48th AIAA
Aerospace Sciences Meeting
Orlando, FL

American Institute of Aeronautics and Astronautics

Flight Testing of a Prototype LOX/Propylene Upper Stage Engine

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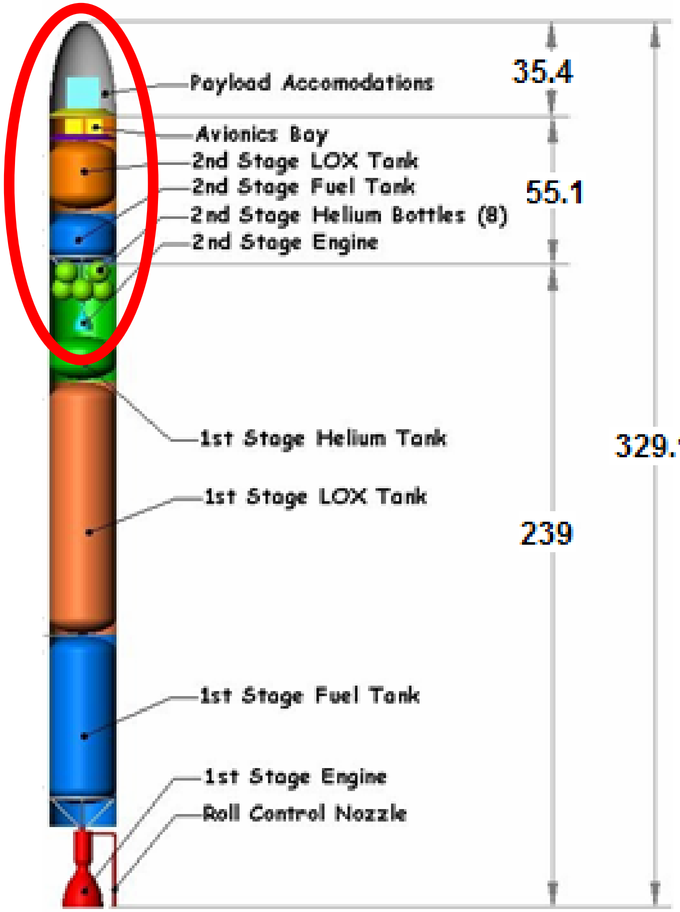
Agenda

- Introduction
  - Propylene as a Propellant
- Upper Stage Engine Development
- Prototype Engine for Sea Level Testing
  - Injector
  - Combustion Chamber Assembly
  - Ignition System
- Static Fire Test
- Flight Test
- Conclusion

Introduction: NLV Baseline

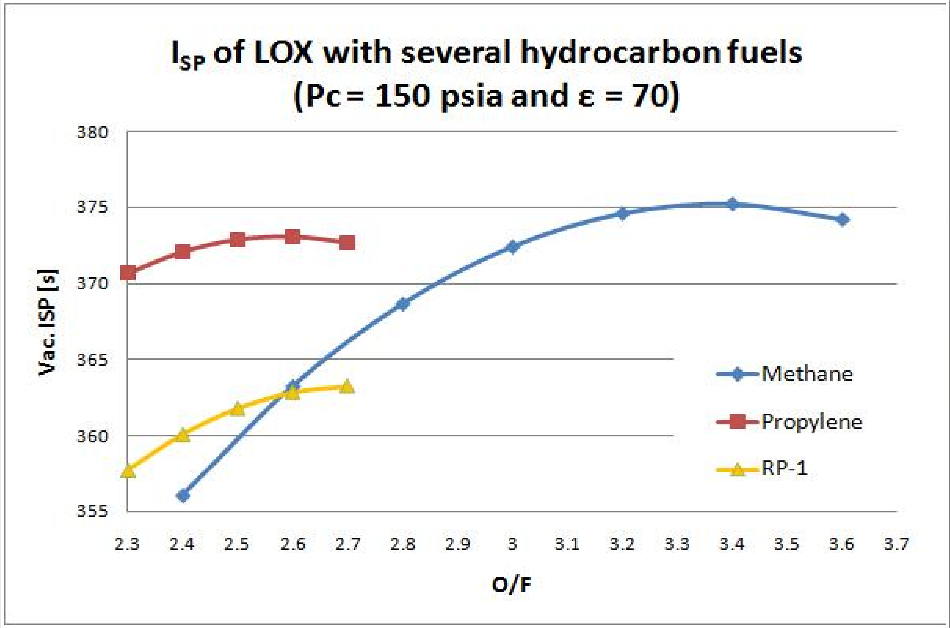
- Concept proposed by CSULB and GSC
- 2-stage pressure-fed LOX densified propylene vehicle
- Mission: place a 10 kg (22 lbm) payload into a nominal 250-km altitude polar orbit

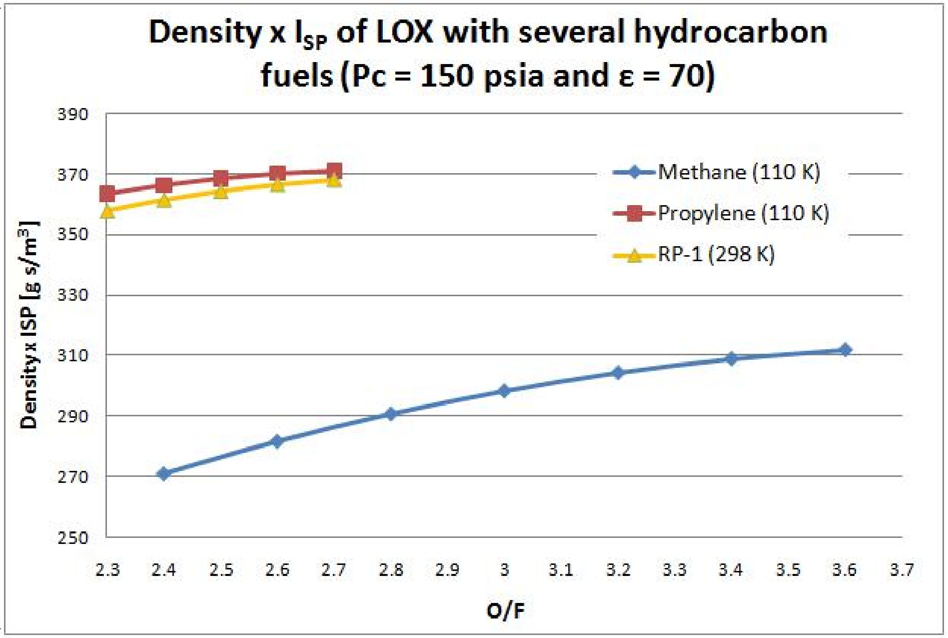
	First Stage	Second Stage
Dry mass	171 kg	30 kg
Stage inert mass fraction	0.131	0.137
Chamber Pressure	2 MPa	1 MPa
Sea-Level Thrust	20000 N	-
Sea-Level ISP	212 s	-
Vacuum Thrust	29600 N	2000 N
Vacuum ISP	314 s	347 s



