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MASA Rocket Technical Summary

University of Michigan

Primary Point of Contact: Mirko Gamba. mirkog@umich.edu

February 22, 2021

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Full Rocket, Tangerine Space Machine

Written by: Jack Taliercio (jtalier)

Characteristics of Performance:

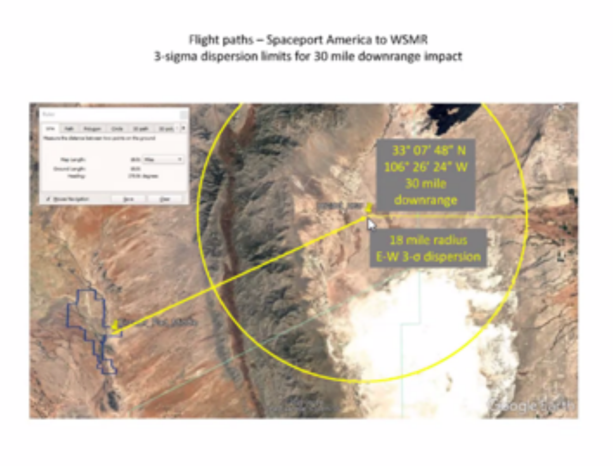
Height:	26’, 8”	Target Apogee:	400,000ft
Diameter:	15.25”	Payload:	10lbs
Thrust:	4,080lbf	Control:	Passive
Total Impulse:	170,000lbf-s	Burn Time:	41.5 seconds
Control:	Passive	Landing Radius:	30-35 miles
Maximum Range:	150-170 miles	Target Range:	30 miles

Objective:

- This rocket is designed to complete the challenge as presented by the Base 11 Space Challenge
- It will launch from Spaceport America and travel to an apogee of 400,000ft

Design Overview:

- Per FAA guidelines, this rocket is classified as a Class 3 Advanced High-Powered Passively Controlled Rocket
- Provided are documents for all the major components that will be present on this rocket
- The rocket is a single stage, LOX, RP-1 rocket using aluminum 6061 propellant tanks
- The engine is a regeneratively cooled, 3D printed, and pressure fed
- The fins are made out of bent 6061 aluminum and provide passive stability for the rocket
- The airframe sections of the rocket are rolled 6061 aluminum

- The nose cone uses a titanium tip, with the rest of the body being rolled 6061 aluminum
- Designed to be launched off at a 60ft Launch rail
- Designed to lift a maximum payload of 10 pounds
- The maximum range is 150-170 miles if a rail angle was selected to maximize range, however under no situations will a rail angle be selected that would allow this. Further, and more importantly, the rocket is not designed and probably would not be able to handle the increased loading conditions from a flight of this type.
- 

Flight paths – Spaceport America to WSMR
3-sigma dispersion limits for 30 mile downrange impact

Sources:

- No sources have been used to design the overall architecture of the rocket. Sizing of the engine and tanks were based on simple impulse equations and flight simulations. An extensive list of sources is provided in each component document.
  - The 'Flight Simulation' document contains software used to size and simulate our vehicle
- Base 11 Space Challenge Site: https://www.herox.com/spacechallenge
- Spaceport America Launch Site: https://spaceportamerica.com
- Launch Rail: https://friendsofamateurrocketry.org

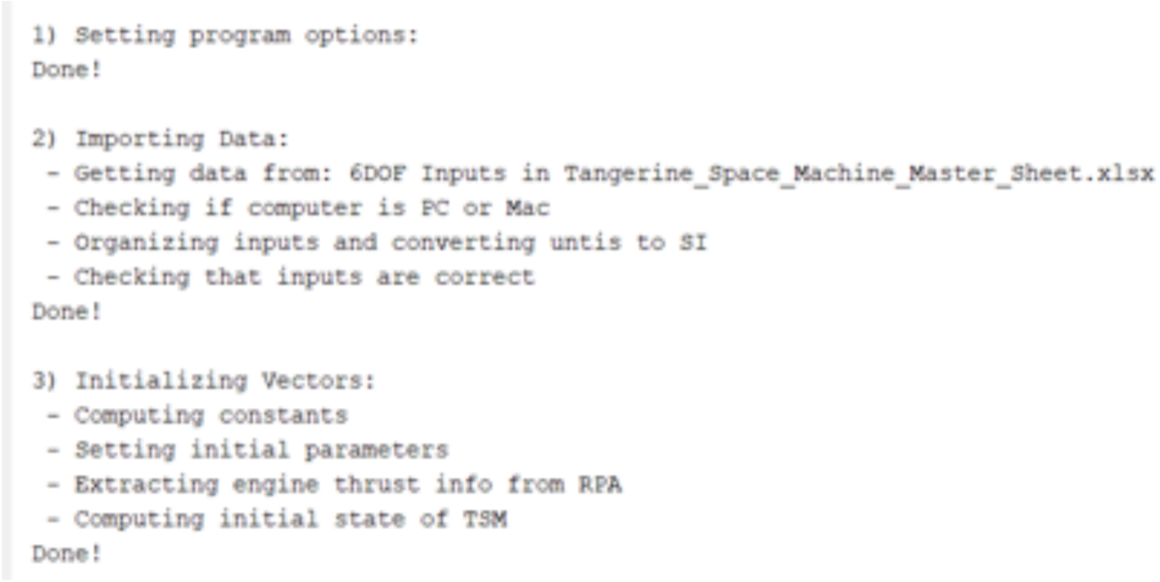
Commercial Interactions:

- Base 11, Competition discussion, submissions, and planning https://www.base11.com
- All other commercial interactions are listed in component documents
- Planned interactions with the FAA. https://www.faa.gov

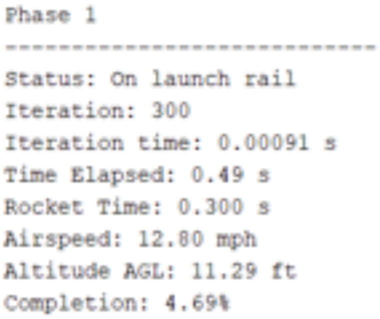
Aerodynamics:

6DOF Flight Simulator:

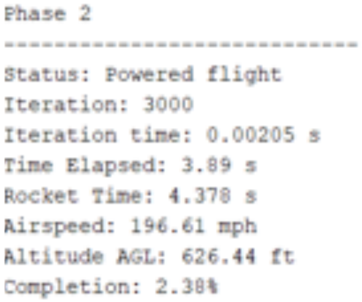
Written by: Dan Maguire (maguired), Keon Koochesfahani (koochesf), Jose Luiz Vargas de Mendonca (joselvdm)
-Images of display of software while performing calculations



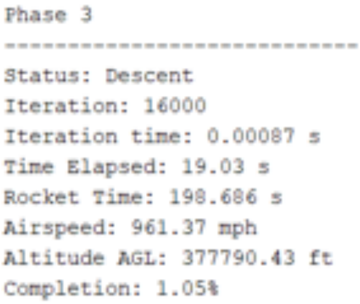
```
1) Setting program options:
Done!

2) Importing Data:
 - Getting data from: 6DOF Inputs in Tangerine_Space_Machine_Master_Sheet.xlsx
 - Checking if computer is PC or Mac
 - Organizing inputs and converting untis to SI
 - Checking that inputs are correct
Done!

3) Initializing Vectors:
 - Computing constants
 - Setting initial parameters
 - Extracting engine thrust info from RPA
 - Computing initial state of TSM
Done!
```



```
Phase 1
----------------------------
Status: On launch rail
Iteration: 300
Iteration time: 0.00091 s
Time Elapsed: 0.49 s
Rocket Time: 0.300 s
Airspeed: 12.80 mph
Altitude AGL: 11.29 ft
Completion: 4.69%
```



```
Phase 2
----------------------------
Status: Powered flight
Iteration: 3000
Iteration time: 0.00205 s
Time Elapsed: 3.89 s
Rocket Time: 4.378 s
Airspeed: 196.61 mph
Altitude AGL: 626.44 ft
Completion: 2.38%
```



```
Phase 3
----------------------------
Status: Descent
Iteration: 16000
Iteration time: 0.00087 s
Time Elapsed: 19.03 s
Rocket Time: 198.686 s
Airspeed: 961.37 mph
Altitude AGL: 377790.43 ft
Completion: 1.05%
```

Stats:

Sim Software	Matlab

Component Objective:

- Programmed to simulate flight trajectory of the rocket using 6 Degrees of Freedom (3 rocket mass center coordinates and 3 rotational coordinates of rocket mass center momentum)
- Ensure the rocket will reach the aimed apogee of 380,000 ft
- Simulate how uncertainty can affect the trajectory of the rocket
- Estimate dimensional tolerance in the parts of the rocket

Design Overview:

- The program was designed using MATLAB
- It extracts rocket data from a spreadsheet and organize it in MATLAB structs
- The structs are divided into Constant Vector (variables that do not change over time), State Vector (variables representing where it is and how fast it is moving), Parameter Vector (variables that do change over time), Options Boolean (tell whether or not to display graphs, write flight summary, turn on winds)
- The computation is divided into 3 phases that take into consideration different aspects of flight. Phase 1 calculates the motion on the launch rail. Phase 2 calculates the motion while the engine is on until it turns off (powered flight) and from when it turns off until the rocket reaches apogee (coast). Phase 3 calculates the descent after apogee taking into consideration the deployment of the drogue and main parachute.
- For continuity purposes, the last state vector of the previous phase is the first state vector of the following phase
- The stochastic simulator is based on the Monte Carlo approach, where variables are randomly modified to simulate small perturbations
-

Sources:

- The Flight Simulator was programmed using MATLAB (https://www.mathworks.com/products/matlab.html), using the Aerospace Toolbox to call specific libraries and functions, such as atmosisa, egm96geoid, 1976Atm
- The equations of motion used in the program are described in Box, S. “Stochastic Six-Degree-of-Freedom Flight Simulator for Passively Controlled High-Power Rockets”. Based on this paper, we also structured the program in the three phases mentioned in “Design Overview”
- The organization of the program was based on NASA’s Technical Note “REVISED THREE DEGREE OF FREEDOM PARTICLE TRAJECTORY PROGRAM C03E FOR THE IBM 7094 COMPUTER”

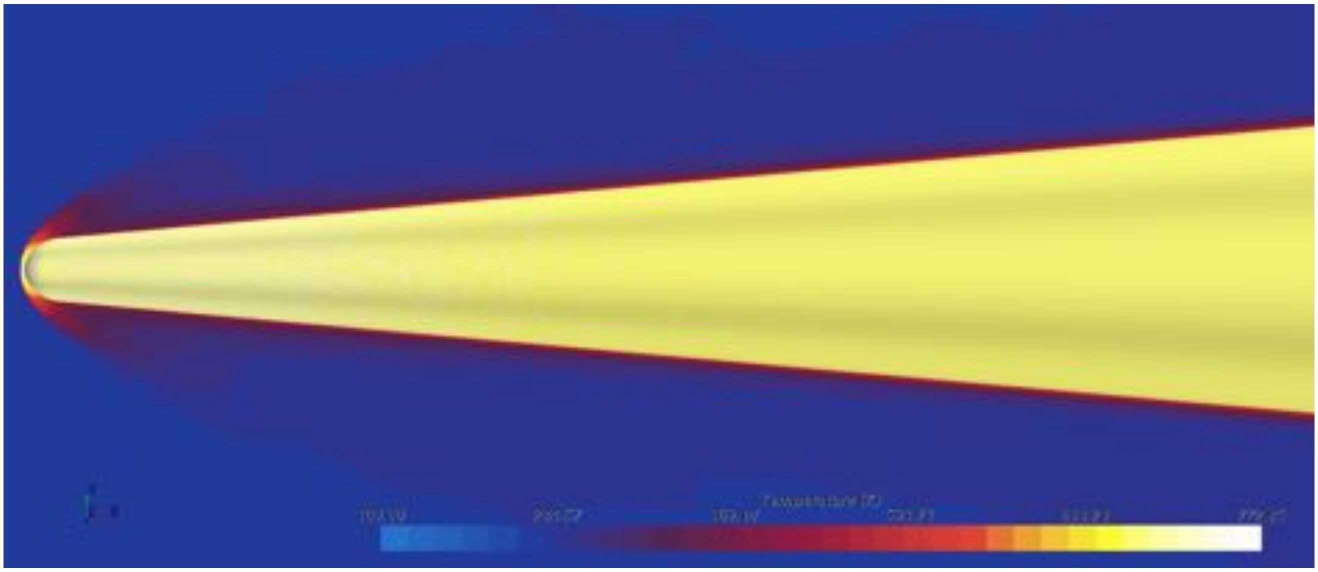
- Calculations of aerodynamics coefficient and thrust damping were based on Box, S. “Estimating the dynamic and aerodynamic parameters of passively controlled high power rockets for flight simulation”
- Other resources were Khalil, M. “Trajectory Prediction for a Typical Fin Stabilized Artillery Rocket”, Newlands, R. “Rocket vehicle loads and airframe design ” and NASA’s Contract Report “MOMENT OF INERTIA AND DAMPING OF LIQUIDS IN BAFFLED CYLINDRICAL TANKS ”

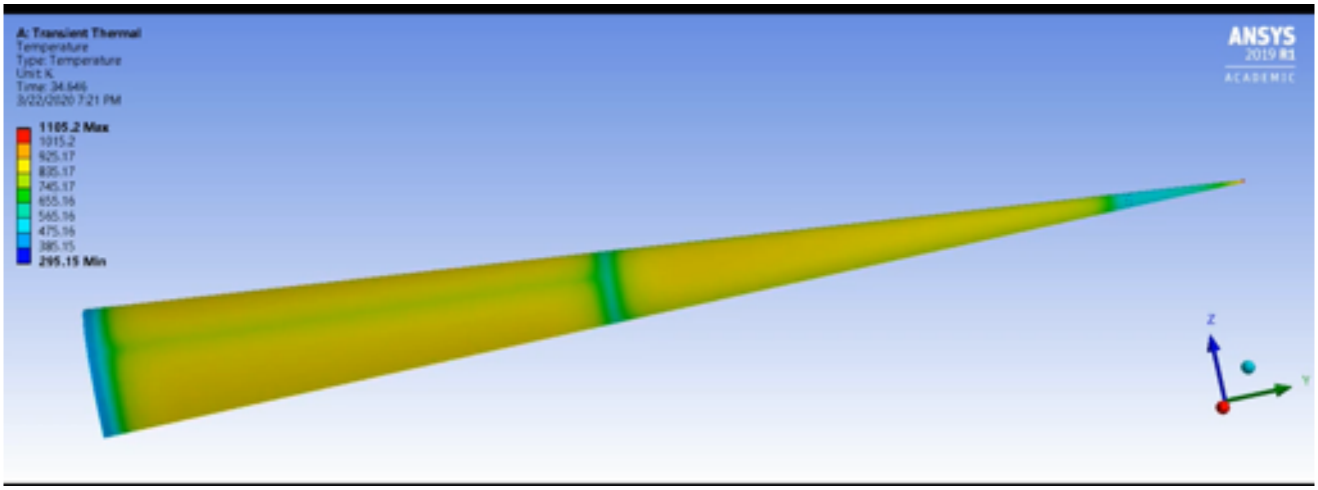
Commercial Interactions:

- Contact with Northrop Grumman to ask about the implementation of Monte Carlo into the simulation. Mainly about how to plot parameters and which variables were more sensible while calculating rocket trajectory

Aerodynamic Heating Analysis

Written by: Edward Tang, tanged





Stats:

Simulation Software	Siemens STAR-CCM+ ANSYS Workbench MATLAB

Component Objective:

- Determine a methodology for finding aerodynamic heating
- Establish said methodology given constraints of readily available commercial software and publicly available research papers
- Find the skin temperature that our rocket experiences during flight

Design Overview:

- Since a testing in a hypersonic wind tunnel is not viable for a student organization, MASA had instead simulated TSM's flight regime to get temperatures caused by aerodynamic heating.
- It was determined that a nose cone would experience the brunt of aerodynamic heating.
- Simple nose cone model was CAD'd in SolidWorks.
- Using a two step process, we simulated the heat that builds up within our nose cone during flight.
  - To begin, we found the temperature of the air at our wall throughout our flight profile. Using STAR-CCM+ and known atmospheric data, we ran a number of CFD simulations at various critical time steps and wall conditions.
  - From this data we interpolated to solve for air temperature at the nose cone wall as a function of time.
  - Now with this new data set, we plugged it into a transient thermal simulation such as ANSYS, and solved for convection heat onto our nose cone as a function of time.
- With this we have a realistic answer as to the temperature our nose cone experiences during flight.

Sources:

- Design was completed in Solidworks Educational Software https://www.solidworks.com
- All transient thermal simulation were completed in ANSYS https://www.ansys.com
- All CFD was run in STAR-CCM+ https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html
- All meshing was done in Pointwise https://www.pointwise.com/
  - Y+ data was found here https://www.cfd-online.com/Wiki/Dimensionless_wall_distance_(y_plus)
- All mathematical modeling/postprocessing was done in MATLAB https://www.mathworks.com/products/matlab.html
- General framework and guidelines for heating calculations sourced from Richard B. Dow, Fundamentals of Advanced Missiles, p. 162-170.

https://www.amazon.com/Fundamentals-Advanced-Missiles-Wiley-Technology/dp/1258626845

- CFD heating transfer analysis sourced from
  Adam Neale, Dominique Derome, Bert Blocken and Jan Carmeliet,
  Determination of surface convective heat transfer coefficients by CFD
  https://www.researchgate.net/publication/267426300_Determination_of_Surface_Convective_Heat_Transfer_Coefficients_by_CFD

Commercial Interactions:

- Design review held with employee at Northrop Grumman
- Design review held with employees at Corvid Technologies LLC

Fins

<u>Written by:</u> Andi Zhou (andizhou)

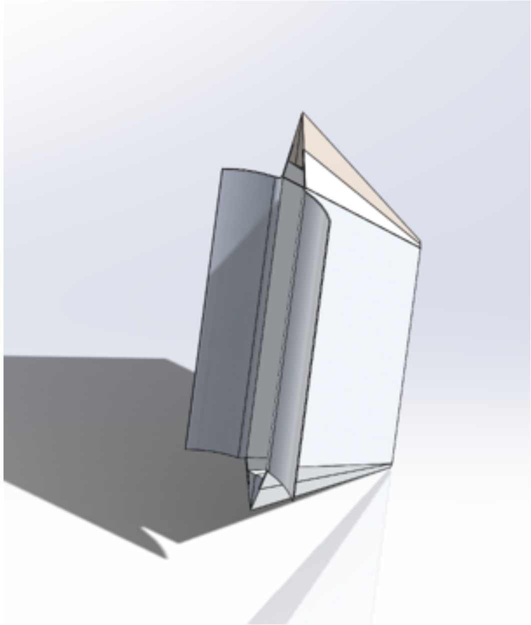


Figure 1 Full Fin Assembly

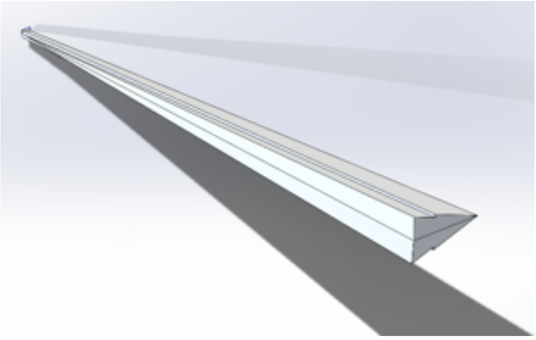


Figure 2 Trailing Edge

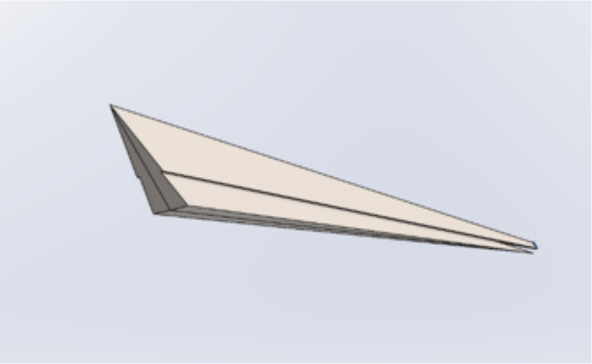


Figure 3 Leading Edge

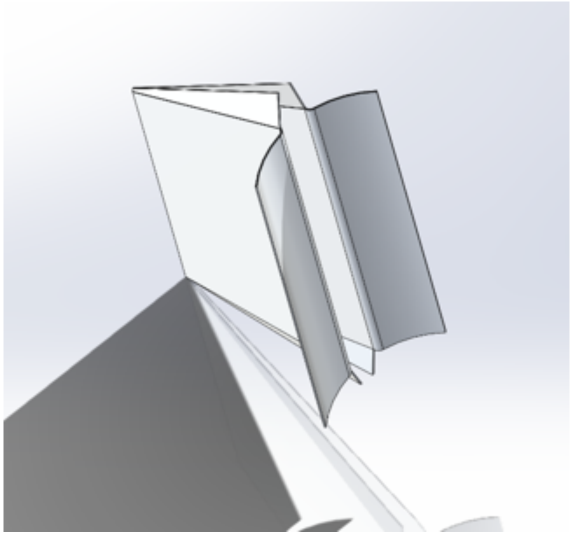


Figure 4 Fin Main Body

Materials:	Aluminum 5052, Grade 5 Titanium	Diameter	14.12 in (Fin Can) 34.36 in (Full Fin)
Manufacturing:	Sheet metal bending, CNC Mill CNC Lathe, welding	Height	36.4 in
Simulation / Design:	ANSYS Solidworks Pointwise RasAero Autodesk MATLAB	Components	Leading Edge Trailing Edge Fin Main Body

Component Objective:

- Ensure the aerodynamic stability of the rocket
- Ensure that the rocket stays on a straight trajectory during flight
- Prevents fluttering

Design Overview:

- Utilizes a 5052 Aluminum for main fin body and trailing edge
- Utilizes grade 5 titanium for leading edge
- Static structural simulations were completed in ANSYS Structural
- Aerodynamic simulations were completed using RASAero and ANSYS Fluent
- Modal simulation is completed using ANSYS Modal
- Transient flutter analysis were completed using ANSYS coupled analysis using both ANSYS Transient Structural and ANSYS Fluent
- Main fin body would be manufactured using CNC Sheet Metal Bender
- Leading edge and trailing edge would be manufactured using CNC Mill
- The structure will be bolted and welded together
- Tolerance will be checked on a CMM machine
- The structure would be tested using ANSYS simulated

Sources:

- Design was completed in Solidworks Educational Software https://www.solidworks.com
- All static structural, transient structural and aerodynamic simulations were completed in ANSYS https://www.ansys.com
- CAM machining operations for CNC will be completed in Autodesk Student https://www.autodesk.com/education/home

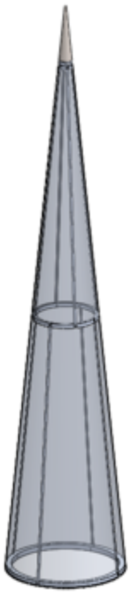
- Microsoft Excel for documenting elastic axis data https://www.microsoft.com/en-us/microsoft-365/excel
- MATLAB for demonstrating the location of the elastic axis and basic flutter calculation https://www.mathworks.com/products/matlab.html
- ANSYS student support for simulation troubleshooting: https://studentcommunity.ansys.com/
- Pointwise for structure meshing: https://www.pointwise.com/
- ApogeeRockets for basic flutter information and equation: https://www.apogeerockets.com/
- Introduction to Structural Dynamics and Aeroelasticity textbook by Dewey H.Hodges; G.Alvin Pierce https://www.amazon.ca/Introduction-Structural-Dynamics-Aeroelasticity-Hodges/dp/110761709X

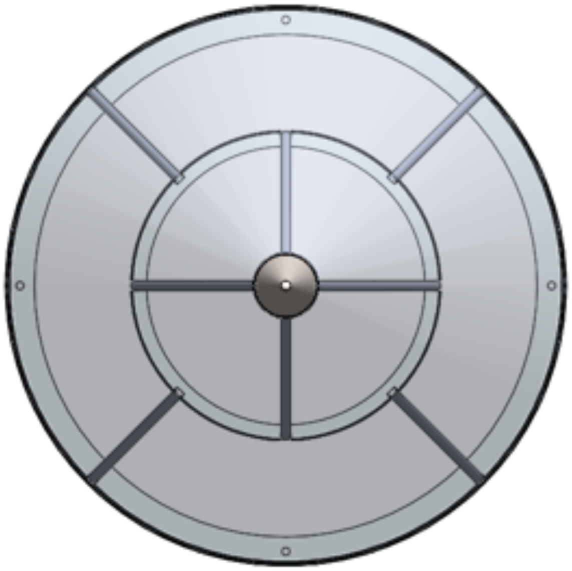
Commercial Interactions:

- Stock will be purchased from Online Metals https://www.onlinemetals.com
- Components will be purchased from: https://www.mcmaster.com, https://www.grainger.com, etc
- CNC Bending and Milling will be handled by Xometry https://www.xometry.com/
- Welding will take place at Custom Tech Fabricating, Duane Fiegel (734)-845-7311

Nosecone

Written by: Stefan Greenberg (sfgreen)





Stats:

Materials:	6061 Aluminum 5052 Aluminum Alloy Steel 6Al-4V Titanium	Height:	72.5 inches
Manufacturing:	CNC mill CNC lathe Waterjet CNC sheet metal rolling Welding	Diameter:	14.5 inches
Weld Filler:	5356 Aluminum	Thread Lock:	Loctite 272

Component Objective:

- Provide aerodynamic leading edge for front of rocket
- House parachute for duration of ascent

Design Overview:

- Solid titanium tip to deal with high temperatures
  - Bolted onto aluminum spacer using alloy steel bolt and loctite

- Rolled aluminum sheet metal skin
  - Pattern cut out on water jet
  - CNC rolled into cone
- Frame for sheet metal made by welding aluminum extrusions to 3 CNC machined rings
  - Rings evenly spaced along height of cone
  - Aluminum extrusions serve as ribs that lie along surface of cone
- Aluminum spacer on the tip is welded to the top ring
- Sheet metal skin is tack welded on top and bottom rings, seam is welded and ground flush
- Bottom ring can be modified to mount to or incorporated with separation mechanism for parachute deployment
- Analytic structural and thermal analysis will be performed using ANSYS

Sources:

- Design was completed in Solidworks Educational Software https://www.solidworks.com
- All static structural simulation and transient thermal simulations were completed in ANSYS https://www.ansys.com
- All CFD was run in STAR-CCM+ https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html
- All meshing was done in Pointwise https://www.pointwise.com/
  - Y+ data was found here https://www.cfd-online.com/Wiki/Dimensionless_wall_distance_(y_plus)
- CAM machining operations for CNC will be completed in Autodesk Student https://www.autodesk.com/education/home
- 5356 Weld filler was determined for it material properties from Hobart Brother https://www.hobartbrothers.com/downloads/aluminum_selecti_1IOo.pdf
- Material properties were determined using ASM matweb http://asm.matweb.com/

Commercial Interactions:

- Stock will be purchased from Online Metals https://www.onlinemetals.com
- Hardware and extrusions will be purchased from: https://www.mcmaster.com
- Welding will take place at Custom Tech Fabricating, Duane Fiegel (734)-845-7311
- Water jetting will occur at Leading Edge Fabrication: https://www.leadingedgefab.com
- Sheet metal rolling will occur at A1 Rolling: https://www.a1roll.com

Recovery Systems

Written by: Hunter Sagerer (hsagerer), Erin Levesque (erinleve)

Stats:

Materials:	Nylon parachute canopy, kevlar tethers, nylon cord, aluminum
Manufacturing:	CNC, Sheet metal rolling
Simulation Software:	RasAero, Matlab
Parachute Sources:	The Rocketman
Design Sources:	Northrop Grumman, Airborne Systems

Component Objective:

- Designed to allow for safe descent and recovery of the vehicle
- Ensure rocket achieves a safe landing speed of around 13 ft/sec to prevent damage to the rocket and minimize risks associated with the descent process
- Lower the amount of aerodynamic force and shock felt by the vehicle upon descent and upon the opening of parachutes

Design Overview:

- Recovery system is composed of a pilot parachute, a 7ft drogue parachute, and a 50ft main parachute
- Nylon parachutes are connected by Kevlar tethers to each other and attachment points on the rocket made from aluminum.
- Force calculations for deployment of all three parachutes were conducted using flight simulations with RasAero and Matlab
- Parachutes will be purchased from Rocketman
- Nylon tethers will be purchased from USNetting or Rocketman
- Attachment points will be bolted to or welded to the airframe of the rocket
- Pyrotechnic and Electric-activated line cutters will be used to sever lines allowing parachutes to deploy.
- Energy Modulators designed to further reduce shock
    - Folded-over Kevlar tethers with nylon stitching that only break at a certain force
    - Spread out forces from deployment over a longer period of time, reducing shock
- Deployment of all systems is activated by the main flight computer https://docs.google.com/document/d/14GkxDiHudKNj7AYI1-1PfPMYPyAvKuLr4oNK1XfdXjo/edit

    - Deployment of the separation mechanism at apogee will result in the release of a pilot chute
    - Pressure altimeters will deploy the drogue parachute at some point above 30000 ft
    - Pressure altimeters will deploy the main parachute at some point just above 1500 ft over ground level

Sources:

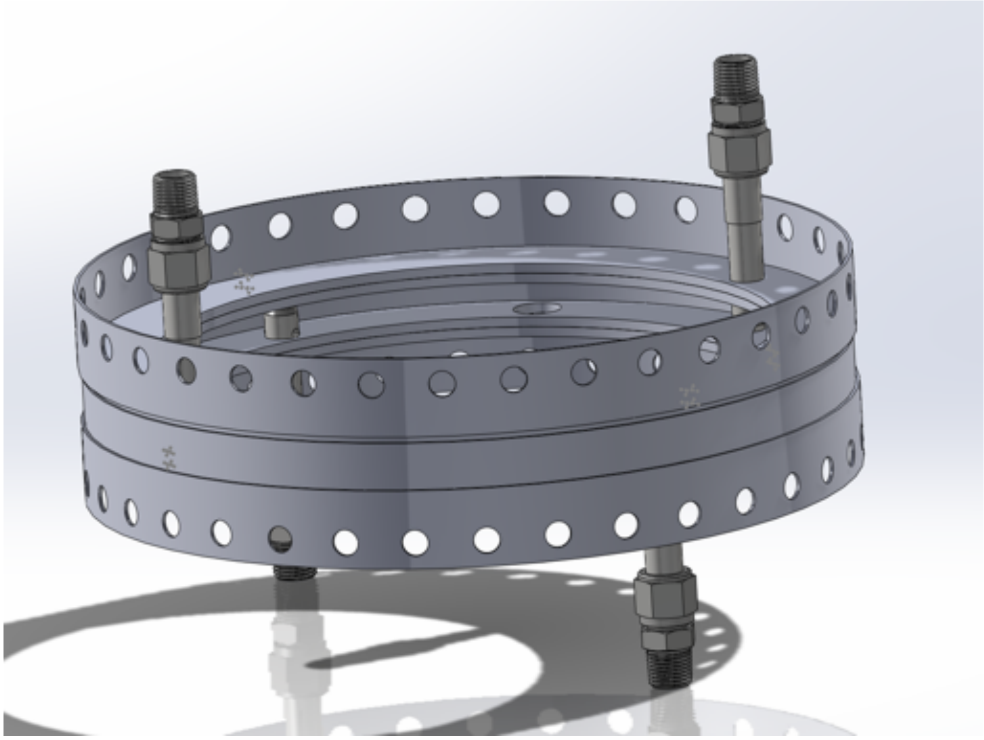
- Simulations conducted with RasAero http://www.rasaero.com/ and Matlab https://www.mathworks.com/products/matlab.html
- Math and data processing utilized Excel https://www.microsoft.com/en-us/microsoft-365/excel
- Parachutes found using The Rocketman https://the-rocketman.com/
- Kevlar material properties found using https://www.christinedemerchant.com/rope_material_aramid.html and The Rocketman https://the-rocketman.com/
- Energy Modulators designed using ideas given through https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170004416.pdf
- Design reviews with Airborne Systems North America, Inc https://airborne-sys.com/home/ and Northrop Grumman Corporation https://www.northropgrumman.com/
- All designs without a source for manufacturing will be produced in house at the University of Michigan

Commercial Interactions:

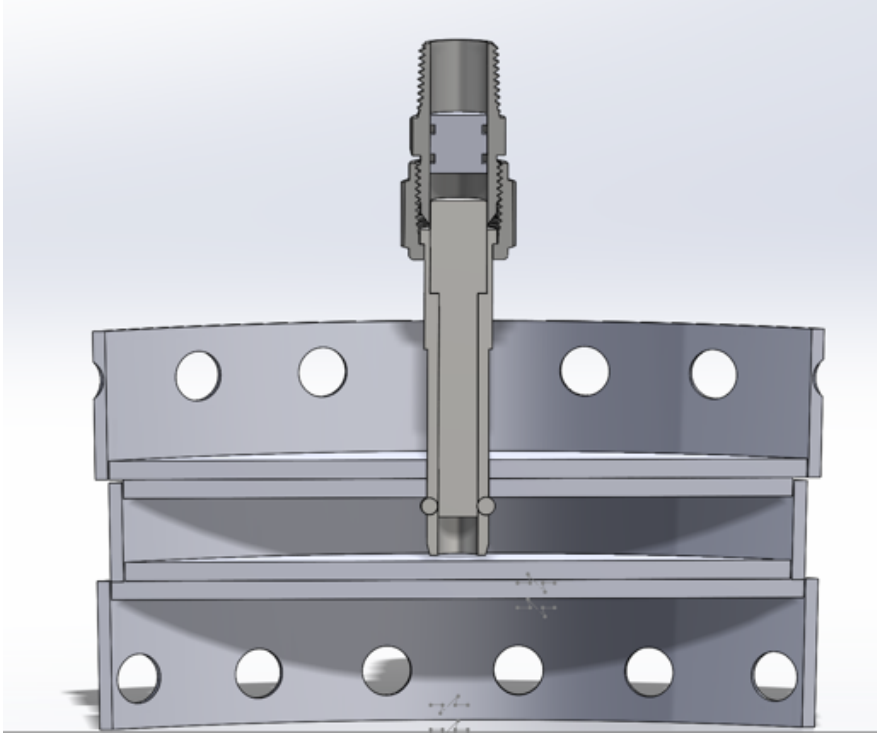
- Multiple design reviews have taken place with Northrop Grumman Corporation with Michael Kaplan and Airborne Systems North America, Inc. with Kevin Crilley
    - Both representatives were former members of our rocketry team
    - Agreed to help with designing a recovery system without disclosing export-controlled information
- Parachutes will be purchased from The Rocketman https://the-rocketman.com/
- Components will be purchased from The Rocketman https://the-rocketman.com/, US Netting https://www.usnetting.com/rope/kevlar/, and McMaster https://www.usnetting.com/rope/kevlar/

Separation Mechanism

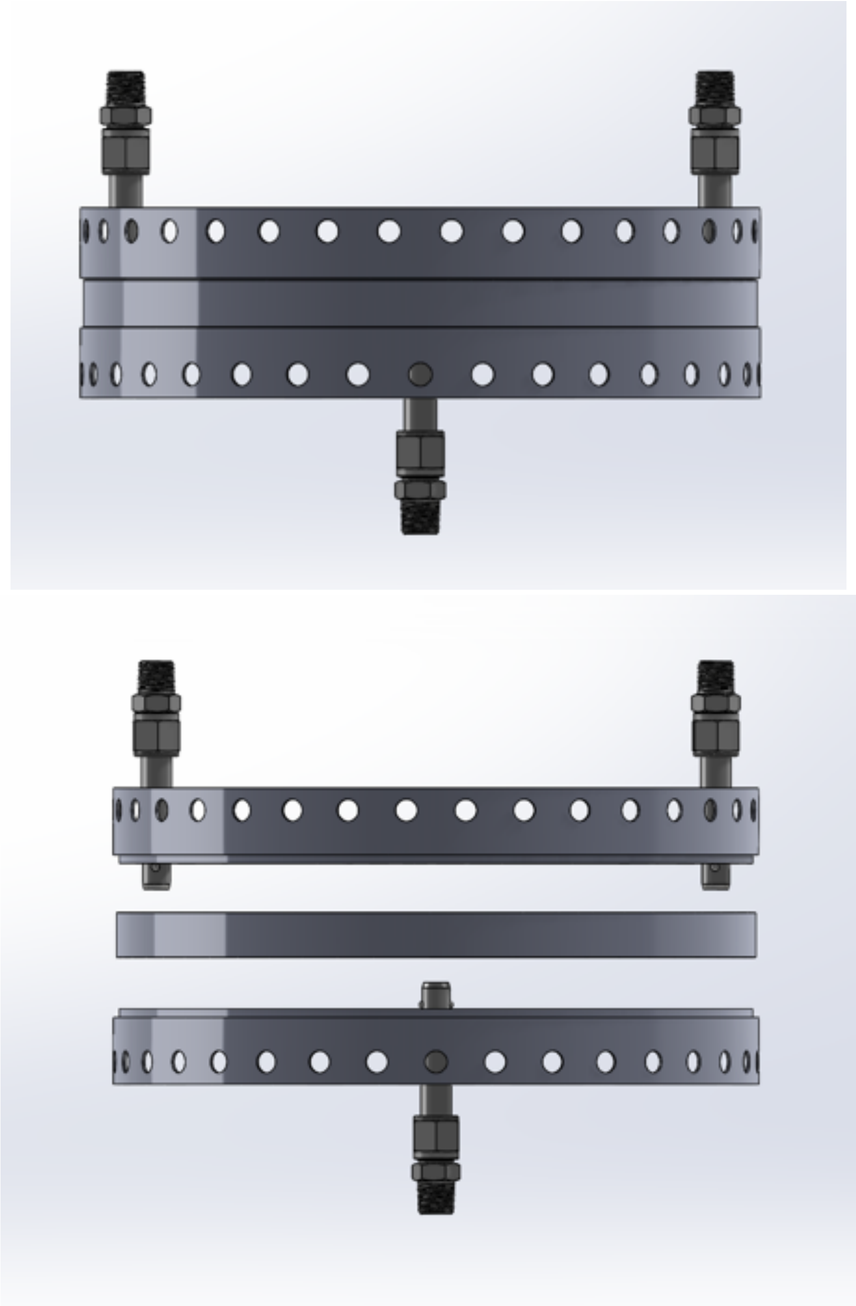
Written by: Federico Benazzo (fbenazzo)



Isometric view of locked, in-flight mechanism



Ball lock pin in position in the mechanism (one of four overall)



Separation mechanism before (top picture) and after (bottom picture) apogee and thus the activation of the locking pins

Stats:

Materials:	Aluminum 6061-T6, steel inside the commercially purchased pins	Components:	Three disks: two for nose-cone and rocket interface and one for redundancy of the system. Four modified pneumatic pins with pressurized vessels for activation

Manufacturing:	Waterjet, metal rolling, welding and milling	Diameter:	14.5’’ for the mechanism disks. 0.8’’ for the pin mechanism
Simulation software:	ANSYS for static and transient analysis of loads	Height:	3’’ for nose-cone interface disk, 1’’ for redundancy disk and rocket interface disk

Component Objective:

This mechanism is responsible for deploying the nose-cone at apogee. The mechanism is pneumatic and will have a double redundancy, one half of the mechanism working with compressed helium from the helium tank, and one half with CO2 cartridges. The compressed air will open 4 ball-lock pins that hold the nose-cone in place against the force of springs between the main rocket and the nose-cone.

Design Overview:

The design of the separation mechanism consists of the following:

- Utilizes a 6061 Aluminum parts welded together
- Static and transient structural simulations were completed in ANSYS Structural
- Components that are thin enough will be manufactured on a water jet machine and then rolled and welded together. This method has proven successful during the manufacturing of a small scale working prototype
- The structure will then be assembled with springs tensioning the locking pins and the piston chambers of the latter connected to plumbing systems in the nose-cone and helium bay of the rocket
- Tolerance will be checked on a CMM machine
- Corrected functioning and timing of the system will be tested by assembling the system without the nose-cone and airframe
- Structural integrity for the expected loads on the mechanism will be tested using a press machine

Sources:

- Design was completed in Solidworks Educational Software https://www.solidworks.com
- All static structural simulation were completed in ANSYS https://www.ansys.com
- 4643 Weld filler was determined for its material properties from http://www.alcotec.com/us/en/support/upload/a4643tds.pdf
- Design of the o-ring and piston in the locking pin was performed from: https://www.marcorubber.com/o-ring-groove-design-dynamic-piston.htm

- The loads for which the mechanism was simulated were obtained from Rocket Science and Engineering Technologies found at http://www.rsandt.com/reports.html
    - BENDIT7.xls was an Excel worksheet utilized to find bending moments of a sounding rocket
    - Code in the excel spreadsheet was translated into a MATLAB script for easier use
- The maximum allowable loads on the locking pins to check if they would not fail under launch stress were derived from: https://www.fixtureworks.net/store/pc/catalogpdfs/Quick_Release_Pins_Fasteners.pdf

Commercial Interactions:

- Stock will be purchased from Online Metals https://www.onlinemetals.com
- Components will be purchased from: https://www.mcmaster.com, https://www.jericoinc.com/, https://www.jegs.com/
- Welding will take place at Custom Tech Fabricating, Duane Fiegel (734)-845-7311
- Water-jet manufacturing will take place at Leading Edge Fabricating inc., 5315 Industrial Park Dr. Montague, MI 4943, (231)-893-2605
- Rolling of the metal sheets will take place at A-1 Roll Company, 301 Church Street Mt. Clemens, MI 48043, (586)-783-6677
- Load testing will occur at U of M Mat Sci lab

Avionics:

Engine Controller

Written by: Joshua Azrin (jazrin)

List of Integrated Circuits

Integrated Circuit	Part Number
Microcontroller	STM32F446VET6
Oscillator	DSC6001CI2A-016.0000T
Current sense chip	INA181AX
Analog to Digital Converter	MAX11131
Voltage reference	MCP1501
Temperature sensor	LM61
Resistance temperature detector chip	MAX31865AAP+(SSOP)

Instrumentation Amplifier	MAX4461UESA+
Multiplexer	CD74HC154M96
Thermocouple chip	MAX31855KASA
Rs422 transceiver	MAX3491
Voltage regulator	TL1963A-33DCYR
Voltage regulator	LM2931
Flash memory chip	W25N01GVZEIG
EEPROM memory chip	M95M01-RMN6TP
Instrumentation Amplifier	AD8227
Operational amplifier	OP1177
DC-DC converter	LT1930

Component Objective:

The engine controller can control fluid flow into the engine and sense the state of the engine and its associated components. It can also monitor and control fluid flow in the propellant tanks and fill system. It can control valves, read pressure transducers, thermocouples, resistance temperature detectors, and load cells. Actuation and sensing can be controlled and monitored from a computer connected to the engine controller. This allows us to control and sense the engine from far away.

Design Overview:

The engine controller is a 4 layer printed circuit board. It is designed on KiCad, fabricated at a board house (advanced circuits), and components are soldered on by hand. Firmware is written based on knowledge from coding classes to operate the board and to communicate with the board.

