Source: Blue Origin [35]

Rocket Propulsion Capstone Team 3

Shannon Comstock, Remington Dasher, Andrew King, Grace Morris

Project Description

Create a propulsion system for a high-power level 2 rocket:

- Develop a unique Ammonium Perchlorate Composite Propellant (APCP)
- Create casing for rocket motor
- Design rocket nozzle
- Create two small scale rockets for testing
- Optimize rocket motor

Create a test stand to gather thrust data during testing

- Ensure safe and accurate data gathering
- Collaborate with an Electrical Engineering capstone team

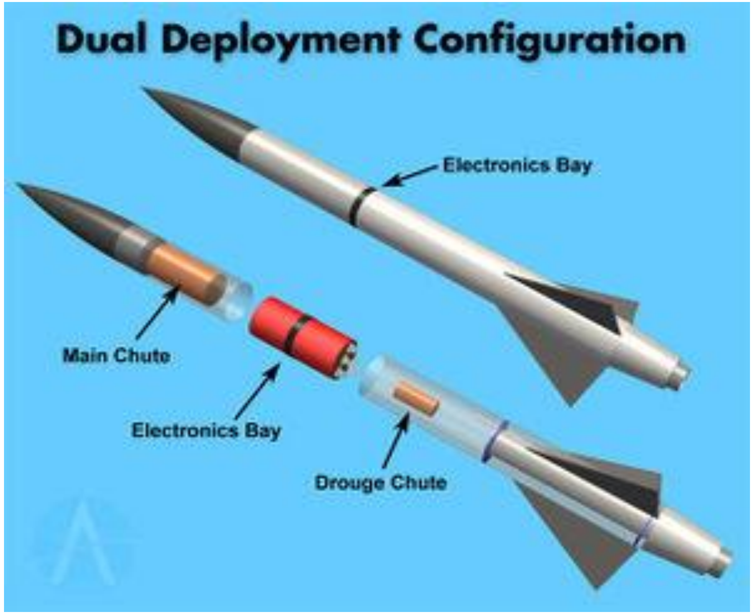


Figure 1: Rocket Diagram
Source: Stanford SSI [36]

Project Purpose

- Assist with future projects of the NAU Rocket Club
- Research and develop new formulas for rocket propellants
- Assist in development of aerospike nozzle design
- Gain an understanding of rocket propellant design and experience in the field of aerospace

Funding and Sponsorships:

- A budget of $2000 has been provided for the project
- Our teams GoFundMe has raised $300 thus far

Figure 2: Rocket Launch
Source: Canadian Association of Rocketry [37]

Background and Benchmarking – Test Stands

Aerocon Systems Horizontal/Vertical Test Stand

Pros (Figure 3.):

- Various ring sizes for different motors
- Affordable - ~$600 with all the clamps

Cons:

- Aluminum body offers low melting temperature which is not ideal for this application
- No measurement for impulse which requires more tools

Figure 3: Test Stand 1 Source: [29]

FUTEK | Rocket Engine Trust Measurement Stand

Pros (Figure 4.):

- Incredibly sturdy, made from steel and formed sheet metal
- Multi-axis sensors, load cell and wireless capabilities allows for safe operation

Cons:

- Work order required to purchase, not readily available, long lead times
- Single load cell ~$6,000, with four of them, this is 12 times our budget

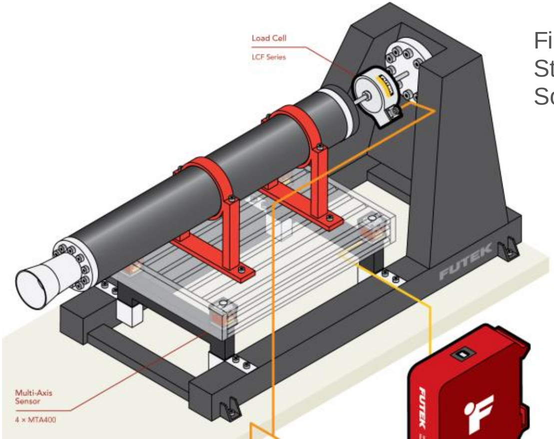


Figure 4: Test Stand 2 Source: [30]

Background and Benchmarking – Test Stand

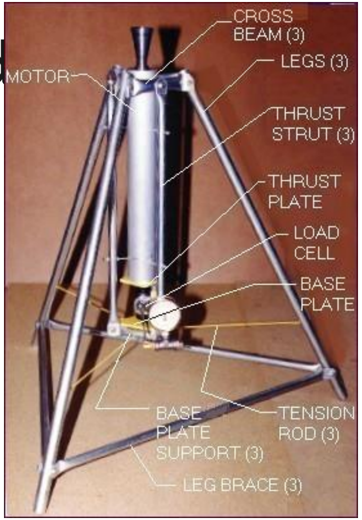


Figure 5: Test Stand 3
Source: [31]

Richard Nakka's STS-5000 Static Test Stand for Rocket Motors
Pros (Figure 5.):
- Vertical orientation allows for realistic firing position
- Materials are cheap and the system is simple

Cons:
- Not available for purchase, requires the customer to buy the parts separate and build
- Design is very improvised and most likely will not take the forces we are dealing with

AeroTech RMS 75/1280 Motor
Pros (Figure 6.):
- Follows safety standards set by manufacturer's
- Fulfills size requirements

Cons:
- Not affordable- Costs about $500
- Not in accordance with the Tripoli Rocket Level system

Figure 6: 1280 Motor
Source: [32]

Background and Benchmarking- Propulsion System

Aerotech High-Power M1350W-P 75mm

Pros (Figure 7.):

- Complies with all Tripoli standards
- Fulfills size requirements

Cons:

- Not affordable- Costs about $800
- Requires level 3 certification to purchase

Figure 7: 1350 Motor
Source: [33]

