Kyle Adler

Half-Badger

5/23/2025

Half-Badger

Objective: Design a liquid rocket to compete in the FAR-OUT competition

Goal and Constraints

Prior Experience

- Success with many solid competition rockets, successfully hot fired methane/oxygen torch igniter

Goal

- Design, build, and test a liquid bi-propellant rocket to compete in FAR-OUT competition in May 2025

Constraints

- Budget: ~$10,000
- Timeline: 9 months
- Rocket performance: 15,000 ft altitude, rail exit velocity >100 ft/s

FAR-OUT/Half-Badger Summary

FAR-OUT Competition:

- May 2025 in Mojave, CA
- Liquid and hybrid rockets

Engine Specs:

- 1000 lbf, ~5s burn time
- Total impulse of ~23,000 Ns
- Ethanol and LOX

Rocket Specs:

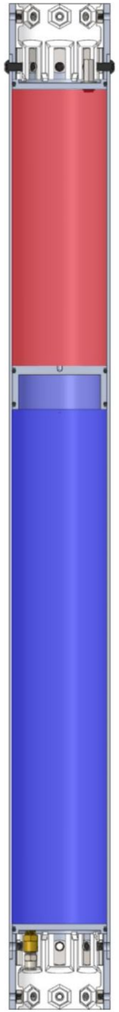
- 5″ diameter, 15′ tall, ~125 lbs dry, 15k ft apogee
- Composite, aluminum and 304/316 SS construction

Half-Badger Initial Design and Concerns

- Inspired by HalfCat Sphinx design
- Designed for ~450 lbf thrust
- Aluminum construction
- Isopropanol and N2O in a common-bulkhead piston tank

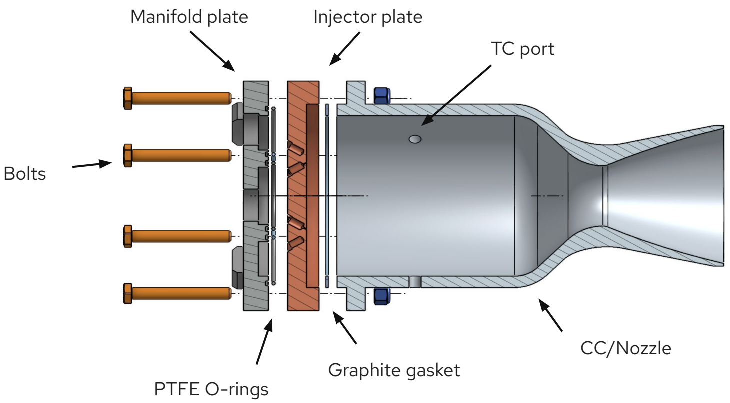
Main concerns with N2O piston tank:

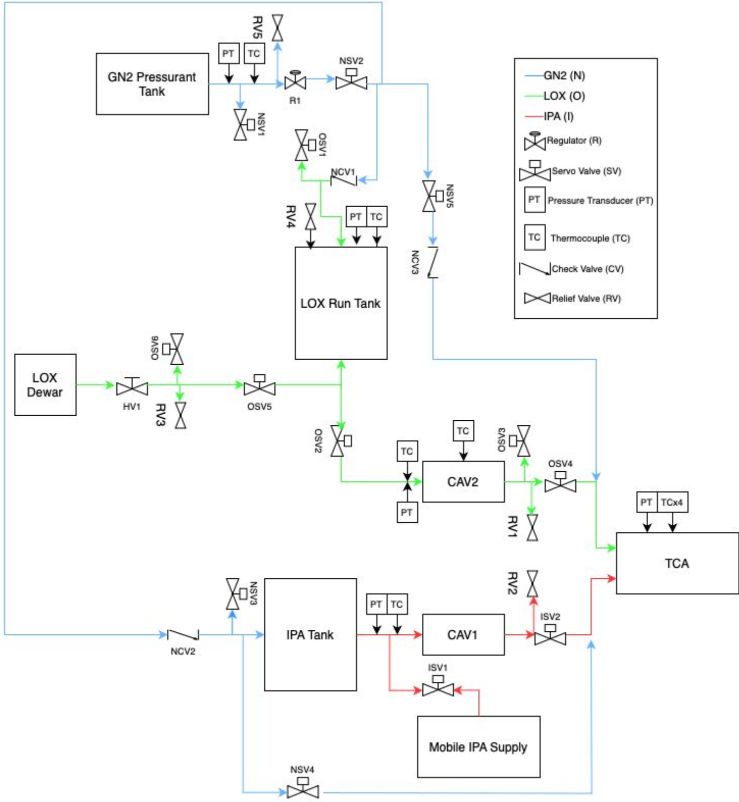
- Risk of pressure oscillations accentuated by piston design
  - Sphinx mitigates this with extremely high injector stiffness (>60%), reducing performance
- Saturated N2O is unpredictable and two-phase flow hard to characterize
- Decomposition and dieseling risk



Fluid System/TCA Design

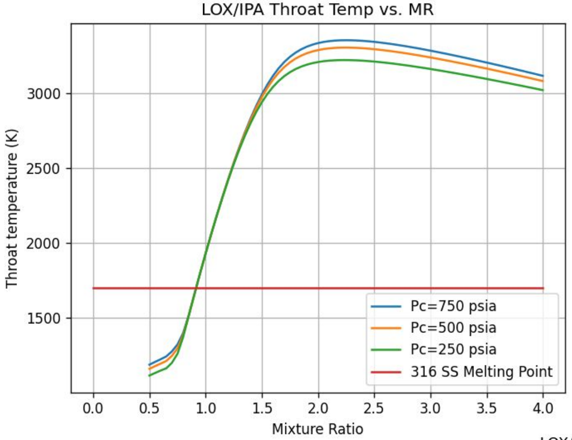
- Designed injector, manifold, combustion chamber/nozzle for manufacturability
- Designed IPA/LOX fluid system to meet competition requirements (relief valves, pressure testing) and LOX safety standards (vent valves, no trapped LOX)