Sources:

- Electrical concerns and requirements were checked using SATURN PCB Toolkit http://saturnpcb.com/pcb_toolkit/
- All schematic and PCB layout were done on KiCad using Eeschema and Pcbnew https://kicad-pcb.org/
- Electrical simulations and preliminary qualification will be done using LtSpice https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html
- Design requirements surrounding each component on the PCB were determined from their respective datasheets

- Pinout configurations for the microcontroller and boilerplate code generation were generated using STM32CubeMX
  https://www.st.com/en/development-tools/stm32cubemx.html
- Firmware was written using Truestudio STM32 Atollic
  https://atollic.com/truestudio/

Commercial Interactions:

- All electrical components will be purchased from Digikey and Mouser Electronics
  https://www.digikey.com/
  https://www.mouser.com/
- Board will be fabricated by advanced circuits
  https://www.4pcb.com/
- Vibrations testing will occur at U of M lab

Black Box

Written by: Nicholas Janne (njanne)

Stats:

Materials:	GHI SCM202250E	Volume: 1	Microcontroller with filesystem and .NET mobile framework
	J1B1211CCD	Volume: 4-6	Ethernet connection cable
	TL1963A-33DCYR	Volume: 1	Linear voltage regulator
	INA181AX	Volume: 1	Current sense amplifier
	MAX3491	Volume: 4-6	3.3V RS-422 Transceiver
	0483910003	Volume: 1	USB 3.0 Connector
	SanDisk 1TB Extreme Pro	Volume: 1	Rugged External SSD
	Aluminum, Rolled		
Manufacturing:	CNC, 3D Printing, Out-of-house PCB printing, soldering	Weight:	3 lbs

Component Objective:

- Read in RS422 communication from other flight devices
- Write all data to external hard drive

Design Overview:

- Using an outsourced microcontroller circuit, we link ethernet connectors carrying RS422 signals to UART transceivers
- These transceivers pass UART communications to the microcontroller, which then makes use of its built in file system to write to an external hard drive
- The enclosure can be made entirely out of an aluminum sheet using bends and a CNC machine for the associated ports, switches, and connectors.

Sources:

- PCB design done entirely using KiCad
- Housing design done entirely in Solidworks

Commercial Interactions:

- Stock will be purchased from Online Metals https://www.onlinemetals.com
- Components will be purchased from: https://www.mouser.com https://www.ghielectronics.com
- Data recovery difficulties will be handled at Data Savers, CA, USA

Pressurization Board

Written by: Arthur Zhang (arthurzh), Josh Azrin (jazrin)

Name	Part number	Quantity	Comments
Microcontroller	STM32F446VE	1	Primary Microcontroller
Three Phase Brushless Motor Driver	L6234PD	2	HBbridge Driver for Brushless Motors
Brushed Motor Driver	VNH7070ASTR	2	Hbridge Driver for Brushed Motors
Current Sensing Chip	INA181AX	7	2 for valves, 2 for motors, 2 for voltage regulators, 1 for battery
ADC	MAX11131	1	Voltage & Current readings
5V Linear Voltage Regulator	LM2931	1	Ducer & 3v3 regulator power
3v3 Linear Voltage Regulator	TL1963A-33DCYR	1	micro & other ic power
Accurate 3v3 regulator	MCP1501	1	Vref for adcs
XT60 connector	PRT-10474	1	Power Connector for Battery
Jtag 6 pin Programming Header	952-2121-ND	1	Programming micro pin header
P-MOSFET	IPD650P06NMATMA1	2	Valve actuation
BJT NPN	MMBT3904FSCT-ND	2	Valve actuation
Quartz Oscillator	DSC6001CI2A-016.0000T	1	micro clock
Reset Button	8-1437565-0	1	Power cycling board
Power LEDS	LT Q39E-Q1OO-25-1	3	Inidicating power status on board
Micro LEDS	LT Q39E-Q1OO-25-1	4	Indicate micro function
Flash Memory	W25N01GVZEIG	1	Non-volatile memory for data logging
37 Pin Circular Connector	2-208224-2	3	Primary pin interface for peripherals
RS-422 Communications IC	MAX3491	2	Full Duplex RS-422 communications
Thermocouples	MAX31855KASA	5	Fast response temperature sensing

Component Objective:

The primary purpose of the pressurization board is to regulate and balance the pressure inside the propellant tanks when the engine is firing. The board will do this by constantly monitoring tank pressures in each tank and adjusting a variable orifice and shut off valve to regulate the flowrate into the two tanks.

In addition, the board will constantly provide the flight computer with data regarding the status of the fuel tanks and respond to abort case commands from the flight computer as necessary.

Design Overview:

- The functionality of each component is straightforward, however, their individual requirements are not. The components that handle high current and voltage: BJT's and MOSFET's for driving valves, in-series resistors with high power, and motor drivers were all specifically selected to be able to handle more than the expected power. The 37 pin circular connectors selected were also given special consideration to ensure that no pins would be fried by the high power draw from certain components.

- The linear voltage regulators were chosen to reduce the noise of highly sensitive components, such as the ADCs, which use the 3v3 voltage level to carry out analog to digital conversions.

- The microcontroller interfaces with high power components using multiple methods. For peripherals where the microcontroller receives feedback from, like encoders and potentiometers, the feedback signal is split by a voltage divider to protect the microcontroller. The microcontroller signal used to toggle the valves on the rocket is protected by a NPN transistor, which allows the microcontroller to drive high power components.

- In addition, components that provide analog feedback are passed through low pass filters immediately to reduce noise in the signals. The ADC converters are also used to average multiple consecutive samples before returning results. By reducing the noise both at the analog and digital level, we hope to reduce incorrect sensor readings, which are critical to judging the rocket state.

- The connectors were also selected with high power components in mind. Each pin on the connector as well as traces on the board were double checked with software to minimize the risk of overheating in the connector pins and traces on the board.

Sources:

- Electrical concerns and requirements were checked using SATURN PCB Toolkit http://saturnpcb.com/pcb_toolkit/
- All schematic and PCB layout were done on KiCad using Eeschema and Pcbnew https://kicad-pcb.org/
- Electrical simulations and preliminary qualification will be done using LtSpice https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html
- Design requirements surrounding each component on the PCB were determined from their respective datasheets
- Pinout configurations for the microcontroller and boilerplate code generation were generated using STM32CubeMX https://www.st.com/en/development-tools/stm32cubemx.html
- Firmware was written using Truestudio STM32 Atollic https://atollic.com/truestudio/

Commercial Interactions:

- Electrical components will be purchased from Digikey and Mouser Electronics
  https://www.digikey.com/
  https://www.mouser.com/
- PCB printing service to be used will be Advanced Circuits https://www.4pcb.com/
- Vibrations testing will occur at U of M lab

Recovery Board

Written by: Nathaniel Kalantar (nkalan), Lauren Cooper (lacoop)

Stats:

Material	Part Number	Quantity
Microcontroller	STM32F446VET6	1
Quartz Oscillator	DSC6001CI2A-016.0000T	1
Reset Button	8-1437565-7	1
Jtag 6 pin Programming Header	952-2121-ND	1
Flash Memory	W25N01GVZEIG	1
SD Card Reader	5031821852	1
Current Sensor	INA181AX	9
BJT NPN	MMBT3904FSCT-ND	6
P-MOSFET	IPD650P06NMATMA1	6
Pressure Altimeter	MS5607-02BA	3
Thermocouple	MAX31855KASA	3
3.3V Regulator	TL1963A-33DCYR	1
5V Regulator	LM2931	1
3.3V Reference	MCP1501	1
ADC	MAX11131AUI	2
RS422 Transceiver	MAX3491	1*
37 Pin Circular Connector	2-208224-2	1*
24 Pin Circular Connector	213798-3	1*
6-Screw Terminal Block	282836-6	1
LEDs	LT Q39E-Q1OO-25-1	7
PCB materials (copper layers, etc)	n/a	

Component Objective:

- Dedicated circuit board to go in the rocket nose cone
- Monitors pressures and temperatures in the nose cone
- Activates nose cone separation mechanism at apogee
- Deploys parachute(s) from nosecone
- Receives GPS altitude from flight computer and measures altitude with pressure altimeter
    - After the nose cone separates, the connection to the flight computer is lost, hence the need for an onboard altimeter

Design Overview:

- PCB is manufactured out of house (see Commercial Interactions section) and components are soldered on in house
- Testing will occur in UM labs, likely with vibe table and vacuum chambers
- Design is done in KiCad

Sources:

- PCB design was done in KiCad
  https://kicad-pcb.org/
- STM32CubeIDE/STM32CubeMX were used to check microcontroller pin functions and generate code
  https://www.st.com/en/development-tools/stm32cubeide.html
  https://www.st.com/en/development-tools/stm32cubemx.html
- *The Art of Electronics* (Horowitz, Hill) was referenced
  https://www.amazon.com/Art-Electronics-Paul-Horowitz/dp/0521809266
- LTSpice will be used for simulations
  https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html
- Datasheets for electronics from suppliers' websites were referenced and are were downloaded from digikey
  https://www.digikey.com/

Commercial Interactions:

- Electronics are purchased from Digikey and Mouser
  https://www.digikey.com/
  https://www.mouser.com/
- Advanced Circuits will manufacture the PCB
  https://www.4pcb.com/
- Testing will occur at U of M labs for vibrations and functionality in a vacuum

Telemetry System

Written by: Julia Weiss (julweiss), Nick Janne (njanne)

Stats:

Components	Antenna (2) Radio Amplifier SMA Connectors
Radio Frequency	220 - 420 MHz
Software	Operates on firmware written using standard embedded engineering implementations received in class

Component Objective:

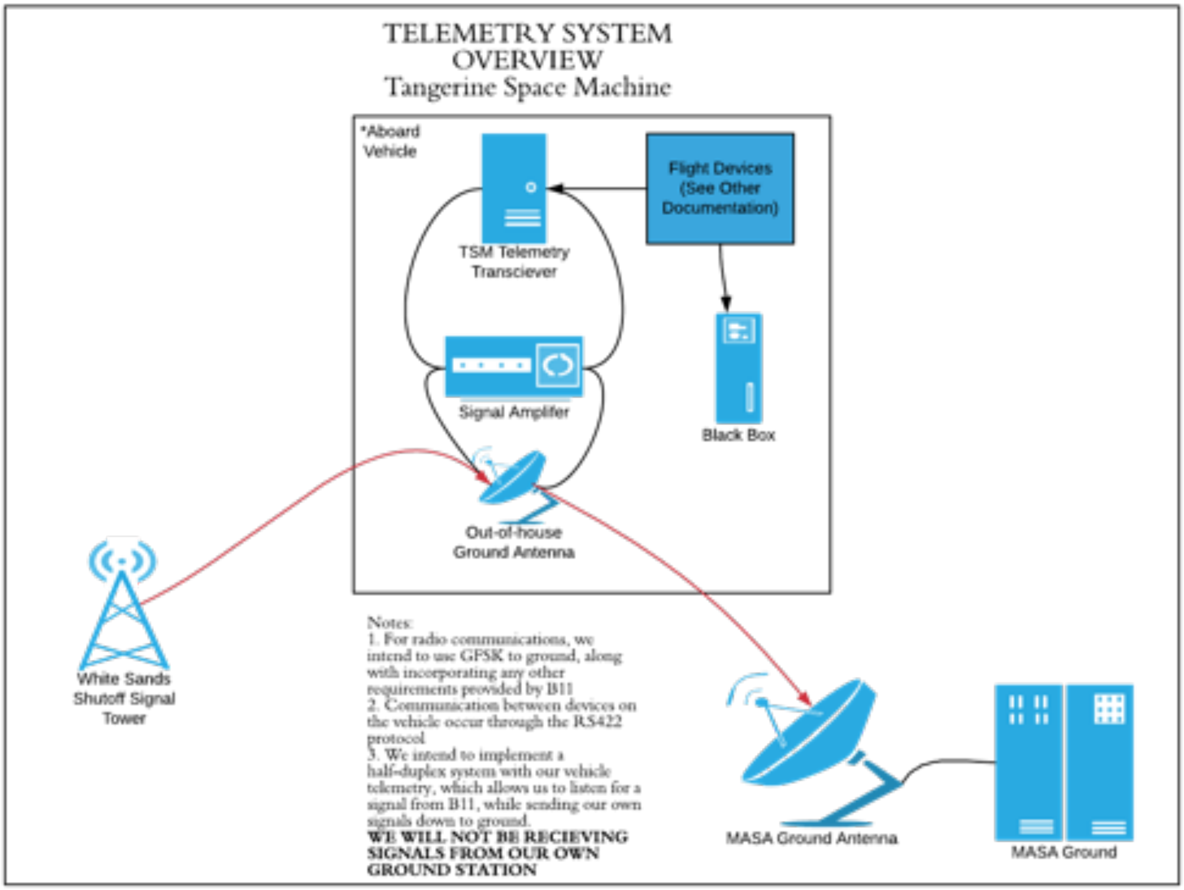
The telemetry system has two main purposes:

(1) Obtain real time data during flight
(2) Send critical commands to the rocket

Main parameters we will be tracking during flight will be tank pressures and other sensor readings.

After receiving our desired information, we will have the ability to communicate with the rocket as necessary. When we reach apogee, we will send a signal to the flight computer to activate the separation mechanism to deploy the parachute. We also will have the ability to send the abort command to the rocket, in which the command will shut off of the engine.

Design Overview:



Notes:
1. For radio communications, we intend to use GFSK to ground, along with incorporating any other requirements provided by B11
2. Communication between devices on the vehicle occur through the RS422 protocol
3. We intend to implement a half-duplex system with our vehicle telemetry, which allows us to listen for a signal from B11, while sending our own signals down to ground.

WE WILL NOT BE RECIEVING SIGNALS FROM OUR OWN GROUND STATION

After obtaining our components, we will perform in-house testing on the system. We will test the system's communication abilities and antennae signals over long ranges.

Sources:

- System description of Copenhagen Suborbitals' Nexo II rocket: https://www.youtube.com/watch?time_continue=2588&v=HYRxlJpPvi8&feature=emb_title
- Telemetry and Antenna Advice: https://www.rocketryforum.com/
- Ameteur Radio Bands: http://www.arrl.org/files/file/Regulatory/Band%20Chart/Band%20Chart%20-%2011X17%20Color.pdf

Commercial Interactions:

The telemetry system is expected to have the following commercial interactions:

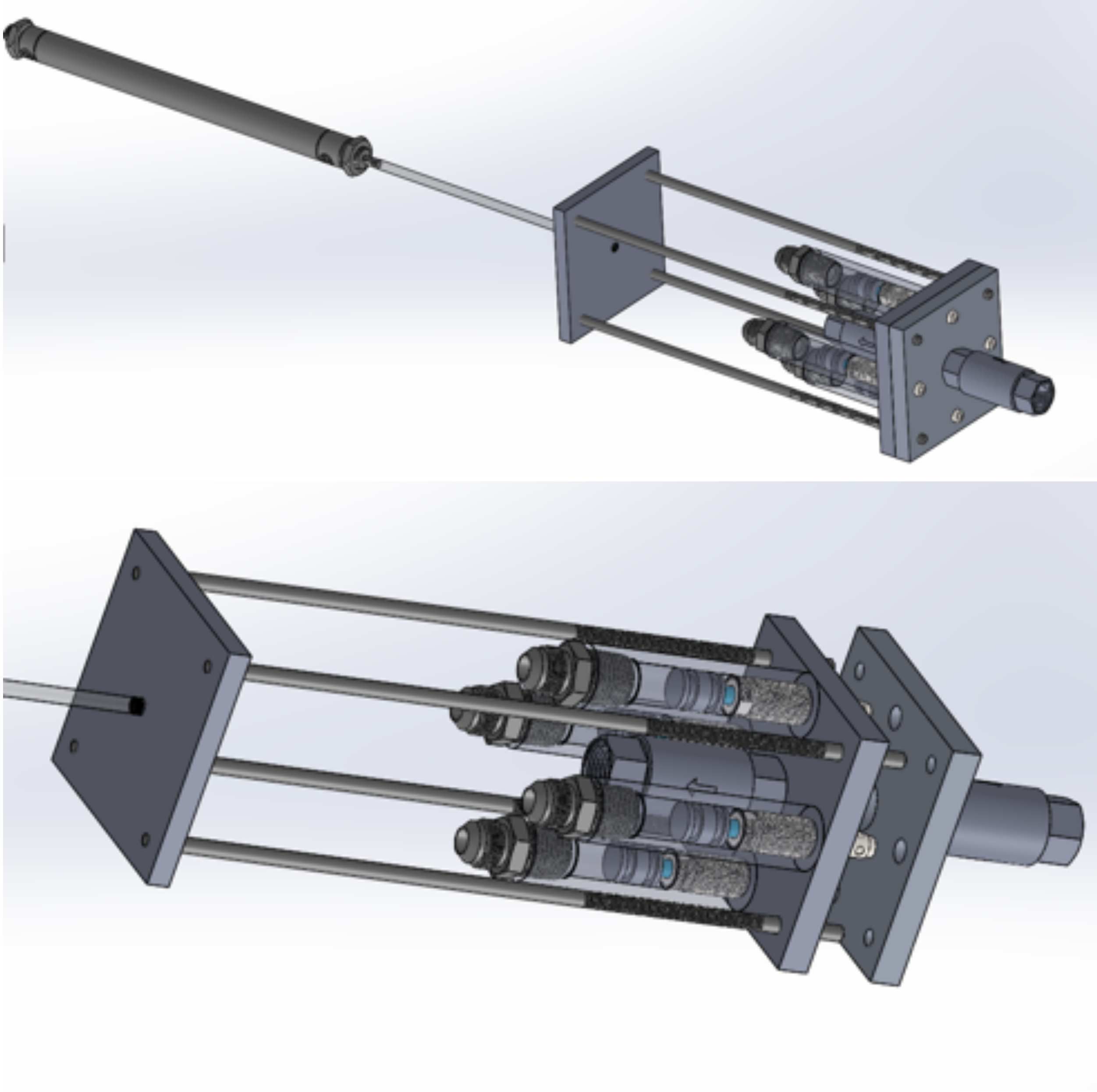
- We will obtain a radio from: https://www.semtech.com/products/wireless-rf

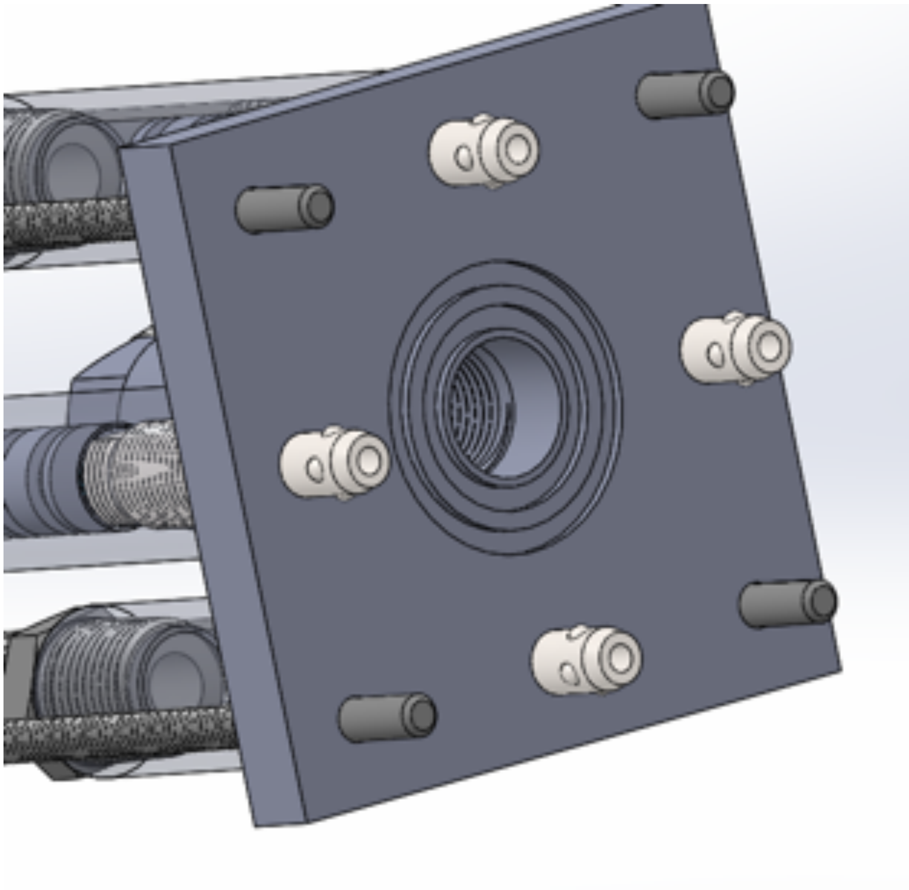
- We will purchase the rocket antenna from Haigh Farr: https://www.haigh-farr.com/functionality/telemetry
- We will obtain an amplifier from: https://www.digikey.com
- We will purchase the ground antenna from Solid Signal: https://www.solidsignal.com/pview.asp?p=frx380
- We will obtain SMA connectors from: https://www.fairviewmicrowave.com/sma-connectors-category.aspx?msclkid=7316ae7fedb719d2cd16f0b284b161c7&utm_source=bing&utm_medium=cpc&utm_campaign=Connectors%20New&utm_term=sma%20connectors&utm_content=SMA%20Connectors

ATLO:

Quick Disconnect

Written by: Arjun Sundararajan (arjunsun)





Materials:	6061 Aluminum for manufactured components	Outer Dimensions:	Sealing plates: 4.00”x4.00”x0.490” Cylinder plate: 4.00”x4.00”x0.38” Piston: 0.311”radius x 0.70” Piston Housing: .50” radius x 3.80”
Manufacturing:	Manual mill, manual lathe, CNC operations for o-ring grooves	Software used:	Solidworks Student Edition

Component Objective:

- Allow for the rocket to be fueled when the QD is still connected
- Safely separate the rocket and fill system so that the two systems are completely separate and neither leaks

Design Overview:

- Utilizes two 6061 Aluminum plates and viton o-rings to create a face seal to avoid leaks while the rocket and fill system are connected
- Utilizes two check valves facing opposite directions (flow into the system) to prevent flow out of both the rocket and the fill system after the plates are disconnected. A small 6061 Aluminum rod will hold the check valves open while the QD is connected.
- A third 6061 Aluminum plate, 4 threaded rods, and a small pneumatic cylinder will physically separate the plates.
- The plates will be held together using modified ball lock pins (the housings will be removed and replaced with piston cylinder assemblies). These pins will be disengaged right before disconnecting.
- The plates will be manufactured on a manual and CNC mill. The pistons and cylinders for the piston cylinder assemblies on the ball lock pins will be manufactured on a manual lathe. All other components will be purchased.
- Will be tested using shop air, both when testing for leaks and when testing overall functionality

Sources:

- The Parker O-ring guide was consulted for sizing O-ring grooves. https://www.parker.com/Literature/O-Ring%20Division%20Literature/ORD%205700.pdf
- Our design for the ball lock pin separation mechanism was modeled after a different design from within our team (nosecone separation mechanism).
- We used the following papers and presentations to help inform our overall design: “Liquid rocket disconnects, couplings, fittings, fixed joints, and seals” (NASA, 1976), “Hydrogen vent ground umbilical quick disconnect - flight seal advanced development” (Girard, Jankowski, Minich, and Yu), and “Ares 1 linear mate umbilical plate and collet” (Manley, Tamasy, and Maloney, 2012)
    - These papers and presentations are all from NASA
- Design was completed in Solidworks Educational Software https://www.solidworks.com
- CAM machining operations for CNC will be completed in Autodesk Student https://www.autodesk.com/education/home

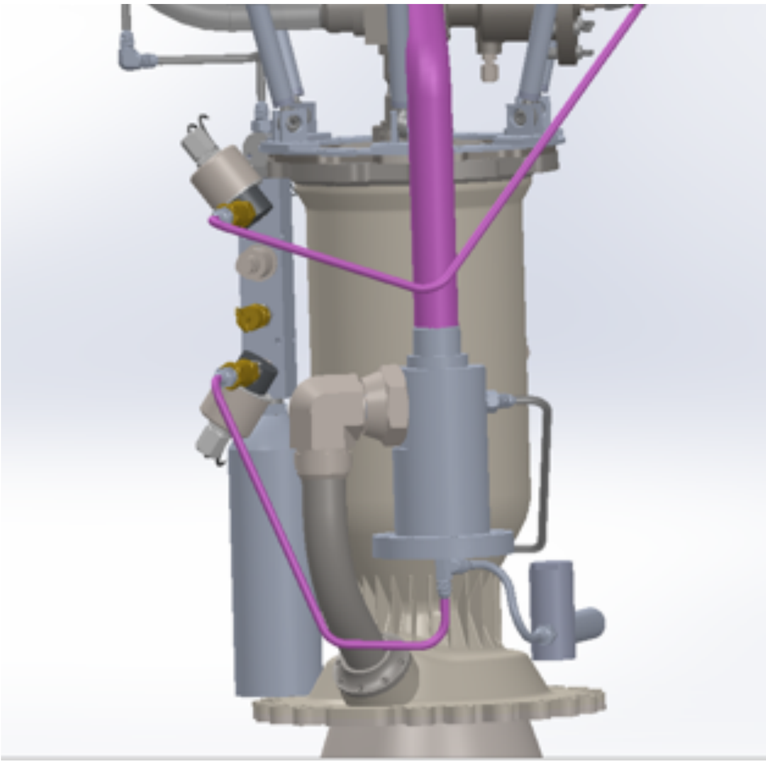
Commercial Interactions:

- The only commercial interactions relevant for this part are component and stock purchasing. Components have been and will be purchased from: McMaster Carr (https://www.mcmaster.com/), Automation Direct (https://www.automationdirect.com/), Carr Lane (https://www.carrlane.com/en-us/), and Amazon (https://www.amazon.com/).

- Stock will be purchased from Online Metals https://www.onlinemetals.com

Flight Plumbing Systems

Written by: Paige Adams (adamsp)



Engine Bay Plumbing - Solidworks

Intertank Bay Plumbing - Solidworks

Helium Bay Plumbing - Solidworks

Stats:

Materials:	304 Stainless Steel, 6060 Aluminum, Brass	Diameter:	Tube diameters: ¼”, ⅜”,½”, 1”, 1 ¼”
Manufacturing:	In house: tube flaring, bending, swaging Out of house: cnc tube bending, flaring	Max Pressure:	4,300 psig

Component Objective:

- Designed to transfer fluids to different parts of the rocket
- Pressurization of tanks and separation mechanisms
- Movement of propellant from tanks to engine
- Engine pre and post burn purge
- Normal and emergency actuations of main propellant valves
- Normal and emergency venting of pressurized systems
- Safety pressure relief
- Pressure sensing in system

Design Overview:

- Transfer of following fluids: gaseous helium, carbon dioxide gas/foam, RP-1, liquid oxygen

- Usage of aluminum and stainless steel tubing with diameters ¼", ⅜",½", 1", 1 ¼"
- Tube thicknesses calculated with appropriate safety factor for MEOP
- Use of braided flex hoses
- Use of AN 37 degree flare fittings, NPT fittings, Swagelok fittings to connect tube and components
- Use of check valves, needle valves, ball valves to regulate flow
- Use of DC solenoids to electronically regulate flow
- Use of LiPo batteries to power solenoids
- Use of relief valves and burst disks for safety pressure relief
- Use of pressure transducers to measure pressures (psig)
- Quick Disconnect from fill systems
- All components purchased will be rated above their operating pressures

Sources:

- Cv and flow rates for valve and component sizing were calculated with equations from Swagelok Calculators https://www.swagelok.com/en/toolbox/cv-calculator
- Minimum tube thickness taken from equation with safety factor https://www.hunker.com/13400828/how-to-calculate-minimum-wall-thickness
- Pressure drops calculated with http://www.pressure-drop.com/Online-Calculator/
- Design was created in AutoCad student for 2D plumbing and instrumentation diagrams https://www.autodesk.com/
- Design was completed in Solidworks Educational Software with routing feature https://www.solidworks.com

Commercial Interactions:

- Gases obtained from: https://www.airgas.com/, http://cryogenicgas.com/, https://www.dickssportinggoods.com/products/paintball-co2-tanks.jsp
- Propellants obtained from: http://cryogenicgas.com/, https://www.haltermannsolutions.com/,https://www.cryofab.com/,
- Solenoids purchased from: https://www.magnatrol.com/, https://www.jegs.com/, https://peterpaul.com/
- Pressure transducers purchased from: https://www.transducersdirect.com/, https://www.digikey.com/product-detail/en/honeywell-sensing-and-productivity-solutions/MLH01KPSB01A/480-2530-ND/1248865thi
- Fittings purchased from: https://www.jegs.com/, https://www.mcmaster.com, https://omega1.com/, https://stainlessteelfittings.com
- Tubing purchased from: https://www.mcmaster.com

- Relief devices purchased from: https://www.generant.com/product-category/relief-valve-manufacturers/, https://www.highpressure.com/, https://www.gasequipment.com/
- Additional Components will be purchased from: https://www.mcmaster.com, https://www.grainger.com, https://www.jegs.com/
- CNC tube bending location will likely be Crest Bending Inc http://www.crestbending.com/index.html
- Assembly and testing completed at University of Michigan - Ann Arbor facilities by MASA students

Structures:

Airframe Sections

Written by: Akashdeep Pawar (pawarak)

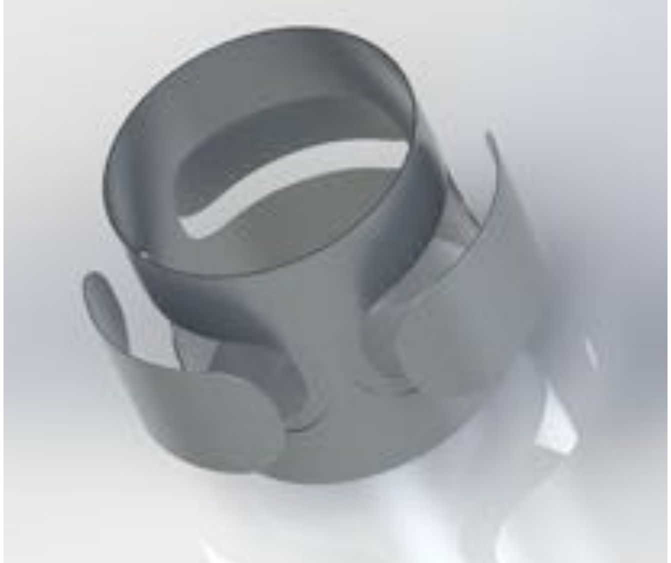


Figure 1. Exploded view of the inter-tank plumbing bay and access panels

Figure 2. Upper plumbing bay with access panels below the COPV removed

Component Summary:

Included Components:	1. Inter-tank plumbing bay 2. Upper plumbing bay
Dimensions:	Inter-tank plumbing bay: - 14.5” outer diameter (OD) - 0.125” thickness - 14” long Upper plumbing bay: - 14.5” OD - 0.063” thickness - 58” long
Materials:	For both components - Flush steel rivnuts - Stainless steel shoulder bolts - Airframe tube
Dependencies:	Inter-tank plumbing bay: - Radially fastened to bottom of LOx flight propellant tank assembly’s airframe coupling ring - Radially fastened to top of RP-1 flight propellant tank assembly’s airframe coupling ring Upper plumbing bay: - Radially fastened to the separation mechanism on the nose cone - Radially fastened to top of LOx flight propellant tank assembly’s airframe coupling ring
Manufacturing (Does not include manufacturing completed before purchase of part):	Water Jetting: - All components Rolling: - All components Welding: - All components

Component Objective:

The purpose of the airframe sections is to function as the primary outer structure of the rocket outside the propellant tanks (which also function as airframe) and the fin structure. In doing so the airframe sections provide:

- Structural integration of major extra-engine components into the full rocket assembly (stack) via radial fastening
    - The upper plumbing bay integrates the nose cone and the Liquid Oxygen (LOx) propellant tank
    - The inter-tank plumbing bay integrates the Liquid Oxygen (LOx) and RP-1 Fuel propellant tanks
- Housing and mounting for the helium composite overwrapped pressure vessel (COPV), rocket plumbing, avionics, and payload as well as access panels to these components
- Interfaces and mounting for the rocket's exterior raceway system, which delivers helium from the COPV in the upper plumbing bay to both propellant tanks and LOx from the LOx propellant tank to the engine

Design Overview & Methodology:

The airframe sections were designed in Solidworks (student and academic research license) to meet the design objectives. Initially, basic beam equations (as taught in AEROSP 215 and AEROSP 315) were used to approximate the required airframe thickness. After the initial design stage, static structural Finite Element Analysis (FEA) simulations were conducted in ANSYS Workbench Student, where known or predicted boundary conditions were applied to the Solidworks CAD model which was refined until it met all component objectives for every loading scenario.

To meet the component design objectives, the airframe sections were designed to be capable of withstanding all thrust and aerodynamic loads they are subjected to while in flight, testing, and transport. These include

- The aerodynamic forces such as drag and the rocket weight transferred into the rocket skin
- The thermal stresses due to the temperature gradient between the interior of the rocket at cryogenic temperatures and the exterior of the rocket, being heated during supersonic flight
- The aerodynamic bending moment on the rocket

Sources:

Software

- CAD design was completed in Solidworks Educational Software https://www.solidworks.com

- All static structural simulations were completed in ANSYS Workbench Student https://www.ansys.com
- Bill of Materials (BoM), preliminary design spreadsheets, and other parameters are calculated and documented in Microsoft Office Excel (https://www.microsoft.com/en-us/microsoft-365/excel) and Google Sheets (https://www.google.ca/sheets/about/)
- Design characteristics and progress are documented and shared in Microsoft Office Powerpoint (https://www.microsoft.com/en-us/microsoft-365/powerpoint), Google Slides (https://www.google.ca/slides/about/), Google Docs (https://www.google.ca/docs/about/), and the MASA wiki (http://masaumich.mywikis.net).
- CAD models, code, and simulation files are hosted on Google Drive via the university's Google Suite license (https://drive.umich.edu) and the U-M EECS department Gitlab (https://gitlab.eecs.umich.edu/)

Technical

- Welding minimum design requirements set by Duane Fiegel at Custom Tech Fabricating (Phone: (734)-845-7311)
- Thin-walled beam equations and theoretical structural analysis and finite element model background taught by Prof. Aaron Johnson (AEROSP 215) and Prof. Veera Sundararaghavan (AEROSP 315) at the U-M Aerospace Engineering Department
- Compression, buckling, and bending analysis equations and calculations were obtained from Analysis and Design of Flight Vehicle Structures by E.F. Braun (https://www.amazon.com/Analysis-Design-Flight-Vehicle-Structures/dp/0961523409) and the NASA Astronautics Structures Manual (https://ntrs.nasa.gov/search.jsp?R=19760071125)
- Design requirements and parameters of the fastening system to the nose cone and propellant tanks coupling ring was obtained from the NASA Fastener Design Manual (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19900009424.pdf)
- Structural properties for Al-6061-T6 as well as stainless steel retrieved from the Matweb database (http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6)

Commercial Interactions:

During the initial design phases, MASA Structures members met with various aerospace industry professionals for design advice and reviews. It was made clear to the engineers that we contacted that no export controlled information would be disclosed. These include representatives from:

- Northrop Grumman Innovation Systems (now Space Systems)

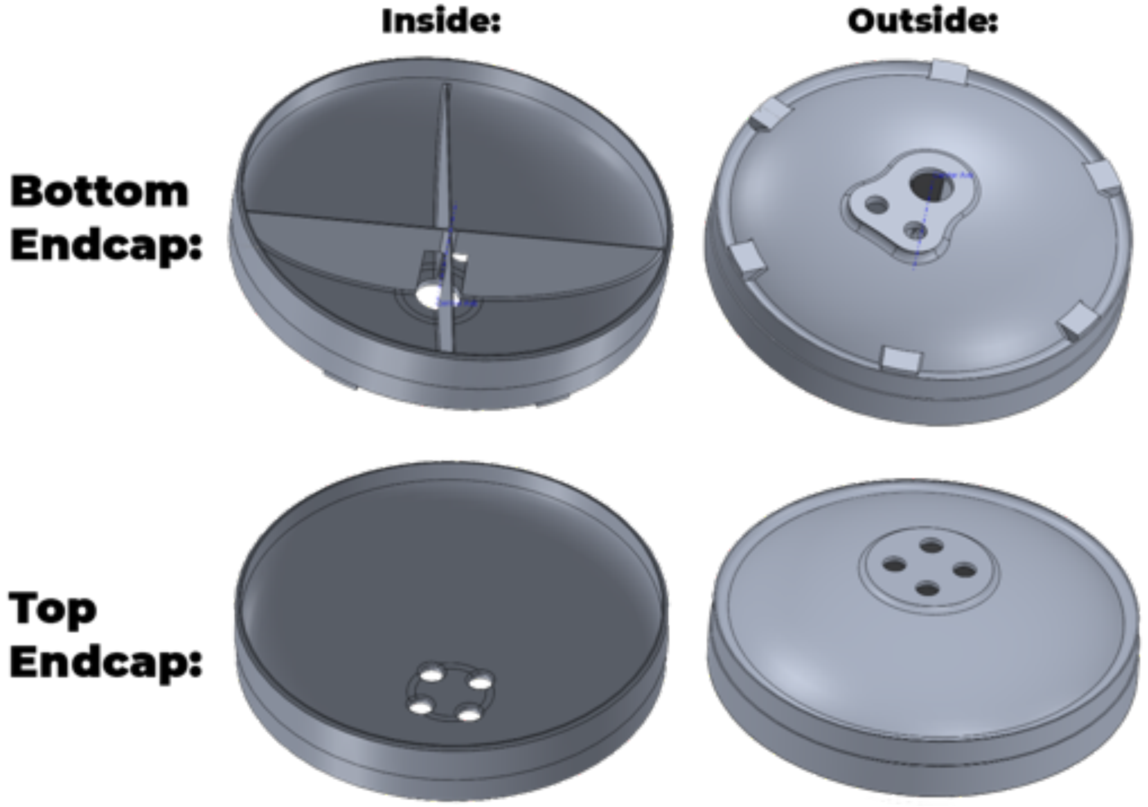
- Raytheon Technologies
- Relativity Space

The manufacturing and testing of the airframe sections is expected to proceed as follows, and with the following commercial interactions:

- Aluminum 6061-T6 sheet metal stock is purchased at Alro Steel (https://www.alro.com/), Online Metals (https://www.onlinemetals.com), or Midwest Steel Supply (https://www.midweststeelsupply.com/store/?gclid=EAIaIQobChMI2onSzsjN6QIVB4vICh0zEAHLEAAYASAAEgKg1PD_BwE)
- The airframe section geometry and features are waterjet out of the sheet metal stock by Leading Edge Fabricating, Inc. (https://leadingedgefab.com/) on a five-axis waterjet
- The sheet metal sections are then rolled into the rocket’s diameter at A1 Roll Co. in Mt Clemens, MI (https://a1roll.com)
- They will then be seam welded by professional welder Duane Fiegel at Custom Tech Fabricating (Phone: (734)-845-7311)
- The airframe sections may then be tested for defects, as well as possible vibrational/destructive testing at the U-M Climate and Space Sciences and Engineering (CLASP) (https://clasp.engin.umich.edu)
- They may be fastened and assembled to the airframe coupling rings which are welded on the propellant tanks and nose cone via steel flush-mounted rivnuts and shoulder bolts obtained from McMaster-Carr (https://www.mcmaster.com/)

Flight Tank Endcaps

Written by: Theo Rulko (trulko)



Component Summary:

Materials:	Aluminum 6061-T6	Dimensions:	14.5” OD, 4.25” height
Manufacturing:	CNC milling of part, welding into tank assembly	Weight:	Top Endcap: 6.1 lbs Bottom Endcap: 6.5 lbs
Dependencies:	Endcaps welded to tank tubes & airframe coupling rings. Bottom endcap on RP-1 Tank welded to TTS	Weld-on bung fitting ports:	Top Endcap: Any four of 4AN, 6AN, 8AN Bottom Endcap: 1x 20AN, any two of 4AN, 6AN, 8AN
Simulation & Design Software:	CAD in Solidworks Student, static structural FEA in Ansys Student	Other Software:	Documentation in Google Slides, Google Sheets, Google Docs, MS Excel, MS Powerpoint, MS Word, MyWikis Mediawiki

Component Objective:

The purpose of the LOx and RP-1 Flight Tank Endcaps is to provide universal and interchangeable top and bottom to each of the main Liquid Oxygen (LOx) and Rocket Propellant-1 (RP-1) tanks on Tangerine Space Machine (TSM) while also providing:

- An interface between the tank-as-airframe rocket sections and the airframe sections such as the Intertank Bay; and
- Ports for AN-type bung fittings to be welded on and connected to rocket plumbing through which fuel or oxidizer lines, helium pressurant lines/diffusers, and avionics sensors can pass.

Furthermore, the bottom LOx and RP-1 Flight Tank Endcaps must:

- Incorporate anti-vortex baffling; and
- Interface with the Thrust Transfer Structure (TTS) so that engine thrust can be transferred from the engine to the rest of the vehicle.

Design Overview & Methodology:

The endcaps were designed in Solidworks Student to meet the design objectives, and were ultimately qualified through a step-wise refinement process which resulted in iterative design changes to the endcaps as the loads became increasingly well defined and understood. Initially, basic thin-walled pressure vessel equations (as taught in AE215 and AE315) were used to approximate required endcap dome thickness. After the initial design stage, static structural Finite Element Analysis (FEA) simulations were conducted in ANSYS Workbench Student, where known or predicted boundary conditions were applied to the Solidworks CAD model which was refined until it met all component objectives for every loading scenario.