Aerotech High-Power L875DM-PS 75mm

Pros (Figure 8.):

- Requires level 2 certification to purchase
- Fulfills size requirements

Cons:

- Not affordable- Costs about $800
- Requires purchasing additional tools to adjust

Figure 8: L875 Motor
Source: [34]

Customer Requirements

- Functionality – Fulfills the major engineering requirements
- Cost – Designate allowed expenditures for each category to remain under $2000 + 10% from fundraising
- On-time – Need to be able to get the deliverables in the required amount of time
- Scalable – Design to test smaller, safer rockets first
- Compliance – Comply to Tripoli Rocketry Association Safety Standard

Figure 9: Falcon Heavy
Source: SpaceX Falcon Heavy [38]

Engineering Requirements

Rocket Propulsion:

- Reach altitude of 10-15 kilometers
- Design a solid rocket propellant formula
- Create test stand which can resist the forces of the rockets thrust
- Motor that is between 28-38mm in diameter and able to be scaled up to a full-size 75mm shell
- Within Tripoli Rocketry Association (TRA) safety standards
- Completed by February-March 2024

Test Stand:

- Able to withstand 5120 Newton-Seconds of impulse

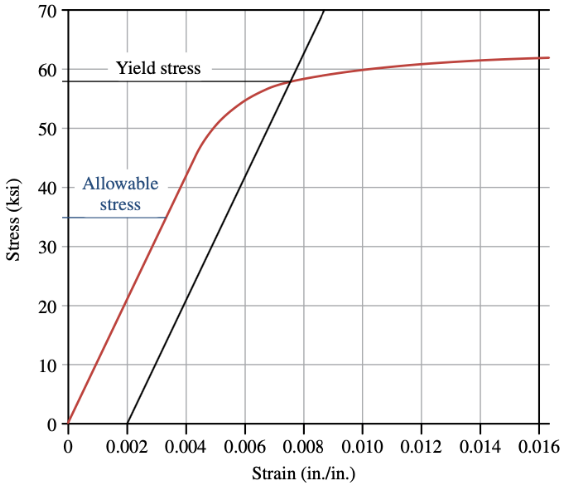


Figure 10: Allow able Stress Source:

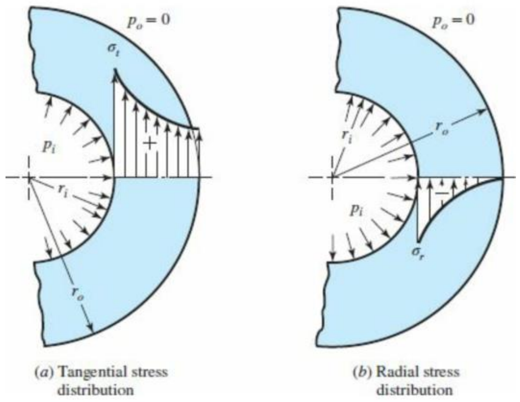


Figure 11: Pressurized Cylinder Source:

QFD

Figure 12.

System QFD

Project:	Rocket Club CAPSTONE
Date:	9/18/23

Legend	
A	Aerocon
B	FUTEK
C	Richard Nakka's
D	75/1280 Motor
E	M1350W
F	L875DM

		1	2	3	4	5
1	Reach minimum altitude					
2	Dimensions meet constraints of rocket size	6				
3	Stand withstands impulse of rocket testing	0	3			
4	Comply with Tripoli Rocketry Association Safety Standards	0	3	9		
5	Complete final launch by march 2024	3	3	0	0	

	Customer Needs	Customer Weights	Reach minimum altitude	Dimensions meet constraints of rocket size	Stand withstands impulse of rocket testing	Comply with Tripoli Rocketry Association safety standards	Complete final launch by march 2024	1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
			Technical Requirements					**Customer Opinion Survey**				
1	Functional	4	9	6	9	9	3		A B C	F	E	D
2	Scalable	3	3	9	3	9	9		C		A B	D E F
3	Sturdy	4	9	3	9	6	0	C D E F	A			B
4	Safety	5	6	3	9	9	9	C	A D	E		B F
5	Timely	3	3	0	3	0	9	B	C	A D E F		
	Technical Requirement Units		km	mm	N-s	NA	Months					
	Technical Requirement Targets		10	75	5120		3					
	Absolute Technical Importance		120	78	135	132	111					
	Relative Technical Importance		3	5	1	2	4					

A Literature Review: Nozzles

Textbooks:

- [1] Rocket Propulsion Elements, Ninth Edition
  - Performance values, correction factors, phenomena and losses, boundary layers, multiphase flow.
  - Equations that account for variable thrust

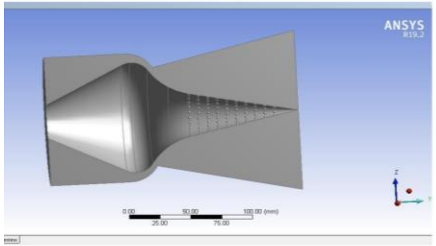
- [2] Fluid Mechanics
  - Compressible flow through converging and diverging nozzles
  - Shockwave propagation through a compressible fluid, and how they travel through nozzles

Scholarly Articles:

- [3] Short Nozzles Design for Real Gas Supersonic Flow Using the Method of Characteristics
  - Explains the process of using method of characteristics (MOC) to develop a nozzle of the shortest possible length
  - Explains the process of MOC with axisymmetric and planar nozzles, as well as ideal vs. real gasses.
- [4] Design and Optimization of Aerospike Nozzle Using CFD
  - Explains how to design an aerospike nozzle using computational fluid dynamics (CFD)
  - Provides info on how MOC and CFD can be used together for design optimization
- [5] Effects of Nozzle Throat and Combustion Chamber Design Variables on Divergent Portion of the Nozzle
  - Explains the importance of material strength of nozzles showing calculations performed using finite element analysis (FEA)
  - Explains how combustion chamber conditions/converging portion of nozzle affect the geometry of the diverging section of the nozzle