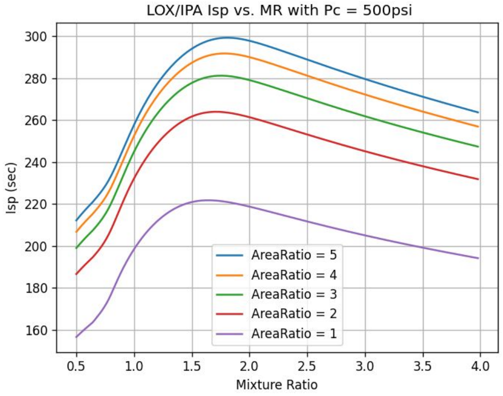


Half-Badger Initial Propulsion Characterization

- Chose MR of 1.0
  - Used Python and CEA to graph
  - Offers decent compromise between temperature and performance
- Chose thrust of 1000 lbf
  - Keeps TWR ~10 for 125lb rocket
- Chose chamber pressure of 500 psi
  - Reasonable for tank pressure ~650 psi (after injector/CV drops) and nozzle throat size
- Used CEA thrust coefficient to determine throat area



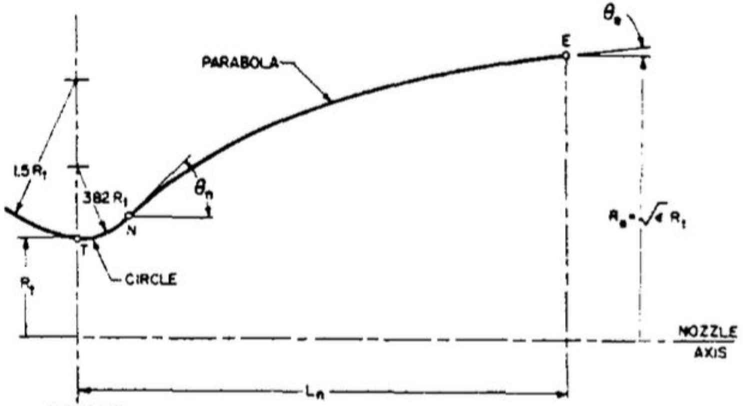
$$C_f = \frac{F}{A_t (p_c)_{ns}}$$

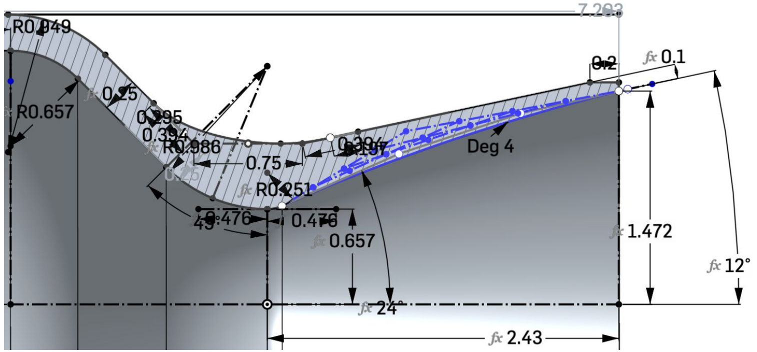


Design of Liquid Rocket Propellant Rocket Engines, 2ed, Huzel & Huang

Half-Badger Nozzle Design

- Rao parabolic approximation
- Expansion ratio set for atmospheric
    - Small deviation from atmospheric during flight
- 80% bell nozzle length for good efficiency (~98.5% ideal)





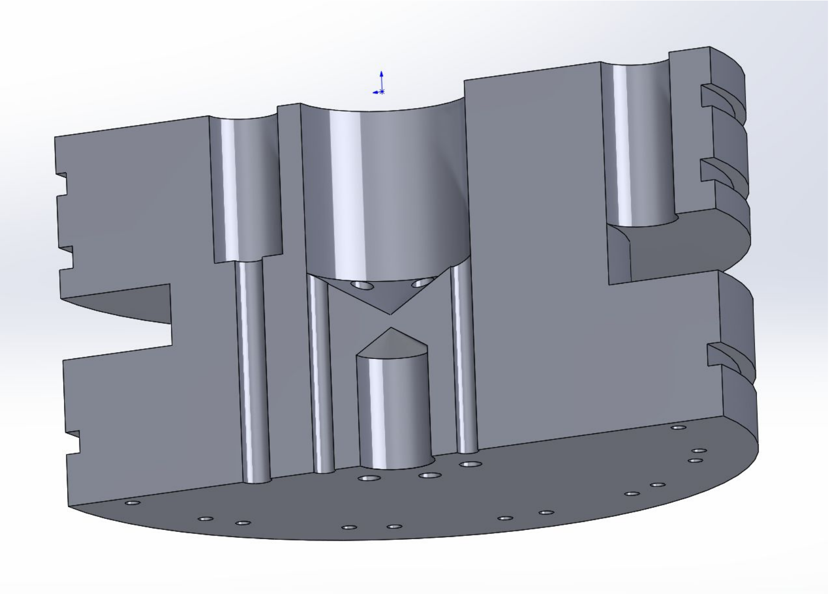
Design of Liquid Rocket Propellant Rocket Engines, 2ed, Huzel & Huang

Half-Badger Injector Design

Objective: Design an injector for isopropanol/LOX prioritizing simplicity and manufacturability