NLV Baseline. Dimensions in inches

Fuel Performance Analysis



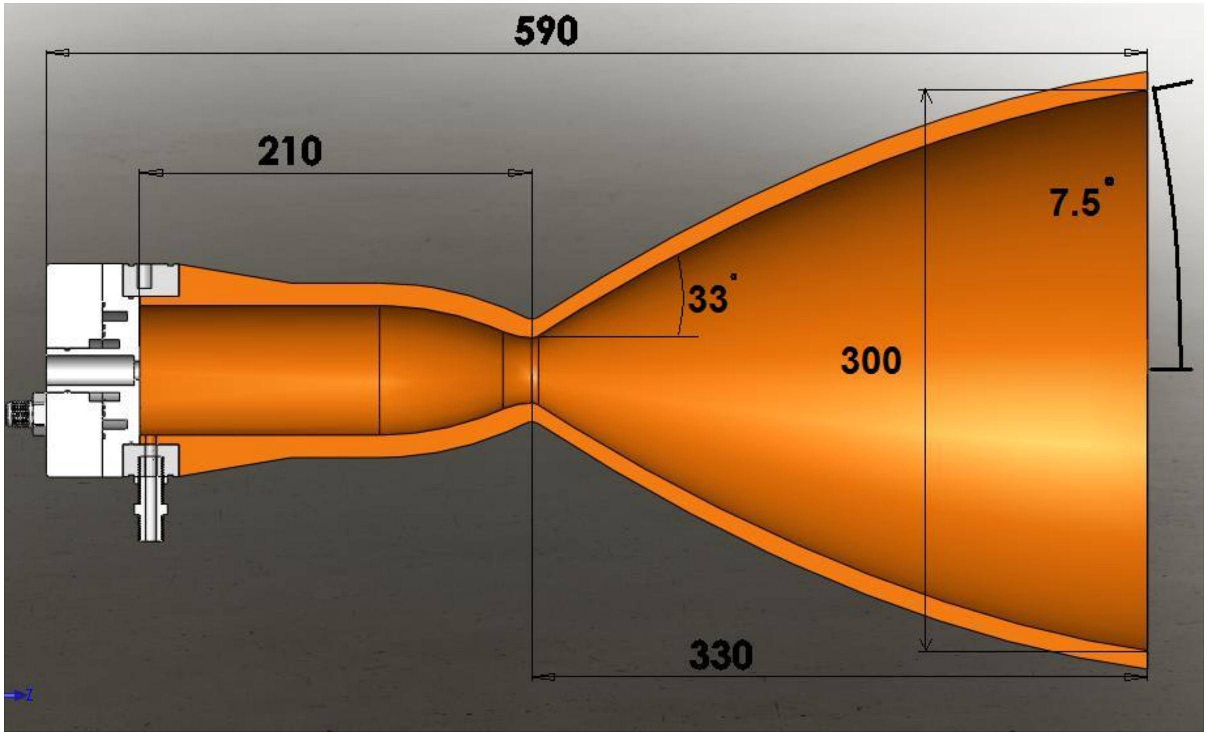


<u>Propylene Advantages:</u>

- Very close performance to Methane
- Can be stored at room temperature in liquid form at about 100 psi (unlike Methane)
- Non-toxic
- Available and Cheap

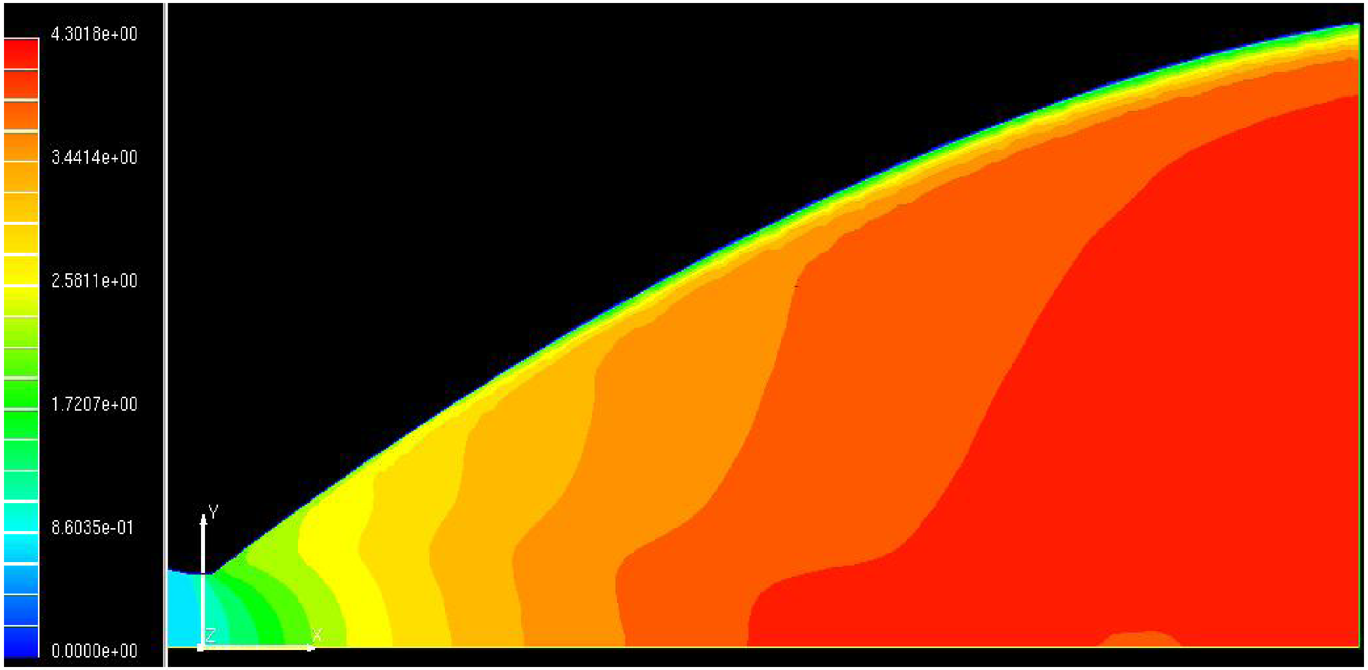
Upper Stage Engine Specs.

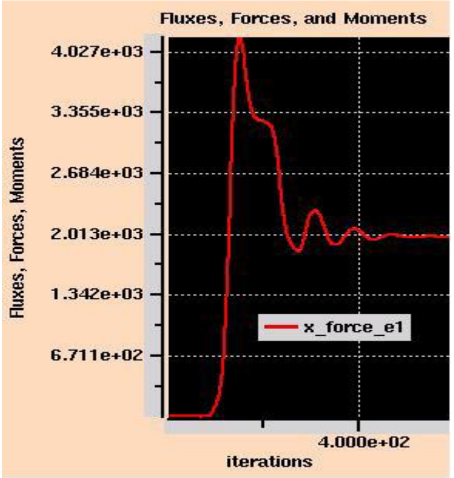
- Propellants: LOX/propylene (cryogenic)
- Expansion Ratio: 70
- Chamber Pressure: 1 MPa
- Thrust: 2000 N
- O/F: 2.6
- λ : 0.95
- η_{c*}: 0.90
- Isp: 319 s

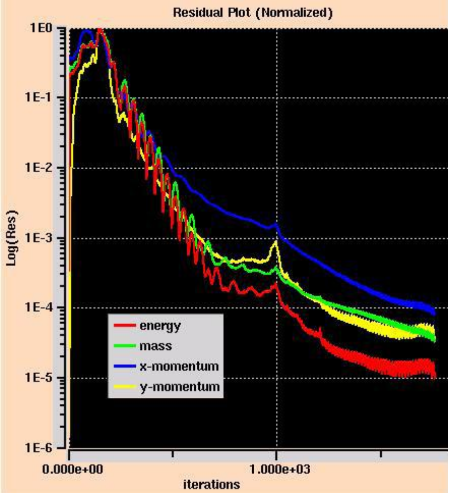


LOX/propylene Ablative Engine Concept. Dimensions in mm

Engine Validation: CFD







Exit Mach number: 4.3
Estimated force: 1979 N

<u>Plots shown:</u>
Mach number distribution (left)
Forces (upper right)
Residuals (lower right)

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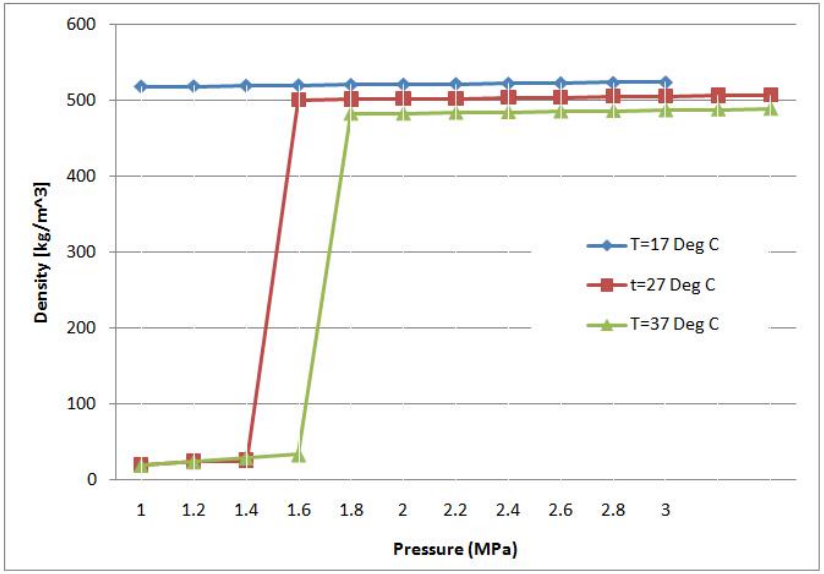
Prototype Engine – Additional Requirements

Engine needs to accommodate the test site Mojave desert (95 kPa, 20 to 45 deg Celsius)

Truncating the engine to an expansion ratio of 4 yields an exit pressure of 55 kPa at nominal chamber pressure