Online Sources:

- [6] https://www.grc.nasa.gov/WWW/K-12/airplane/shortp.html (Propulsion Index)
  - Information/animations explaining thrust equations, atmospheric conditions, and thermodynamics.
- [7] https://ntrs.nasa.gov/api/citations/19770009539/downloads/19770009539.pdf (NASA Standard Atmosphere)
  - Provides equations for atmospheric conditions of pressure and temperature at different altitudes
  - Will help with calculating rocket performance



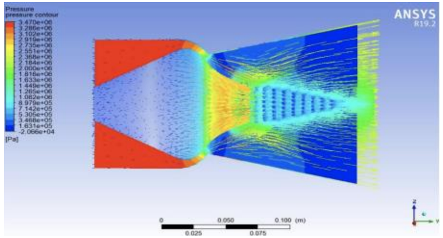


Figure 13: Pressure Plot Aerospike Nozzle Source: Aerospike Nozzles [42]

Andrew
9/18
Rocket
Propulsion
Team 3

A Literature Review: Test Stand and Motor Casing

Scholarly Articles

- [8] "Design and analysis of composite rocket motor casing"
  - Compares Carbon Fibers and Epoxy's for motor casing material
  - Provides formulas for calculations of material analysis
- [9] “Design and structural analysis of solid rocket motor casing hardware used in aerospace applications”
  - Provides equations for calculating thickness of motor casing
  - Analyzes rocket design to determine factor of safety
- [10] "Nondestructive Testing of High-Strength Steel Rocket Motor Cases"
  - Crack propagations
  - Testing of motor cases

Textbooks

- [11] Shigley's Mechanical Engineering Design
  - Describes formulas for stresses in pressurized cylinders
  - Assists with calculations for determining factor of safety
- [12] Mechanics of Materials
  - Analysis of the all materials
  - Choose materials based on the calculated forces

Online Sources

- [13] NASA's "Rocket Laboratory Safety and Design Manual"
  - Discusses procedures for safety precautions before test flights
  - Discusses health hazards for certain chemicals typically involved in rocket assemblies and propellants
- [14] "Rocket Safety Plan Template For Recreational Use or for Academic and Outreach Classes"
  - Provides a safety checklist which can be modified for our specific testing procedure
  - Discusses required roles for the team during test flight

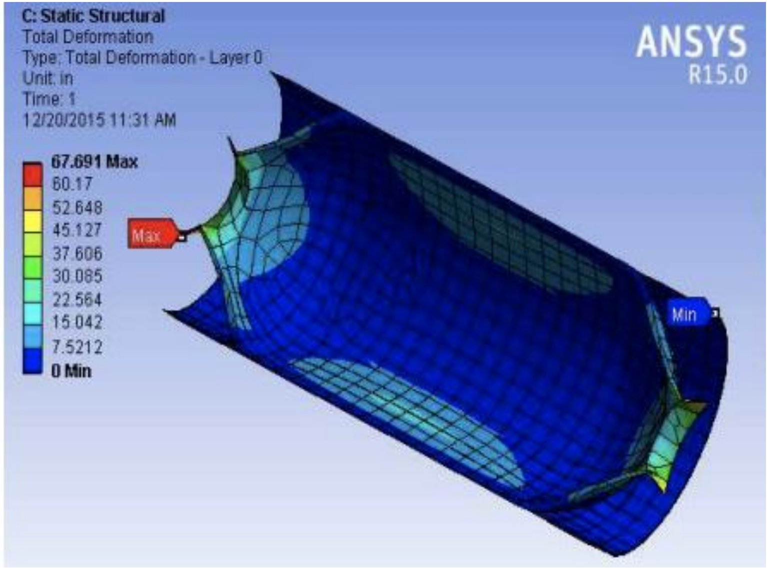


Figure 14: Casing Structural Analysis
Source: Cabon Epoxy IM10/8552 composite [8]

Shannon
9/18
Rocket Propulsion Team #3

A Literature Review: Test Stand and Propellant

Textbooks:

- [15] Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics (Volume 185)
  - Depicts the decomposition of pure Ammonium Perchlorate as well as the mixtures of the different possible mixtures
- [16] Fundamentals of Aerodynamics, Sixth Edition
  - Gives the fundamentals and important equations for flow in air as well as the compressibility effects

Scholarly Articles:

- [17] Ammonium Perchlorate Composite Basics
  - Gives fundamental equations for the combustion and measurements of the rocket
  - Grain geometries and their associated burn curves
- [18] Combustion of Solid Propellants
  - Gives various chemical properties of rocket chemicals like Ammonium Perchlorate, atomized aluminum, and resins
- [19] Ammonium Perchlorate as an Effective Additive for Enhancing the Combustion and Propulsion Performance of Al/CuO Nanothermites
  - Tests different Ammonium Perchlorate mixture compositions and graphs what the different displacements are.

