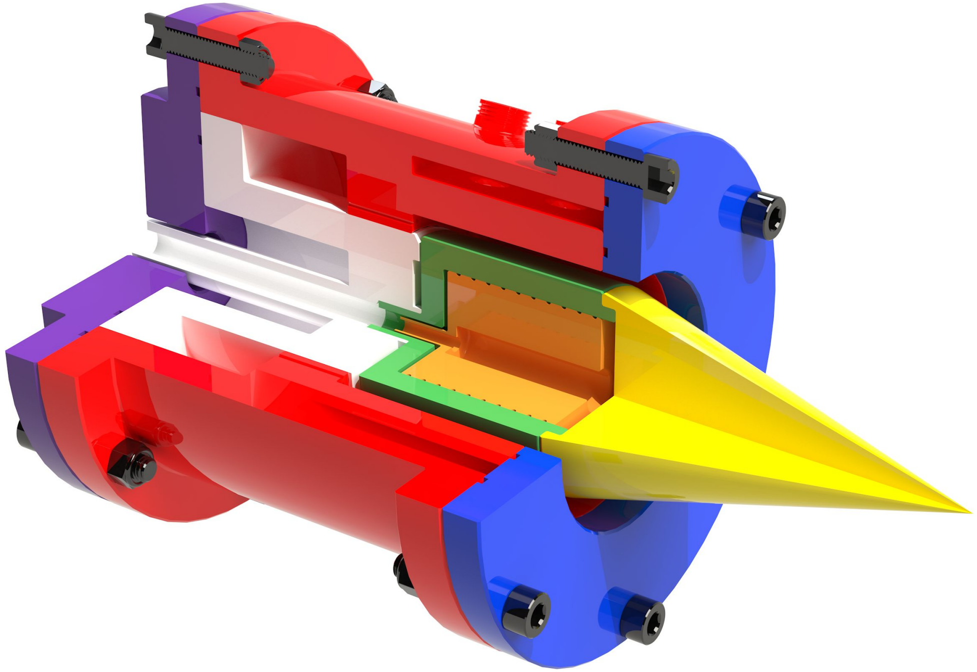
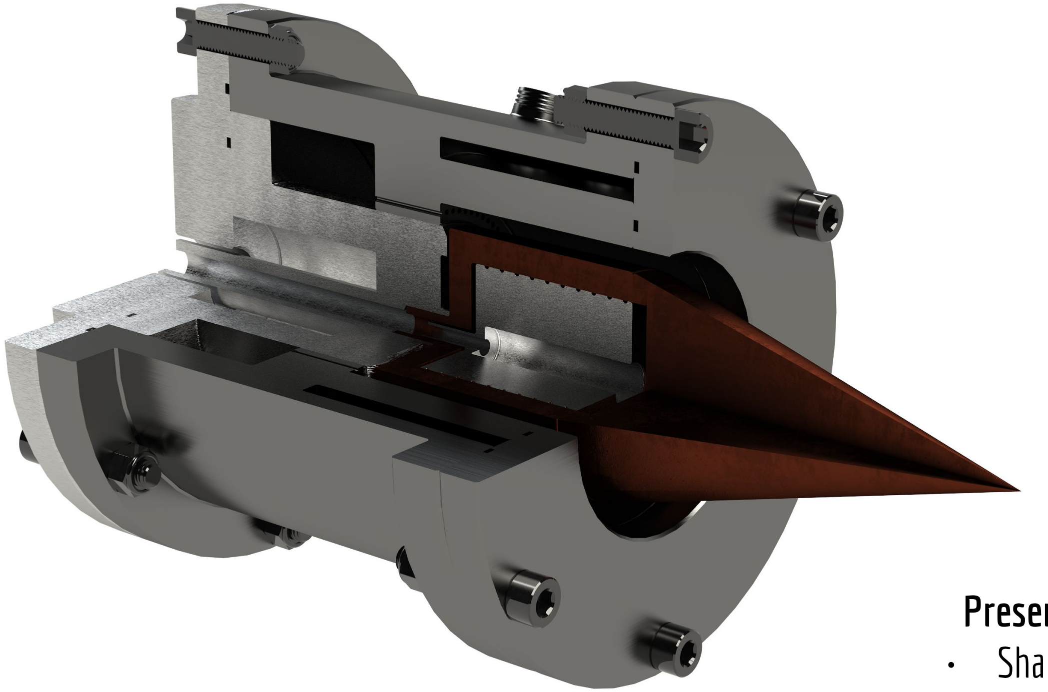
DETechnologies

Initial Presentation





The Launch Canada
November 2023

Presentation Team

- Shakib Miri
- Logan Palmer
- Patrick Cleary
- Aidan Clark

Agenda

- The Team
- Introduction
- Project Timeline
- Summary of Costs
- Technical Overview
- Numerical Analysis - Results and Next steps
- Testing Plan
- Safety Measures

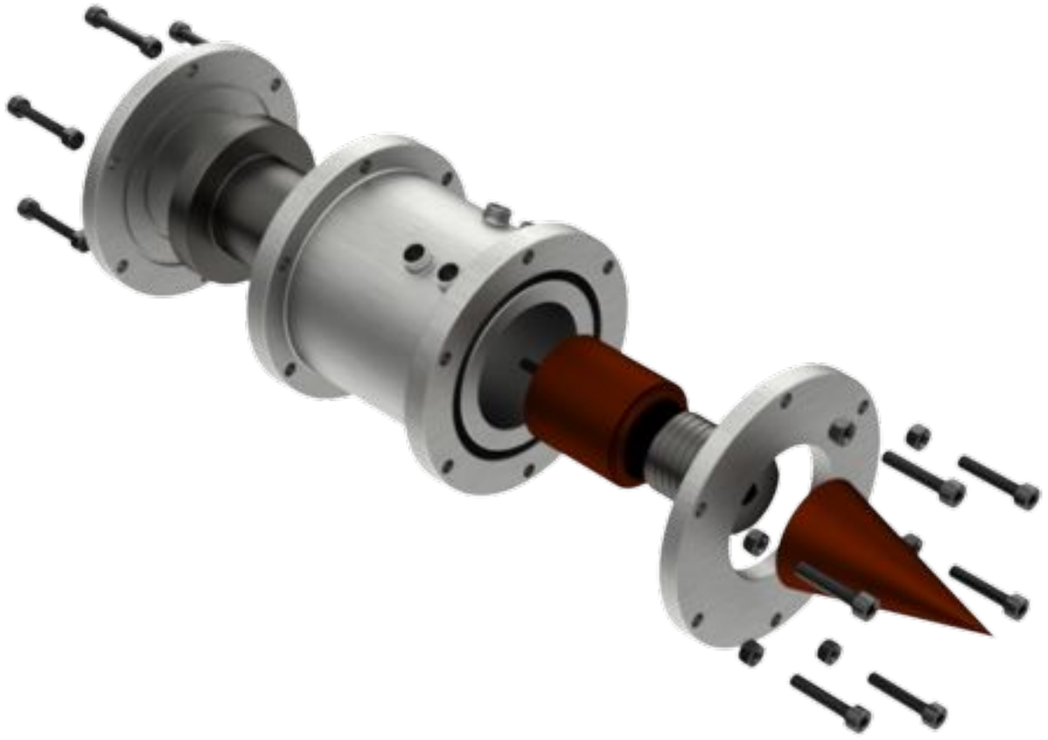


Figure: Exploded view of early preliminary design.

The Team - Leadership

Shakib Miri

- Team Lead
- Former Memorial Baja Project and Team Co-Lead
- *Work experience:* Electronics packaging, Marine Propulsion, Aerospace Propulsion

Logan Palmer

- Chief Engineer
- Former Memorial Baja Project Lead and Team Co-Lead
- *Work Experience:* Digital twinning, industrial processing equipment design.