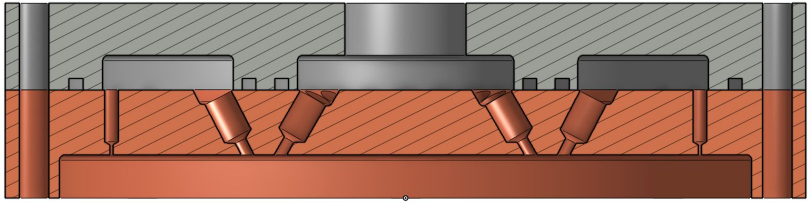
Initial Injector Design

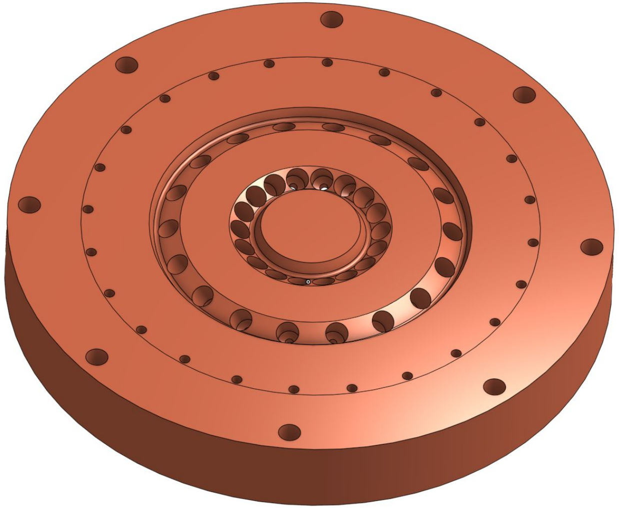
- Initially chose a scrintle design to mirror Half Cat Rocketry's Sphinx rocket design
- Groove-manifolds allow for relatively easy machining
- However the scrintle isn't ideal for film cooling, which is very important now that we're using LOX



New Injector Design

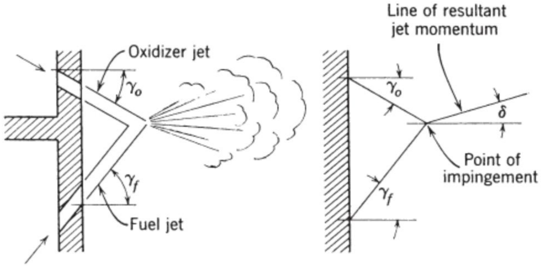
- Designed as two parts for simplicity
- Small-ish manifolds; wanted short fill times but reasonable flow velocities
- Designed for manufacturability
    - Grooves can be milled out before drilling angled holes
    - Larger holes drilled before finishing with small bits





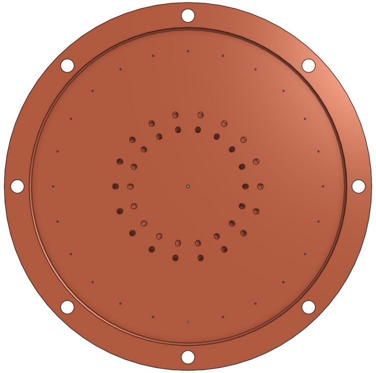
Injector Orifices

- Parametrically designed impinging injector
  - Easy iteration based on mass flow rates, propellant properties, discharge coefficients, and injection areas
- Beta angles calculated for slightly negative net momentum (away from wall)
- Film cooling orifices based on 10% fuel
- Discharge coefficients to be updated after a water pressure drop test



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

$$\dot{m}_o v_o \sin\gamma_o = \dot{m}_f v_f \sin\gamma_f$$



Manufacturable Injector

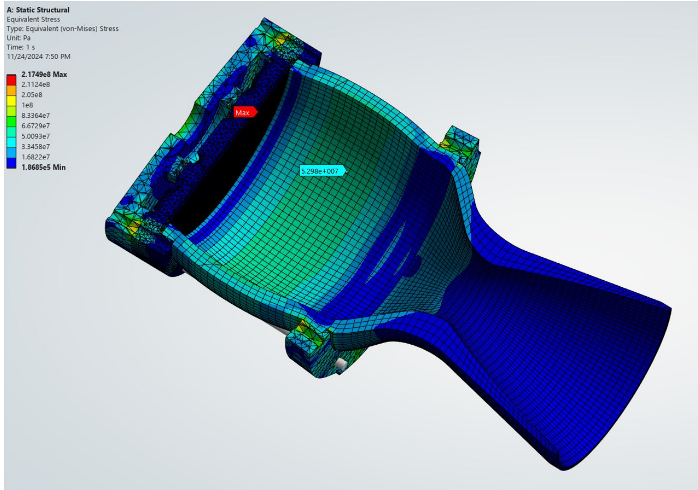
Name	Variable type	Value	Description
FuelManifoldDiame...	Length	2.9 in	
OxManifoldDiameter	Length	1.25 in	
FuelManifoldThickn...	Length	0.85 in	
RadialOrificeCount	Number	18	
OxAngle	Angle	60 deg	
FuelAngle	Angle	117.36 deg	
FilmCoolingDiameter	Length	3.25 in	
FilmOrificeRadialCo...	Number	24	
rho_fuel	Number	788	
rho_ox	Number	1151	
P_cc_Pa	Number	3447000	
injector_stiffness	Number	0.2	pressure drop over i...
deltaP_inj	Number	689400	
FilmCoolingMassRa...	Number	0.1	fraction of fuel mas...
m_dot_fuel_film	Number	0.097	
m_dot_fuel_inj	Number	0.873	
Cd_fuel	Number	0.65	using guess value fr...
Cd_film	Number	0.65	using guess value fr...
Cd_ox	Number	0.65	using guess value fr...

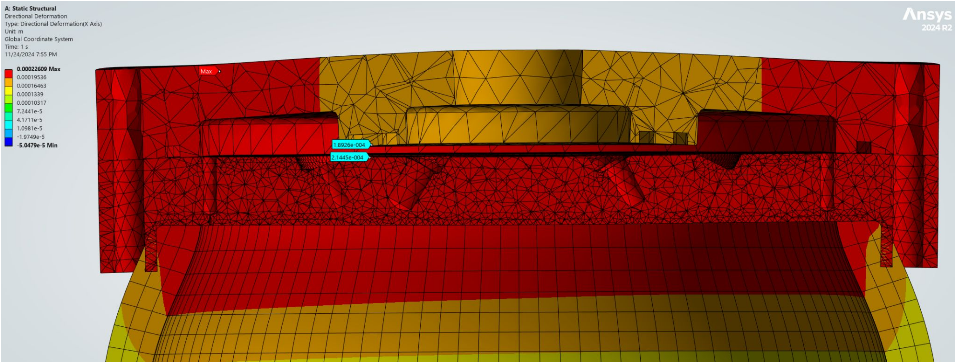
Half-Badger TCA Analysis

Objective: Characterize stress on TCA due to structural loads and identify vibration mode shapes and frequency