Online Sources:

- [20] APCP Solid Propulsion Development
  - Insight on test stands and associated safety precautions that should be taken
- [21] Solid Rocket Boosters
  - Describes how the Solid Rocket Boosters on the Space Shuttle were chemically composed
  - "16% Atomized aluminum powder (fuel), 69.8% Ammonium perchlorate (oxidizer), 0.2% Iron oxide powder (catalyst), 12% Polybutadiene acrylic acid acrylonite (binder), 2% Epoxy curing agent" (NASA)

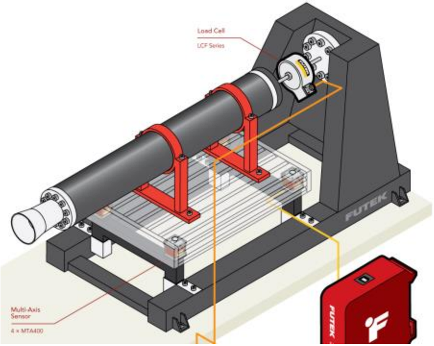
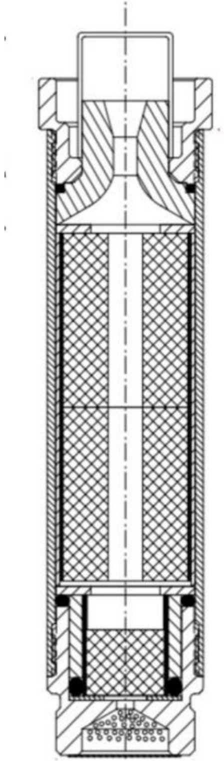


Figure 15: Test Stand
Source: [30]

A Literature Review: Propellant

Figure 16: Propulsion
Source: Solid Propulsion Development [28]



Books:

- [22] Interactive General Chemistry
  - Covers basic chemistry concepts that will be helpful when thinking about the propellant composition
- [23] Experimental Composite Propellant
  - Goes into depth about creating solid propellant
  - Contains a list of recommended minimum safety standards for propellant creation

Scholarly Papers:

- [24] Review on Typical Ingredients for Ammonium Perchlorate Based Solid Propellant
  - Discusses the different ingredient's that can be used for the components of solid rocket propellant
  - Solid propellant is made binder, metal fuel, oxidizer, and additives
- [25] Additive manufacturing of ammonium perchlorate composite propellant with high solids loadings
  - Goes over a procedure for additive manufacturing of rocket propellent
  - Also covers the effects of voids in propellent on the burn rate
- [26] Size and Shape of Ammonium Perchlorate and their Influence on Properties of Composite Propellant
  - Goes over their experimental set up and procedure for creating different composite propellants

Online Sources:

- [27] Tripoli Rocketry Association Safety Code
  - Section 7- General Range Operation Rules
  - Contains info on rocket construction, stability, and more
  - Section 10- Motor Limitations
- [28] APCP Solid Propulsion Development
  - Details how students at Penn State built their rocket test stand and rocket propulsion system

Engineering Tools: Burnsim

- Simulated thrust curve data
- May alter the fuel grain geometry to produce burns that are progressive, regressive

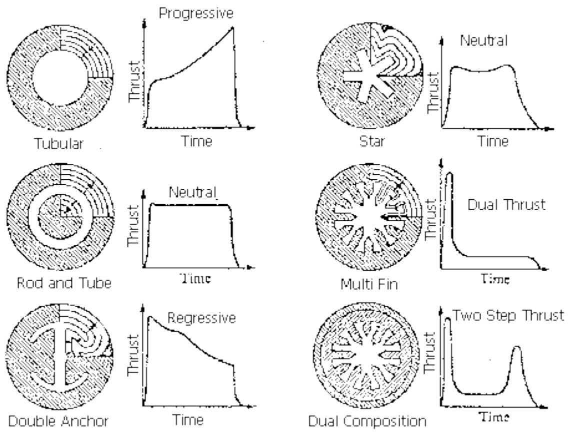


Figure 17: Grain Geometry
Source: Nakka Rocketry [31]

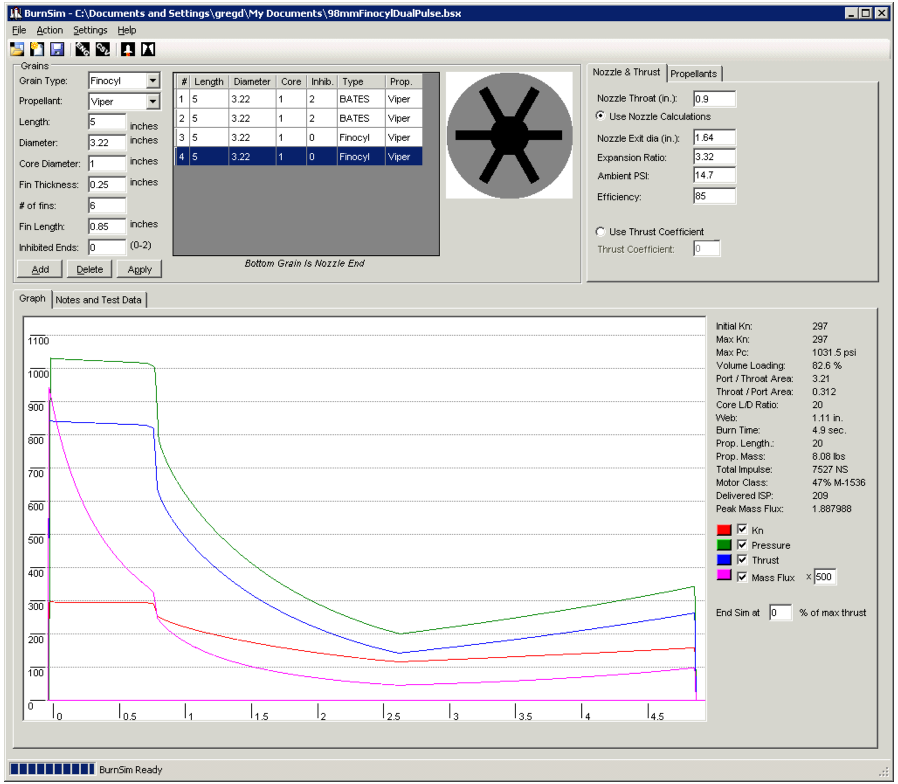


Figure 18: Burnsim Test
Source: Burnsim.com [43]

Engineering Tools: Rocksim

- Simulates aspects of rocket performance such as maximum altitude, velocity, acceleration, flight time, stability margin, etc.
- May use this program to identify how much total impulse and average thrust our motor must have

