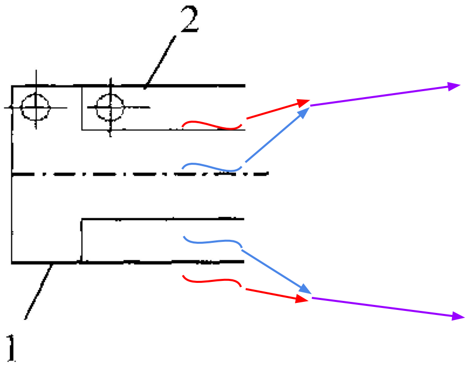
Tip Mixing

- $R_r = 1$
- Impinges at tip of nozzle
- Sensitive to slight changes in engine parameters during flight
- Hybrid of Internal and External mixing mechanisms have been observed



External Mixing

- $R_r < 1$
- Impingement inside of combustion chamber
- Requires high α_1
  - Difficult to achieve with closed Stage 1
- Atomization and chamber gas drive mixing



Decision on Geometry

- **Open Stage 1**
  - Eliminated due to issues with $\alpha_1 < \alpha_2$
- **Closed - Closed**
  - Was initially considered but eliminated due to spacing
- **Closed - Open**
  - Performs with similarly high ηc^* to Closed-Closed
  - Stage 2 fits nicely in the profile of the Stage 1 swirl chamber $R_{n2} < R_{n1}$
- **External Mixing**
  - Eliminated for poor performance
  - Requires lengthening stay-time in order to achieve proper mixing
- **Internal Mixing**
  - High efficiency
  - Stable combustion
    - ~1.5% P_{rms}/P_c
  - Shortened stay-time need for mixing in the chamber
  - High peak frequency helps mixing by creating crests in liquid sheets
    - ~2x that of tip mixing

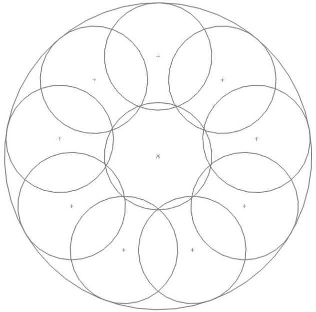
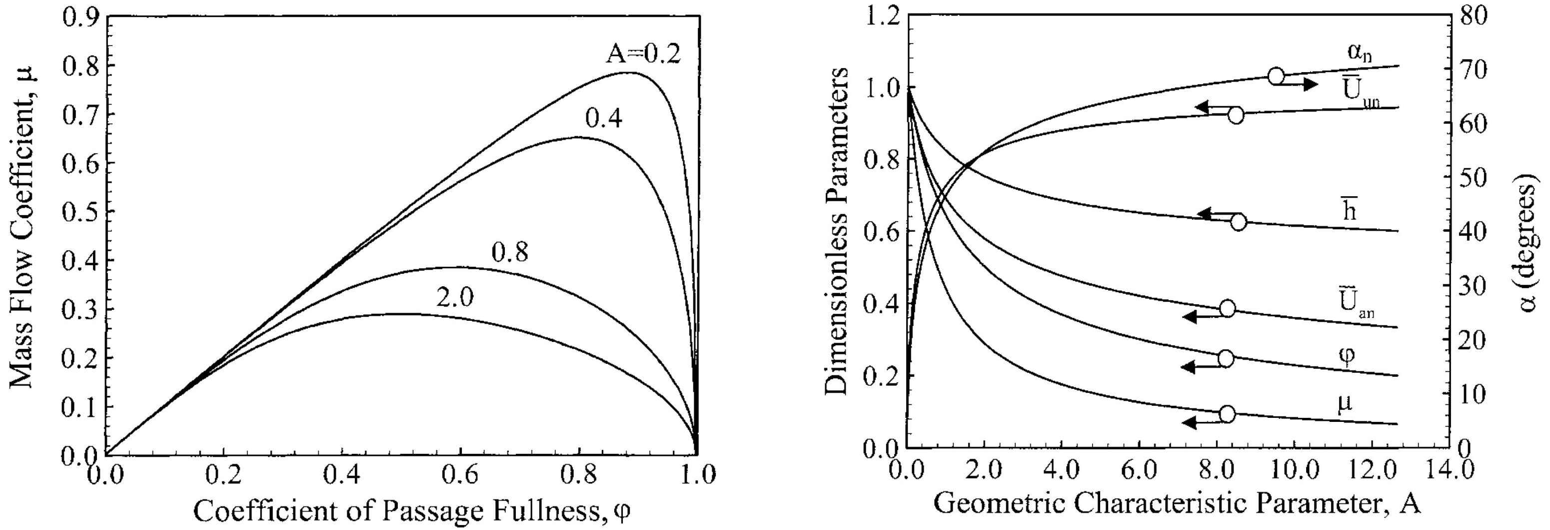