TCA Analysis: Stress Results

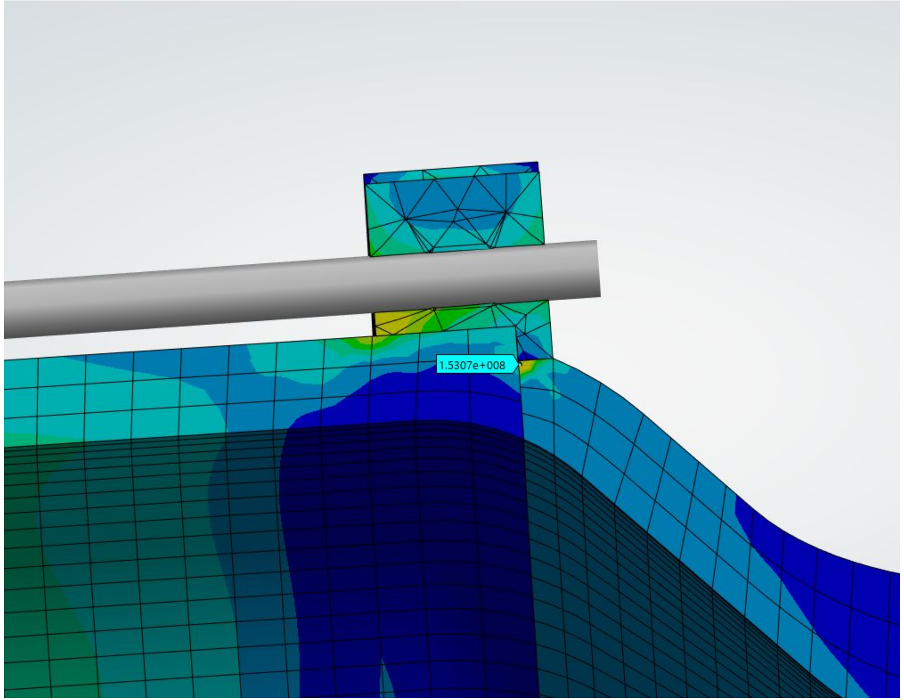
- High stress where TS ring interfaces with CC/nozzle
- Location of interest is gapping caused by bulging of injector and manifold plates
  - 0.2 mm deflection, within tolerance of o ring
  - Has been investigated further in separate analysis





TCA Analysis: Structural Conclusions

- Thrust structure ring needs to interface differently
  - High loads on the current lip interface
  - Consider machining a lip on the CC/nozzle part



TCA Analysis: Film Cooling & Thermal Transient

- Used liquid film cooling correlation from Huzel & Huang to determine 10% fuel film cooling ratio
- Used Bartz correlation for convection coefficient, gas properties from CEA to apply to ANSYS thermal analysis

epsilonoverd = 0.00002718

Re = 1.818E+05

$\dot{m}_{film}$ = 0.06718 [kg/s]

h_g = 26795 [W/m^2-K]

$film_{perc}$ = 6.925 [%] *film cooling percentage of fuel mass flow rate*

η_{film} = 0.3 *film cooling effectiveness*

$$h_g = \frac{0.026}{D^{0.2}} \left(\frac{c_p \mu^{0.2}}{\mathrm{Pr}^{0.6}} \right) (\rho v)^{0.8} \left(\frac{\rho_{am}}{\rho'} \right) \left(\frac{\mu_{am}}{\mu_0} \right)^{0.2}$$

$$\frac{G_c}{G_g} = \frac{1}{\eta_c} \cdot \frac{H}{a(1 + b^{C_{pvc}/C_{pg}})} \qquad (4\text{-}33)$$

Half-Badger Final Propulsion Design Changes

Thrust structure

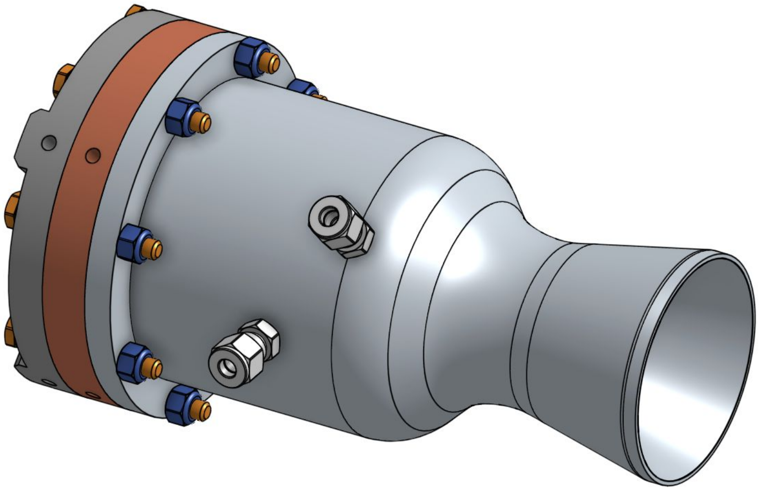
- Removed thrust structure ring in favor of machining flange at top of CC