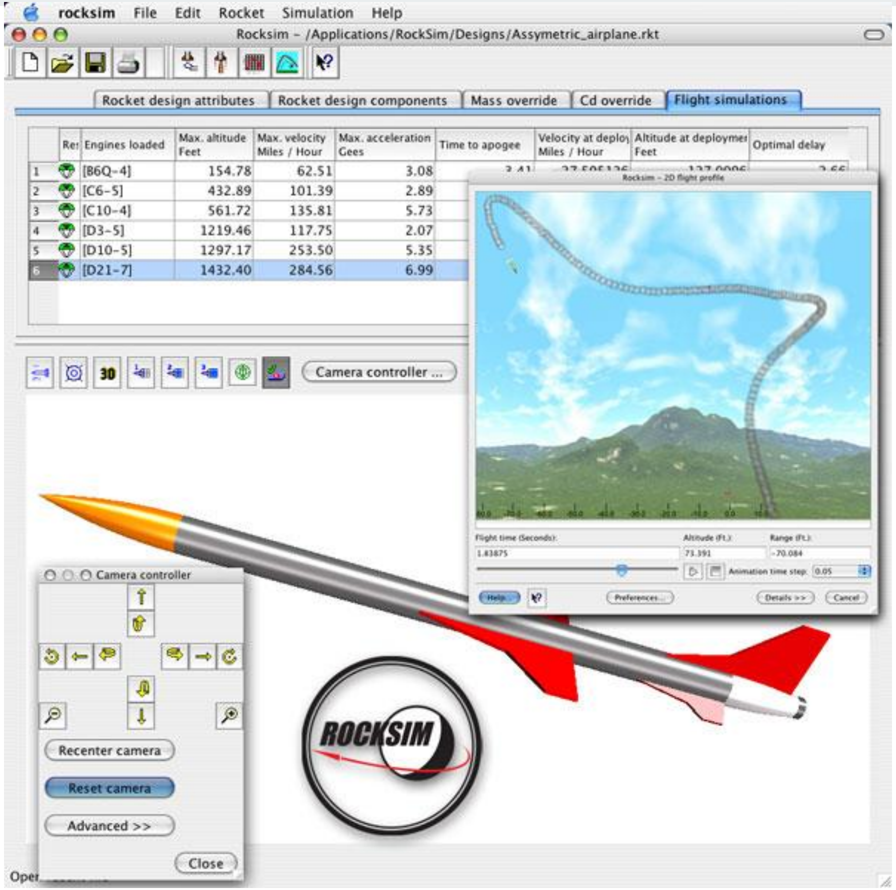


Figure 19: Rocksim Test
Source: Apogee Rockets [44]

Mathematical Modeling: Rocksim

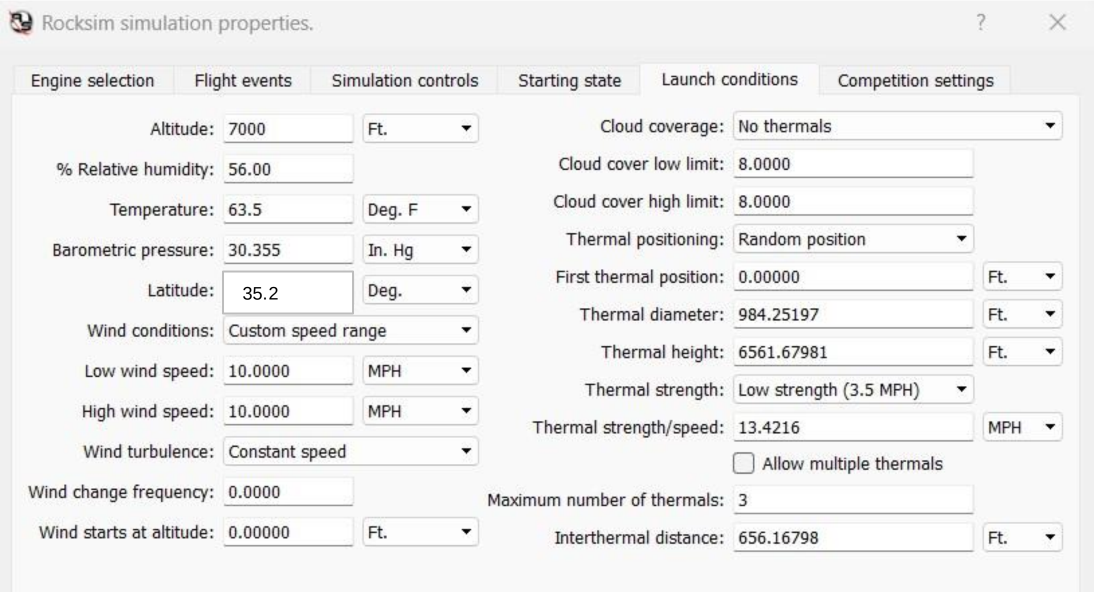
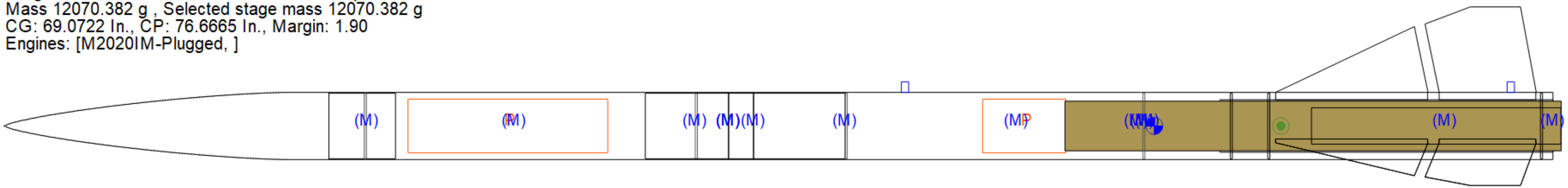