Patrick Cleary

- Mechanical Design Engineer
- Former Paradigm Engineering Team Co-Lead
- *Work Experience:* Subsea, Automotive Body Structures, Automotive Drive-Train Structures

Aidan Clark

- Simulation Engineer
- Former Paradigm Engineering Team Co-Lead
- *Work Experience:* Offshore oil reservoir simulation, Recreational Vehicle Body Structures Simulation

The Team - DETechnologies

- Senior mechanical engineering capstone project; team interested in rocket propulsion. Considered various advanced propulsion technologies; PDE, Scramjet, Electric.
- A Rotating Detonation Engine became the project focus due to its promising efficiency benefits for the rocket industry, and the ability to contribute some amount of research findings to the research space with the design of a prototype.
- Seeing opportunities to inspire the future generation of engineers, and show-off the work possible at MUN, we decided to expand our to work incorporate activities like Launch Canada.

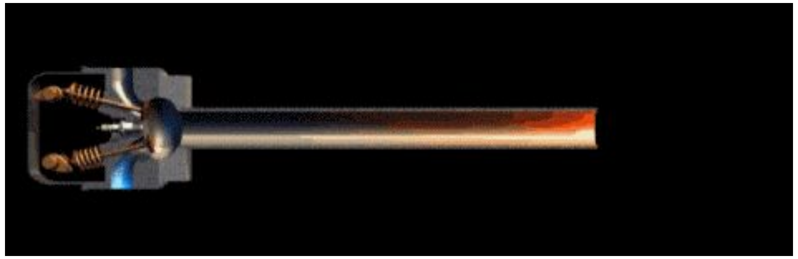


Figure: PDE GIF (AFRL animation) [1]

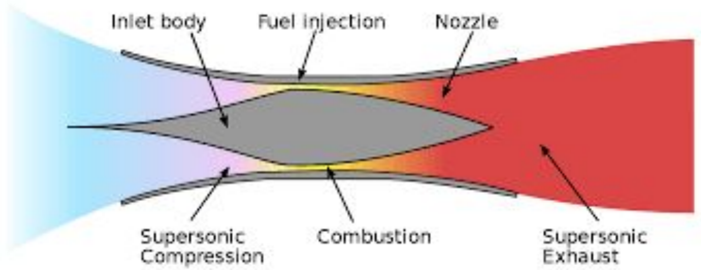


Figure: Scramjet [2]

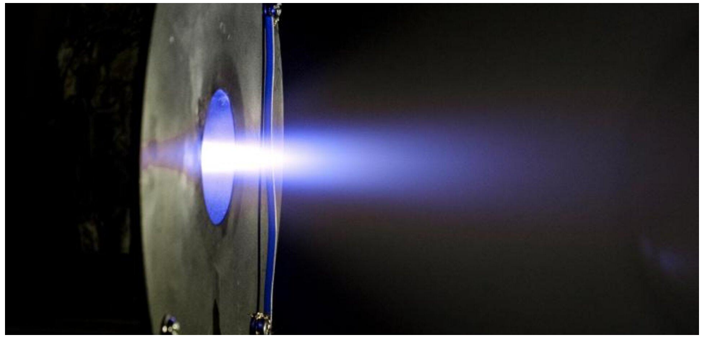


Figure: Pulsed plasma thruster (ESA) [3]

[1] "Pulsed detonation engine," ISSI, https://innssi.com/pulsed-detonation-engine/ (accessed Dec. 5, 2023).
[2] "Scramjet," Wikipedia, https://en.wikipedia.org/wiki/Scramjet (accessed Dec. 5, 2023).
[3] "Plasma propulsion for small satellites," ESA, https://www.esa.int/ESA_Multimedia/Images/2020/09/Plasma_propulsion_for_small_satellites (accessed Dec. 5, 2023).

Introduction - Project Objectives

- Address the limitations of traditional rocket engines used in space exploration (efficiency/specific impulse)
- Develop an RDE prototype
  - Fits in the "Orbital Thruster" engine classification
  - Can be a research bed for further development of RDE technology at MUN
    - Could result in a launchable thruster.
  - Can conduct hot-fire tests
- Contribute development learnings to the international knowledge base through some form of publishing of results and methods.

Figure: Orbital Propulsion Center 200N thruster [2]

Figure: Mid-launch image of the Łukasiewicz – Institute of Aviation RDRE powered Rocket [1]

[1] J. Pieniążek, "The world's first launch of a rocket powered by a detonation engine," Łukasiewicz Research Network – Institute of Aviation, https://ilot.lukasiewicz.gov.pl/en/the-worlds-first-launch-of-a-rocket-powered-by-a-detonation-engine/ (accessed Dec. 6, 2023).
[2] [1] "200n bipropellant thruster," 200 N Bipropellant Thruster, https://www.space-propulsion.com/spacecraft-propulsion/bipropellant-thrusters/200n-bipropellant-thrusters.html (accessed Dec. 6, 2023).

Introduction - What is a RDRE?

Rotating Detonation Rocket Engines (RDREs) are a thruster engine that operates on the principle of Detonation, or supersonic combustion, rather than Deflagration; the typical combustion process, being subsonic combustion [6].

RDREs have theoretical applications as [4].

- Satellite Thrusters
- Launch Vehicle Propulsion
- Defense System Propulsion
- Gas turbines

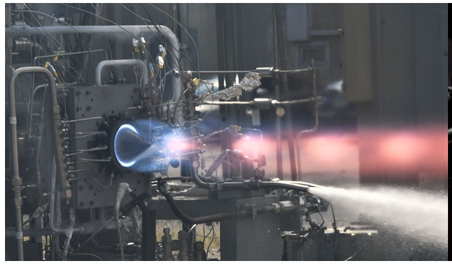


Figure: NASA Marshall RDE [1]

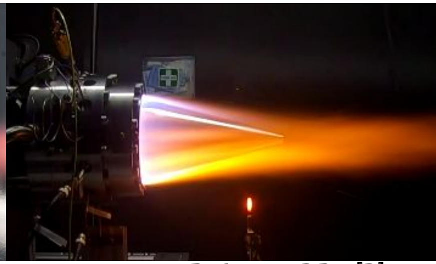


Figure: DefenTex RDE [2]

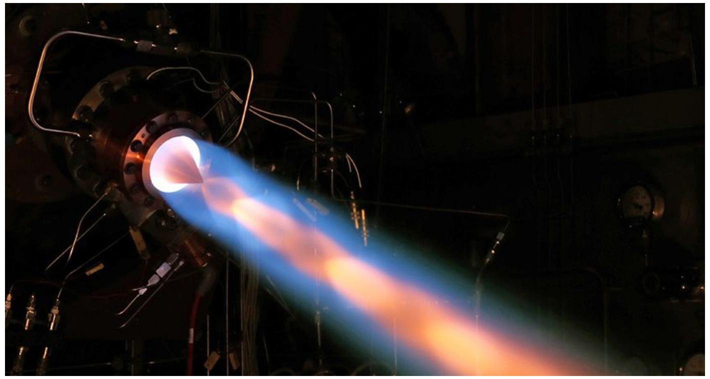


Figure: Zucrow Laboratories (Purdue University) RDE [3]

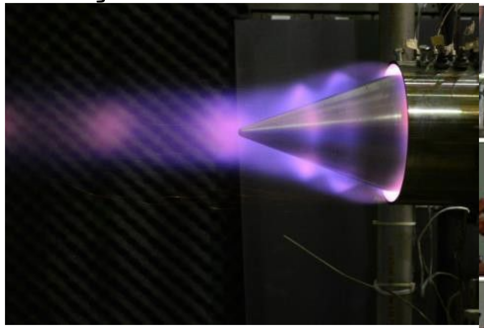


Figure: AFRL RDE [4]

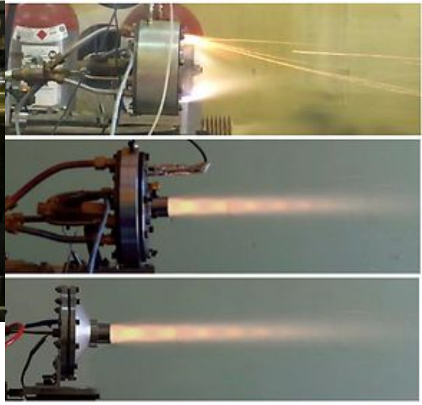


Figure: Warsaw University RDE [5]