CC/Nozzle

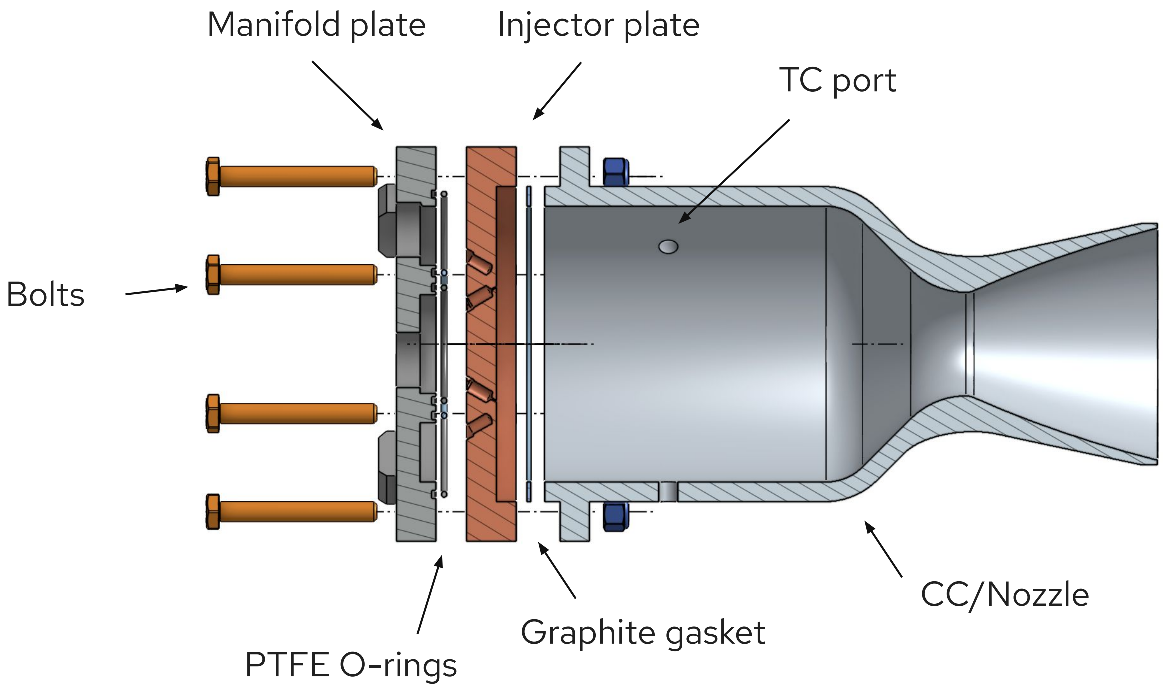
- Thickened converging section near throat at high risk of thermal failure
- Added ports for TCs and PT
    - Type E thermocouples to measure wall/boundary layer temperature, to update guess value in convection coefficient correlation

Injector

- Mass optimized manifold plate



Half-Badger Final Propulsion Design



Test Experience

- Hydrostatic pressure testing tanks
- Injector flow tests to validate atomization and discharge coefficients
- Develop test sequences for chilldown, cold flow, hot fire
- Clean and assemble LOX fluid system and TCA for tests
- Test Conductor for fuel ignition test
- Test Conductor for LOX cold flow test

TEST DESC:	HOTFIRE										
	NOTE:	~T-10				BURN		SHUTDOWN			
VALVE	DESCRIPTION	PRE-SEQ		T+1	T+2	T+3	T+3.5	T+4.5	T+6	T+10	T+11
~~NSV1~~	~~N2 VENT/FILL~~										
NSV2	POST-REG MAIN OUTPUT	OPEN								CLOSED	
NSV3	IPA TANK VENT	CLOSED									OPEN
NSV4	IPA PURGE VALVE								OPEN	CLOSED	
NSV5	LOX PURGE VALVE			OPEN			CLOSED	OPEN		CLOSED	
R1	N2 REG										
OSV1	LOX TANK VENT VALVE	CLOSED									OPEN
OSV2	LOX CAV ISO VALVE	OPEN									
OSV3	LOX DUMP VALVE	CLOSED									
OSV4	LOX MAIN VALVE					OPEN		CLOSED			
OSV5	LOX DEWAR TRANSFER VALVE										
OSV6	LOX TRANSFER LINE VENT/DU										
HV1	DEWAR HAND VALVE										
ISV1	IPA DUMP VALVE										
ISV2	IPA MAIN VALVE				OPEN				CLOSED		
IGN	IGNITER					LIGHT					

Lessons Learned

- Spend less time on initial design, just machine something and test
  - Similarly, build physical prototypes along the way to get a feel for the hardware
- Ensure you have reasons for even small decisions
  - Otherwise you might forget why a decision was made, e.g. IPA vs ethanol
  - Utilize engineering first principles to justify decisions
- Have your design reviewed by others not involved
  - Forces you to talk through your decision process and reconsider choices
  - Keeps you from getting tunnel vision and going down rabbit holes
- Test early and often!

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Reference slides

Material selection

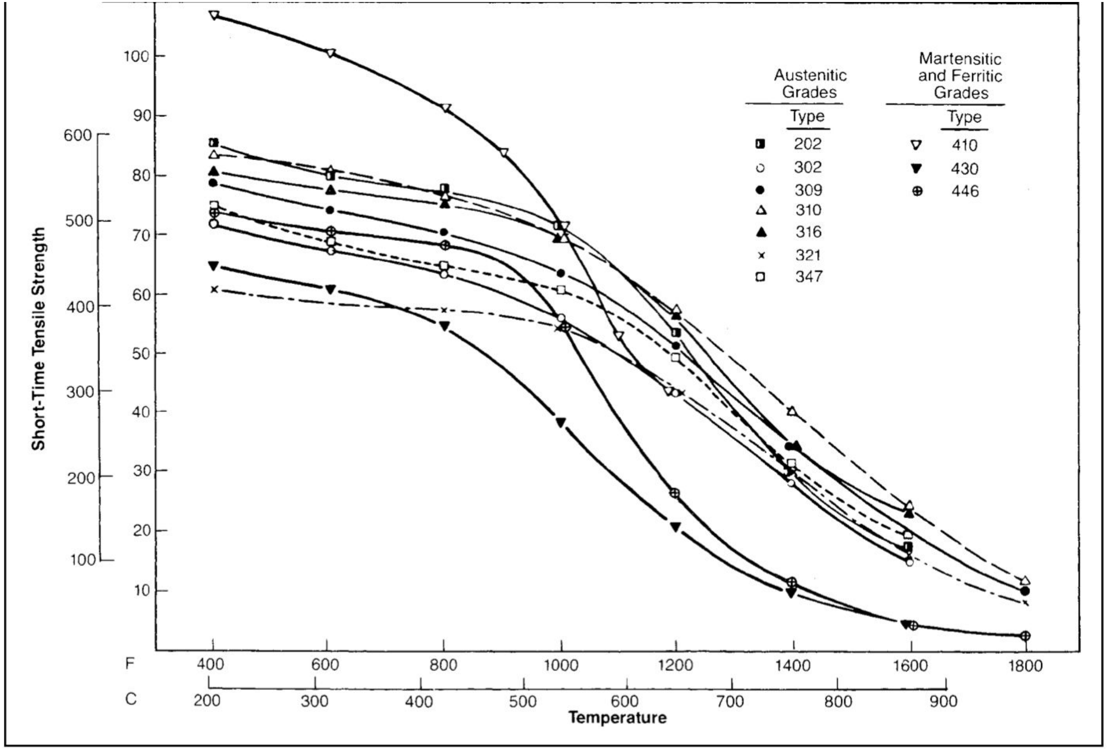
- Stainless steel (304/316)
  - Excellent oxygen compatibility
  - Heavy and expensive
  - **Selected for TCA and LOX tank**
- Aluminum (6061)
  - Cheap and lightweight, easy to manufacture
  - Poor oxygen compatibility
  - **Selected for structure and ethanol tank**
- Copper
  - Excellent thermal conductivity, good oxygen compatibility
  - Expensive and heavy
- Inconel
  - Excellent oxygen compatibility and high-temp strength
  - Very expensive and difficult to manufacture