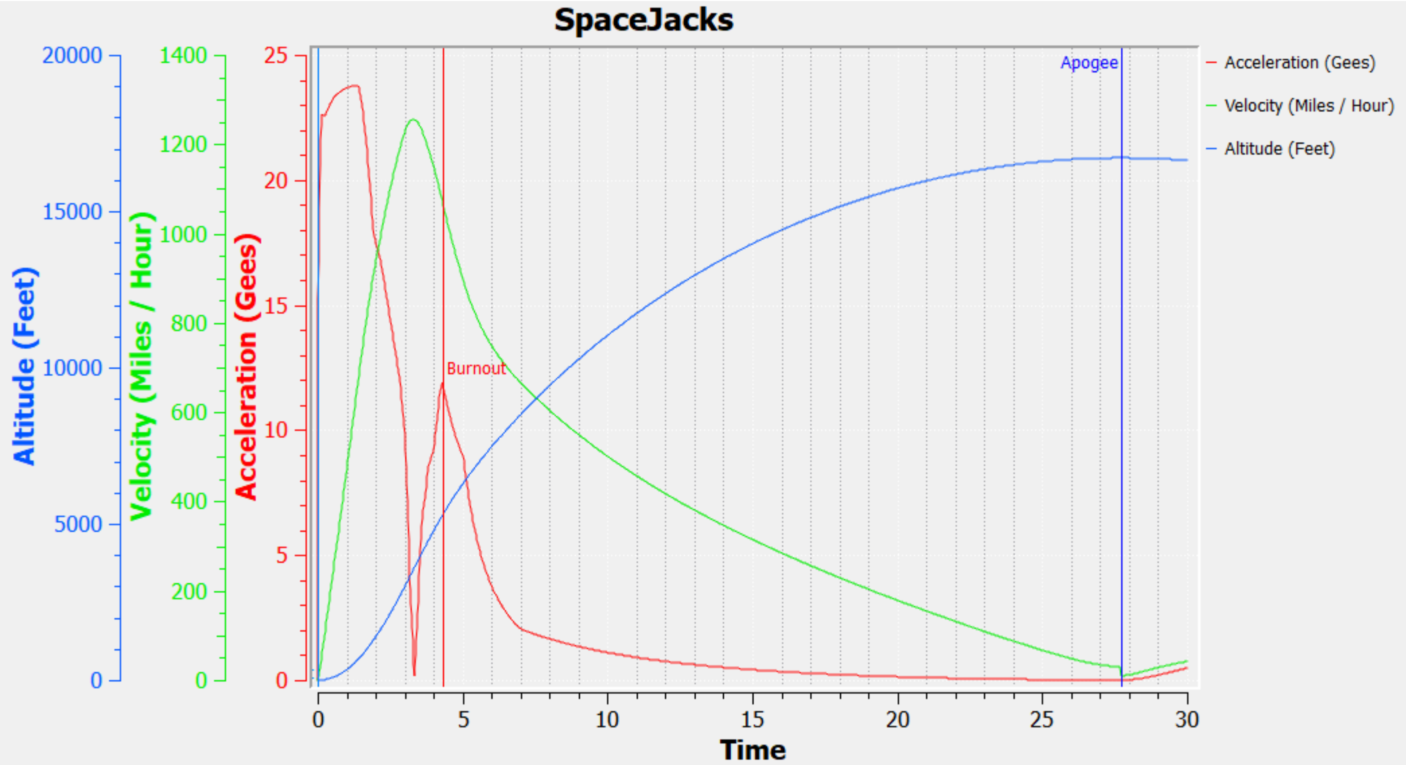
Figure 20: Rocksim Input Parameters
Source: Apogee Rockets [44]

SpaceJacks
Length: 93.4800 In. , Diameter: 4.0000 In. , Span diameter: 14.1790 In.
Mass 12070.382 g , Selected stage mass 12070.382 g
CG: 69.0722 In., CP: 76.6665 In., Margin: 1.90
Engines: [M2020IM-Plugged,]

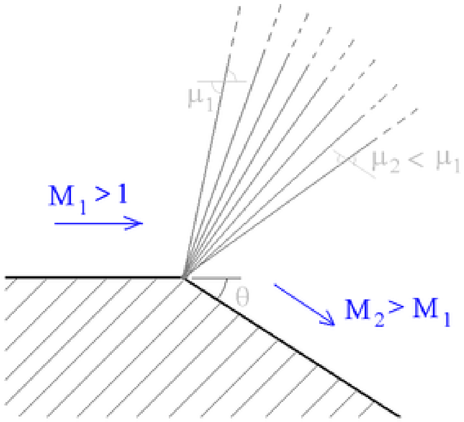


Mathematical Modeling: Rocksim

Figure 21: Rocksim Output
Source: Apogee Rockets [44]