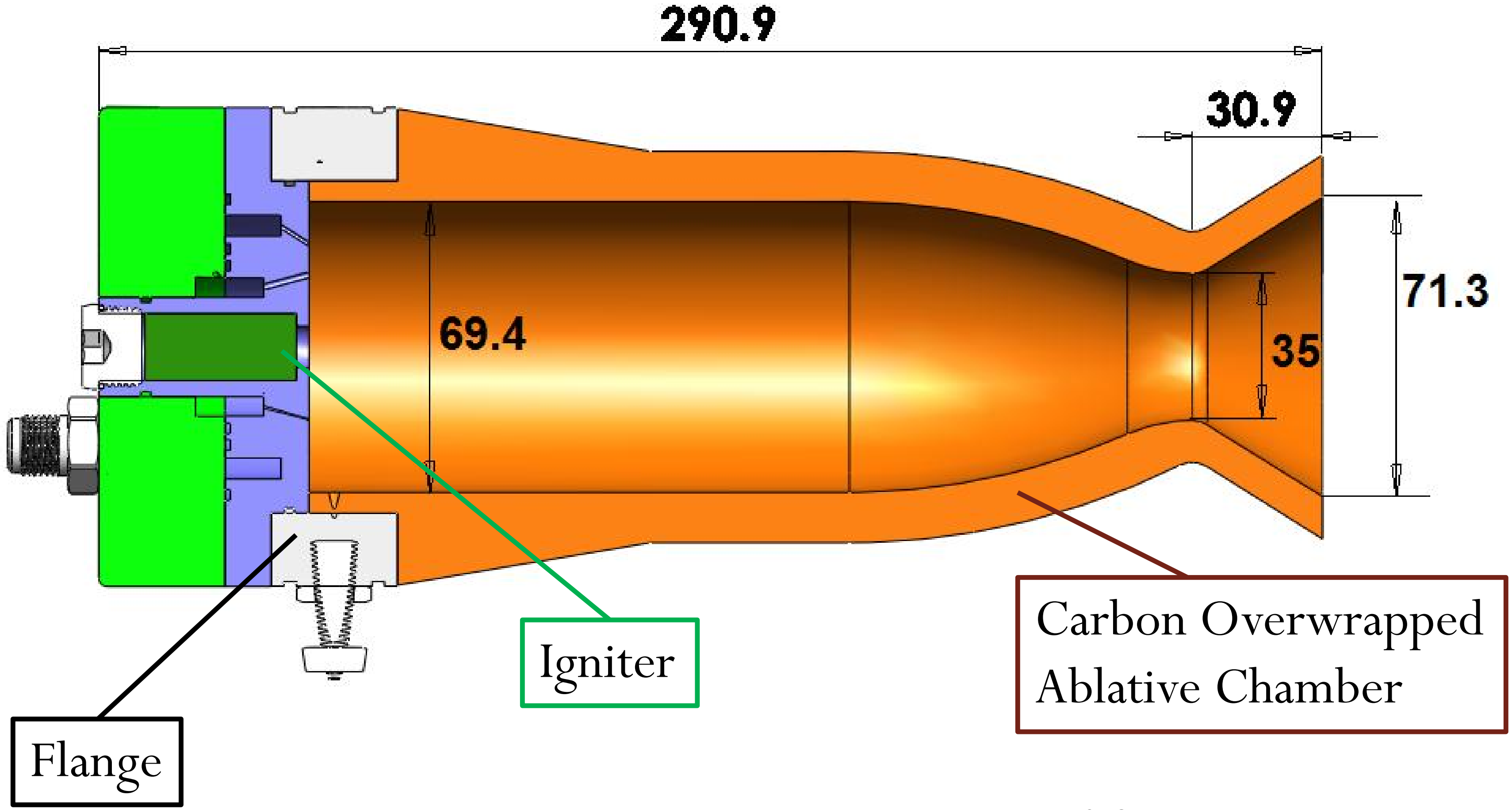
Propylene must stay liquid in feed system and injector