[1] "NASA validates revolutionary propulsion design for Deep Space Missions," NASA, https://www.nasa.gov/centers-and-facilities/marshall/nasa-validates-revolutionary-propulsion-design-for-deep-space-missions/ (accessed Dec. 5, 2023).
[2] "Media release," DEFENDTEX, https://www.defendtex.com/media-release/ (accessed Dec. 5, 2023).
[3] "Purdue projects included in AIAA Year in Review," School of Aeronautics and Astronautics - Purdue University, https://engineering.purdue.edu/AAE/spotlights/2023/2023-0104-aerospace-america-2022-recap (accessed Dec. 5, 2023).
[4] P. Londergan, "ROTATING DETONATION ENGINES (RDE)," Air Force Research Laboratory, https://afresearchlab.com/technology/rotating-detonation-engines-rde/ (accessed Dec. 5, 2023).
[5] M. C. Kawalec, W. Perkowski, B. Łukasik, A. Bilar, and P. Wolański, "Applications of the continuously rotating detonation to combustion engines at the łukasiewicz - institute of aviation," Combustion Engines, http://www.combustion-engines.eu/Applications-of-the-continuously-rotating-detonation-to-combustion-engines-at-the,145409,0,2.html (accessed Dec. 5, 2023).
[6] What's the difference between an explosion and a detonation? (2018, August 01). Bradbury Science Museum, Los Alamos National Laboratory. https://www.lanl.gov/museum/news/newsletter/2018/08/detonation.php#:~:text=Discovered%20in%201881%20by%20French,wave%20initiating%20a%20secondary%20explosion

Introduction - How do they work?

RDREs have an annular combustion chamber allowing for the detonation wave to continue around the chamber indefinitely. Propellant is continually fed axially into the combustion chamber to feed the continually rotating combustion wave (s).

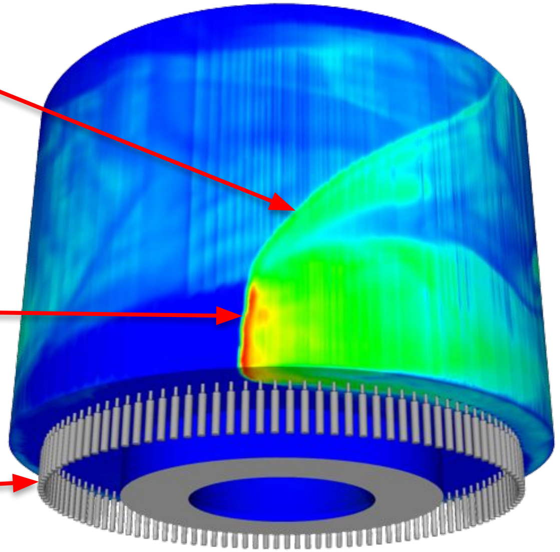
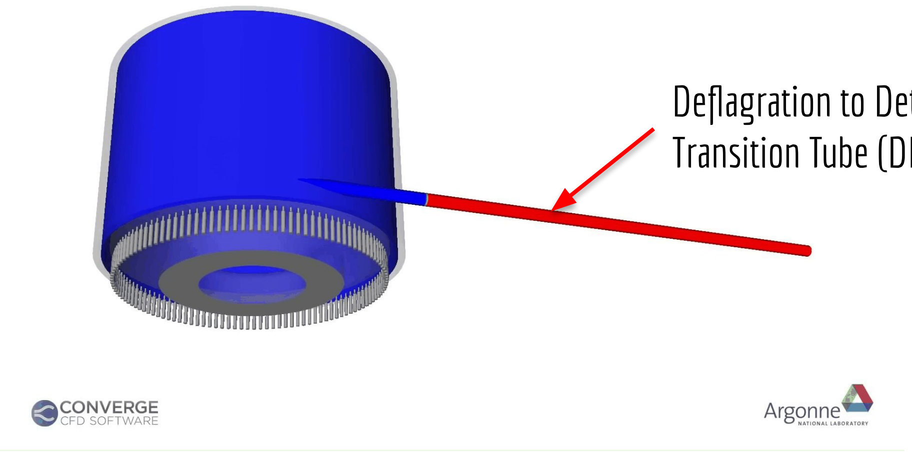


Figure: 3D RDRE CFD Model. Source: ConvergeCFD & Argonne National Laboratory [1][2]



Video: 3D RDRE CFD Model. Source: ConvergeCFD & Argonne National Laboratory [1][2]

[1] P. Pal, G. Kumar, S. A. Drennan, B. A. Rankin, and S. Som, "Multidimensional numerical simulations of reacting flow in a non-premixed rotating detonation engine," in Turbo Expo: Power for Land, Sea, and Air, 58622, V04BT04A050. American Society of Mechanical Engineers, 2019.
[2] E. Favreau, "The collaboration effect: Developing a new generation of gas turbine & rotating detonation engines - converge CFD Software," Convergent Science Press, 2023. Available: https://convergecfd.com/blog/collaboration-effect-developing-gas-turbine-rotating-detonation-engines

Introduction - Why an RDRE?

Supersonic combustion, or Detonation is an incredibly efficient way to extract energy from a fuel source. Harnessing Detonation, RDREs are a staggering 10-25% more fuel efficient than deflagration rocket engines [4].

Our proof of concept, research engine will operate on gaseous Hydrogen and Oxygen propellant, avoiding harmful *carbon* bi-products.

Figure: Aerojet Rocketdyne RL10 [5]

Table: Highlight Performance Parameters Kato RDE vs RL10C-1 [1][2][3][4]

	RDRE	Aerojet Rocketdyne RL10C-1
I_{sp}	3000-5500s	373s-499.7s
Thrust:weight	3.47:1 [3]	57:1 (~110kN)

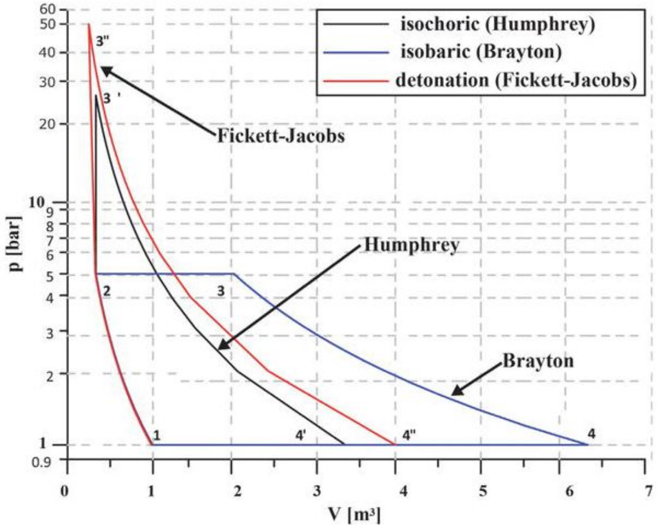


Figure: PV Diagram Comparing Brayton, Humphrey and Fickett-Jacobs Cycles [1].

[1] I. J. Shaw et al., "A Theoretical Review of Rotating Detonation Engines," doi: 10.5772. (n.d.).
[2] E. Favreau, "The collaboration effect: Developing a new generation of gas turbine & rotating detonation engines - converge CFD Software," Convergent Science Press, 2023. Available: https://convergecfd.com/blog/collaboration-effect-developing-gas-turbine-rotating-detonation-engines
[3] Y. Kato, K. Gawahara, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, et al., "Thrust measurement of rotating detonation engine by sled test," in: 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 4034, 2014.
[4] D. Ha, T. Roh, H. Huh, and H. J. Lee, "Development Trend of Liquid Hydrogen-Fueled Rocket Engines (Part 1: Performance and Operation)," International Journal of Aeronautical and Space Sciences, vol. 24, no. 1, pp. 131-145, 2023. DOI: 10.1007/s42405-022-00519-7.
[5] "RL10," Wikipedia. https://en.wikipedia.org/wiki/RL10 (accessed Nov. 19, 2023).