To meet the component design objectives, the endcaps were designed to be capable of withstanding all pressure, thrust, and aerodynamic loads they are subjected to while in flight, testing, and transport to within a Base 11-imposed safety factor of 1.5x to yield. These include:

- The pressure exerted on the endcap dome by the fluid in the LOx and RP-1 tanks on TSM, which are actively pressurized to a near-constant Maximum Expected Operating Pressure (MEOP) of 650 psi
- The aerodynamic forces such as drag and the rocket weight transferred into the endcap circumference by the adjacent tank tube and airframe segments
- The thermal stresses due to the temperature gradient between the interior of the LOx tank at cryogenic temperatures and the exterior of the rocket, being heated during supersonic flight
- The aerodynamic bending moment on the rocket (though the induced stress on the endcaps is minor due to their short height)

- (For the bottom RP-1 endcap) The engine thrust transferred into the endcap by the TTS

Sources:

Software

- CAD design was completed in Solidworks Educational Software https://www.solidworks.com
- All static structural simulations were completed in ANSYS Workbench Student https://www.ansys.com
- CAM toolpath machining operations for CNC were completed in Autodesk Fusion 360 Student Edition https://www.autodesk.com/education/home
- Bill of Materials (BoM), preliminary design spreadsheets, and other parameters were calculated and documented in Microsoft Office Excel (https://www.microsoft.com/en-us/microsoft-365/excel) and Google Sheets (https://www.google.ca/sheets/about/)
- Design characteristics and progress were documented and shared in Microsoft Office Powerpoint (https://www.microsoft.com/en-us/microsoft-365/powerpoint), Google Slides (https://www.google.ca/slides/about/), Google Docs (https://www.google.ca/docs/about/), and the MASA wiki (http://masaumich.mywikis.net).
- CAD models are hosted on Google Drive (https://www.google.com/drive/) and the U-M EECS department Gitlab (https://gitlab.eecs.umich.edu/)

Technical

- Welding minimum design requirements set by Duane Fiegel at Custom Tech Fabricating (Phone: (734)-845-7311)
- Thin-walled pressure vessel equations and theoretical structural analysis and finite element model background taught by Prof. Aaron Johnson (AE215) and Prof. Veera Sundararaghavan (AE315)
- Structural properties for Al-6061-T6 retrieved from the Matweb database (http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6)

Commercial Interactions:

During the initial design phases, MASA Structures members met with various aerospace industry professionals for design advice and reviews. It was made clear to the engineers that we contacted that no export controlled information would be disclosed. These include representatives from:

- Northrop Grumman Innovation Systems
- Raytheon Technologies
- Relativity Space

The manufacturing and testing of the endcaps is expected to proceed as follows, and with the following commercial interactions:

- Endcap raw Al-6061-T6 stock is purchased at Alro Steel (https://www.alro.com/)
- Endcaps are manufactured either in-house by MASA members at the University of Michigan College of Engineering Wilson Student Team Project Center or by Leading Edge Fabricating, Inc. (https://leadingedgefab.com/) on a three-axis CNC milling machine
- Endcaps are then likely tested by a Coordinate Measuring Machine (CMM) at LIFT Technologies (https://lift.technology/) in Detroit to verify that they were manufactured within specifications
- They will then likely be welded to the tank tube section by professional welder Duane Fiegel at Custom Tech Fabricating (Phone: (734)-845-7311)
- The entire tank assembly will then likely be heat-treated to a T6 temper at Modern Metals Processing (https://www.modernmetalprocessing.com/)
- The resultant tank assembly will then likely be tested by MASA members at the MASA Rocket Propulsion Testing Facility on Green Road in Ann Arbor. These tests would include cryogenic sealing & contraction tests, hydrostatic pressure tests, and likely a destructive burst test designed to ensure design objectives were successfully met.

Flight Tanks

Written by: Cameron Sahagian-Crandall (ccrand)

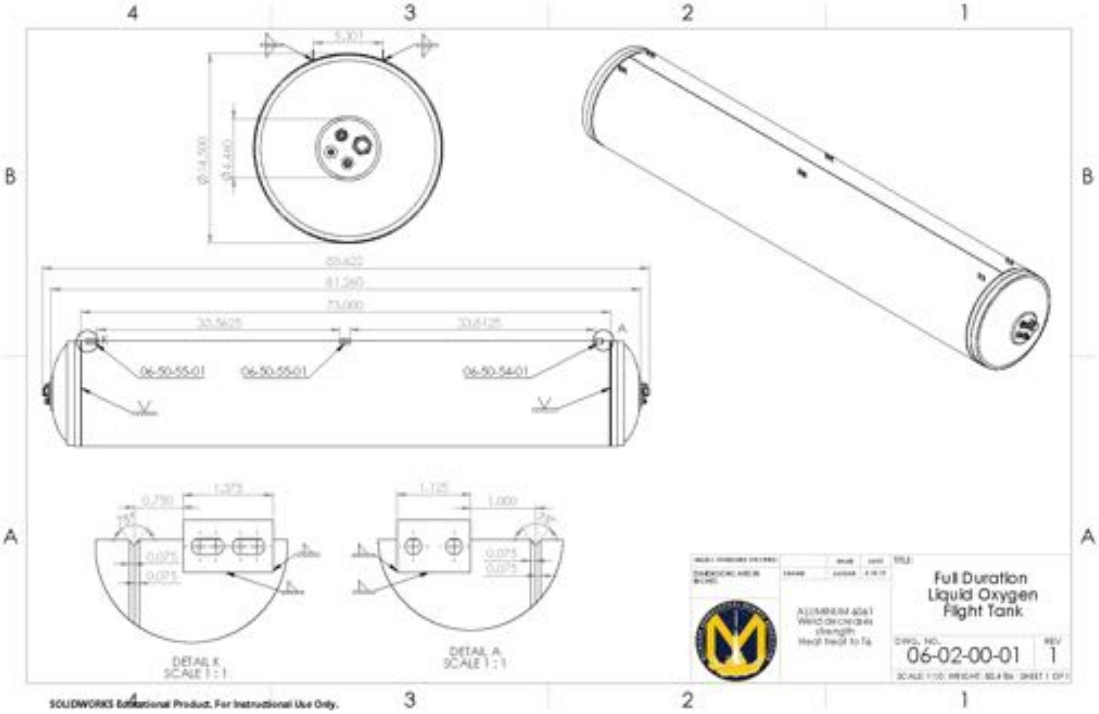


Figure: LOX Flight Tank Drawing

Note: Drawing is no longer current

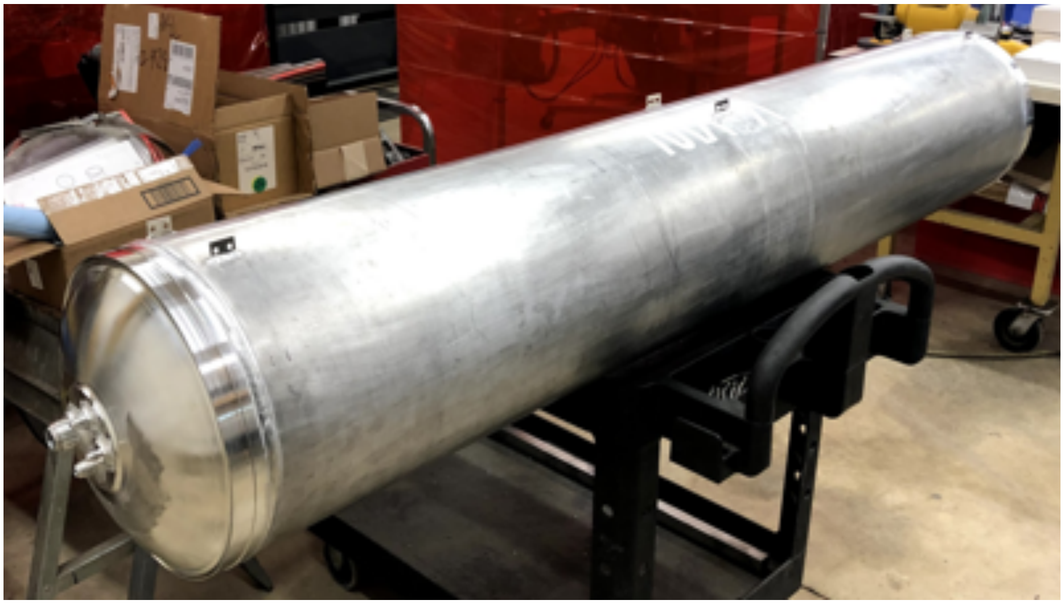


Figure: LOX Flight Tank immediately after Full Assembly Welding

Note: Design is no longer current

Component Summary:

Dimensions:	83.6” Length x 14.5” Diameter
Included Components:	1. LOX & RP-1 Endcaps, Top & Bottom 2. 20 AN, 8 AN, 6 AN, & 4 AN Weld Bungs 3. Airframe Section Coupling Ring 4. LOX & RP-1 Flight Tank Tube 5. Anti-Slosh Baffling 6. External Raceway Weld Flanges
Materials:	Aluminum 6061-T6 (final state): - LOX & RP-1 Endcaps, Top & Bottom - 20 AN, 8 AN, 6 AN, & 4 AN Weld Bungs - Airframe Section Coupling Ring - LOX & RP-1 Flight Tank Tube - Anti-Slosh Baffling - External Raceway Weld Flanges
Manufacturing (Does not include manufacturing completed before purchase of part):	CNC Milling: - LOX & RP-1 Endcaps, Top & Bottom Rolling: - LOX & RP-1 Flight Tank Tube - Airframe Section Coupling Ring Water Jetting: - Airframe Section Coupling Ring - LOX & RP-1 Flight Tank Tube - Anti-Slosh Baffling - External Raceway Weld Flanges Welding: - All components Solution and Precipitation Heat Treating: - All components CMM (Coordinate Measuring Machine) Inspection: - LOX & RP-1 Endcaps, Top & Bottom (not yet confirmed)
Maximum Expected Operating Pressure (MEOP):	650 psi
Factor of Safety:	FOSy: 1.4 FOSu: 1.8
Volume:	LOX Flight Tank: 220.4 L RP-1 Flight Tank: 160.4 L

Component Objective:

The primary objective of the Tangerine Space Machine flight tanks is to hold the fuel and oxidizer and facilitate delivery of the propellant to the engine during flight. Other requirements for the flight tanks include:

- Withstanding the external structural, thermal, and dynamic loads caused by aerodynamics, thermal environments, and thrust from the engine. This is due to a tanks-as-airframe vehicle design, where all rocket body forces are transferred through the propellant tanks.
- Withstanding the internal structural, thermal, and dynamic loads caused by pressurization of the propellant tanks, thermal environments, and propellant sloshing within the flight tanks.

Additionally, the flight tanks must incorporate requirements for other sections of the rocket. This includes:

- Interfacing with the Airframe Sections, Intertank Bay, and Engine Bay through a universal Coupling Ring. The Coupling Ring is welded to each of the RP-1 and LOX Tank Endcaps as described in the Endcap Document and Airframe Sections Document.
- Incorporating 4 AN, 6 AN, 8 AN, and 20 AN weld bungs as inlets and outlets to the Flight Tanks, which deliver propellant to the engine, act as inlets for pressurization gas, and allow for safety monitoring systems such as burst discs, pressure transducers, relief valves, etc.
- Locations to attach an external raceway, which transfers electrical signals, propellant, and pressurization gas to and from different locations along the rocket body. The external raceway is attached via flanges which are welded onto the exterior of the flight tanks.

Design Overview:

The flight tanks are designed with an initial volume, internal pressure, and diameter in mind. From here, simple geometry equations from [1] are used to determine the height of the tanks. The wall thickness of the tanks is initially calculated using hoop stress equations, taught in most Statics or Rigid Body Structures classes such as AE 215 at the University of Michigan [2]. For these calculations, post-heat treat material properties are determined based on sources such as the ASM Handbook [3], the Base11 Space Challenge Safety Guideline [4], and ASM MatWeb [5]. Slosh baffling in the tanks is researched, and designs are created based on information contained in NASA literature [6] and university testing [7]. From here, computer models of the tanks are created in the CAD software SolidWorks Student [8]. An iterative design process is run using the FEA software ANSYS Student [9]. After a final design of the flight tanks is decided, all components of the flight tanks can be manufactured. The manufacturing process is defined below. After all manufacturing has taken place, the resultant tank assembly will then likely be tested by MASA members at the MASA Rocket Propulsion Testing Facility on Green Road in Ann Arbor [10]. These tests would include cryogenic sealing & contraction tests, hydrostatic pressure tests, and likely a destructive burst test designed to ensure design objectives were successfully met.

Commercial Interactions:

During the initial design phases, MASA Structures members met with various aerospace industry professionals for design advice and reviews. It was made clear to the engineers that we contacted that no export controlled information would be disclosed. These include representatives from:

- Northrop Grumman Innovation Systems [11]
- Raytheon Technologies [12]
- Relativity Space [13]

The manufacturing process for the Flight Tanks chronologically consists of:

- Tube, Endcap, Slosh Baffling, and Coupling Ring stock is ordered from a supplier, historically OnlineMetals [14] or Alro Steel [15].
- 4 AN, 6 AN, 8 AN, and 20 AN weld bungs are purchased from Jegs.
- Tube, Slosh Baffling, and Coupling Ring are water jet by Leading Edge Fabricating, Inc. [16]
- The Tube is rolled at A-1 Roll Co. [17]
- Endcaps are manufactured either in-house by MASA members at the University of Michigan College of Engineering Wilson Student Team Project Center or by Leading Edge Fabricating, Inc. on a three-axis CNC milling machine.
- Endcaps are then likely tested by a Coordinate Measuring Machine (CMM) at LIFT Technologies [18] in Detroit to verify that they were manufactured within specifications
- The Tube will be seam welded by professional welder Duane Fiegel at Custom Tech Fabricating [19].
- The Flight Tank assembly (all components) will be welded by professional welder Duane Fiegel at Custom Tech Fabricating.
- The entire tank assembly will then be heat-treated to a T6 temper at Modern Metals Processing [20].

Sources:

1. Circular Cylinder Calculator
   https://www.calculatorsoup.com/calculators/geometry-solids/cylinder.php
2. AEROSP 215, University of Michigan
   https://bulletin.engin.umich.edu/courses/aero/

3. Heat Treating of Aluminum Alloys
   https://materialsdata.nist.gov/bitstream/handle/11115/192/Heat%20Treating%20of%20Aluminum%20Alloys.pdf?sequence=3&isAllowed=y
4. Base11 Space Challenge Safety Guidelines
   https://www.herox.com/spacechallenge/61-safety
5. Aluminum 6061-T6
   http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6
6. Analysis of LH2 and LOX Tanks Sloshing
   https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001500.pdf
7. Baffling of Fluid Sloshing in Cylindrical Tanks
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8. SolidWorks
   https://www.solidworks.com
9. ANSYS
   https://www.ansys.com
10. MASA Rocket Propulsion Testing Facility
    https://goo.gl/maps/8FAq7Exaf6pXXJFM8
11. Northrop Grumman Innovation Systems
    https://www2.northropgrumman.com/suppliers/Pages/InnovationSystemsLanding.aspx
12. Raytheon Technologies
    https://www.rtx.com/en
13. Relativity Space
    https://www.relativityspace.com/
14. OnlineMetals
    https://www.onlinemetals.com/?gclid=EAIaIQobChMIzOj-iaPN6QIVg_7jBx3U8wLkEAAYASAAEgL1qvD_BwE
15. Alro Steel
    https://www.alro.com/
16. Leading Edge Fabricating, Inc.
    https://leadingedgefab.com/
17. A-1 Roll Co.
    https://a1roll.com/
18. LIFT Technologies
    https://lift.technology/
19. Custom Tech Fabricating
    Phone: (734)-845-7311
20. Modern Metals Processing
    https://www.modernmetalprocessing.com/

Additional Sources:

- CAM toolpath machining operations for CNC were completed in Autodesk Fusion 360 Student Edition https://www.autodesk.com/education/home
- Bill of Materials (BoM), preliminary design spreadsheets, and other parameters were calculated and documented in Microsoft Office Excel (https://www.microsoft.com/en-us/microsoft-365/excel) and Google Sheets (https://www.google.ca/sheets/about/)
- Design characteristics and progress were documented and shared in Microsoft Office Powerpoint (https://www.microsoft.com/en-us/microsoft-365/powerpoint), Google Slides (https://www.google.ca/slides/about/), Google Docs (https://www.google.ca/docs/about/), and the MASA wiki (http://masaumich.mywikis.net).
- CAD models are hosted on Google Drive (https://www.google.com/drive/) and the U-M EECS department Gitlab (https://gitlab.eecs.umich.edu/)

Thrust Transfer Structure

Written by: Julia Weiss (julweiss), Sam Boling (bolings)

Rod End Design:

Top View Side View Isometric View

Welded Design:

Stats:

Materials:	Aluminum 6061-T6 18-8 Stainless Steel Zinc Plated Carbon Steel
Dimensions	14.5” OD, 12.65” height
Manufacturing:	CNC Milling, Welding, Heat Treat
Dependencies	Welded to endcap, bolted to engine flange
Simulation & Design Software	CAD in Solidworks Student, static structural FEA in Ansys Student

Component Objective:

The Thrust Transfer Structure (TTS) is designed to transfer the load of the engine into the rest of the rocket aerostructure. It must securely mount the engine to the rest of the rocket. To do this the top of the TTS is welded onto the feet of the bottom endcap of the RP-1 tank and the bottom ring of the TTS will be bolted to the engine flange. The symmetry and parallelism of the TTS aims to evenly distribute the thrust force. Currently, two possible TTS designs are being pursued, a fully welded design where hollow aluminum tubes are fixed to the endcap and engine mount ring using welds, and a rod end design where the tubes have rod ends on either end and are secured to the endcap and engine mount ring using shoulder bolts pin through clevises.

Design Overview (Welded Design):

To meet component design objectives and to minimize the number of individual parts while maximizing rigidity, we are currently designing a fully welding TTS. The fully welded design minimizes the risk of the TTS shifting or adjusting the engine before or during flgiht. The design of the TTS was done in Solidworks. We performed basic stress calculations on the tubes to determine suitable tube thickness and diameter. Static structural finite element analysis (FEA) simulations were completed in ANSYS to verify that the stress experienced meets our safety factor requirement. Once the design is finalized, components will be manufactured in-house by MASA members on a CNC mill. The tubes will then be welded to the endcap and engine mount ring by Custom Tech Fabricating and heat treated by Modern Metals Processing. We will use press fit pins to ensure exact positioning of the tube ends. After the assembly of the TTS is complete we will check tolerance using a Coordinate Measuring Machine (CMM). Then the TTS will be load tested using a press in University of Michigan's Material Science lab to confirm its strength properties.

Design Overview (Rod End Design):

To meet component design objectives and to minimize mass, we are designing a rod end-clevis design. The use of these components offers the ability to adjust to tolerance requirements. The rod end design also allows the tubes to become two force members by allowing the ends to rotate, reducing the stress in the TTS. The design, analysis, manufacturing, and testing of the rod end design will be the same as the welded TTS design.

Sources:

- TTS design was completed in Solidworks Educational Software https://www.solidworks.com
- All static structural simulation were completed in ANSYS https://www.ansys.com
- CAM machining operations for CNC will be completed in Autodesk Student https://www.autodesk.com/education/home
- CAD models are hosted on Google Drive (https://www.google.com/drive/) and the U-M EECS department Gitlab (https://gitlab.eecs.umich.edu/)
- Design characteristics and progress were documented and shared in Microsoft Office Powerpoint (https://www.microsoft.com/en-us/microsoft-365/powerpoint), Google Slides (https://www.google.ca/slides/about/), Google Docs (https://www.google.ca/docs/about/), and the MASA wiki (http://masaumich.mywikis.net).
- Structural properties for Al-6061-T6 retrieved from the Matweb database (http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6)

- 4643 Weld filler was determined for it material properties from http://www.alcotec.com/us/en/support/upload/a4643tds.pdf
- Post heat treat material properties were determined by (https://materialsdata.nist.gov/bitstream/handle/11115/192/Heat%20Treating%20of%20Aluminum%20Alloys.pdf?sequence=3&isAllowed=y)
- Insight into loads on structural filet welds was found in https://www.researchgate.net/publication/283462197_Finite_Element_Calculation_and_Assessment_of_Static_Stresses_in_Load-Carrying_Fillet_Welds

Commercial Interactions:

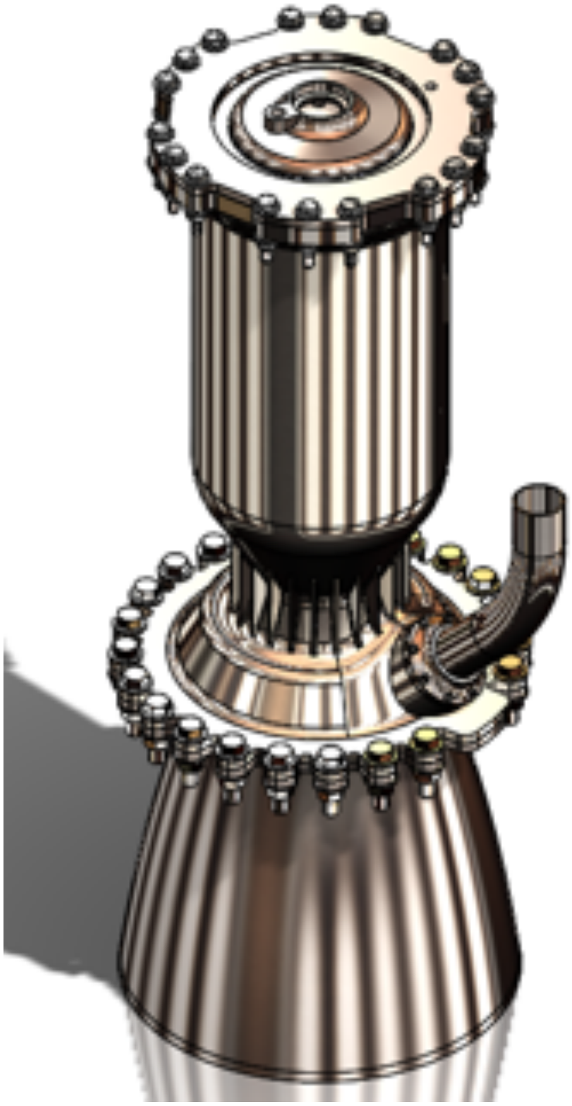
The manufacturing and testing of the TTS is expected to have the following commercial interactions:

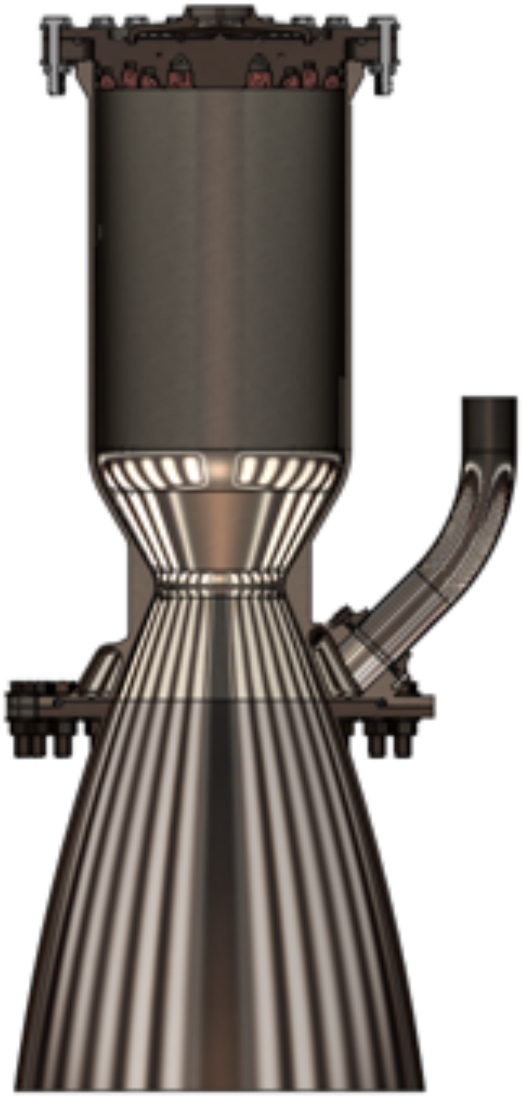
- Aluminum 6061-T6 stock will be purchased from Online Metals (https://www.onlinemetals.com)
- Shoulder screws, nuts, rod ends, and press fit pins will be purchased from: https://www.mcmaster.com
- Welding will take place at Custom Tech Fabricating, Duane Fiegel (734)-845-7311
- Heat treatment to a T6 temper will take place at Modern Metals Processing (https://www.modernmetalprocessing.com/)
- Verification of tolerance requirements will be done at LIFT Technologies in Detroit through a Coordinate Measuring Machine (CMM) (https://lift.technology/)
- Load testing will occur at University of Michigan Material Science lab

Propulsion:

RP-D2 Engine Overview

Written by: Joshua Miller (joshmi)
Date: 5/25/20





Stats:

Materials:	316L Stainless Steel, 304 Stainless Steel, Inconel 718, Ti-6Al-4V (Grade 5 Titanium), C18200 OFHC Copper, NiB Braze filler	Volume:	128.47 in^3
Manufacturing:	3D printing, brazing, cnc, welding, etc	Diameter:	9.57 in (widest)
Thrust:	4072 lbf (Mean sea level)	Max Pressure:	551 psi (Fuel inlets)

Component Objective:

- Responsible for producing and maintaining thrust in a safe and controlled manner
- Produces enough total impulse to propel TSM to the Karman line
- Maintains proper thermal equilibriums to prevent failure of engine during and after burn
- Safely control thrust to prevent injury to personnel and rocket

Design Overview:

- All aspects of the engine were designed using relevant sections of Huzel [1] and Rocket Propulsion Analysis (RPA) [2] which bundles these equations in an easy to use software
- Coupled thermal and structural simulations were conducted using ANSYS, available through the University of Michigan’s CAEN software license [3]
- Computational fluid dynamics simulations on the chamber and injector were carried out using ANSYS Fluent, again accessed through the CAEN software license
- Engine parameters (Isp, thrust, chamber pressure, etc.) were determined as a joint effort between a swath of subteams, specifically ATLO and Structures
- Sub-component specific references (injector, chamber, nozzle) are detailed in their respective papers
- Engine cold flow and hot fire testing will be conducted at our Green Rd. testing facility, provided to us by the University of Michigan
    - Engine parameters (chamber pressure, thrust, Isp) will be measured to validate design

Sources:

[1] Huzel, Dieter K, and David H Huang. “MODERN ENGINEERING FOR DESIGN OF LIQUID-PROPELLANT ROCKET ENGINES.” *American Institute of Aeronautics and Astronautics*, vol. 147, 1992.

[2] Ponomarenko, Alexander. “RPA: Tool for Liquid Propellant Rocket Engine Analysis C Implementation.” *Rocket Propulsion Analysis*, Software Engineering UG, May 2010.

[3] “Software Access & Licensing Restrictions,” *CAEN*. [Online]. Available: https://caen.engin.umich.edu/software/licensing/. [Accessed: 25-May-2020].

Commercial Interactions:

- A design review was conducted with Relativity Space to validate our engine design and to receive helpful criticism on the matter. Relativity ensured us that no export-controlled information was exchanged during the meeting
- See component documents for specifics to their machining processes.

Combustion Chamber

Written by: John Letarte letartej@umich.edu, Josh Miller joshmi@umich.edu

Figure 1: RP-D2 Chamber in middle

Specifications:

Main Chamber	
Materials	Inconel 718

Manufacturing	Sapphire Velo3d printer EDM Welding	
Chamber Pressure	440	psi
Mass Flow rate	8.66	kg/s
MSL Thrust	4080	lbf
MSL ISP	216	s
Throat Diameter	3	in
Mass	11.2	lb
Weld on Flange		
Materials	Stainless 304	
Manufacturing	Waterjet	
Inlet Tube Adapter		
Materials	Stainless 304	
Manufacturing	CNC Lathe, Mill	

Component Objective:

- The only combustor for the RP-D2 engine
- Contains nozzle throat and some of the diverging section of the nozzle
- Regen cooled to prevent overheating and melting.
- Maintains a chamber pressure of 420 psi throughout flight
- Doesn’t buckle under regen channels.
- Maintains constant exit pressure of 19.9 psi

Design Overview:

- Utilizes channel wall design
- Will be manufactured on a Sapphire Velo3d metal printer by Stratasys Direct
- Chamber clearance will be evaluated using a water height comparison
- Durability will be tested in full duration hotfire tests
- Static Thermo-Structural simulations were completed in Ansys Mechanical APDL Student Edition 19.1

We referenced the NASA-SP-8087, “Liquid Rocket Engine Fluid-Cooled Combustion Chambers,” report [1] for many of our design choices. Pages 14-18 and 54 for our cooling channels and pages 49-50 for film-cooling of the nozzle.

Our main tool for design was the Rocket Propulsion Analysis software (RPA) developed by RP Software+Engineering UG in Neunkirchen-Seelscheid, Germany. The software allows us to figure out the size, shape and estimated performance of a rocket engine. The software is available for purchase online on their website, the foundational papers for it are included [2]. They describe the foundational principles for combustion analysis, and we used these papers to gauge the accuracy and improve our understanding of the results which RPA gave us.

For knowing if the chamber was strong enough to withstand the hot combustion gasses, we referenced material properties for Inconel 718 from the manufacturer Special Metals [3] and from EOS [4][5] (manufacturer of metal 3D printing machines and metal powders). For finding the emissivity of inconel we used information from the journal of Nuclear Engineering and Design [6]. For other material properties (bolts, screws, etc), we referenced Military Handbook 5H [7].

For additional reference material on good practices for chamber and TCA design, we utilized sections of Rocket Propulsion Elements 7th edition by Sutton [8] and Huzel and Huang [9]. For Sutton, the definitions and fundamentals section, pages 27-44, and the thrust chambers section, pages 268-320. For Huzel and Huang, Chapter 4, sections 4.1 - 4.4 (pages 67 - 104) were primarily.

Lastly, when sizing the number and size of bolts needed to keep the nozzle and chamber together, we referenced thread tables, bolt stress theory, and torque calculations from “Engineers Edge” and “The Engineering Toolbox” [10-13].

When modeling the chamber, the design was done in Solidworks Education edition [14]. The fluid flow analysis was done using ANSYS fluent Student edition [15], and the steady state thermo-structural analysis was done in ANSYS mechanical APDL Student edition [15]. For predicting the pressure loss in the regenerative cooling channels we used the Darcy-Weisbach friction equations, using research that correlates roughness to absolute roughness [16].

Some planning and some calculations for this component took place in a master spreadsheet made using Google Sheets [17].

Commercial Interactions:

Design reviews were conducted with Nate Scholten of Relativity Space [18] under the express understanding that no restricted information of any kind would be discussed, as foreign nationals were present during the review.

The printing of the chamber is to be performed at a reduced price as part of a sponsorship from Stratasys Direct [19] who also provided insight into the printing capabilities of the printer and recommendations to reduce cost and increase reliability.

Stratasys Direct is using various other companies to perform the post machining, cleaning of any remaining debris, and heat treatment/ hot isopressing of the chamber.

The EDM operations on the chamber meant to create the film cooling holes for the nozzle will be performed by Arc Drilling [20].

Bolt Specifications and the materials were all sourced from Mcmaster Carr [21].

Welding, of the tube to the adapter, and the flange to the chamber will be conducted by Custom Tech fabrication [22]

Sources:

[1] "Liquid Rocket Engine Fluid-Cooled Combustion Chambers." *NASA Technical Reports Server*, NASA Lewis Research Center, 1 Apr. 1972,

[2] Ponomarenko , Alexander. "RPA: Tool for Liquid Propellant Rocket Engine Analysis C Implementation." *Rocket Propulsion Analysis*, Software Engineering UG, May 2010,

[3] "INCONEL 718 Alloy." *Specialmetals.com*, Special Metals, 7 Sept. 2007,

[4] "EOS NickelAlloy IN718 Material Data Sheet." *EOS_NickelAlloy_IN718_en.Pdf*, EOS GmbH - Electro Optical Systems ,

[5] Velo3D, Barnes Group Advisors, Material Property Comparison (IN718), Unpublished Manuscript.

[6] S. E. N. K. L. W. T. K. G. R. V. T. S. K. L. Benjamin P. Keller, "Total Hemispherical Emissivity of Inconel 718," *Nuclear Engineering and Design,* vol. 287, pp. 11-18, 2015.

[7] “METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES.” *MILHDBK5H.Pdf*, Air Force Research Laboratory (AFRL), 1 Dec. 1998

[8] Sutton, George P, and Oscar Biblarz. *Rocket Propulsion Elements* . 7th ed., JOHN WILEY & SONS, INC. , 2001.

[9] Huzel, Dieter K, and David H Huang. “MODERN ENGINEERING FOR DESIGN OF LIQUID-PROPELLANT ROCKET ENGINES.” *American Institute of Aeronautics and Astronautics*, vol. 147, 1992.

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[14] “Solidworks Education Edition” *Dassault Systems -Solidworks,* https://www.solidworks.com/sw/education/6443_ENU_HTML.htm

[15] All static-structural and steady-state thermal simulations were completed in

ANSYS https://caenfaq.engin.umich.edu/software-for-students/ansys-student

[16] T. &. G. C. &. W. H. Adams, "A Simple Algorithm to Relate Measured Surface Roughness to Equivalent Sand-grain Roughness," *International Journal of mechanical Engineering and Mechatronics,* 2012.

[17] https://www.google.com/sheets/about/

[18] https://www.relativityspace.com/

[19] https://www.stratasysdirect.com/

[20] https://arcdrilling.com/

[21] https://www.mcmaster.com/

[22] Custom Tech Fabrication, Duane Fiegel,

8233 Eisman Rd,

Manchester, MI 48158

Injector

Written by: Akhil Vinod, vakhil@umich.edu

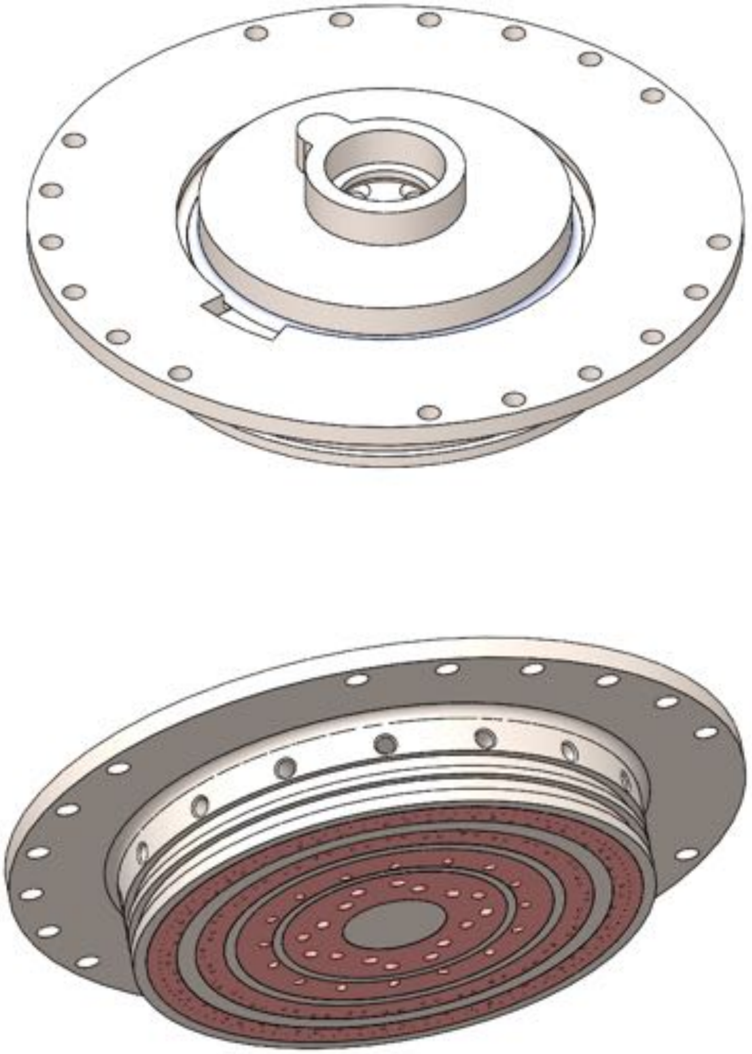


Figure 1: RPD2 Injector

Stats:

Materials:	316L Stainless Steel • Manifold and LOX Dome 304 Stainless Steel • Flange C18200 OFHC Copper • Rings

	BNi-7 Braze Filler
Manufacturing:	CNC Machining • Manifold, LOX Dome, and Ring geometry Welding • Between LOX Dome and Manifold EDM • Copper Ring Orifices Brazing • Between Rings and Manifold
Injector Element Pressure Drop:	70.4 psi (16% of Chamber Pressure)
Injector Efficiency:	89% Estimated Combustion Efficiency
Volume:	35.94 in^3
Diameter:	5.872in - Injector Manifold 8.25in - Flange
Mass:	11.38 lbs

Component Objective:

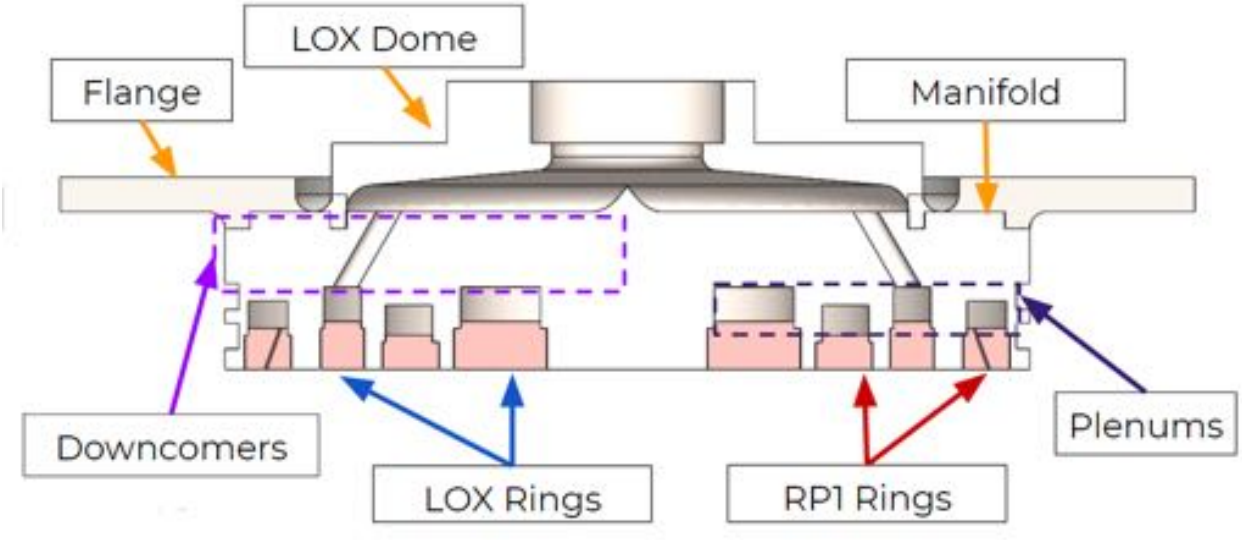


Figure 2: Labeled Injector Geometry (Open-faced Quarter Cross Section)

A liquid rocket engine injector's purpose is to atomize and mix the fuel and oxidizer, RP1 and Liquid Oxygen (LOX), within the combustion chamber to ensure a stable combustion. The injector assembly is built from four major components: the LOX dome, LOX/RP1 rings, manifold, and flange. The LOX enters axially through the LOX Dome which connects to the LOX Valve. The RP1 enters radially through radial inlets after flowing through the Chamber's regenerative cooling channels. Our injector has a four ring design with alternating LOX and RP1 rings starting from LOX inside outwards. The injector element design utilized is a like-impinging doublet.

Design Overview:

The general design of the injector was determined through studying the design of the F-1 engine injector [1]. From the F-1 design we followed a similar plan of constructing a separated liquid oxygen zone and a regen fed fuel inlet. Our injector utilizes a like-doublet element type as shown in Figure 3.

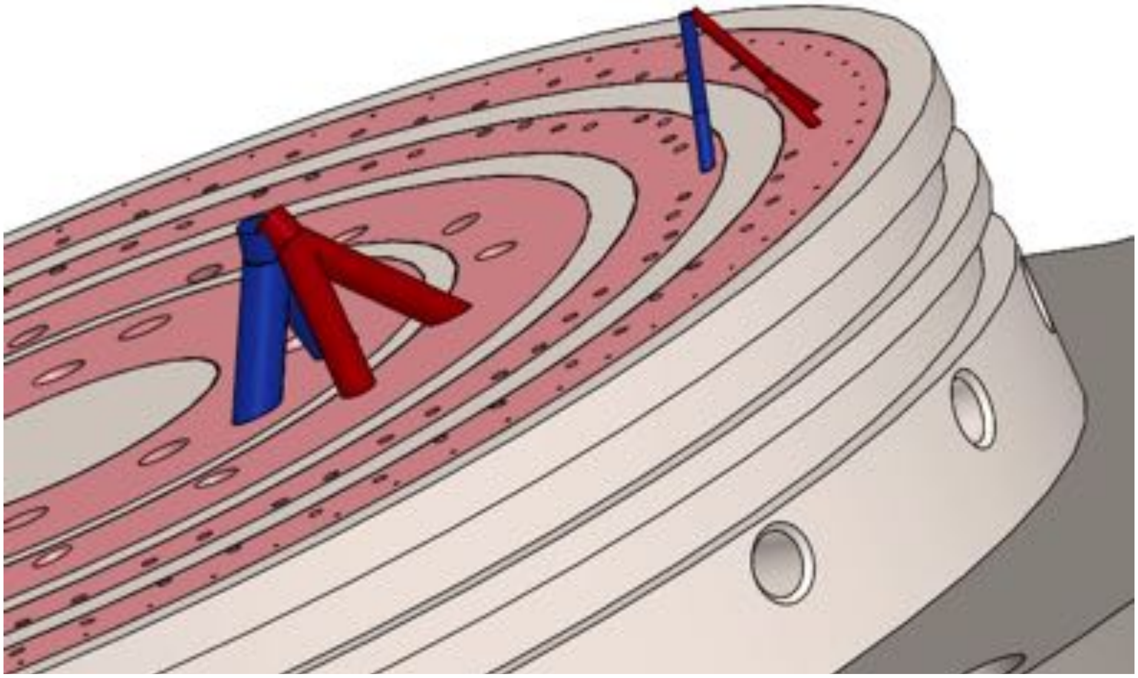


Figure 3: Like-Doublet Configuration

A major resource when designing the injector elements is the NASA LRE Injector Report SP-8089 [2]. The like-doublet design was chosen for its ease to machine and separate the upper flow system geometries (downcomers and plenums). Additionally, the horizontal momentum ratios can easily be adjusted by changing the doublet's relative angles to better ensure the combustion occurs axially through the chamber [2, pp.11-13]. The outer fuel elements are chosen to be the ones closest to the chamber wall to both minimize overall mixing losses and to decrease the chamber wall temperature. The RP-D2 injector elements use a 60° impingement angle between like elements and a 41° cant angle between the unlike elements to increase mixing uniformity [2, pp.15-26]. A 16% injector stiffness, defined as the chamber pressure drop across the injector elements, is chosen to minimize combustion instabilities by recommendations from SP-8089 [2, p. 35] as well as Vigor Yang's study on "Liquid Rocket Thrust Chambers: Aspects of Modeling, Analysis and Design" [3, p. 144].

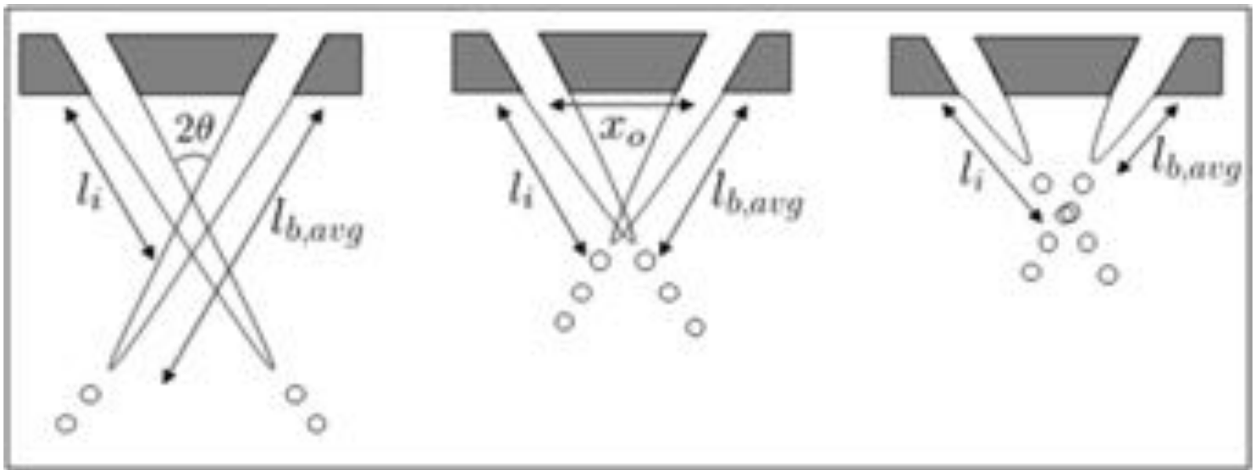


Figure 4: Configurations showing effects of varying jet breakup length (l_b) to impingement length (l_i). Far left is an ideal case. [5, p. 94]

Using Microsoft Excel® we had set up a spreadsheet to finalize the parameters for the injector orifices and elements by enforcing the equations sourced from both SP-8089 [2] and Brian Sweeny’s Dissertation on impingement distance and atomization[4]. Two important non-dimensional parameters exist that relate the length of impingement(li) and length of the orifice(lo) to the orifice diameter(do). They are li/do and lo/do, respectively. The lo/do is important in that the fluid must be given enough length to fully develop in the direction of the orifice to prevent hydraulic flip and flow disturbances [4, p. 96].