Material selection

		316 Stainless Steel		Copper		304 Stainless Steel		6061 Aluminum		Inconel 600	
Criteria	Weight	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Density	1	2	2	2	2	2	2	5	5	2	2
Yield Strength Dropoff Temp	3	3	9	2	6	3	9	1	3	5	15
Cost	5	3	15	2	10	4	20	5	25	1	5
Machinability	3	3	9	2	6	3	9	5	15	1	3
Oxygen Compatibility	5	4	20	5	25	2.5	12.5	-1	-5	5	25
Conductivity	2	2	4	5	10	2	4	4	8	1	2
Weight Score Sum			59		59		56.5		51		52

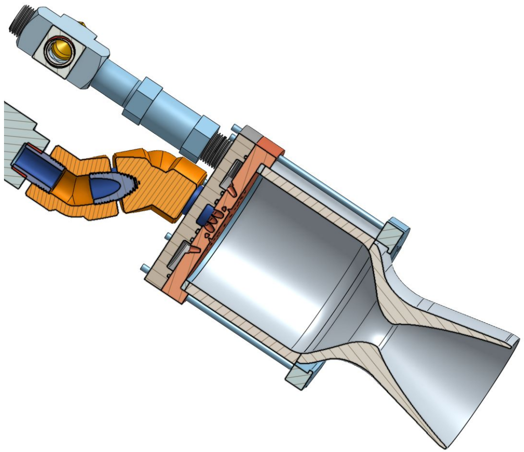
SS yield strength vs temperature

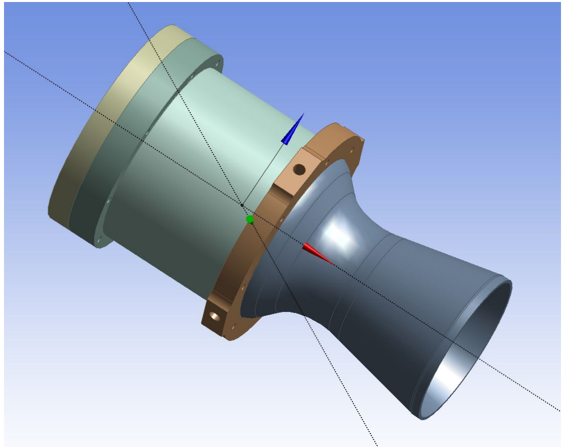
- Steeper drop above 600C for 316



Initial TCA Analysis: Geometry

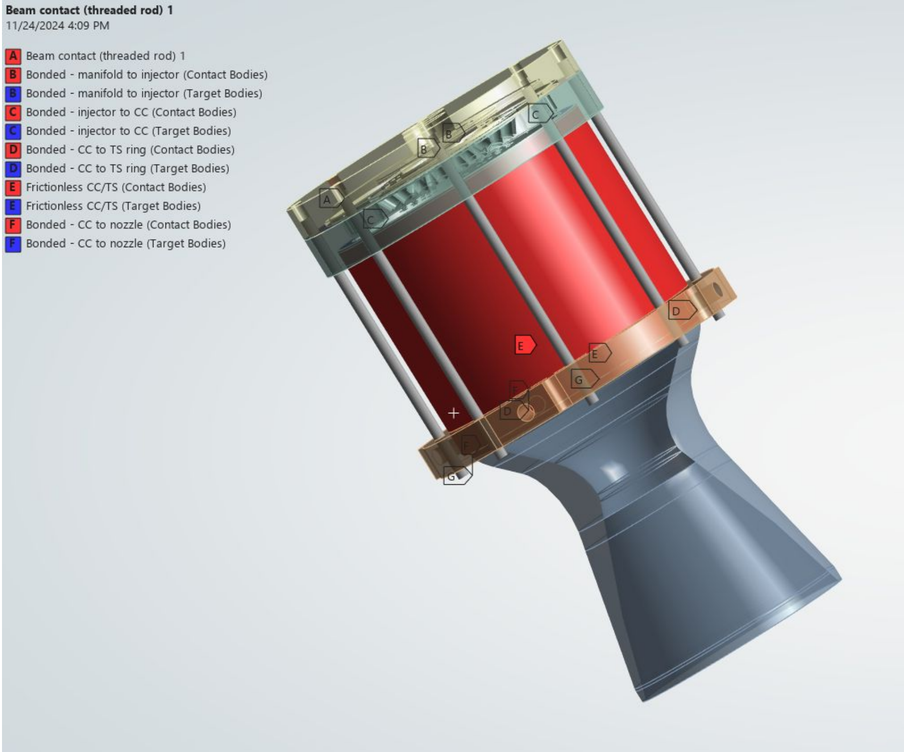
- Removed fluid components and fittings
- Removed PTFE o-rings
- Combined graphite gasket into CC body to simplify analysis
    - Separate FEA for gasket compression
- Removed threaded rods
    - Later replaced with beam contact elements since they can be approximated by 2-force members