Project Timeline

Month	January 2023	February 2023	March 2023	April 2023	May 2023	June 2023	July 2023	August 2023	September 2023	October 2023	November 2023	December 2023
Phases	Project Definition				Literature Review and Design				Fabrication Preparation & Execution			
Objectives					Develop theoretical understanding of the engine topology		Iteration of engine parameters through simulation					Manufacturing drawings
												Material Aquisition
					Outreach to possible sponsors based on upcoming project requirements							

January 2024	February 2024	March 2024	April 2024	May 2023	June 2023	July 2023	August 2023
Fabrication Preparation & Execution				Engine Assembly and Testing			
Component manufacturing		Component validation		Engine testing		Results analysis	Preparations for Launch Canada
Test cell design		Test Cell and Engine Test plan development					
Model control system in MatLab	Component validation Test plan(s) development						

Project Cost & Funding Summary

- Budget for the manufacturing and setup for testing of this engine is about $60k.
- Budget ignores the cost of in-kind donations already committed to the team for this academic year.
- Actively seeking financial, in-kind and technical support from private corporations to help make ends meet with our work this year.

Table: Summary of Projected Costs

*Cloud Computing**	$270.00
Raw Materials	$3,000.00
Fabrication	$4,000.00
Raw Propellant	$3,000.00
Piping, flowmeters, valves	$8,000.00
Sensors	$30,000.00
Safety Equipment	$5,000.00
Thrust Frame (upgrades)	$2,000.00
Team Promotional Gear	$600.00
Investor Relations & Administrative	$500.00
Competition	$7,500.00
Grand Total	**$63,870.00**

*Remainder provided as part of a research grant.

Technical Overview - Theory

- Detonation process 1D approximation based on Chapman-Jouguet (CJ) & Zel'dovich-von Neumann-Doring (ZND) theories.
  - Utilizes Rankine-Hugoniot Relations.
  - CJ theories describe detonation changes across detonation wave front.
  - ZND theories describe the detonation wave structure.

Equations: (i) General form of the Rankine-Hugoniot equation. (ii) Rayleigh line equation [2]

(i) $$\frac{\gamma}{\gamma-1}\left(\frac{p_2}{\rho_2}-\frac{p_1}{\rho_1}\right)-\frac{1}{2}(p_2-p_1)\left(\frac{1}{\rho_1}+\frac{1}{\rho_2}\right)=q$$

(ii) $$\rho_1^2 u_1^2 = \frac{p_2-p_1}{\frac{1}{\rho_1}-\frac{1}{\rho_2}} = \dot{m}^2$$

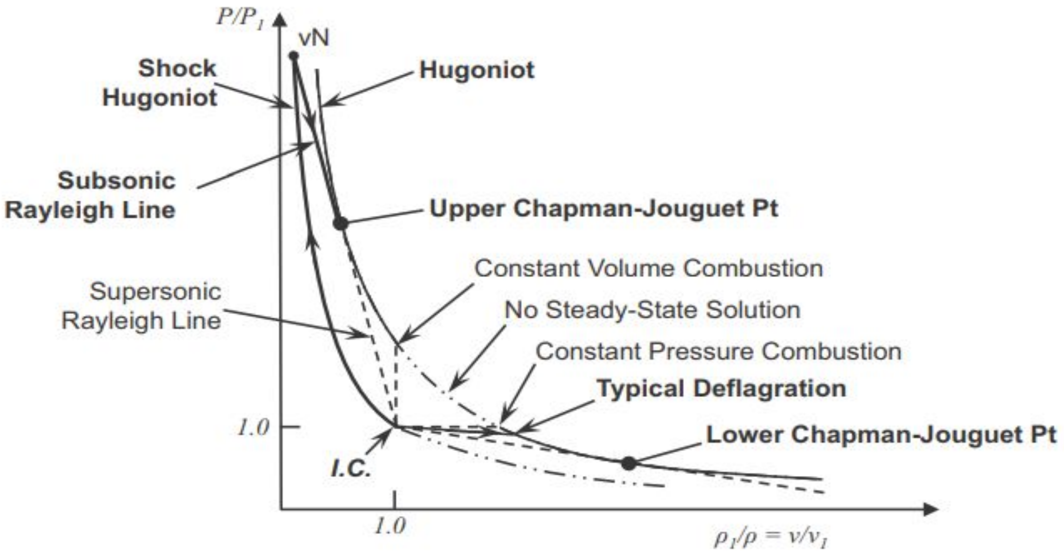


Figure: Rankine-Hugoniot Plot [1][2]

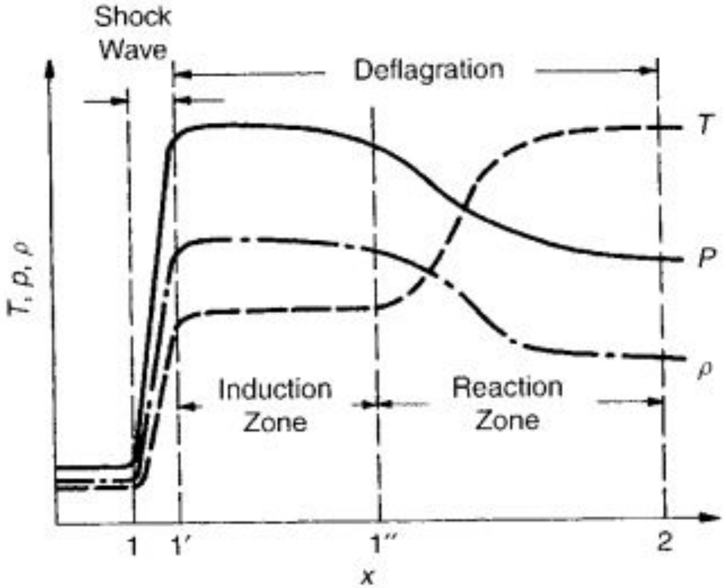


Figure: Temperature, Pressure & Density Across Detonation Wave [2]

[1] Nordeen, C. A. (2013). Thermodynamics of a Rotating Detonation Engine (Doctoral Dissertation). University of Connecticut. Accessed: Apr. 11, 2023. [Online

[2] K. Kuo, "Principles of Combustion" (2nd ed.), John Wiley & Sons. (n.d.).

Technical Overview - Theory

- Detonation Cell Size very important parameter for achieving detonation.
  - Too small, no self sustaining detonation
  - Geometry too small, detonation structure cannot form

  i- **λ_critical (H/O)**= 1.6mm [3]

  ii- **D_critical =** λ/π [6]

- Initiation Energy strongly influences the resulting detonation cell size.
  - The minimum amount of energy required to instigate combustion
  - Directly correlated to cell size [1]
  - Impacted by molecular structure, evaporation energy, and heat capacity [4]

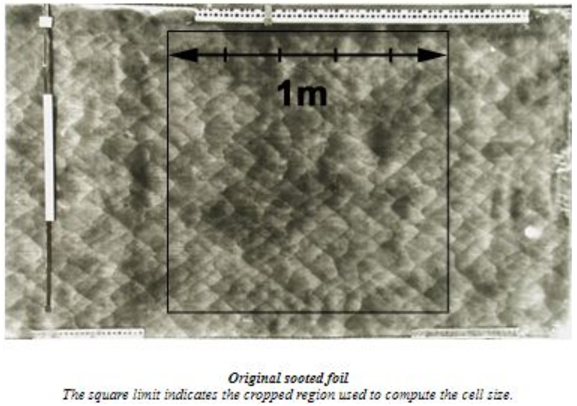


Figure: Soot foil images from detonation tube shots [2]

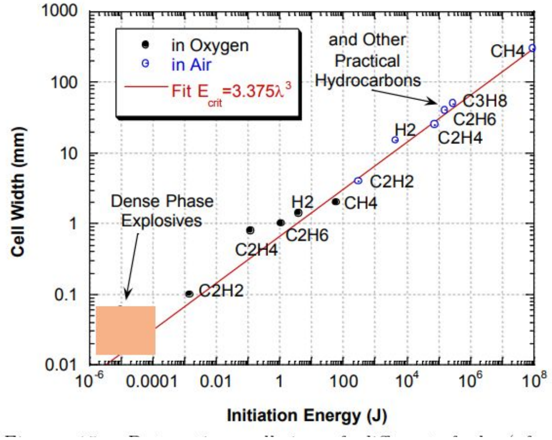


Figure: Plot of Cell Width and Initiation Energy [5]

[1] “Detonations and Shock Waves - Module Fundamentals of Hydrogen Safety: Lecture 10”
[2]”P. Hebral and J. E. Sheperd, “Spectral analysis for cell size measurement,” Cell Size Measurement by Spectral Analysis, https://shepherd.caltech.edu/EDL/PublicResources/CellImageProcessing/cellsize.html#results (accessed Dec. 5, 2023).
[3] F A Bykovskii et al 2018 J. Phys.: Conf. Ser. 1128 012075
[4] Ganbing Yao, Bo Zhang, Guangli Xiu, Chunhua Bai, Peipei Liu, The critical energy of direct initiation and detonation cell size in liquid hydrocarbon fuel/air mixtures, Fuel, Volume 113, 2013, Pages 331-339, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2013.05.081.
[5]] Schauer F.R., Miser C.L., Tucker K.C., Bradley R.P., and Hoke J.L. Detonation initiation of hydrocarbon-air mixtures in a pulsed detonation engine. AIAA-paper 2005-1343, 2005
[6] I. Q. Andrus, “A premixed rotating detonation engine: Design and experimentation,” AIR FORCE INSTITUTE OF TECHNOLOGY WRIGHT-PATTERSON AFB OH WRIGHT-PATTERSON, 2016.