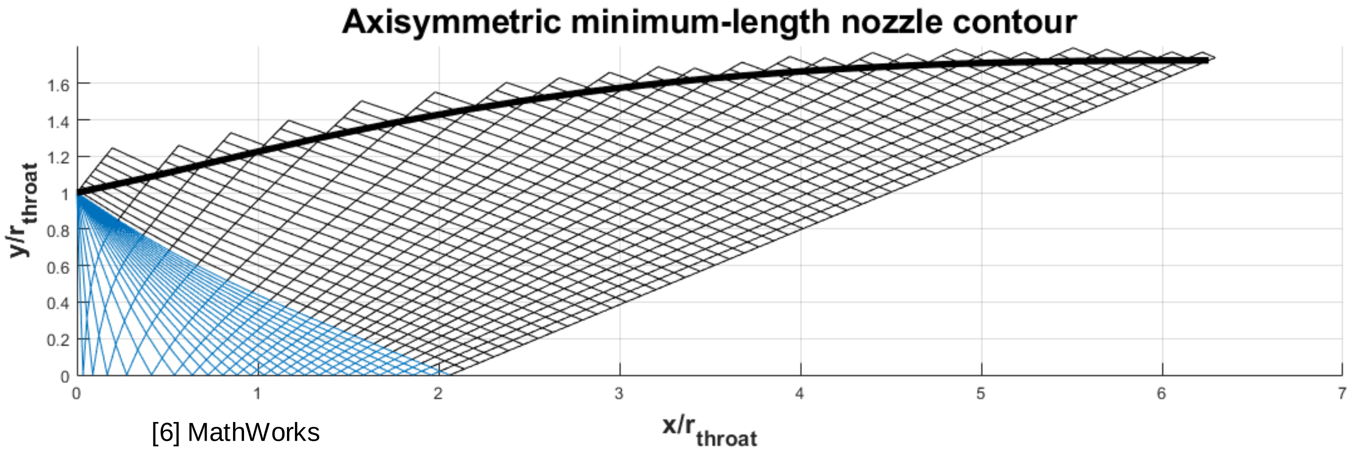


Mathematical Modeling: Compressible Flow



Method of Characteristics

- Utilizes Prandtl-Meyer expansion (figure to the right) to generate nozzle geometry
- Allows for a visualization of compressible flow within the nozzle (shock/expansion waves)
- Optimize nozzle geometry for maximum thrust or specific impulse
- Will help with avoiding unwanted shock wave interactions
- Helps to validate and refine CFD analysis (performed in open FOAM or Ansys)



[6] MathWorks

Figure 22: Nozzle Design Source:

Mathematical Modeling: Burn Rate

The burning rate, r, of a solid propellant is the linear rate of propellant consumption in a direction normal to the burning surface. It typically ranges from 0.1 to 2.0 inches per second and is primarily influenced by the combustion pressure, P_c; propellant composition; and to a lesser degree by the ambient grain temperature and the velocity of gas flow past the burning surface. Burning rate may be expressed by the following equation:

$$r = aP_c^n \quad \text{Equation 1}$$

Burn rate is pivotal in the requirement of altitude. A slow burn rate may only get the projectile to a few thousand feet, but a longer burn rate can allow for a much higher altitude. A slower burn rate may not offer enough force to overcome the local gravity, so we need to make sure that the burn rate is fast enough to keep the rocket straight and on course, but slow enough to maintain this thrust to get to the required altitude.

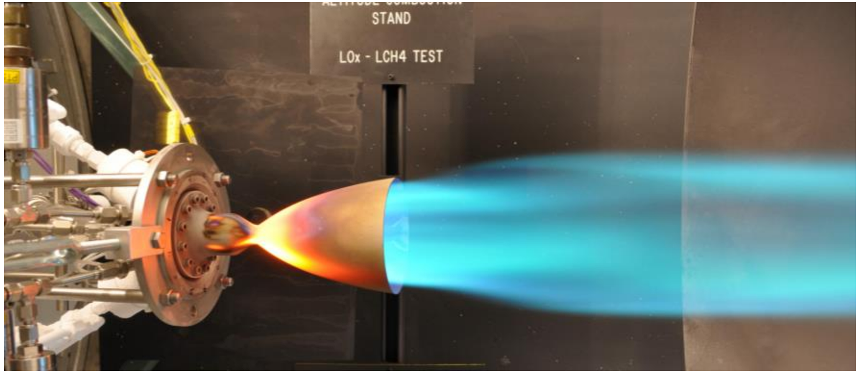


Figure 23: Burn Rate Simulation
Source: Chemical Propulsion Systems [41]

Mathematical Modeling: Motor Casing Thickness

The cylindrical shell thickness is calculated by using conventional formula from ASME Pressure vessel code. It is given by the equation:

Equation 2.

$$t = \frac{P * D * Mismatch\ Factor}{biaxial\ gain * 2 * (SE - 0.6P)}$$

Where from ASME standards:

- Biaxial gain = 1.1(10%)
- Mismatch factor = 1.15 (5%)
- D = Inner Diameter of Casing
- S = Allowable Strength = U.T.S/F.S
- E = Weld Efficiency (desired is 90%)

$$P = B\left(K_n\right)^{\frac{1}{1-n}}$$

Equation 3.

where ***P*** is the pressure in pounds per square inch, ***B*** is a constant for a specific propellant, and ***n*** is the same pressure or burning rate exponent as appears in the burn rate equation

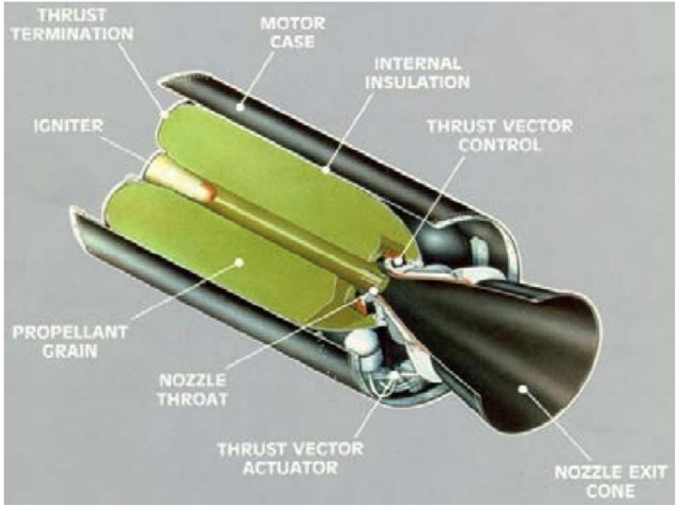


Figure 24: Motor Casing Source: Solid Rocket Motor Casing [9]