Diagram of element spacing in Closed-Closed configuration w/ 10 elements

Closed-Open with internal mixing

Graphical Correlations



Graphical representation of some important parameters; (a) mass flow coefficient vs. passage fullness; (b) dimensionless parameters vs. α and A

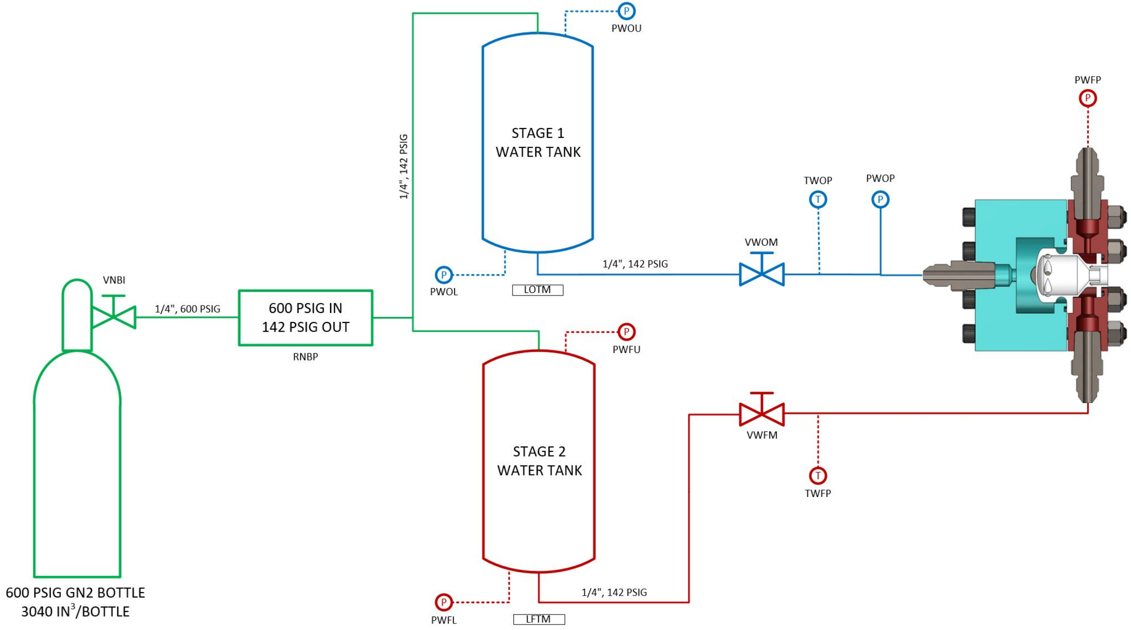
The figure on the left demonstrates the optimum mass flow for a given set of parameters. This is where we're targeting to hit

Injector Variable Relationship Research

This reference slide was pulled from the Spectre CoDR

Cause	Effect	Reasoning
$R_n \uparrow$	$\mu \downarrow$	Increase in injector radius promotes swirling flow which decreases the filling coefficient
$A_{in} \uparrow$	$\mu \uparrow$	Decreased velocity causes swirling flow to be weakened which increases the filling coefficient
$\vartheta \uparrow$	$\mu \downarrow$	An increase in angle can increase tangential velocity and decrease axial velocity which enhances swirl
$L_{in} \uparrow$	$\mu \downarrow$	With a longer tangential inlet port, there is more frictional loss
Convergence Angle $\uparrow$	$\mu \uparrow$	Less friction loss due to a the convergence section becoming shorter
Mercury is in Retrograde	$\mu \downarrow$	The gods look unfavorably on Coax Swirl Injectors being used while Mercury rises in the east
$\Delta p_i, n, A, \vartheta \uparrow$	$\alpha \uparrow$	
$\nu, L_0, P_{plenum}, K \uparrow$	$\alpha \uparrow$	