Technical Overview - Design Specifications

Thrust Class: **1000N**

Fuel: **Hydrogen (gaseous)**

Oxidizer: **Oxygen (gaseous)**

Hot-Fire Run-Time: **⩾ 1 second**

Injection Type: **Non-premixed**

Ignition Type: **Deflagration-To-Detonation-Transition Tube**

Maximum Expected Temperature: **3900K**

Maximum Expected Pressure: **3.5 MPa**

Back Pressure: **101.325 kPa**

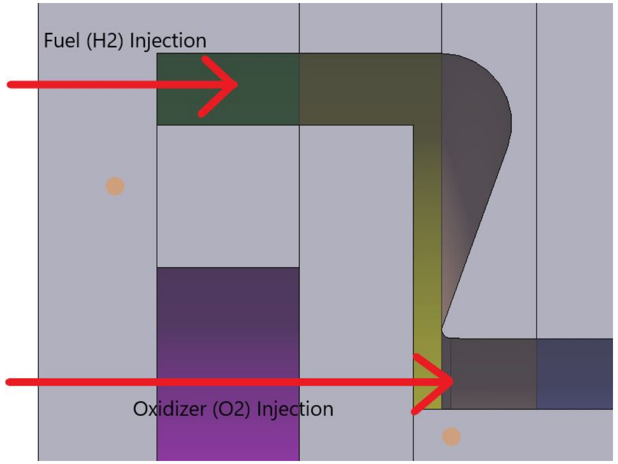


Figure: WIP Main Propellant Injection Geometry

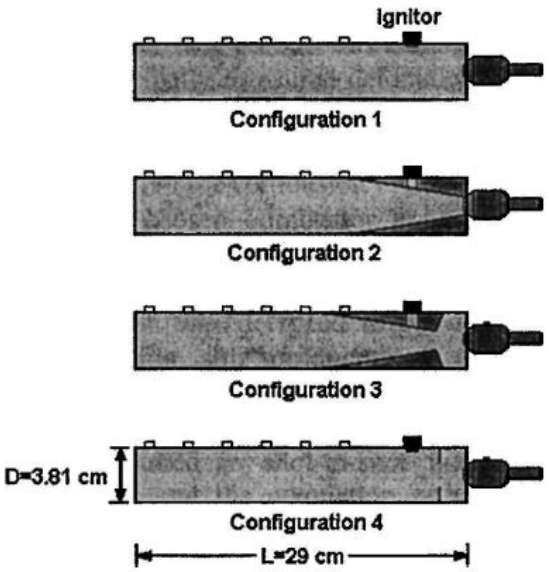


Figure: PDE Tube Configurations - Relating to DDTT configuration [1]

[1] C. Brophy, D. Netzer, and D. Forster, "Detonation studies of JP-10 with oxygen and air for pulse detonation engine development," in 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 1998, pp. 4003

Numerical Analysis - Analytical Modeling

- Designed to be used to select operating point of engine: Input parameters, engine geometry/size, expected loads and outputs.
- Relies heavily on adapting scripts from Caltech published SDToolbox Matlab add-in [1]
  - Thermochemistry; Initial state, vN state, CJ state, ZND detonation structure* [5]
- Correlations adapted from published literature to expand SDToolbox capabilities to allov for full design and specification of engine. E.g.:
  - Detonation Cell Size/Engine Geometry [6]
  - Mass Flow Rate(s) [2]
    - Fill Area [3]
  - Thrust [2]
  - Specific Impulse [1]
  - Wave Number [3]

```
%% Calculating von Neumann Point
vN_Point = vN_State(P1, T1, FAR, mech, gas1);

%% Calculating CJ State
CJ_Point = CJ_State(P1, T1, FAR, mech, gas1);

%% Calculating ZND Detonation Structure
Detonation_Structure = ZND_Structure_Shak(P1, T1, FAR, mech, gas1); %we only

%% Geometry Definition
% Equations taken from:
% - "Detonation cell size of liquid hypergolic propellants: Estimation from
% Alex R. Keller, Nicolas Q. Minesi, Daniel I. Pineda, R. Mitchell Spearrin]

% Dimension are in millimeters
cell_gav=Detonation_Structure(1,22);
Minimum_Channel_OD = 40*cell_gav*1000;
Minimum_Channel_Width = 2.4*cell_gav*1000;
Minimum_Chamber_Length = 24*cell_gav*1000;
Minimum_Channel_ID = (Minimum_Channel_OD - Minimum_Channel_Width);
```

Figure: Snippet of Analytical Model Code

[1] Browne, S. T. and J. Ziegler. "Numerical Solution Methods for Shock and Detonation Jump Conditions." (2004).
[2] J. E. Shepherd and J. Kasahara, "Analytical Models for the Thrust of a Rotating Detonation Engine", California Institute of Technology, Mar. 2020.
[3] Wola, Piotr et al. "Rotating Detonation Wave Stability." (2011).
[4] Naples, Andrew G. et al. "Rotating Detonation Engine Interaction with an Annular Ejector." (2014).
[5] A.I Gavrikov, A.A Efimenko, S.B Dorofeev, A model for detonation cell size prediction from chemical kinetics, Combustion and Flame, Volume 120, Issues 1–2, 2000, Pages 19-33, ISSN 0010-2180, https://doi.org/10.1016/S0010-2180(99)00076-0.
[6] Anil P. Nair, Alex R. Keller, Nicolas Q. Minesi, Daniel I. Pineda, R. Mitchell Spearrin, Detonation cell size of liquid hypergolic propellants: Estimation from a non-premixed combustor, Proceedings of the Combustion Institute, Volume 39, Issue 3, 2023, Pages 2757-2765, ISSN 1540-7489, https://doi.org/10.1016/j.proci.2022.06.015.

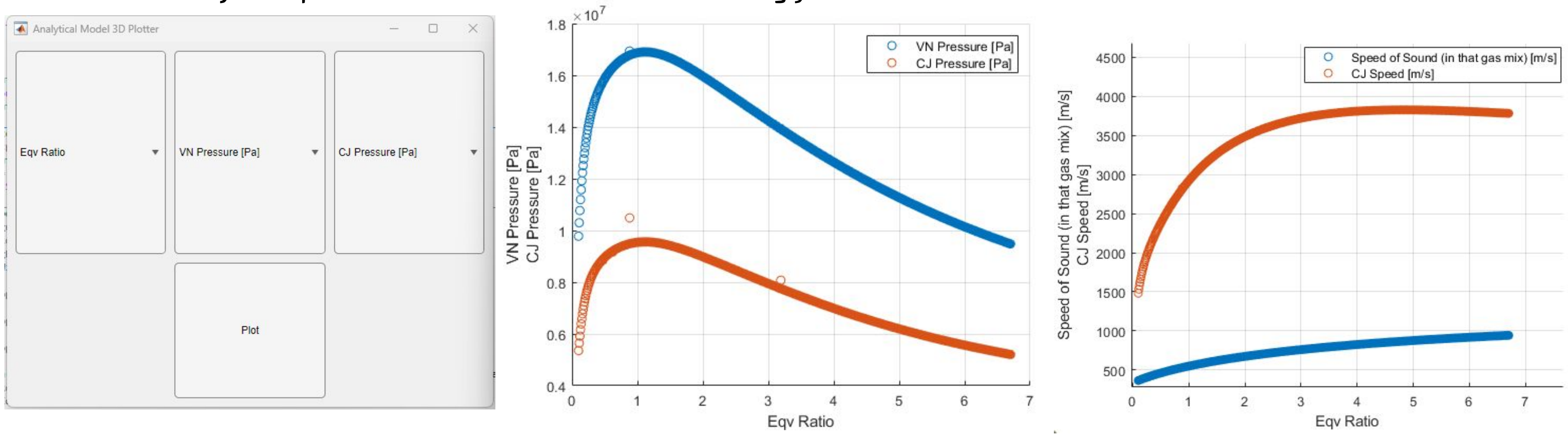
Numerical Analysis - Analytical Modeling - con't

Current Status

- Not confident in the mass flow rate calculations (compared to similarly sized engines)
  - Thrust is proportionally lower
- Comparing to other RDEs, calculations up to mass flow rate (Temp/Pressure/speeds) seem reasonable.