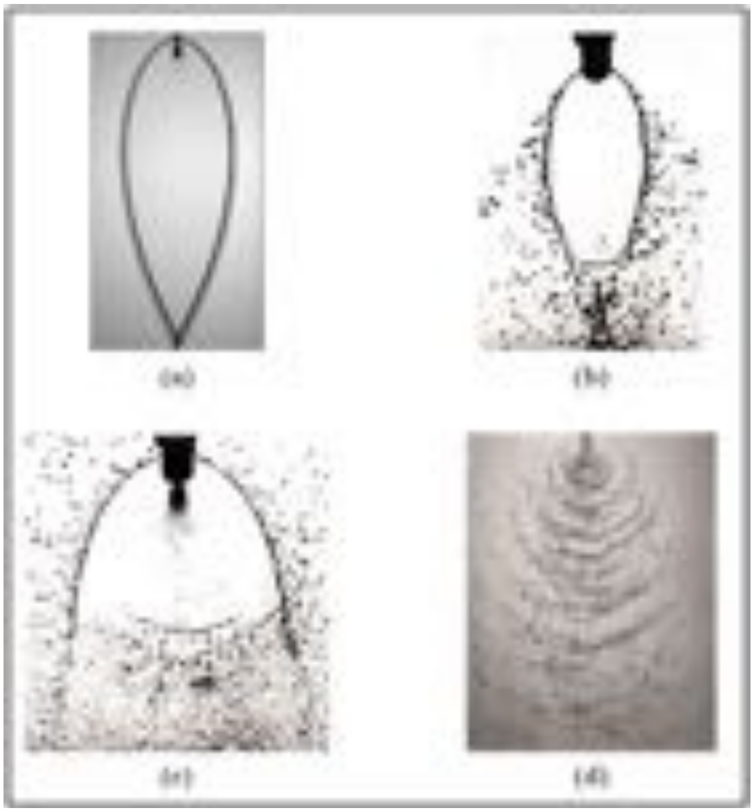


Figure 5: Spray fan regimes. (a) Closed-Rim (b) Periodic-Drop (c) Opened-Rim (d) Fully-Developed [4, p. 74]

The weber number, ratio between the inertial force and the surface tension force, and the flow velocity out of an injector element were limited to be under 2000 and over 10 m/s respectively. This results in a fully developed flow post second impingement which ensures proper mixing between the fuel and oxidizer. Keeping a low weber number additionally aids in the minimization of any aerodynamic instabilities [4 pp.72-77].

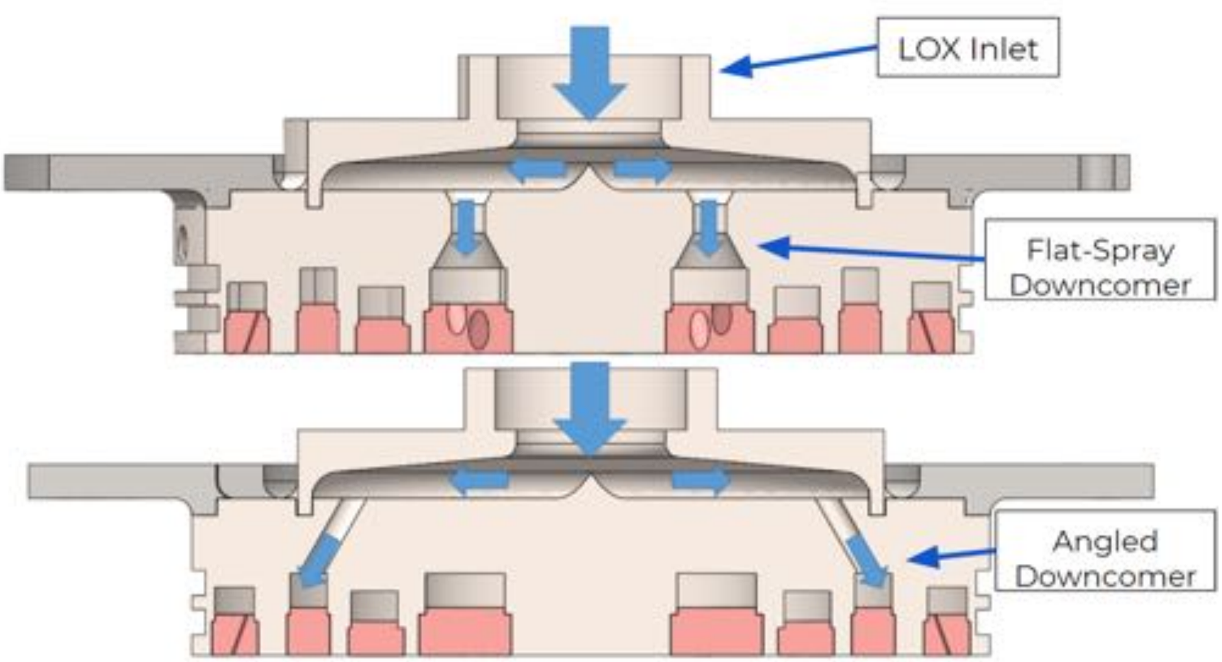


Figure 6: Injector Cross Sections with LOX Fluid Flow Paths

The injector downcomer and radial inlet geometries were designed in accordance with the recommendations from section 2.1.3 of SP-8089 [2]. The LOX fluid flow begins at the inlet and then the flow is split with a local deflector plate and directed to the two sets of downcomers. The LOX downcomers include both flat-spray downcomers and angled downcomers which are spaced evenly to act as a distribution ring [2, pp.48-52].

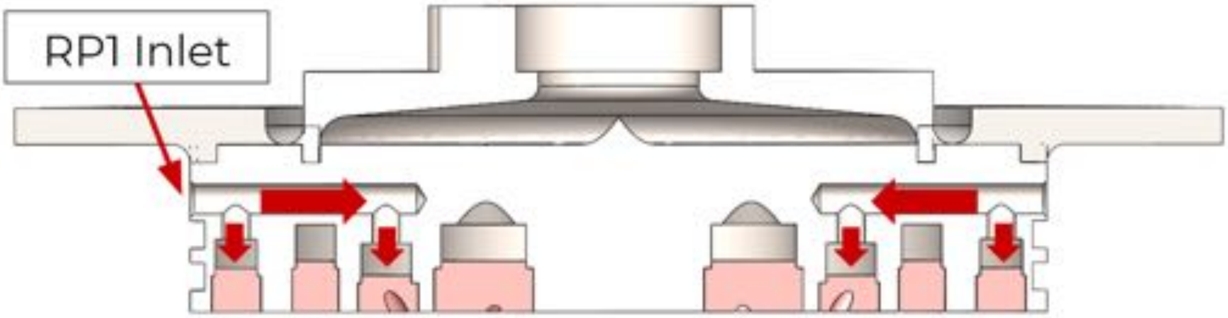


Figure 7: Injector Cross Section with RP1 Fluid Flow Paths

The RP1 fluid flow begins after the regenerative cooling outlets as the fuel passes through an annular plenum to enter one of the sixteen radial inlets. A distribution ring of two ports per radial inlet is used to direct the RP1 to its respective plenums [2,pp. 46-47].

Adjustments to the downcomer and orifice geometries are made after analysis through computational fluid dynamics (CFD) analysis through ANSYS Fluent, which is a commercialized CFD software accessed through a CAEN license through the University of Michigan.

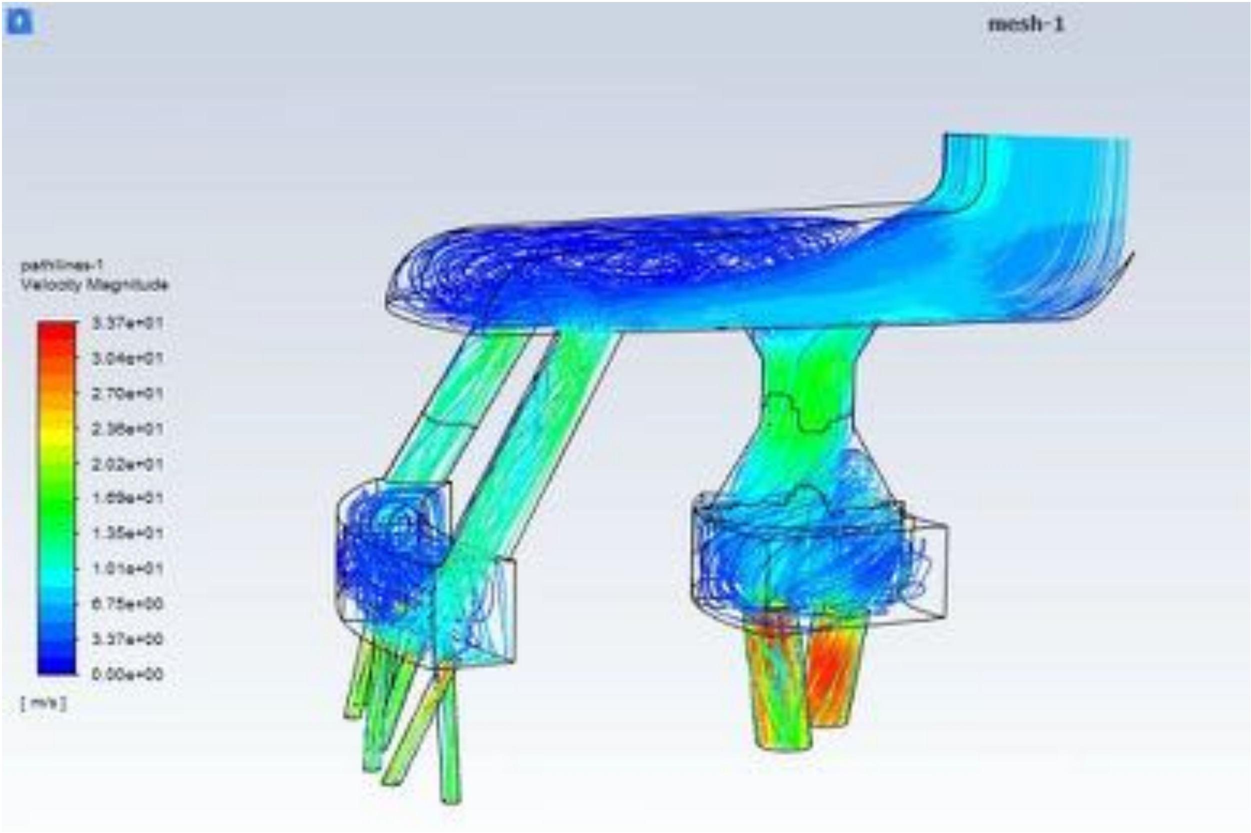


Figure 2: LOX Fluid Flow Simulation Results - Velocity Pathlines - ANSYS Fluent

The oxidizer to fuel ratios of the inner and outer rings of the injector are fixed based on the values given in a NASA technical report [6]. A lower oxidizer-to-fuel (OF) ratio at the outer/zone rings decreases concern of extreme heating near the chamber walls. There is a 70-30% split of mass flow rate of fuel and oxidizer to the core and zone respectively. The overall OF ratio of 2.1 was set based on the ideal stoichiometric OF between LOX and RP1. This overall OF is calculated as a mass weighted average between the two enforced OF ratios of 2.3 in the core and 1.65 in the zone [6, pp.12-18].

Additionally, 5% of RP1 flowing to the outer fuel plenum is directed towards film cooling to further decrease the temperature of the chamber walls. The film cooling holes are angled by 70 degrees from the vertical as tangential coolant holes create a longer more lasting film [7, pp.9-10]. The heat fluxes and temperatures through the chamber walls and injector face were determined through Rocket Propulsion Analysis (RPA), a rocket engine design software. The results from RPA were used to determine the percentage of film cooling required. The license for the software was purchased by the Michigan Aeronautical Science Association.

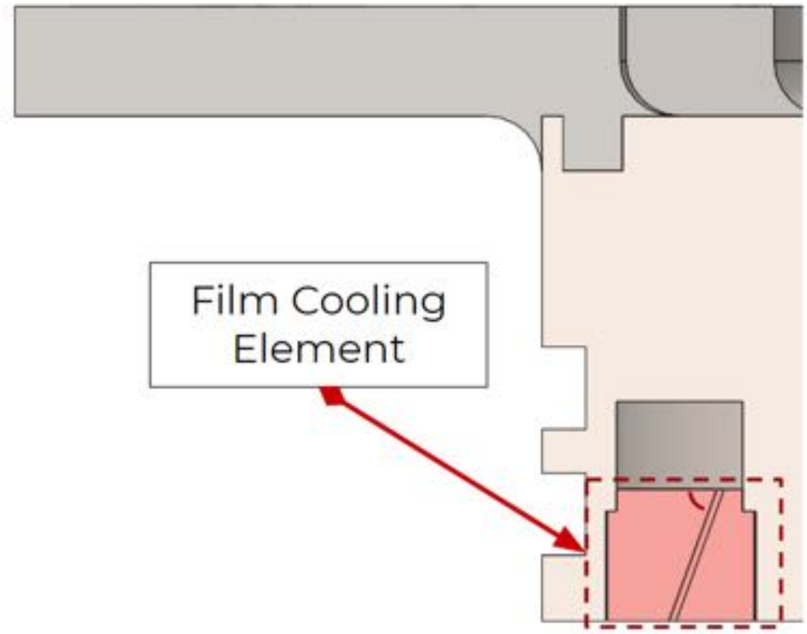


Figure 8: Film Cooling Element Cross Section

The manifold, rings, and flange materials were selected based on the material properties found in the CES EduPack made by Granta Design. To ensure the injector components withstood loading conditions, Finite Element Analysis (FEA) was conducted using ANSYS suite of thermal and structural analysis. The yield stresses and thermal conductivity values for all injector materials were taken from the CES Edupack or the relevant datasheets. Access of the material database and the FEA software was provided through the CAEN license.

To seal the injector, three O-rings are required, with two radial O-rings and one face sealing O-ring. The O-ring surface finish requirements and compression requirements were taken from the Parker O-ring Handbook section 3.1 [9].

As per the design recommendations from section 2.2.1 of SP-8089 [2, p. 60], the copper rings will be brazed to the injector manifold. A braze allows the connection of two dissimilar materials with a leak-tight, structurally sound connection. The braze filler material used is a Nickel braze paste (BNi-7), which was found to be compatible with C18200 and 316L Stainless Steel through atmosphere brazing [8, pp.4-7]. The braze joint design is done based on the recommendations from Brazing 2nd Edition, by Mel Schwartz. The lap length calculation is done using the results from FEA and the equations from Schwartz [10, pp.313-318].

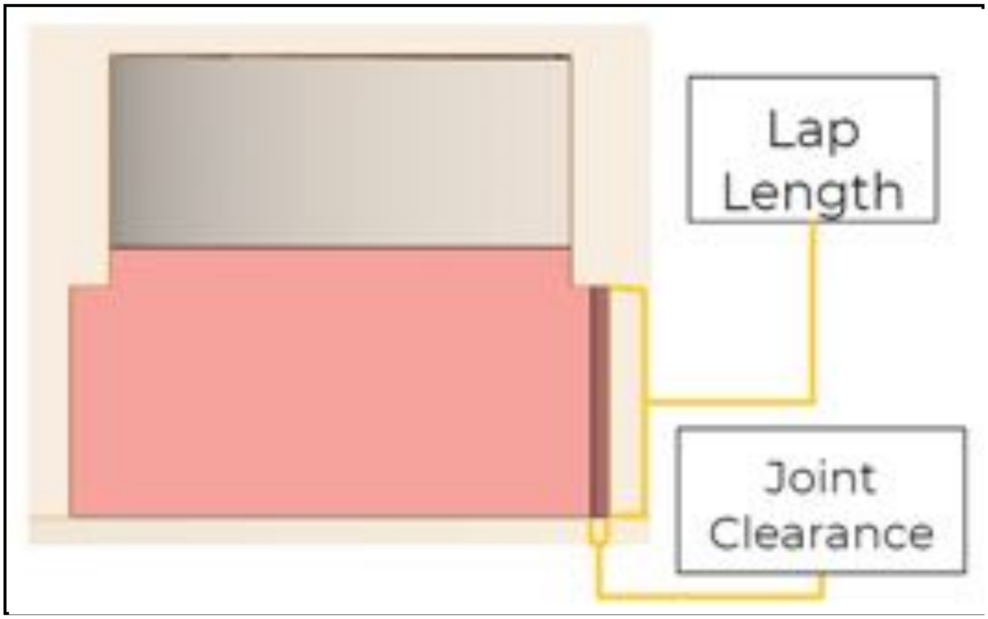


Figure 9: Injector Braze Joint Cross Section

The injector ring orifices are to be drilled via electro discharge machining (EDM). From section 2.1.2 of SP-8089 we find that the EDM process enables a freedom in orifice sizing while reducing burrs and maintaining a constant stiffness between ring orifices [2, pp.39-40].

<u>**Commercial Interactions:**</u>

- During the design process of the RPD2 Engine, the MASA propulsion team met with Relativity Space to evaluate the engine design and provide recommendations for adjustments.
    - During this meeting no export controlled information was disclosed, all suggestions made reflected research found within the sources listed.
- Injector material stock sourced from McMaster-Carr and ALRO Steel
- Pressure transducer and LOX dome fittings are sourced from JEGS, Fittings Space, and Pegasus Auto Racing Supplies
- Injector CNC Machining and Welding will be completed at:
    - The Wilson Student Team Project Center (WSTPC) at the University of Michigan - Ann Arbor
    - Accurate Tooling Solutions - New Baltimore, MI
    - New Method Steel Stamps - Taylor, MI
- Injector Brazing to be completed at a commercial metal processing company
    - Bluewater Thermal Solutions at Coldwater, MI
- Injector EDM to be completed at a commercial EDM Manufacturer
    - ARC Drilling Inc. - Cleveland, OH

<u>Sources:</u>

[1] M. Jetzer, “F-1 Engine Injector,” Heroic Relics. [Online]. Available: http://heroicrelics.org/info/f-1/f-1-injector.html. [Accessed: 02-Jan-2020].

[2] G. S. Gill, W. H. Nurick, R. B. Keller, and H. W. Douglass, Liquid rocket engine injectors. Cleveland: National Aeronautics and Space Administration, Lewis Research Center, 1976.

[3] V. Yang, Liquid rocket thrust chambers: aspects of modeling, analysis and design. Reston, VA: American Institute of Aeronautics and Astronautics, 2004.

[4] Brian A. Sweeney and Robert A. Frederick Jr., Jet Breakup Length to Impingement Distance Ratio for Like Doublet Injectors: Journal of Propulsion and Power 2016 32:6, 1516-1530.

[5] Huzel, Dieter K, and David H Huang. “MODERN ENGINEERING FOR DESIGN OF LIQUID-PROPELLANT ROCKET ENGINES.” American Institute of Aeronautics and Astronautics, vol. 147, 1992.

[6] J. M. Winter, A. J. Pavli, and A. M. Shinn, Design and evaluation of an oxidant-fuel-ratio-zoned rocket injector for high performance and ablative engine compatibility. Washington, D.C.: National Aeronautics and Space Administration, 1972.

[7] S. Shine and S. Nidhi, “Review on film cooling of liquid rocket engines,” Propulsion and Power Research, vol. 7, no. 1, pp. 1–18, 2018.

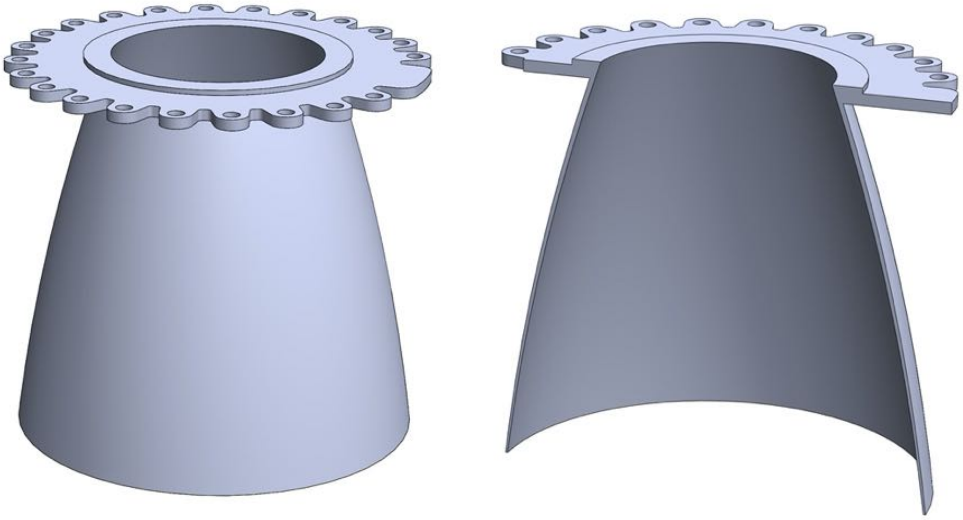
[8] “An Introduction to Brazing” Oerlikon metco, Issue 4, BRO-0010.4. [Online]. Available:https://www.oerlikon.com/ecomaXL/files/metco/oerlikon_BRO-0010.4_Introduction_to_Brazing_EN.pdf&download=1. [Accessed: 06-Feb-2020].