Waterflow Testing P&ID



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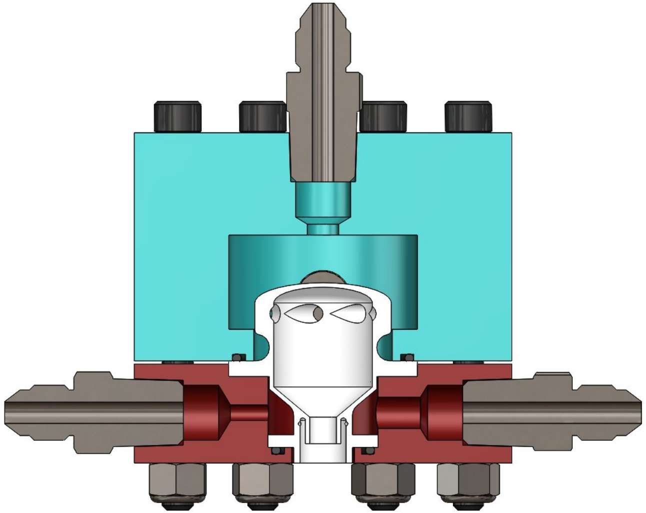
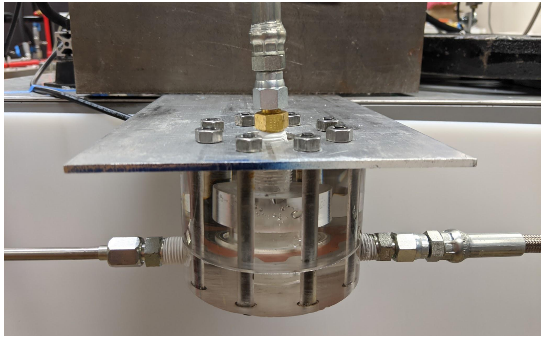
Boson University Rocket Propulsion Group
Spectre Injector Article Testing P&ID
Rev 1.0, 11/16/2019

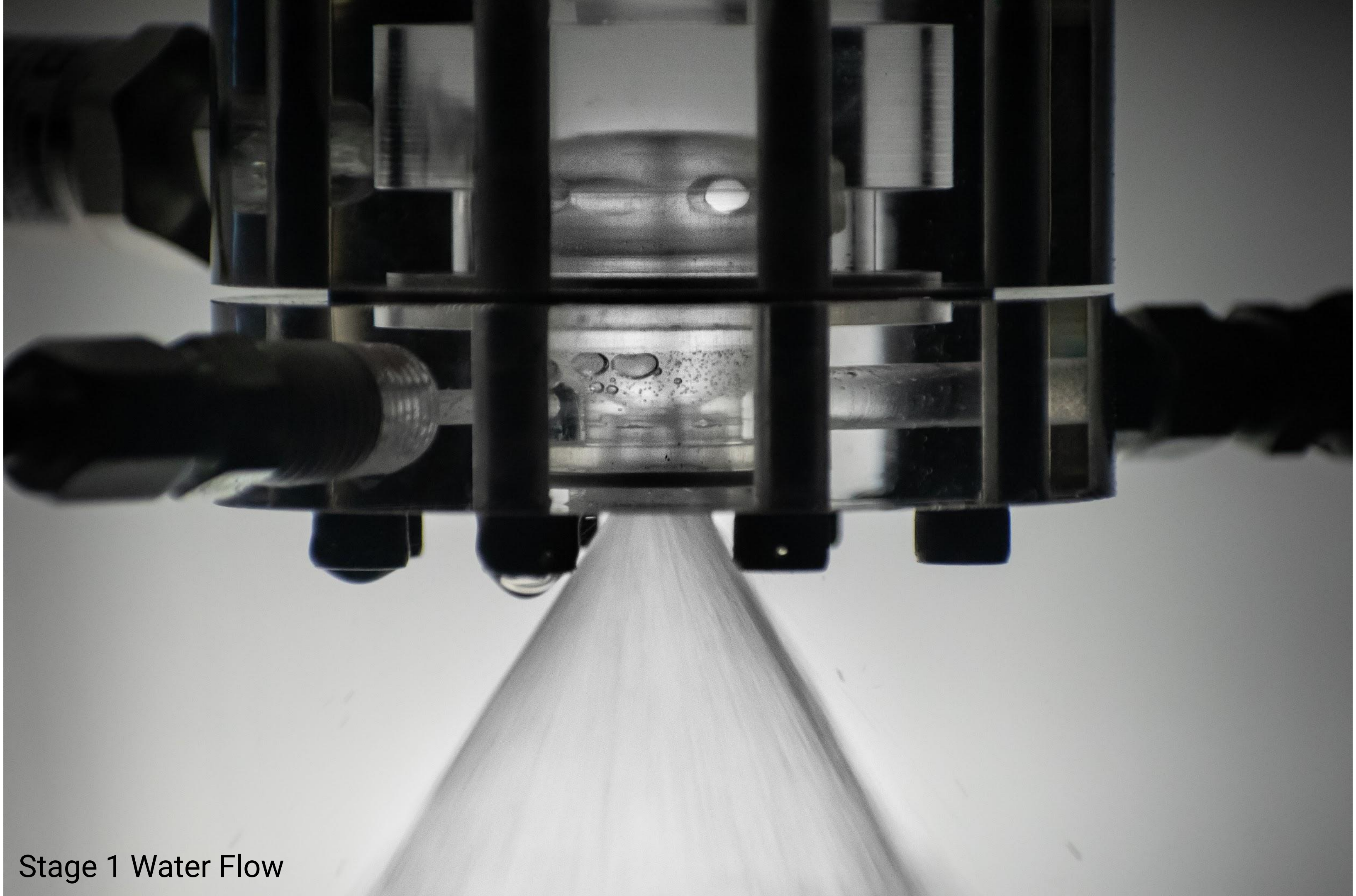
LEGEND			
NITROGEN (GAS)	STAGE 2 WATER LINE (REPRESNTING FUEL)	STAGE 1 WATER LINE (REPRESENTING OXIDIZER)	INSTRUMENTATION (VARIOUS)