Future Works

- Size DDTT and Schlekan spiral
- Transient thermal analysis of combustion chamber and cooling jacket(s).



Figures: Analytical Model Rapid Plotting Procedure (2D Rapid Plotting GUI not shown)

Numerical Analysis - Next Steps

- Select engine input parameters based on successful full factorial testing of our analytical model.
    - Choosing input pressure, temperature and equivalence ratio aligning with requirements for:
        - thrust (~1000N)
        - overall engine size (larger is generally easier to work on)
        - combustion temperature and pressure (to avoid harming sensors)
        - wave number (>=1)
- Validate analytical model with CFD simulations.
- Finalize CAD & DFMA based on the selected geometry resulting from selected input parameters.
    - Finalizing FEA analysis of combustion chamber.
- Outsourced manufacturing
- Modifications to existing test frame we have access to
    - CAD/DFMA; manufacturing
- Prepare publishable material on: analytical model

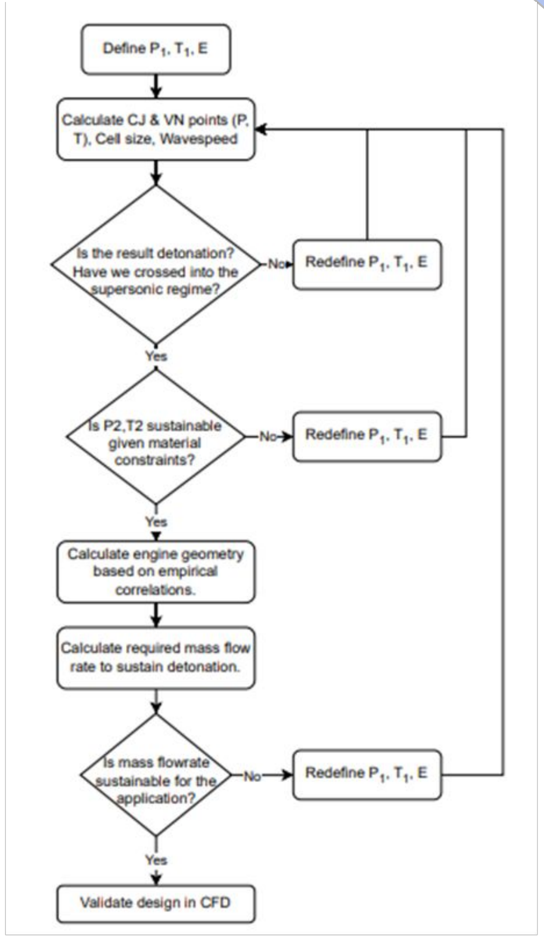
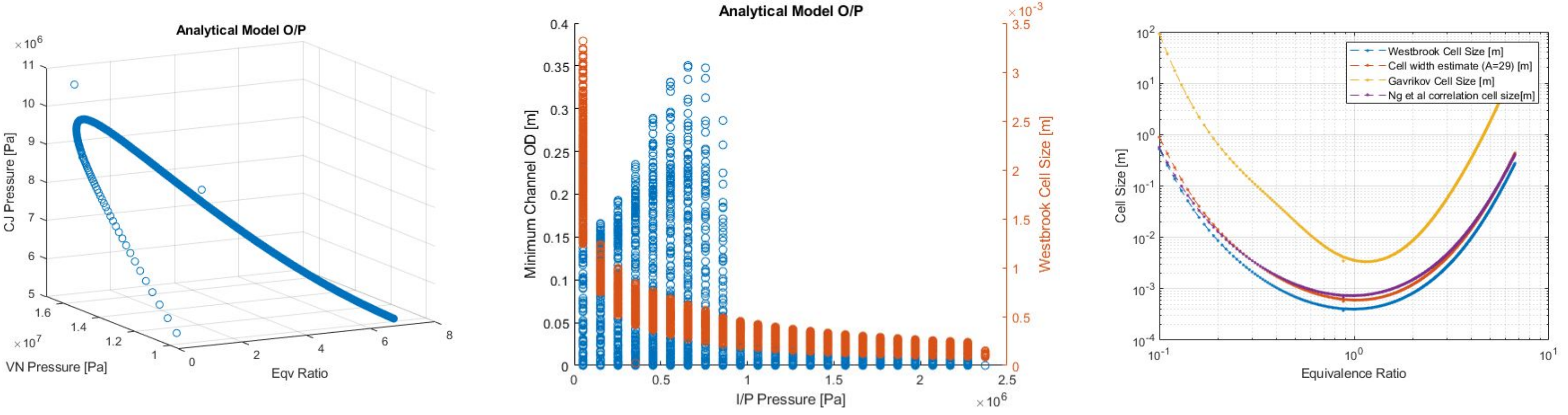


Figure: Proposed sizing methodology Flowchart (P – Pressure, T- Temperature, E – Equivalence Ratio)

Numerical Analysis - Next Steps

- Analyzing critical operation parameter from a full factorial numerical experiment for a 1000N thrust class RDRE (example figures below).
- Selecting suitable input pressure, temperature (stagnation), and equivalence ratio, and mass flow rate.
- Objectives: maximizing outside diameter of the engine, minimizing normal shockwave peak pressure, detonation wave peak temperature, injection pressure, temperature, and mass flow rate.



Figures: Full-factorial numerical experiment output plot examples (WIP data only)

Numerical Analysis - CFD

Converge CFD is a purpose built CFD software used for modelling combustion. Some work has been done on developing a 2D [1] and 3D [2] model with good correlation to empirical results using ConvergeCFD. Building a full encompassing RDE CFD model is not wholly within the scope of an undergraduate research project. ConvergeCFD through a sponsorship agreement with DETechnologies have provided access to a Hydrogen-Air 2D RDE model to support bridging this gap.