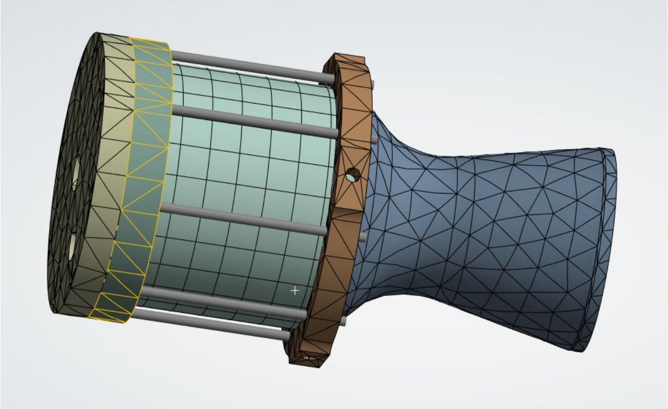
Initial TCA Analysis: Contacts

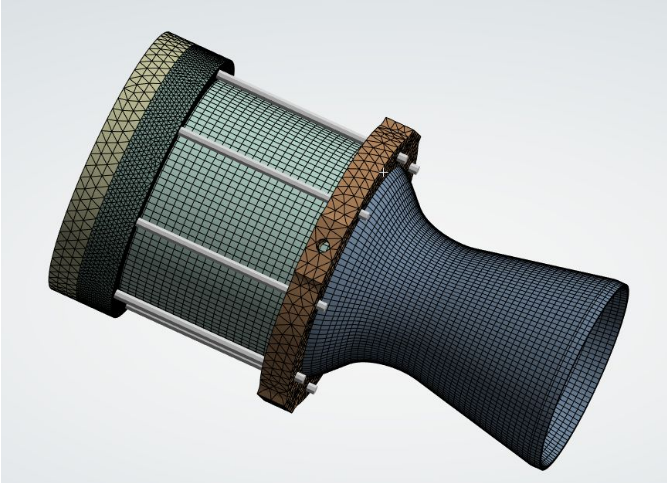
- Bonded contacts between faces compressed together
  - Never expected to separate
- Left o-ring grooves between injector and manifold plates unbonded
  - To analyze gapping in o-rings due to bulging due to manifold pressure
- Threaded rods modeled with beam188 elements
  - While beam189's have quadratic behavior, under pre-stress bending isn't a main concern



Initial TCA Analysis: Mesh

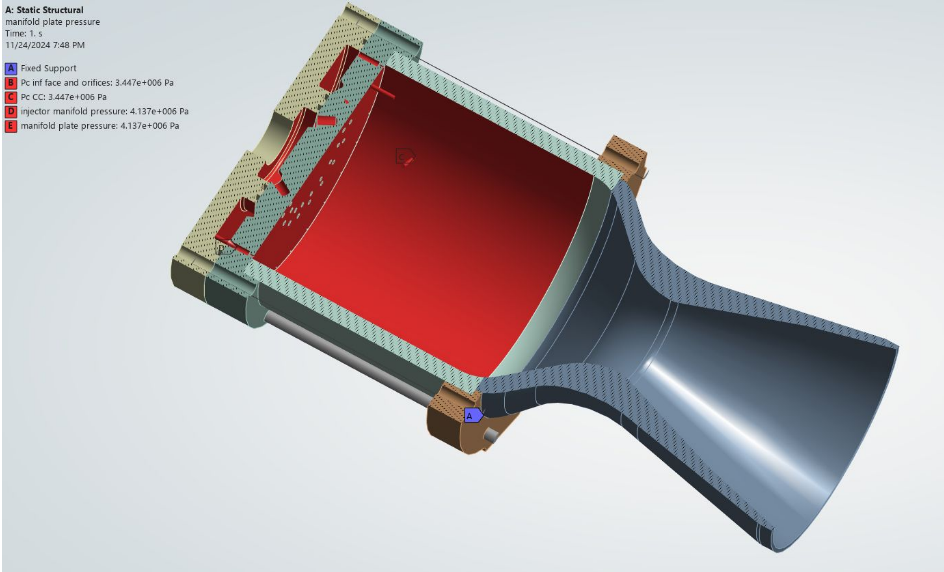
- Initial mesh isn't solvable due to small geometry and large elements, lots of refinement needed
- Edge and mapped face sizing for CC/nozzle, needed to split bodies apart to get good hex mesh
- Local face sizing for faces near injection orifices
- CC/nozzle wall 3 elements thick





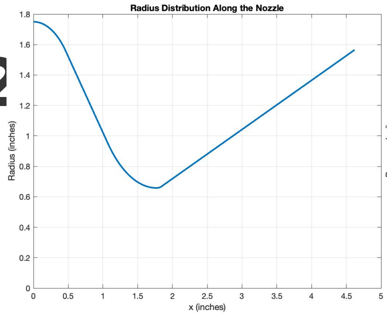
Initial TCA Analysis: Loads 1

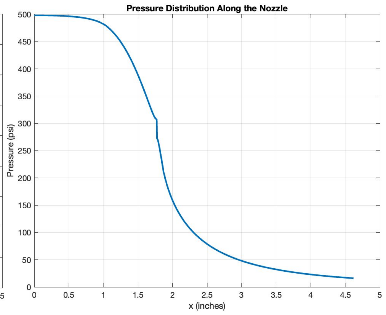
- Fixed support on thrust structure ring holes
  - Bolts will be providing the connection to rest of rocket
- Chamber pressure of 500 psi applied to inside of CC and injector face & halfway into orifices
- Manifold pressure of 600 psi applied to inside of manifold and injector plates, and halfway into orifices