Schedule Report 1 Oct 27 Report 2 Nov 24

Task	Timeline
Research	9/5/23 - 10/2/23
Design	9/18/23 - 10/12/23
Design Review	10/12/23
Re-Design	10/12/23 - 10/19/23
Design Approval	10/19/23
Finalize BOM	10/19/23
Build	10/19/23 - 11/4/23
Safety Checklist	11/4/23
Test 1	11/4/23
Test Report 1	10/30/23 - 11/24/23

Task	Timeline
Redesign/Modify	11/9/23 - 11/16/23
Redesign Approval	11/16/23
Build	11/16/23 - 11/24/23
Test 2	11/25/23
Test Report 2	11/25/23 - 12/8/23
Scale Up & Build	01/15/23 - 02/19/24
Obtain Launch Approval	02/19/24
Flight Readiness Review	02/19/24 - 03/01/24
Final Flight	03/02/24
Post-Flight Review	03/04/24 - 03/15/24

Budget

Budget Items	Percent of Budget	Dollar Amount	Notes	Funding total	2300
75mm Final Rocket Motor	30.00%	690		Gore Fund	2000
38mm Test Rocket Motor	15.00%	345		GoFundMe	300
Test Rocket Motors	10.00%	230			
Nozzle	10.00%	230	Primarily funded through undergraduate research		
Casing	5.00%	115			
Test Stand	7.00%	161			
Test Stand Electronics	18.00%	414			
Miscellaneous	5.00%	115			
Total	100.00%	2300			

Figure 29.

- Existing Funds
  - $2,000 have been procured by the client
  - $300 total have been fundraised by the team
- Continued Funding Plan
  - Fundraising through GoFundMe
  - Fundraising through the Rocket Club

Literature Citations: Andrew

Textbooks:

- [1] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*. Hoboken, NJ: Wiley, 2017.
- [2] R. C. Hibbeler, *Fluid Mechanics*. Hoboken, NJ: Pearson, 2015.

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- [3] J. C. Restrepo, A. F. Bolaños-Acosta, and J. R. Simões-Moreira, “Short nozzles design for real gas supersonic flow using the method of characteristics,” *Applied Thermal Engineering*, vol. 207, pp. 1–14, May 2022. doi:10.1016/j.applthermaleng.2022.118063
- [4] K. N. Kumar, M. Gopalsamy, D. Antony, R. Krishnaraj, and C. B. Viswanadh, “Design and optimization of aerospike nozzle using CFD,” *IOP Conf. Series: Materials Science and Engineering*, vol. 247, 2017. doi:10.1109/icraae.2017.8297246
- [5] N. Önder and C. Tola, “Effects of Nozzle Throat and Combustion Chamber Design Variables on Divergent Portion of the Nozzle,” *2019 9th International Conference on Recent Advances in Space Technologies (RAST)*, pp. 223–230, Jun. 2019. doi:10.1109/rast.2019.8767796

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- [6] N. Hall, Ed., “Short index of propulsion slides,” NASA, https://www.grc.nasa.gov/WWW/K-12/airplane/shortp.html (accessed Sep. 18, 2023).
- [7] “NASA Technical Reports Server (NTRS),” NASA, https://ntrs.nasa.gov/api/citations/19770009539/downloads/19770009539.pdf (accessed Sep. 18, 2023).

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- [9] D. Kumar B and S. Nayana B, “Design and structural analysis of solid rocket motor casing hardware used in aerospace applications,” *Journal of Aeronautics & Aerospace Engineering*, vol. 5, no. 2, 2016. doi:10.4172/2168-9792.1000166
- [10] J. A. Hendron, “Nondestructive testing of high-strength steel rocket motor cases,” *Symposium on Recent Developments in Nondestructive Testing of Missiles and Rockets*. doi:10.1520/stp44520s

Textbooks:

- [11] R. G. Budynas and J. K. Nisbett, *Shigley’s Mechanical Engineering Design*. New York, NY: McGraw Hill LLC, 2024.
- [12] F. P. Beer, E. R. Johnston, J. T. DeWolf, and D. F. Mazurek, “Chapter 4 Design Concepts,” in *Mechanics of Materials*, New York: McGraw-Hill Education, 2020

Online Resources:

- [13] Glenn research center | NASA, https://www1.grc.nasa.gov/wp-content/uploads/Rocket-Lab-Safety-Manual-1959.pdf (accessed Sep. 17, 2023).
- [14] EHS – EHS, https://ehs.mit.edu/wp-content/uploads/2020/01/Rocket_Safety_Plan_Template.docx (accessed Sep. 17, 2023).

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- [15] W. Anderson, M. Beckstead, and R. Behrens, *Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics*, vol. 185. Reston, VA: American Institute of Aeronautics and Astronautics, Inc, 2000.
- [16] J. D. Anderson, *Fundamentals of Aerodynamics*, 6th ed. New York, NY: McGraw-Hill Education, 2017.

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- [17] R. R. Sobczak, “Ammonium Perchlorate Composite Basics ,” *Journal of Pyrotechnics*, no. 3, pp. 1–12, 1993.
- [18] G. Lengelle, J. Duterque, and J. F. Trubert, “Combustion of Solid Propellants,” *Internal Aerodynamics in Solid Rocket Propulsion/STO Educational Notes*, pp. 27–31, May 2002.
- [19] Ji Dai, Fei Wang, Chengbo Ru, Jianbing Xu, Chengai Wang, Wei Zhang, Yinghua Ye, and Ruiqi Shen, *The Journal of Physical Chemistry C* **2018** *122* (18), 10240-10247, DOI: 10.1021/acs.jpcc.8b01514

Online Resources:

- [20] “APCP solid propulsion development,” Brandon Fallon, https://brandonfallon.com/apcp-solid-propulsion-development/ (accessed Sep. 17, 2023).
- [21] B. Dunbar, “Solid rocket boosters,” NASA, https://www.nasa.gov/returntoflight/system/system_SRB.html (accessed Sep. 17, 2023).

Literature Citations: Grace

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Thank you

Source: High Power Rocketry [39]