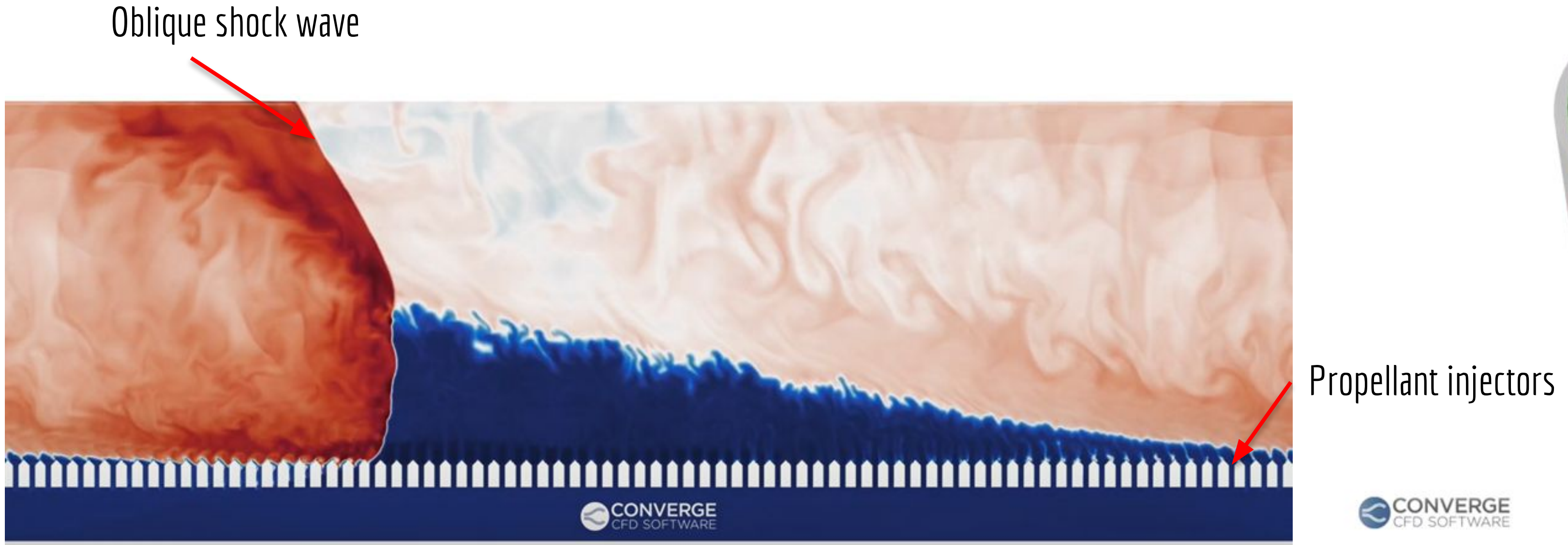


Figure: 2D Unrolled RDE Numerical Simulation in ConvergeCFD [1]

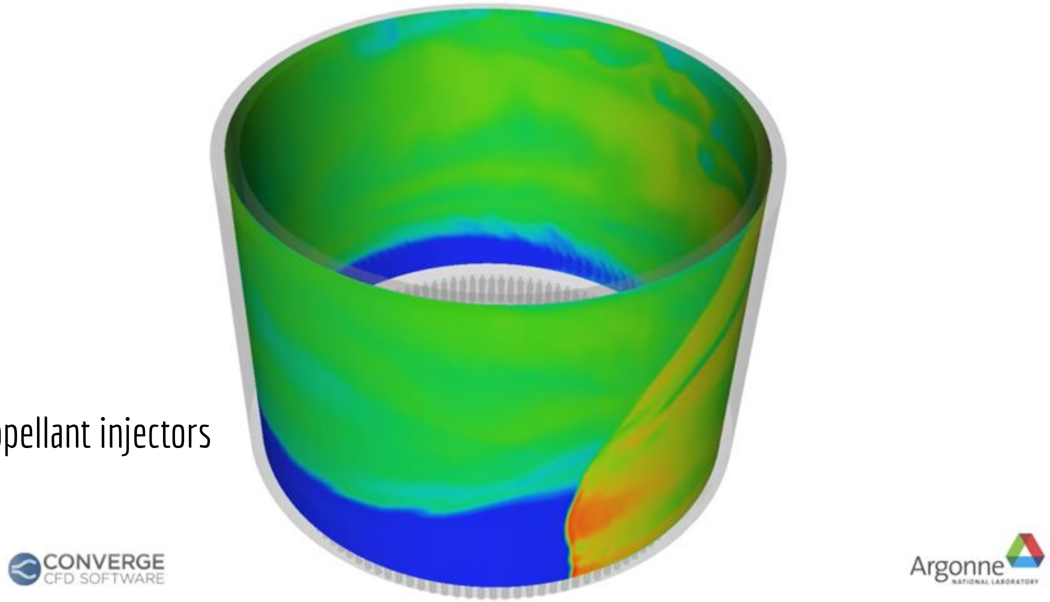
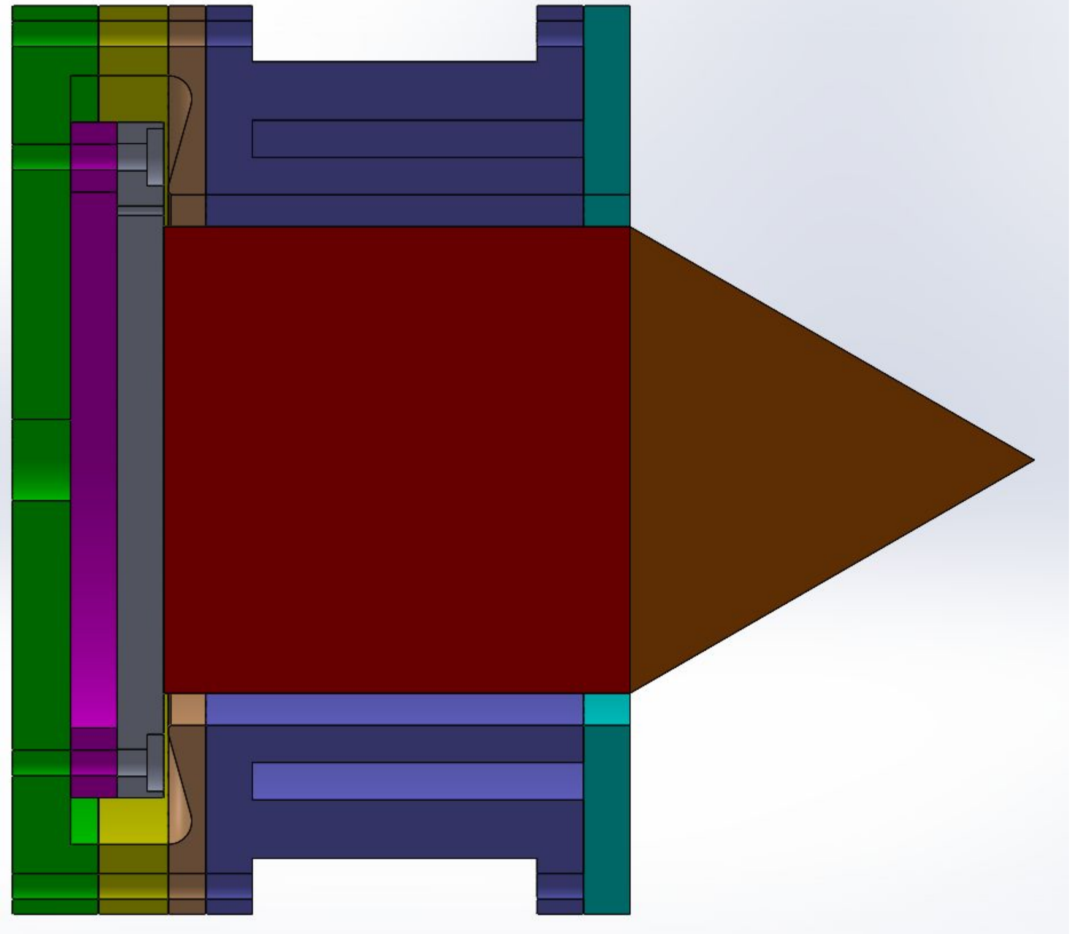


Figure: 3D RDE Numerical Simulation in ConvergeCFD [1][2]

[1] E. Favreau, "The collaboration effect: Developing a new generation of gas turbine & rotating detonation engines - converge CFD Software," Convergent Science Press, 2023. Available: https://convergecfd.com/blog/collaboration-effect-developing-gas-turbine-rotating-detonation-engines
[2] P. Pal, G. Kumar, S. A. Drennan, B. A. Rankin, and S. Som, "Multidimensional numerical simulations of reacting flow in a non-premixed rotating detonation engine," in Turbo Expo: Power for Land, Sea, and Air, 58622, V04BT04A050. American Society of Mechanical Engineers, 2019.