→ change nominal P_c



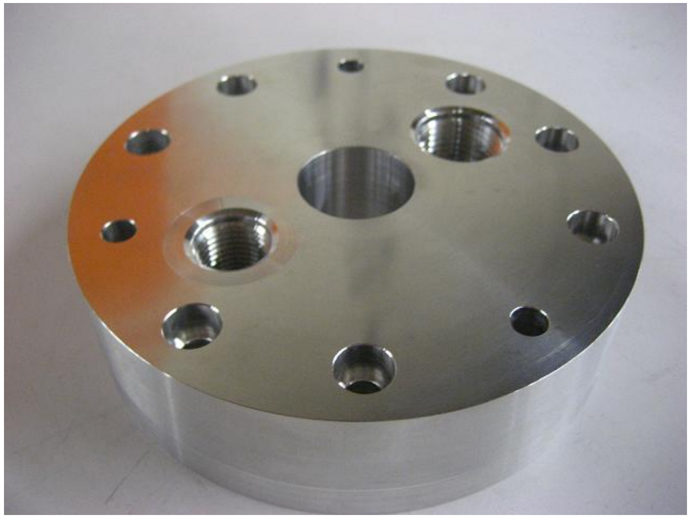
Vaporization Properties of Propylene

Prototype Engine - Overview

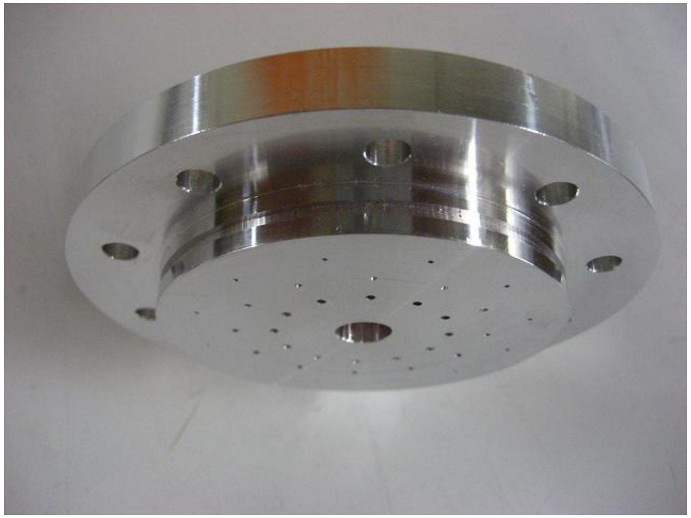


L* = 0.8   Dimensions: mm

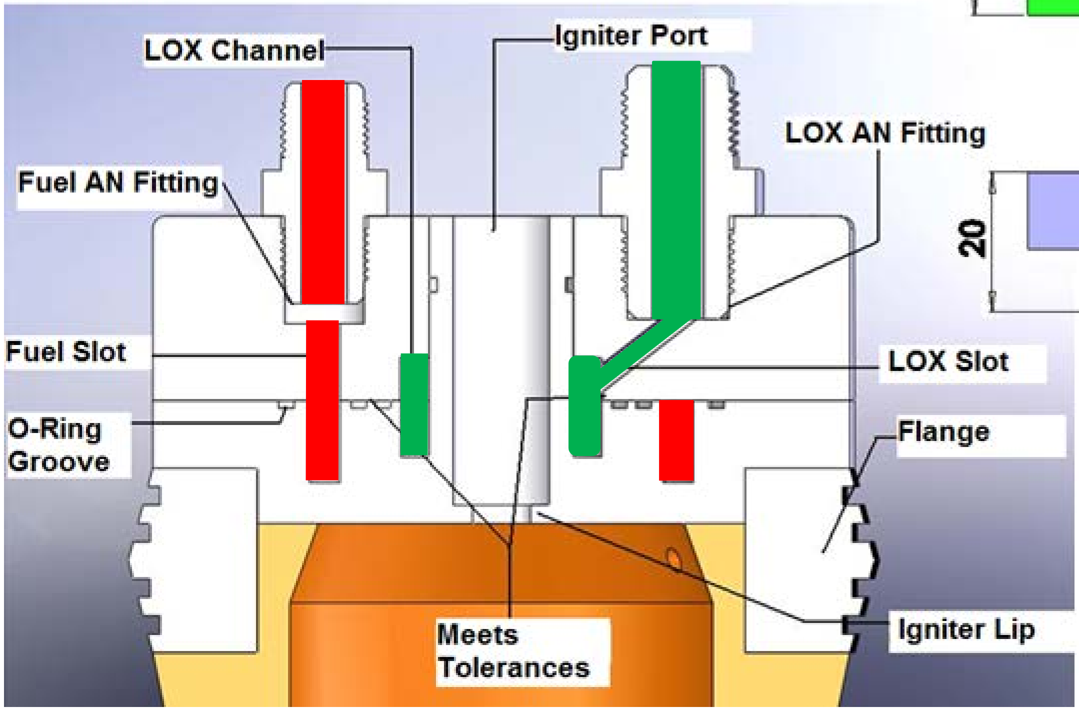
Injector

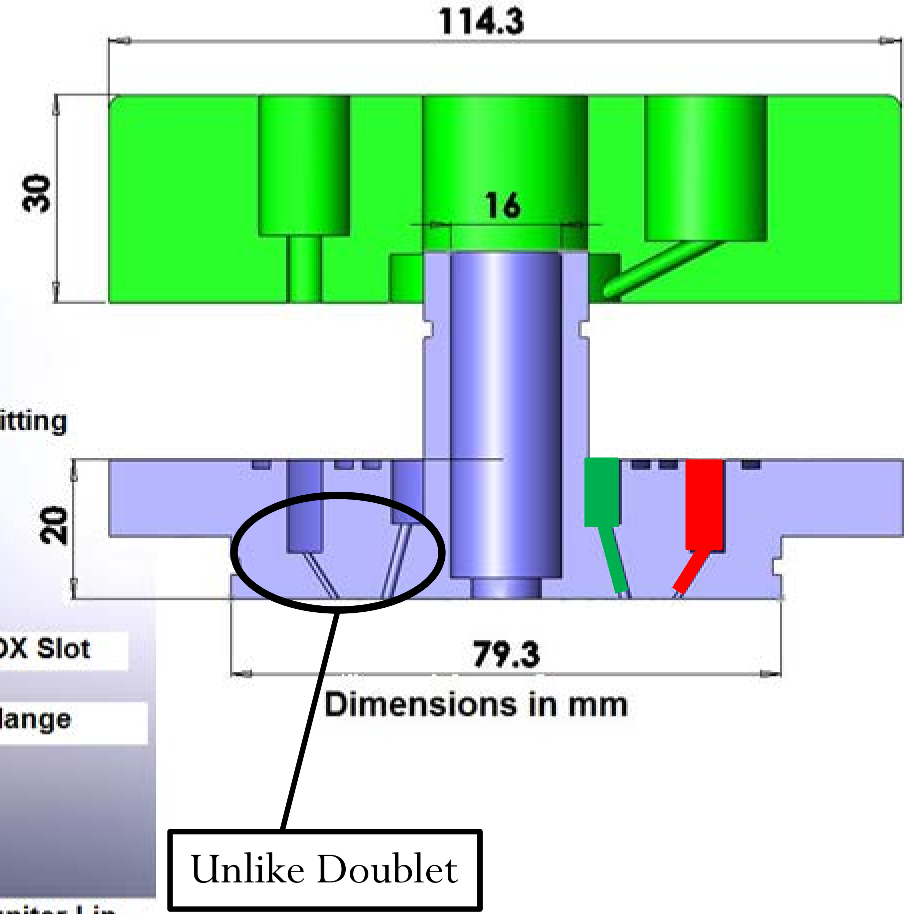


- Flathead Design
- Center Mounting Igniter Port
- Doublet Orifice Pattern
- O-Ring grooves for Sealing
- 16 % Film Cooling

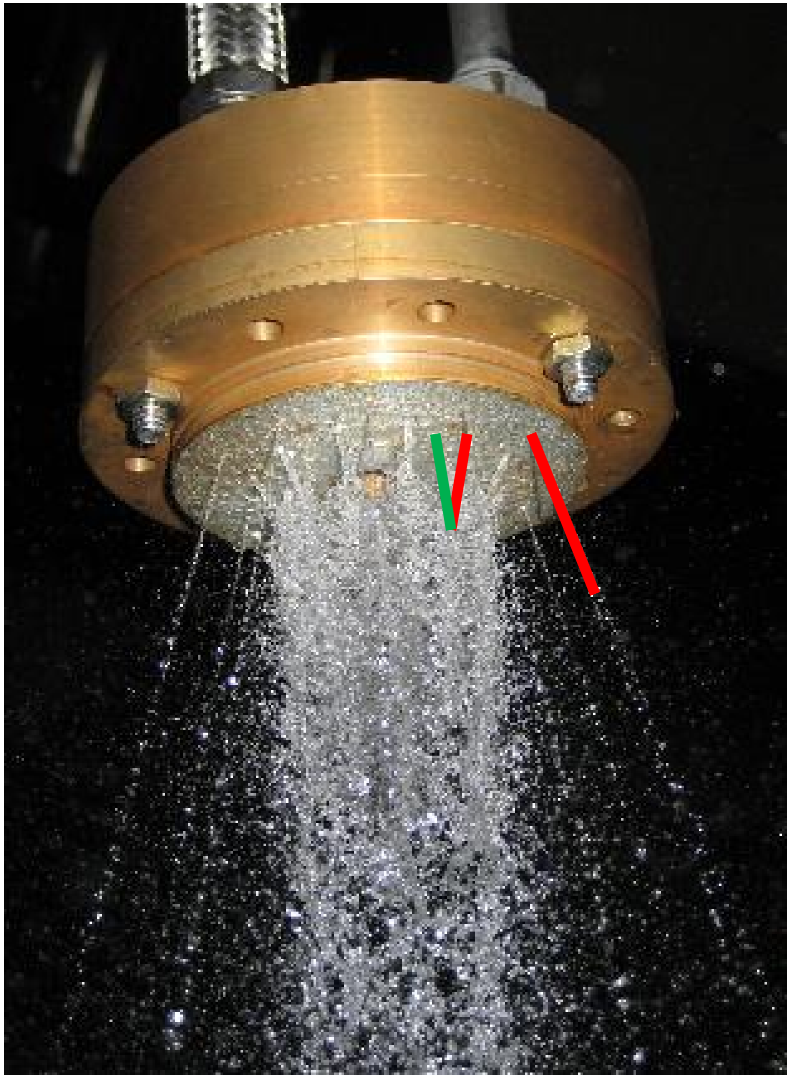


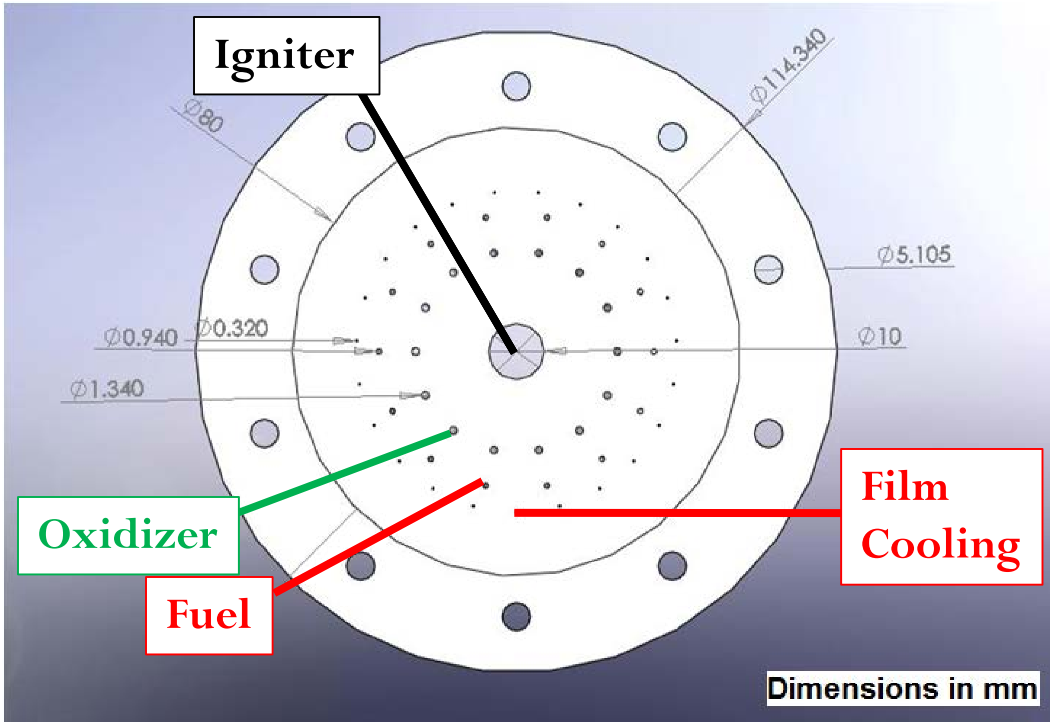
Injector – Cross Sectional View





Injector – Orifices and WFT





Water flow test Objectives:

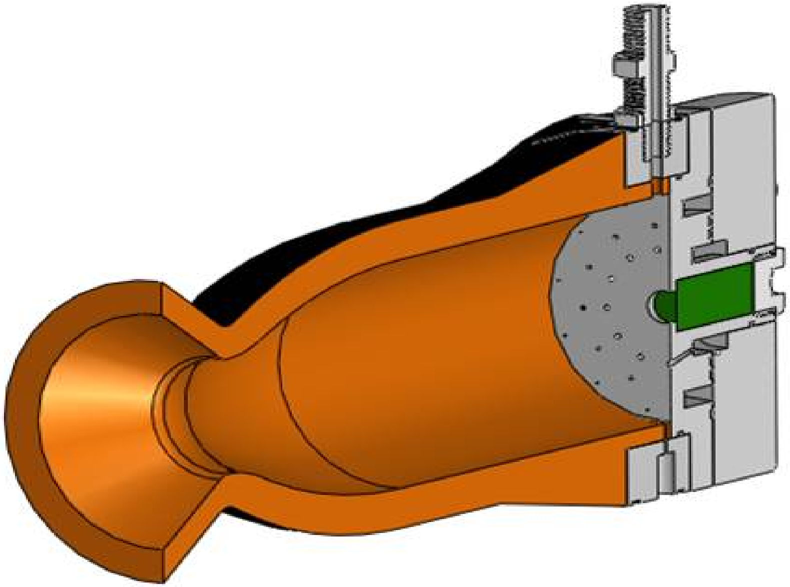
Check impingement

Measure discharge coefficients and pressure drop

$Cd_{fuel} = 0.765$, $Cd_{LOX} = 0.668$, $\Delta P = 96.77$ psi

Actual O/F: 2.51

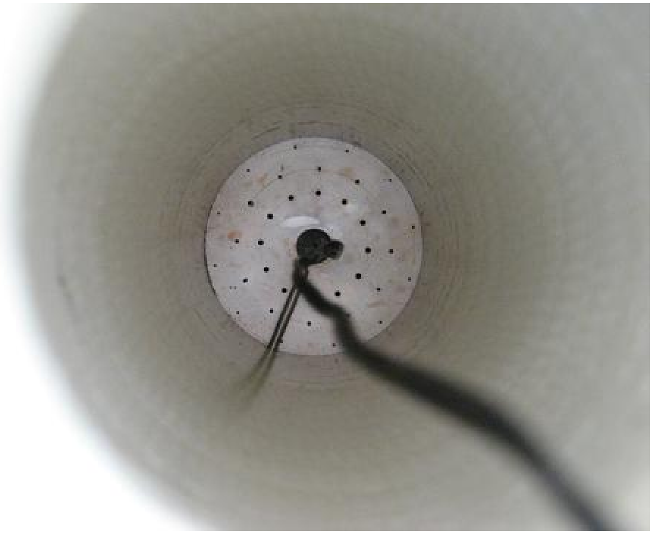
Combustion Chamber Assembly



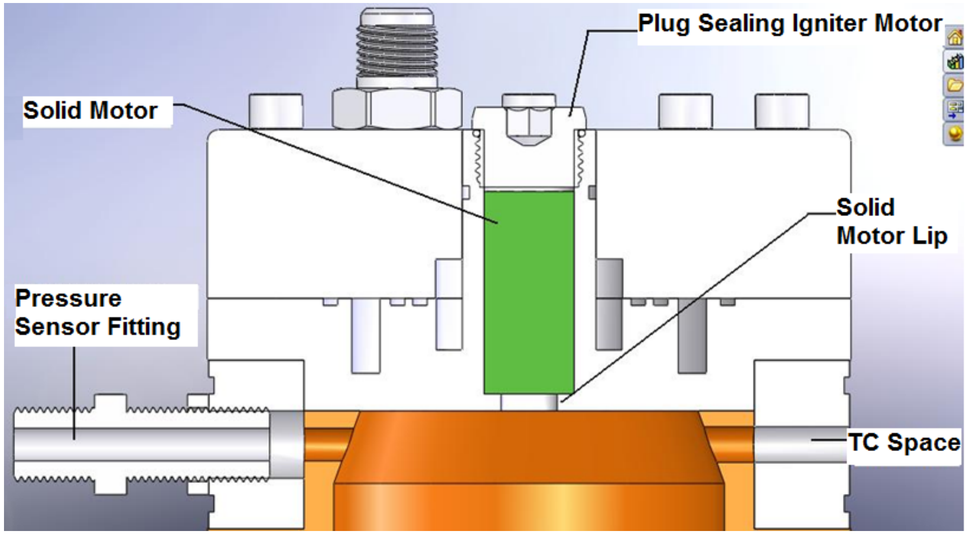
- CCA includes Flange, Combustion Chamber, and Nozzle
- Aluminum Flange is embedded in the Combustion Chamber
- Flange to mate CCA with Injector Plates
- Combustion Chamber and Nozzle incorporated in 1 piece, layed-up using Silica Fibers/High temp. Epoxy as Ablative
- Carbon Fiber is overwrapped to provide structure

Ignition System

- Pyrotechnic Charge used for SFT and Flight Test
- Sealed using a plug with O-ring
- Tested before Use
- Spark Torch system will likely be used for Upper Stage Engine



CCA, Bottom up view with ignition system



Cross Sectional View of the Injector

Ignition Test

Play Full Screen

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Static Fire Test (SFT)

Play Full Screen

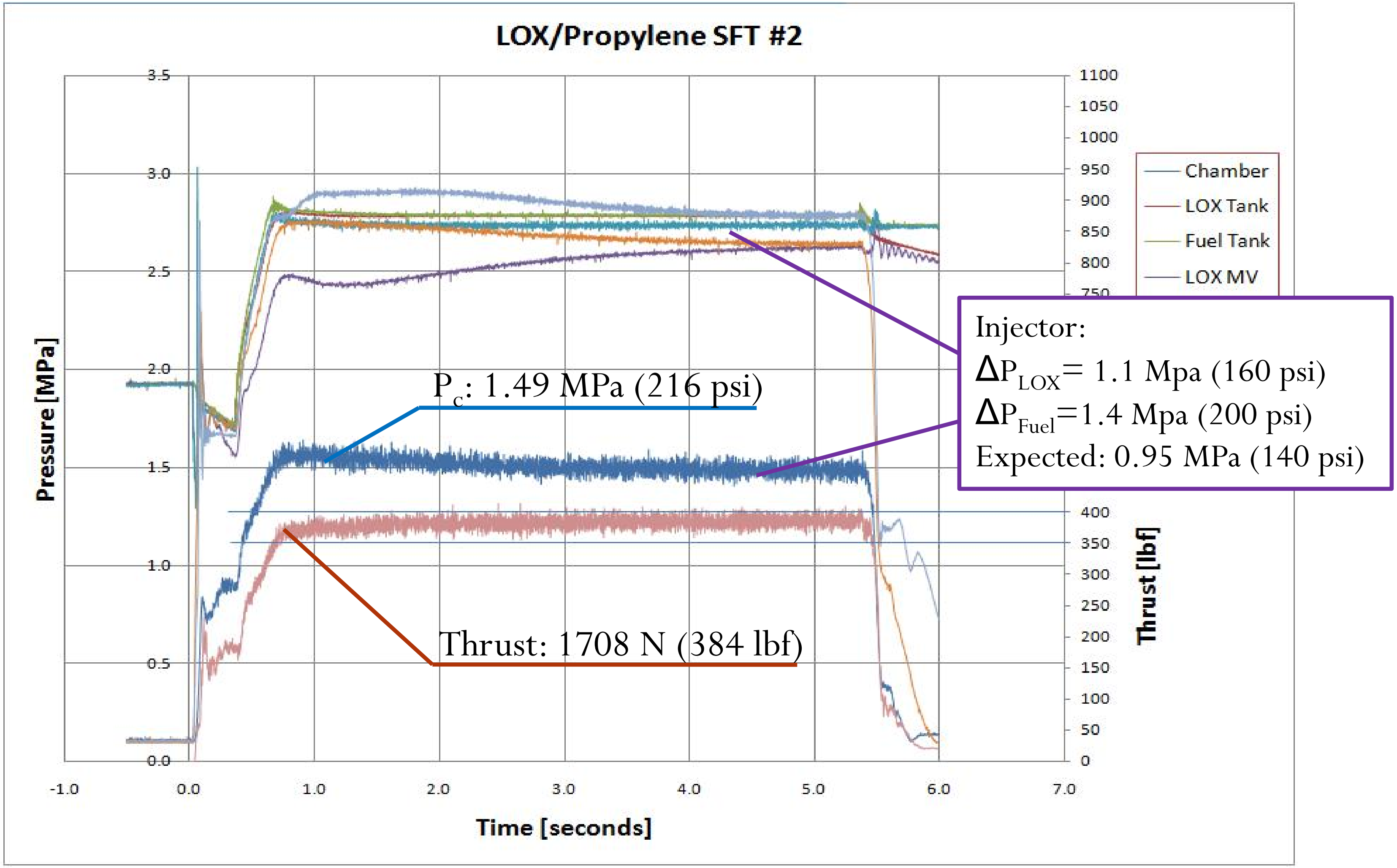
LOX/Propylene
SFT No. 2
Nov 2008, Mojave