[9] *Parker O-ring handbook*. Lexington, KY: Parker Seal Group, O-Ring Division, 2001.

[10] Schwartz, M. M. (2003). *Brazing*. ASM international.

Nozzle Extension

Written by: Austin Barthelme (atbart)



Stats:

Material:	Ti-6Al-4V (Grade 5 Titanium)
Manufacturing:	CNC Machining
Interior Coating:	Zirconium-oxide paint (Zircwash)
Height:	9.09”
Exit Diameter:	9.56”
Mass:	4.81 lbm
Software:	Rocket Propulsion Analysis (RPA) SolidWorks Ansys

Component Objective:

- Nozzle converts combustion gas internal energy to kinetic energy
    - Achieved by accelerating gas to supersonic velocities
- Nozzle takes high pressure, low velocity combustion gases and turns them to low pressure, high velocity gases
    - Optimized to certain altitude, set by Propulsion lead

MASA’s design for the liquid RP-D2 engine has a diverging nozzle extension, bolted onto the bottom of the single combustion chamber/converging nozzle part. The nozzle extension, approximating the contour of a Rao bell nozzle, expands the high pressure, low velocity gases produced in combustion to low pressure, high velocity gases at the exit. The nozzle extension accelerates the hot gas to supersonic velocities, producing thrust by Newton’s laws.

Design Overview:

- Diverging nozzle extension, converging portion part of chamber
- Nozzle extension secured onto bottom of chamber via bolts
    - Sealed with metal C-ring from Parker Seals [1]
- Designed using Rocket Propulsion Analysis (RPA) [2]
    - Available for purchase online, including documentation
    - Utilizes Rao bell nozzle contour
- Portions of Modern Compressible Flow by Anderson were used to compare calculations
    - Chapter 5: Quasi-One-Dimensional Flow, Pages 120 - 145 [3]
- CAD modeling for nozzle extension used SolidWorks [4]
    - Available with University of Michigan’s CAEN software license
- Static structural and steady-state thermal simulations utilized ANSYS [5]
    - Available with University of Michigan’s CAEN software license
- Manufactured on a CNC mill and lathe from Ti-6Al-4V Grade 5 Titanium
    - Material properties taken from Military Handbook 5H, Section 5.4, Pages 5-51 [6]
- Zirconium-oxide paint will be applied to inside of nozzle extension to make it more thermally resistant
    - Commercial-off-the-shelf brand called Zircwash [7]
    - Design inspiration sourced from NASA report SP-8120 Page 77 [8]

- The nozzle will be tested in multiple hydrostatic and hotfire tests. Each of these will be conducted at MASA’s personal testing facility on campus. All equipment is publicly available or custom-manufactured.

Commercial Interactions:

- Relativity Space held a design review with MASA in February 2020, in which the nozzle extension was discussed. A mutual agreement and understanding between Relativity and MASA prohibited export controlled information from Relativity being shared with MASA.

- The specific company to manufacture the nozzle has not been selected. However, MASA has been in close contact with multiple CNC machine shops in the local Michigan area. Going forward, we plan to acquire more quotes and select the most economical option.

- The stock titanium billet that will be machined for the nozzle extension has been sourced from TMS Titanium. The grade 5 titanium rod is publicly available to purchase from the company's website [9] by anyone.

Sources:

[1] Parker Metal Seal Design Guide. https://www.parker.com/Literature/Seal%20Group/CSS%205129.pdf

[2] Ponomarenko , Alexander. "RPA: Tool for Liquid Propellant Rocket Engine Analysis C Implementation." *Rocket Propulsion Analysis*, Software Engineering UG, May 2010

[3] Anderson, John David. *Modern Compressible Flow: with Historical Perspective*. McGraw-Hill, 2004.

[4] Design was completed in Solidworks Educational Software https://www.solidworks.com

[5] All static-structural and steady-state thermal simulations were completed in ANSYS https://www.ansys.com

[6] "METALLIC MATERIALS AND ELEMENTS FOR AEROSPACE VEHICLE STRUCTURES." *MILHDBK5H.Pdf*, Air Force Research Laboratory (AFRL), 1 Dec. 1998

[7] "Zircwash," *ZYP Coatings Inc.* [Online]. Available: https://www.zypcoatings.com/product/zircwash/. [Accessed: 25-May-2020].

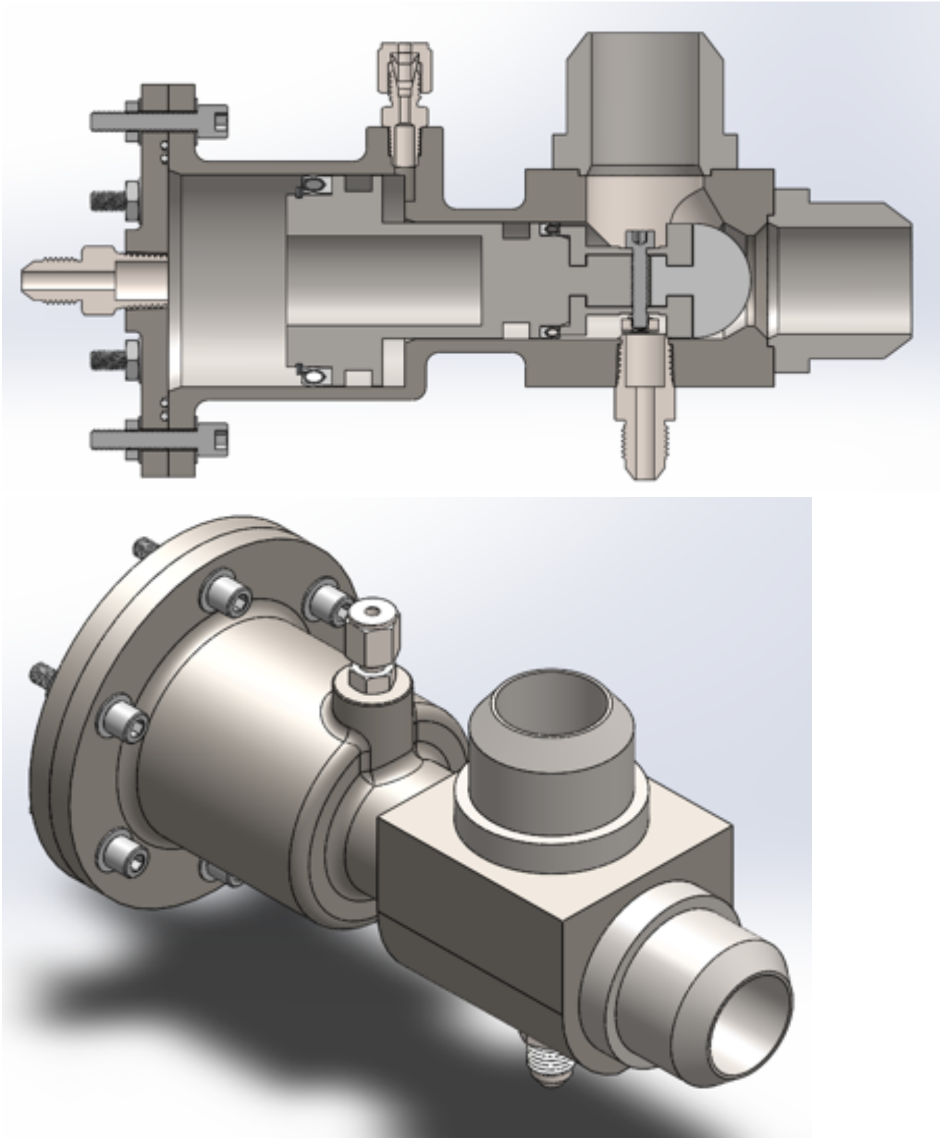
[8] Douglas, Howard W. "Liquid Rocket Engine Nozzles." *NASA Technical Reports Server*, NASA Lewis Research Center, July 1976

[9] Titanium billet sourced from TMS Titanium - Poway, CA.

https://store.tmstitanium.com/products/3419/titanium-round-bar/6-4-grade-5/9.5700-dia-9.2000-long

Liquid Oxygen Main Propellant Valve

Written by: Prachet Jain (prachetj), Josh Miller (joshmi)



Materials:	304 Stainless Steel, 316L stainless Steel, PTFE, Viton, Permachem 6235, Torlon 4301, Black oxide alloy steel	Volume:	21.02 in^3

Manufacturing:	CNC machining, welding	Mass:	5.85 lbs
Max Pressure:	580 psi (at inlet)	Weld Filler:	Stainless Steel 308L

Component Objective:

- Designed to control the flow of Liquid Oxygen (LOX) from the main LOX tank to the engine.
- Designed to minimize pressure drop from the inlet of the valve to the outlet.

Design Overview:

- Valve seals using a hemispherical PTFE (Teflon) poppet [1]
- Housing, piston, end cap, and collars are made out of Stainless 304 [2]
- Fittings are made out of Stainless 304 and 316L [3]
- O-rings are made out of Viton, sourced from McMaster-Carr
    - Sizing calculations were done based on Parker-Hannifin’s O-ring handbook [4]
- Two spring seals are utilized, both made of Permachem 6235 [5]
- Two bearings are used, both made out of Torlon 4301 [6][7]
    - Bearing wear rate and PV calculations were based on formulae from Shigley’s Mechanical Engineering Design textbook [8]
- Designed using SolidWorks, provided by the University of Michigan CAEN software license [9]
- Static structural simulations were completed in ANSYS Mechanical using the CAEN license [9]
- Computational Fluid Dynamics (CFD) simulations were completed in ANSYS Fluent with the same CAEN license [9]
- Components will be manufactured on a CNC mill and lathe
    - CAM produced using Fusion 360, free to use for students [10]
- Stainless 308L is used as a weld filler [11]
- Google Sheets was used for various calculations related to the valve, including, but not limited to: Bolt stresses, force balance parameters, bearing PV rating and wear rate calculations, etc.
- Google Docs was used for documentation of various procedures.
- Will be tested using a vibration analysis table (at the UM CLaSP department), a waterflow apparatus, and other methods using in-house manufactured test articles.
- Validated in both cold flows and hot fires at MASA’s Green Rd facility, provided to us by the University of Michigan
- Inert Helium gas is being used to purge the valve

Sources:

[1] "Material Properties of Thermoplastic Teflon - Polytetrafluoroethylene", Dielectric Manufacturing. [Online]. Available: https://dielectricmfg.com/knowledge-base/teflon/ [Accessed 25 May 2020].

[2] "ASM Material Data Sheet", Asm.matweb.com. [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mq304a [Accessed 25 May 2020].

[3] "ASM Material Data Sheet", Asm.matweb.com. [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MQ316Q [Accessed 25 May 2020].

[4] Parker Hannifin [Online]. Available: https://www.parkerhannifin.ru/upload/iblock/3bd/catalog_o_ring_guide_ode5712_en.pdf [Accessed 25 May 2020].

[5] “Materials - Polyurethane, Nitrile, Viton, Rubber, EPDM, Silicone, Hytrel, Kalrez, Aflas, Nylatron, Acetal, PTFE, Peek - American High Performance Seals,” *AHP Seals*. [Online]. Available at: https://www.ahpseals.com/permachem-materials/ [Accessed 25 May 2020].

[6] Solvayultrapolymers.com. n.d. Torlon PAI Design Guide. [online] Available at: https://www.solvayultrapolymers.com/en/binaries/Torlon-PAI-Design-Guide_EN-227547.pdf [Accessed 25 May 2020].

[7] Polytechindustrial.com. n.d. Torlon 4301 (Polyamide-Imide) | Poly-Tech Industrial. [online] Available at: https://www.polytechindustrial.com/products/plastic-stock-shapes/torlon-4301 [Accessed 25 May 2020].

[8] "Shigley’s Mechanical Engineering Design", I-element.org. [Online]. Available at: http://www.i-element.org/PDF/D05.pdf [Accessed 25 May 2020].

[9] Caenfaq.engin.umich.edu. n.d. CAEN Knowledge Base. [online] Available at: https://caenfaq.engin.umich.edu/software-for-students [Accessed 25 May 2020].

[10] “Fusion 360 for Students & Educators: Online CAD/CAM Design Software,” *Autodesk*. [Online]. Available at: https://www.autodesk.com/products/fusion-360/students-teachers-

educators?mktvar002=3509233%7CSEM%7C903575221%7C49799944033%7Ckwd-296643913869 [Accessed 25 May 2020].

[11] Weldwire.net. n.d. Stainless 308L Technical Information. [online] Available at: http://www.weldwire.net/wp-content/uploads/2013/08/ER308L.pdf [Accessed 25 May 2020].

Commercial Interactions:

- Housing, piston, collar, poppet and end cap will be manufactured by a local machine shop in the Ann Arbor area
- Welding will take place at Custom Tech Fabricating, Duane Fiegel (734)-845-7311
- Other plumbing components and seals will be purchased from: https://www.mcmaster.com, https://www.ebay.com/, and https://www.ahpseals.com/
- Vibration analysis will occur at UM CLaSP
- Other tests will also take place at the Wilson Center

Fuel Main Propellant Valve

Written by: Cian Mullen (cianm), Minori Higashiyama (minorih)

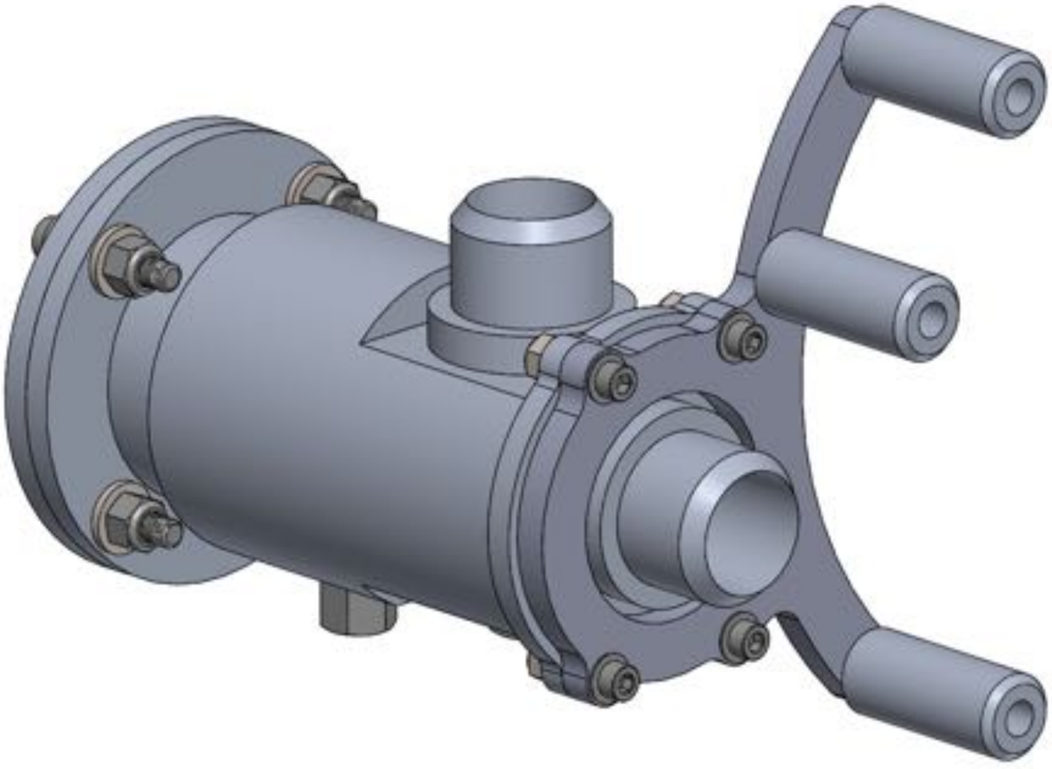


Figure 1: Valve Prototype 1 Isometric View

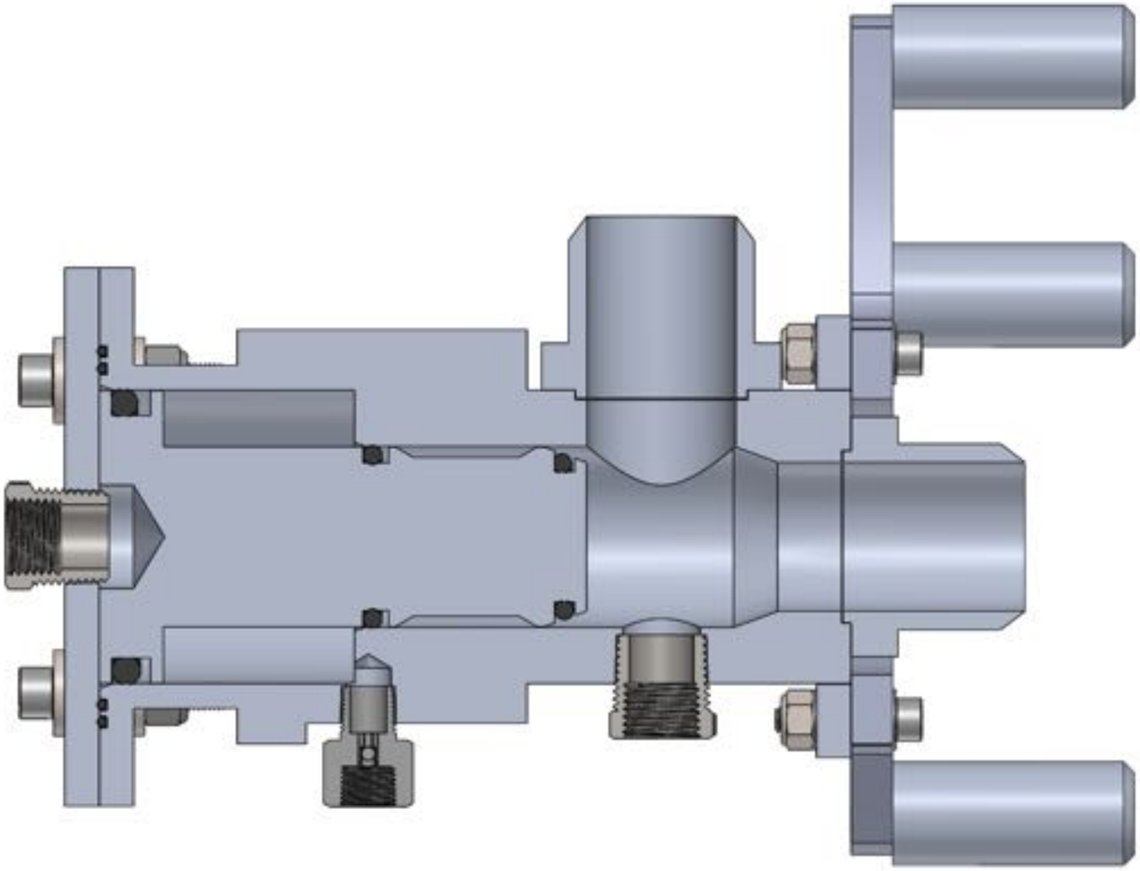


Figure 2: Valve Prototype 1 Cutaway View

Table 1: Fuel Valve Information

Length (without mount):	7 in
Diameter (without mount):	4 in
Mass:	3 lbs
Materials:	304 Stainless Steel, 316 Stainless Steel, Viton (FKM) Fluoroelastomer, Grade 8 Steel, Grade 5 Steel, Aluminum 6061-T6
Manufacturing:	CNC Lathing/Milling Welding
Weld Filler:	Aluminum 4043
Max Operating Pressure:	650 psi

Component Objective:

- Control the flow of fuel to the engine, opening to allow it to start and closing to shut it down.
- Provide a connection for a line that inert gas will flow through to purge the fuel system downstream of the valve.
- Keep both pneumatic gas and fuel leakage to a minimum.
- Minimize pressure drop across the fuel valve.

Design Overview:

- The valve is designed to have a poppet type seal and a 90 degree flow path bend. It is pneumatically actuated.
- Inert gas can be input through the bottom port to purge the downstream fuel system.
- CFD simulation was done on ANSYS to estimate pressure drop across the valve.
- Valve made of aluminum 6061-T6 with Viton o-rings.
- Bungs are welded to valve housing.
- The valve was manufactured in-house
- The valve has been partially tested for seal quality, pressure drop, performance in low temperature, and durability. These tests use water and compressed nitrogen gas.

Sources:

- O-ring sizing and gland design done with Parker O-ring handbook https://www.parker.com/Literature/O-Ring%20Division%20Literature/ORD%205700.pdf
- Valve calculations done in Microsoft Excel
- CAD modeling done in Solidworks educational edition https://www.solidworks.com
- Pressure drop and structural simulations done in ANSYS https://www.ansys.com/
- Equations for caculating bolt pretorques and number of of bolts required https://mechanicalc.com/reference/bolted-joint-analysis#external-thread-areas
- Material properties referenced from AZO materials https://www.azom.com/
- Documentation done in google docs
- Aluminum welding information referenced from the ALCOA aluminum welding handbook https://babel.hathitrust.org/cgi/pt?id=uc1.b5049388&view=1up&seq=8

Commercial Interactions:

- Components and stock purchased from https://www.mcmaster.com/
- 20 AN bungs purchased from https://www.anhosefittings.com/
- O-ring quote and brief correspondence with https://www.parker.com
- Out of house manufacturing quote from Protolabs https://www.protolabs.com/