Current Preliminary Design

- Stacked plate & cylinder design
- Centerbody and outerbody water jacket(s)
- Aerospike for improved multi-environment high performance
- Multi-circumferential propellant injection ports for even plenum pressure distribution
- Current Chamber Parameters*:
  - Injection Pressure: 1 MPa
  - Injection Temp: 323.15 K
  - Chamber Width: 6.8 mm
  - Chamber OD: 113.824 mm
  - Chamber Length: 68.23 mm
  - Detonation Cell Size: 2.8 mm
- Simple cylindrical DDTT



Testing Plan

- Size 44 compressed gas cylinders with Swagelok plumbing feeds the engine and DDTT
- Individual Component Tests:
  - Stepped DDTT testing
  - Injection plate
  - Hydrostatic pressurization of plenums/manifold
  - Emergency Shutoff
  - Propellant Feed
  - Coolant Loop
- Full Hot Fire Tests

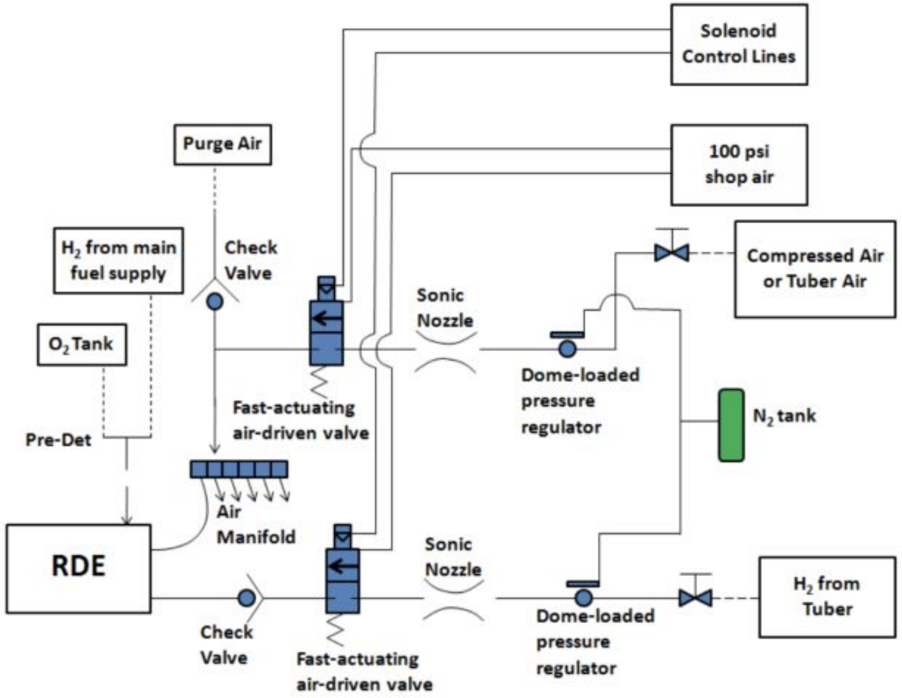


Figure: Example P&ID for the RDE propellant feed/purge system [1]

[1] Shank, Jason C., "Development and Testing of a Rotating Detonation Engine Run on Hydrogen and Air" (2012). Theses and Dissertations. 1065.

Safety Measures

Safety is the number one priority to our team during the development of this engine. Critical systems are designed to incorporate safety measures during each step of the design process to align with our overarching goal to have 100% crew safety but also salvaging engine components in the event of component or entire sub-system failures.

- Propellant supply/injection systems
  - Fluid diode geometry injectors to limit backflow.
  - Complete, tested sealing between fuel and oxidizer plenums.
  - Back-flow, and pressure release valves built into both propellant supply lines.
  - Automatic, and manual override into Nitrogen purge mode of operation.
- Hands-free engine operation
  - Fast acting, fail closed valves selected for propellant and fast-acting fail open valve selected for Nitrogen supply line.
  - Engine firing duration will be computer controlled and overseen by the team. Short duration operation will be tested and validated before arming the system.
  - Secondary feedback, and live video feed will cover the testing bay; no one enters the danger zone without 100% confidence of operation mode the system is in.
  - ICE: propellant tank volume is considered and operators will stay away until supply vessels are ensured empty and the area purged.

Safety Measures - cont'd

- Cooling System *
  - Pressure release valves built in
  - Coolant with high vaporization temperature will be selected.
  - Open loop cooling to ensure no net coolant temperature gain.
  - Flange bolts sized to fail below the capable pressure level of the coolant chamber

- Outdoor testing facilities
  - Clear surroundings, radius TBD.
  - Safety vessel constructed around the engine testing area
  - Operation station will be set up well outside the danger region, with full control and visual feed of the testing area.

Appendix:
Reference Slides

Current RDRE Technology Limitations

<u>**Current Research focus**</u>

- Controlling multi-wave detonation.
- Metallurgy - alloy development.
    - Nasa's GR-series alloys (P. Gradl et al. , 2023) .
- Cooling: maximum runtime without thermal degradation has been 18s, with an integrated cooling system (DefendTex).

<u>**Limitations**</u>

- High heat and pressure generated
    - Heat: 3954K (D - @5atm) [3]
    - Pressure: 172.10 atm (NS - @5atm) [3]

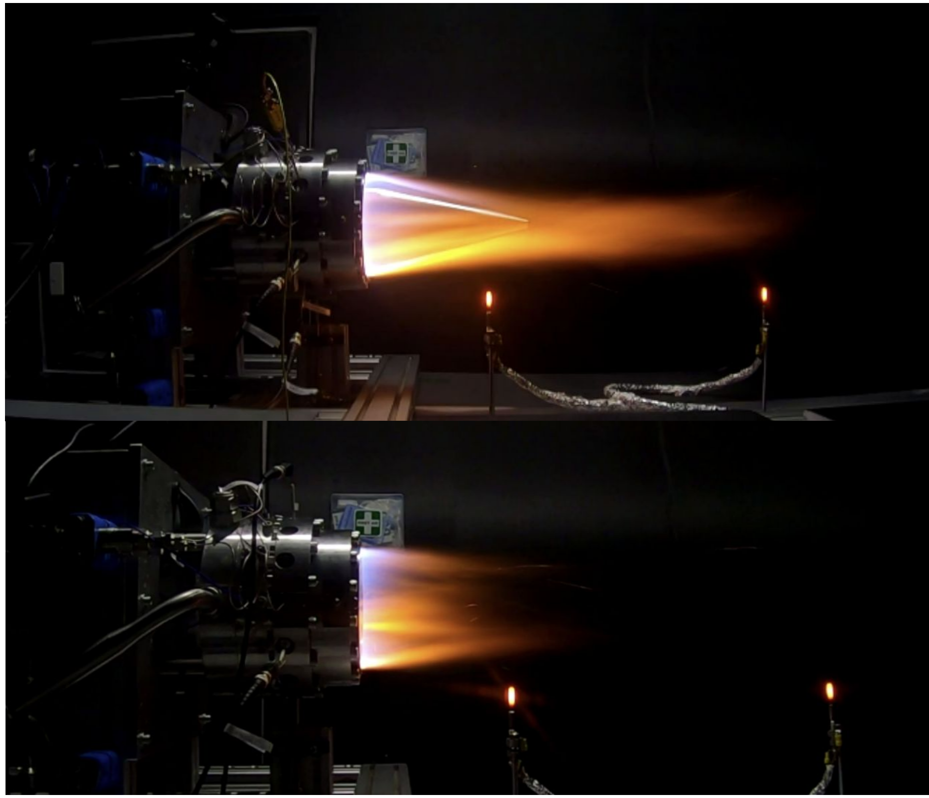


Figure: DefendTex RDRE with and without Aerospike [1].

[1] "Media release," DEFENDTEX, https://www.defendtex.com/media-release/ (accessed Dec. 5, 2023).
[2] P. R. Gradl, C. Protz, K. Cooper, C. Garcia, D. Ellis, and L. Evans, "GRCop-42 Development and Hot-fire Testing Using Additive Manufacturing Powder Bed Fusion for Channel-Cooled Combustion Chambers," in Proceedings of the 55th AIAA/SAE/ASEE Joint Propulsion Conference (Paper AIAA-2019-4228), 2019.
[3] L. E. Bollinger and R. Edse, "Thermodynamic Calculations of Hydrogen-Oxygen Detonation Parameters for Various Mixtures," Ohio State University, Columbus, Ohio, pp. 251-256. (n.d.).

Research Opportunities (Gaps)

RDREs offer an exciting advancement in aerospace propulsion technology. There are research opportunities to further RDRE technology in the following areas:

- Numerical simulation of RDRE operation.
  - Computational Fluid Dynamics (CFD) improvement to align better with empirical results; or discover the difference.
  - Developing more accurate relationships to describe the combustion restriction.
- Metallurgy for combustion chamber; alloy development to withstand high heat and pressure.
- Advanced control systems; to stabilize dynamics of multi-wave detonation.
- Advanced thermo-fluid & combustion research; improving understanding of ignition process, maintaining combustion and increasing efficiency.