<u>Objectives:</u>

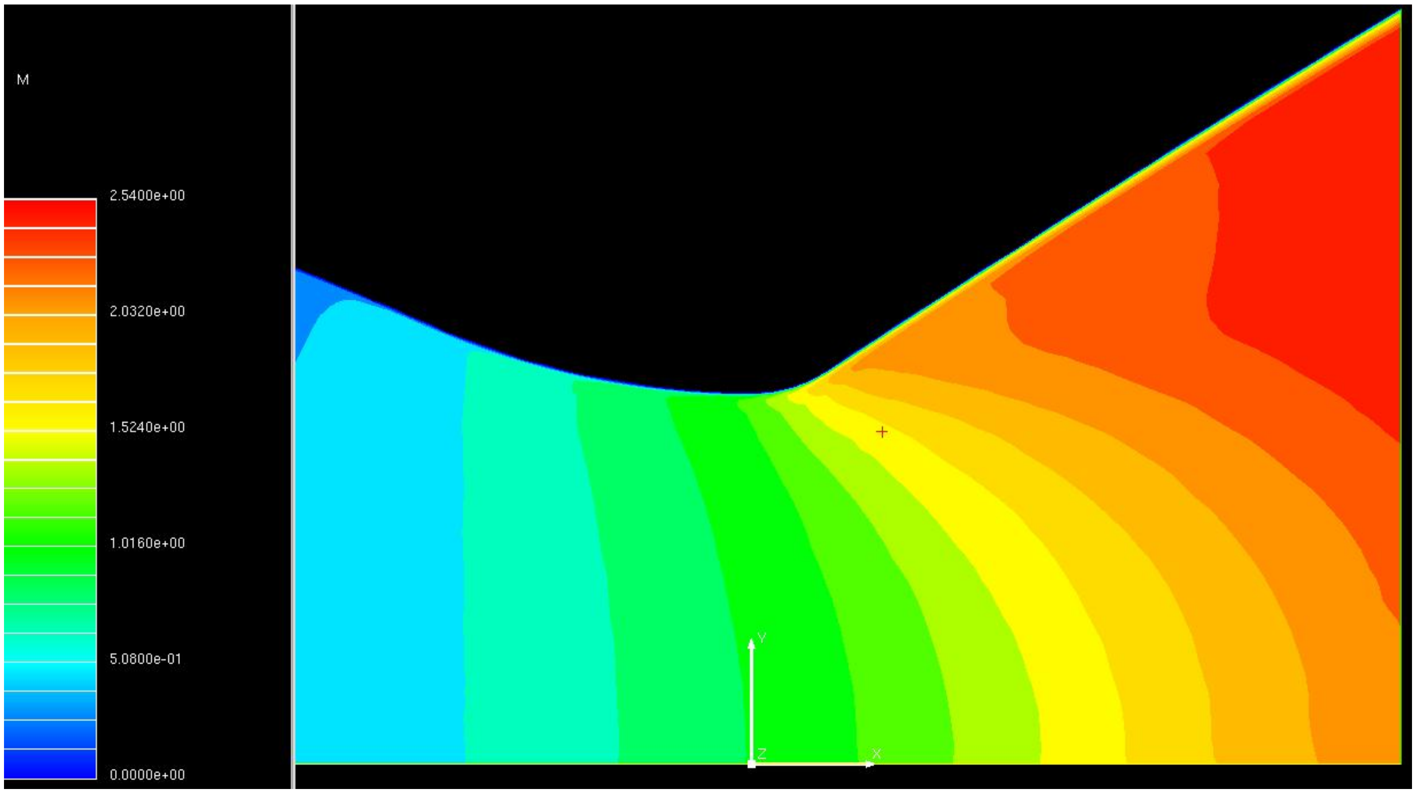
- Ignition
- 5 second burn
- Record Pressures and Thrust

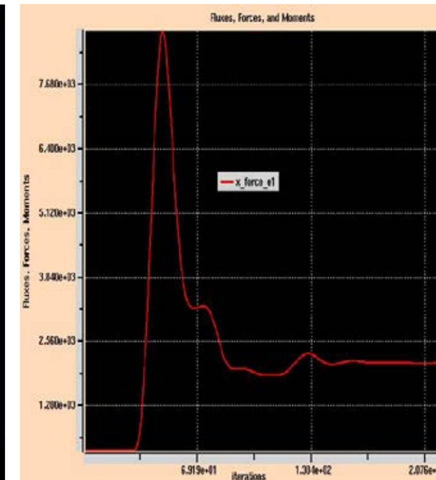
Burn time: 5.5 s
Isp: 205s

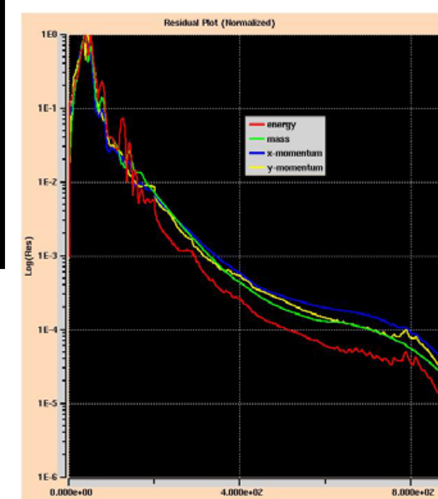
SFT – Recorded Data



CFD Analysis (SFT Conditions)







Exit Mach number: 2.5

Calculated force: 2123 N

Measured Force: 1708 N

P_e = 100 kPa (not uniform)

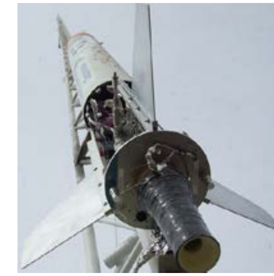
<u>Plots shown:</u>

Mach number distribution (left)

Forces (upper right)

Residuals (lower right)

Flight Test

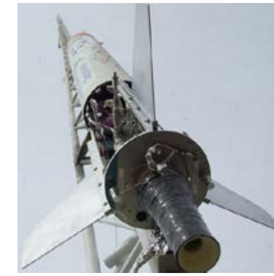


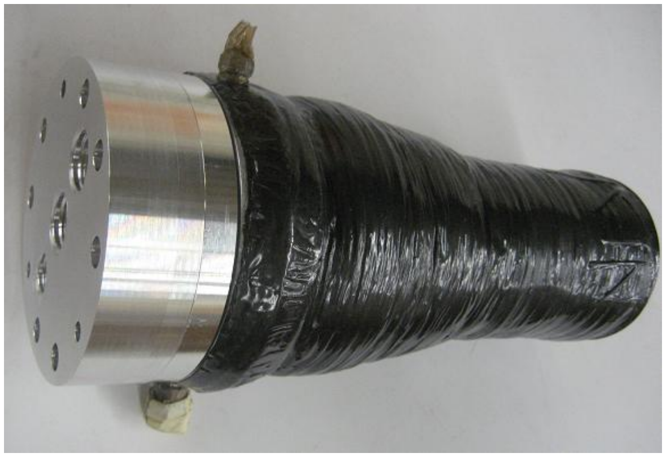
Play Full Screen

P-13 Specs:

GLOW: 122 lbs
T/W: 3.7
Thrust: 2000 N
Isp: 190 s
Burn time: 13 s
Apogee: 5211 ft

Conclusion





Designed an upper stage Engine and manufactured a prototype for sea level testing during Senior Design