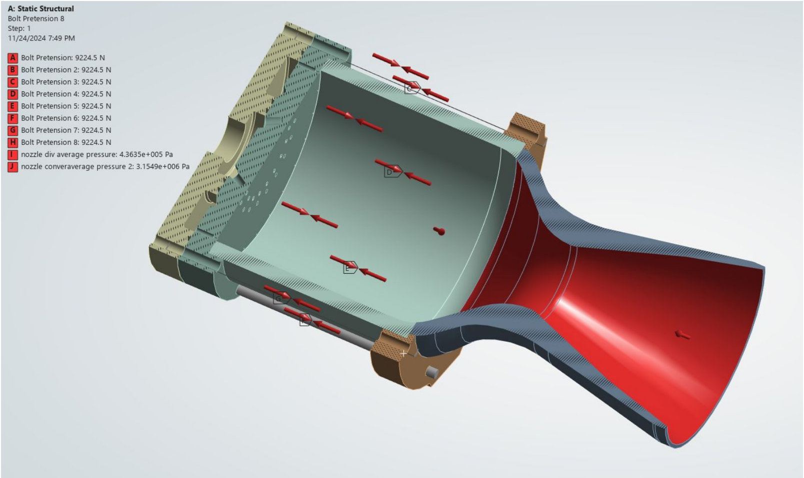


Initial TCA Analysis: Loads 2

- Bolt pretension of ~2074 lbs applied to each beam contact
- Pressure along nozzle calculated via mach relations in MATLAB
    - Diverging section approximated as conical
    - Pressure averaged in converging and diverging sections for simplicity





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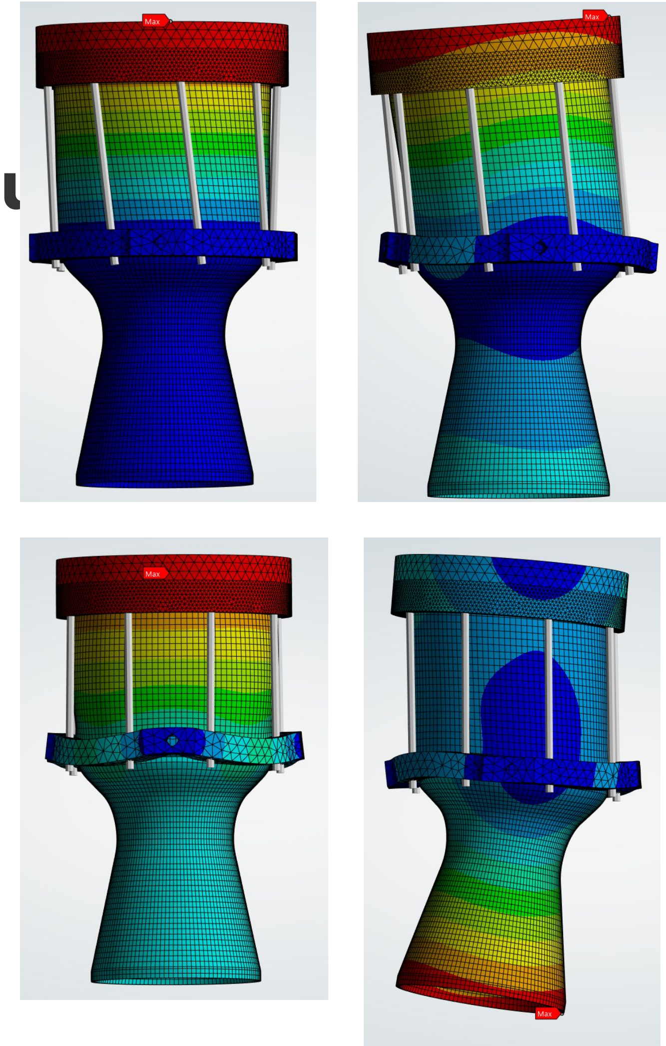
Average Pressure from x = 0 to minimum R: 457.5748 psi
Average Pressure from minimum R to nozzle exit: 63.2872 psi
Average Pressure from x = 0 to minimum R: 3154868.5935 Pa
Average Pressure from minimum R to nozzle exit: 436350.202 Pa
```

Initial TCA Analysis: Modal Resu

- Static Structural pre-stress
- 6 mode shapes correspond to expected shapes:
  - 2 wobbling of CC/Injector (618 Hz)
  - 1 torsional (1326 Hz)
  - 1 axial linear (1617 Hz)
  - 2 wobbling of nozzle (1890 Hz)



Design of Liquid Rocket Propellant Rocket Engines, 2ed, Huzel & Huang

Initial TCA Analysis: Modal Conclusions

- Check mode frequencies against combustion instability frequency estimates calculated from Huzel & Huang:
    - Longitudinal: 4629 Hz
    - Tangential: 7697 Hz
    - Radial: 15915 Hz
- Small engine so our structural frequencies much lower than estimated combustion instabilities, we don't directly predict resonant failure
    - 618 Hz, 1326 Hz, 1617 Hz, 1890 Hz

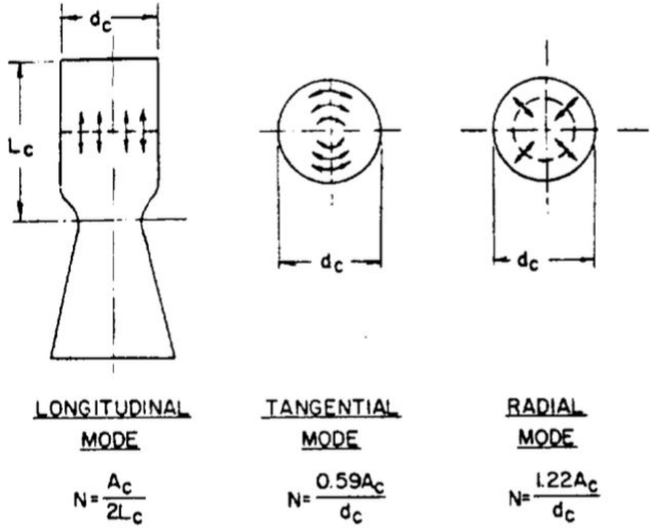


Figure 4-59.—Three modes of instability. L_c = combustion chamber length (injector face to throat); d_c = combustion chamber diameter; N = normal acoustic frequency; A_c = velocity of sound in chamber.