Waterflow Test Stand

This reference slide was pulled from the Spectre CoDR







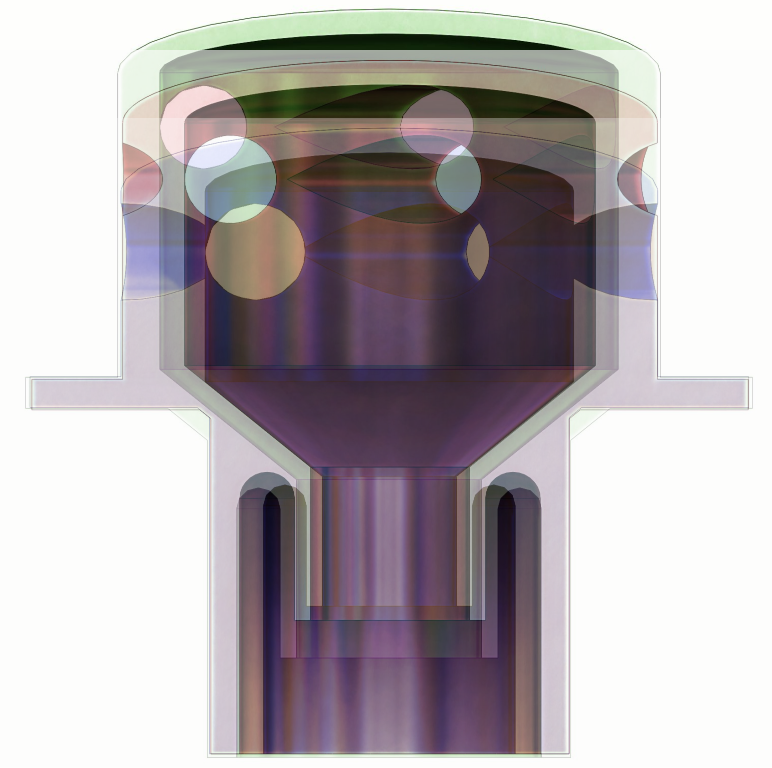
Stage 1 Water Flow

Element Overlay Comparison

Aggressive Impingement

Nominal Impingement

Softer Impingement



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