Two successful static fire tests in Nov 2008

Successful first launch of a LOX/propylene engine

References

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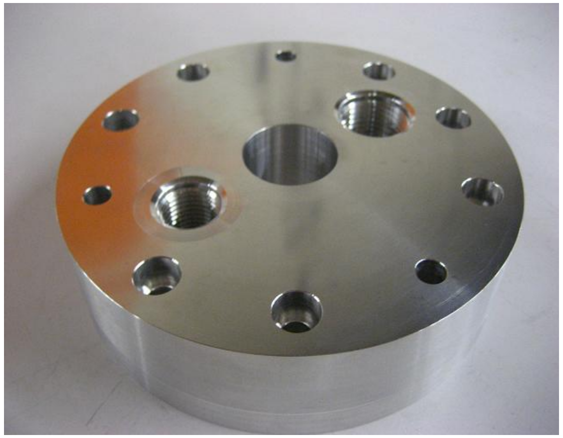
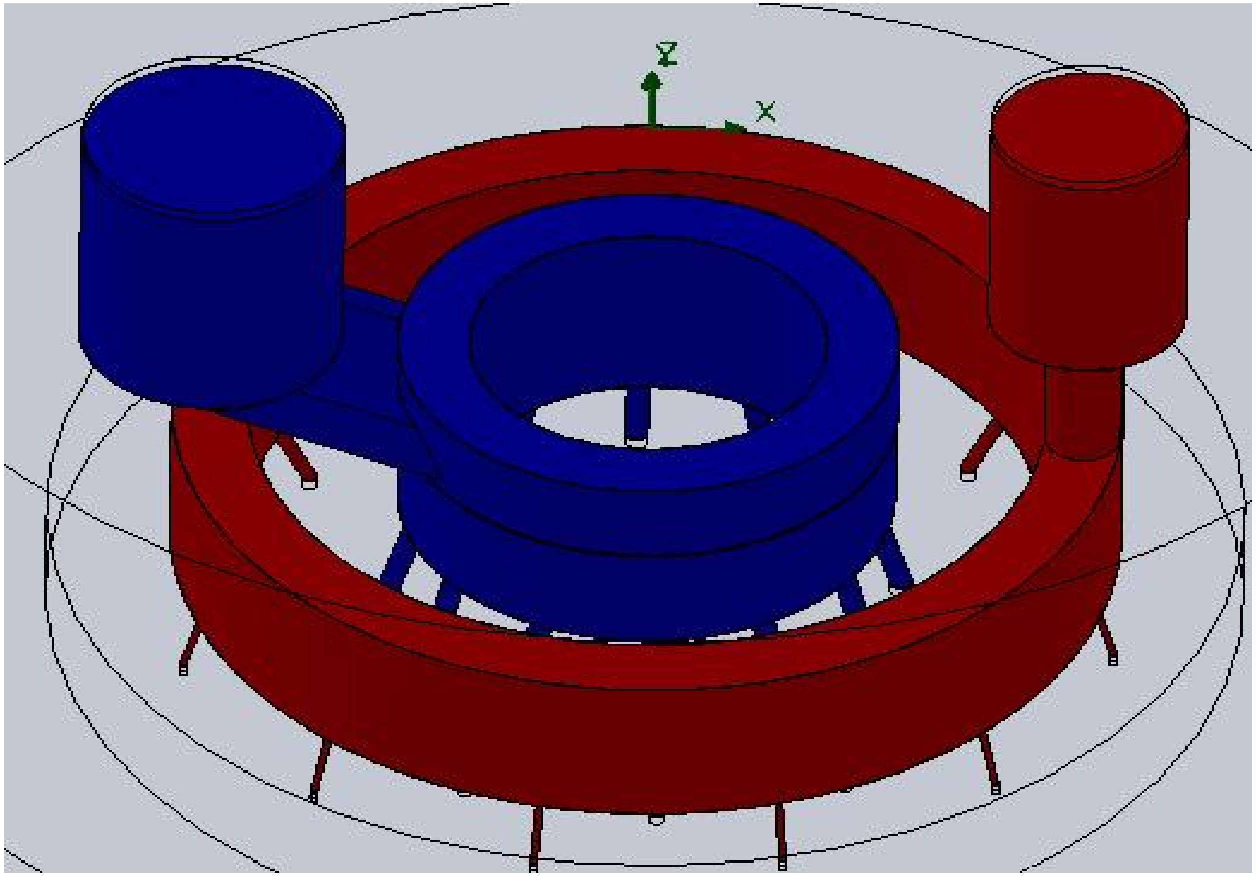
- K. Gemba, D. Verma and E. Besnard, "Development and Testing of a Prototype LOX/propylene Upper Stage Engine," AIAA Paper No. 2008-4839, July 2008
- Hunzel, Dieter K. (1992). "Modern Engineering for Design of Liquid-Propellant Rocket Engines."Volume 147, Washington DC: AIAA
- Humble, Ronald W. (1995) "Space propulsion Analysis and Design" 1th edition, New York: McGraw-Hill Companies, Inc.
- "Two Dimensional Kinetic (TDK) Code". 17 May, 2008 http://www.sierraengineering.com/TDK/tdk.html
- "Chemical Equilibrium with Applications ", NASA Code. 02 March, 2009 http://www.grc.nasa.gov/WWW/CEAWeb/
- "Chemistry Web Book". 17 May, 2008 http://webbook.nist.gov
- E. Besnard, D. Verma, and G. Haberstroh, "Development and Flight Testing of a Pressure-Fed 1,000 lbf LOX/methane Rocket Engine," Paper presented at the 4th LPS, 55th JANNAF Propulsion Meeting, Orlando, Florida, December 2008

Questions

Floworks Analysis - Setup

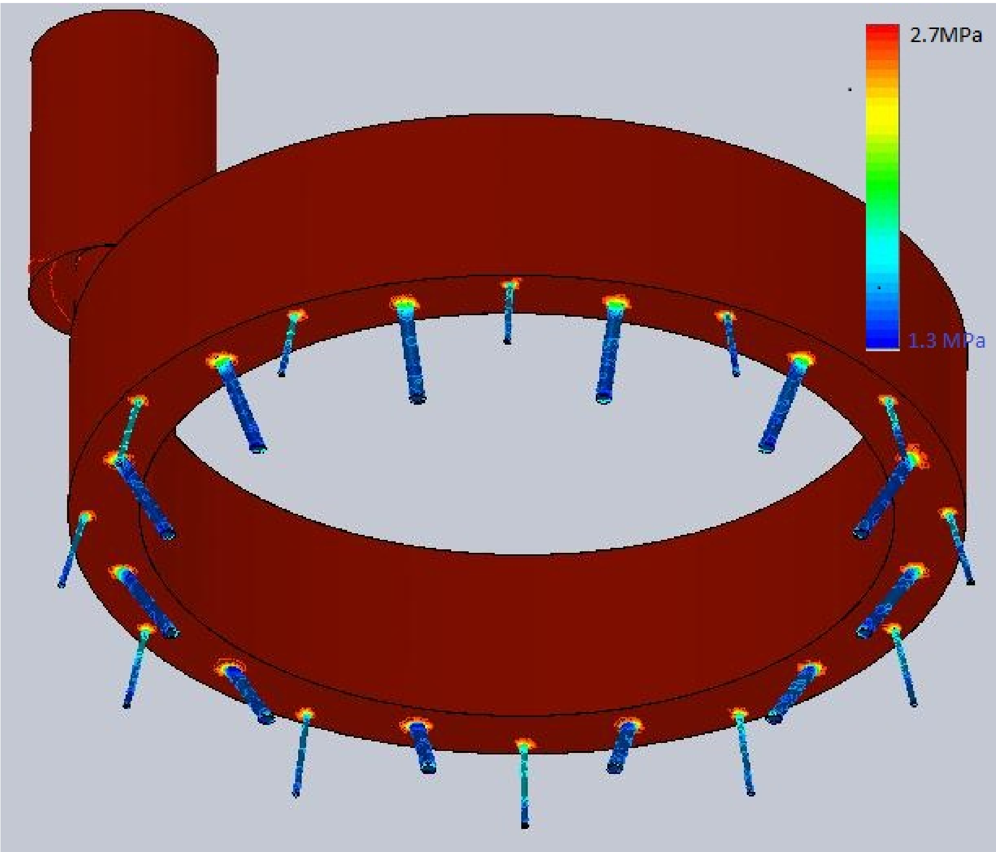


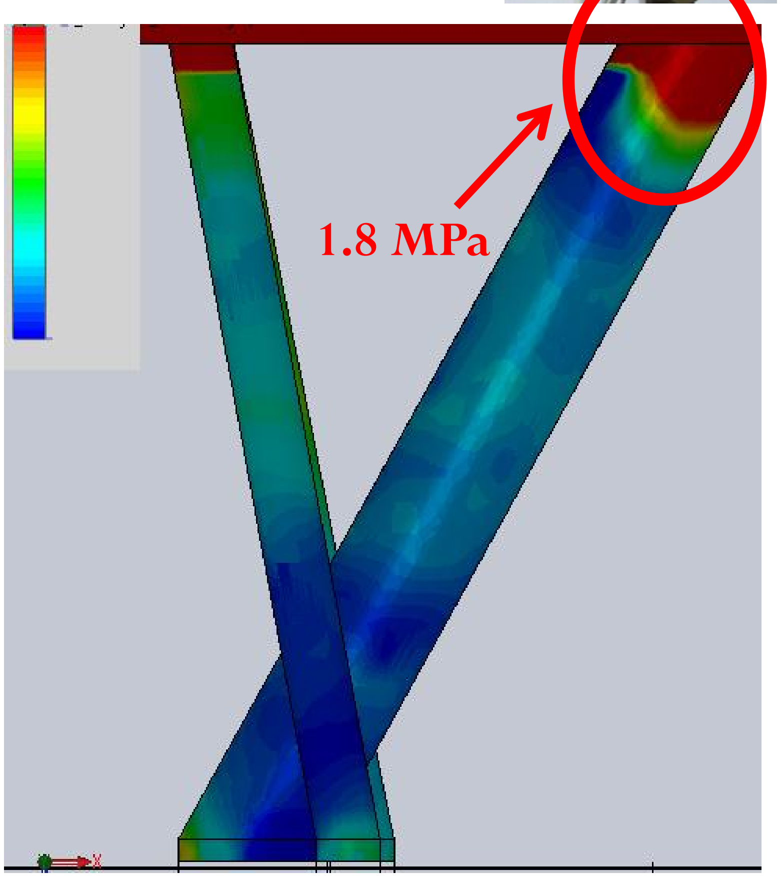
Test Hardware (Injector)



Injector CFD Analysis: LOX (blue), Fuel (red)

Floworks Analysis - Fuel



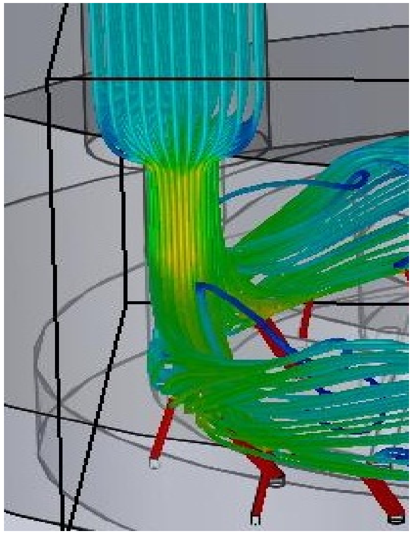


Fuel Analysis at SFT conditions (1.3-2.7 MPa)

Cavitations within orifices (P_{vapor} = 1.4 MPa @ 305 K)

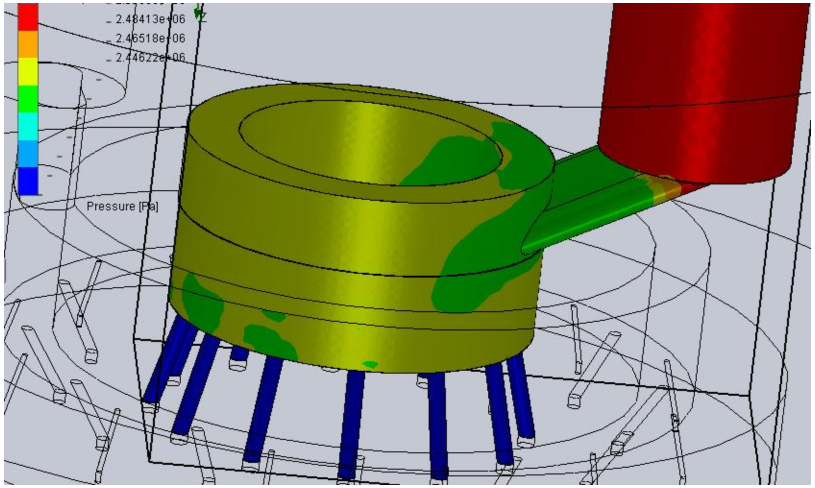
Recommendations - Fuel

- Reduce the pressure drop of the injector to a maximum of 30% (SFT: 49%)
- Round orifice entrances
- Configure the static fire test stand for the maximum tank pressure of 3.1 MPa (450 psi)
- Cool the propylene before the test
- Pre-chill the fuel tank (Liquid Nitrogen)
- Increase volume of Fuel feed

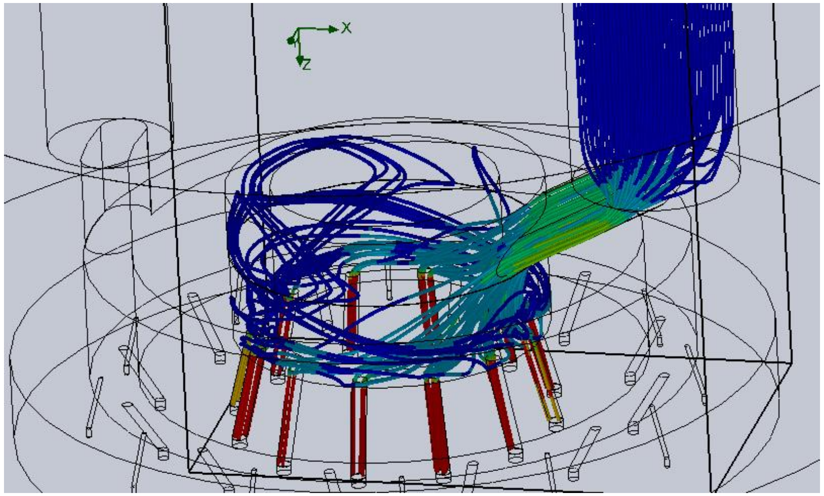


Velocity distribution in the Fuel feed (0-15m/s)

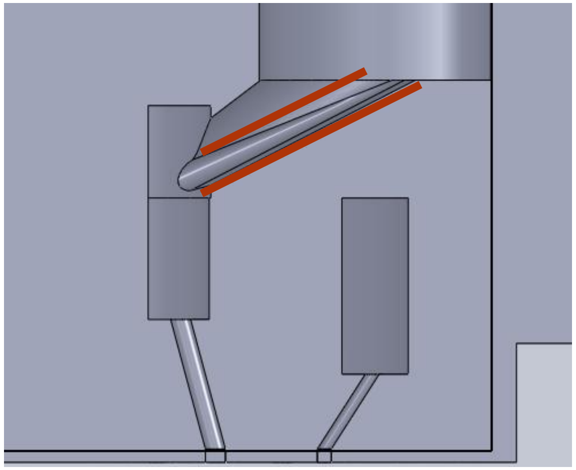
Floworks Analysis - LOX



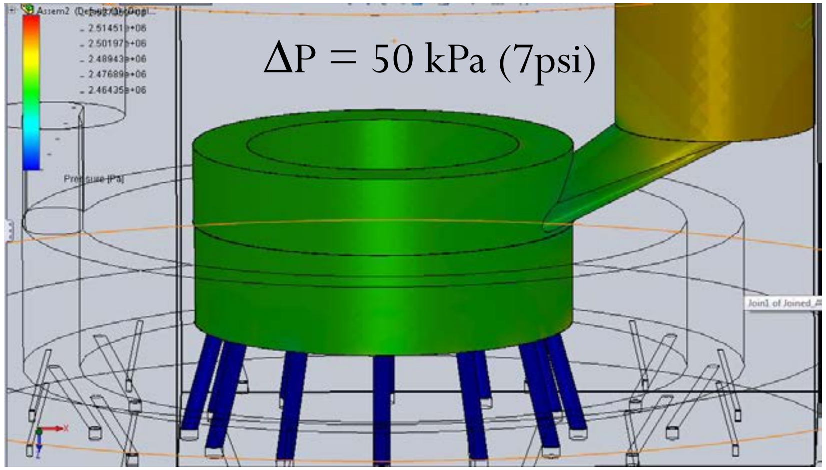
Pressure Profile (2.3-2.5 MPa)



Velocity Profile (0-25 m/s)



Changed Geometry of LOX Feed



New Geometry: Pressure Profile (2.4-2.5 MPa)

Recommendations - LOX

- Change the geometry of the slanted LOX channel
- Round orifice entrances

Additional Steps

- Investigate injector pressure drop
  - Perform additional tests, increase the range of test conditions
- Change position of the thermocouple
- Reduce injector weight (T/W: 50 → 100)
- Reduce Engine Weight
  - Model required thickness of carbon fiber overwrap
- Cryogenic Fuel?