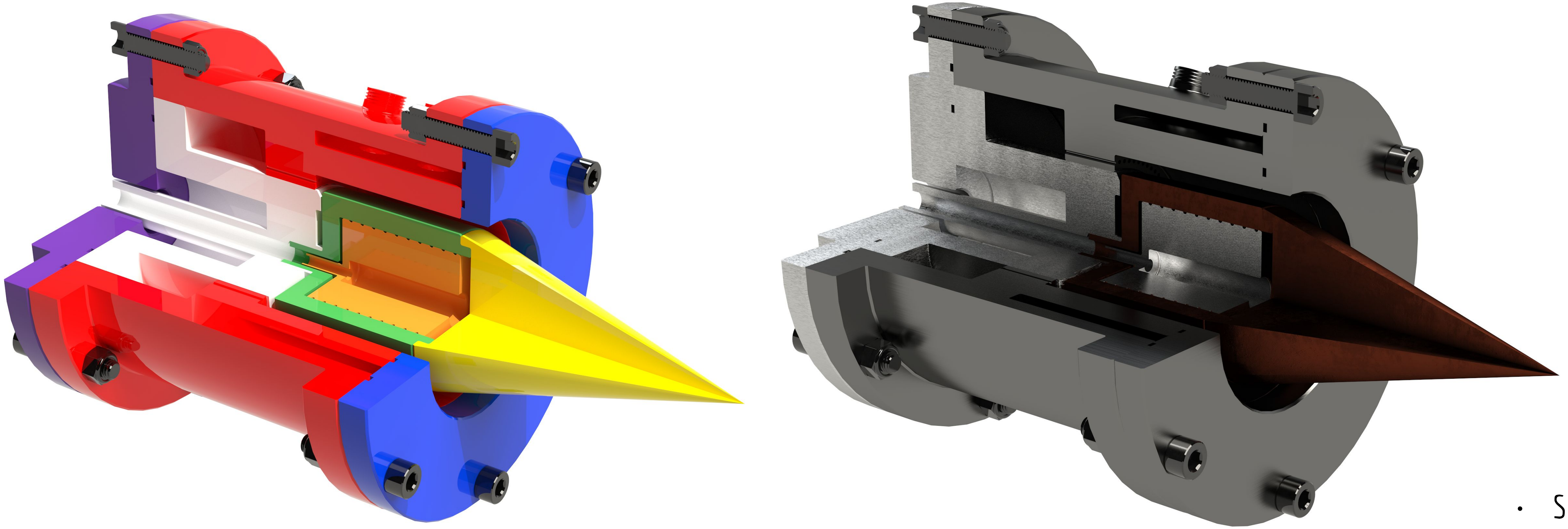
DETechnologies

Interim Presentation



February 12, 2024

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- Logan Palmer
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Agenda

- Topic Introduction
- Summary of Project Formulation
  - Problem Definition ✓
  - Alternate Solutions ✓
  - Constraints ✓
- Detonation Theory
- Engineering tools: Design Approach
- Economics: Budget
- Design Progress
  - Current Work

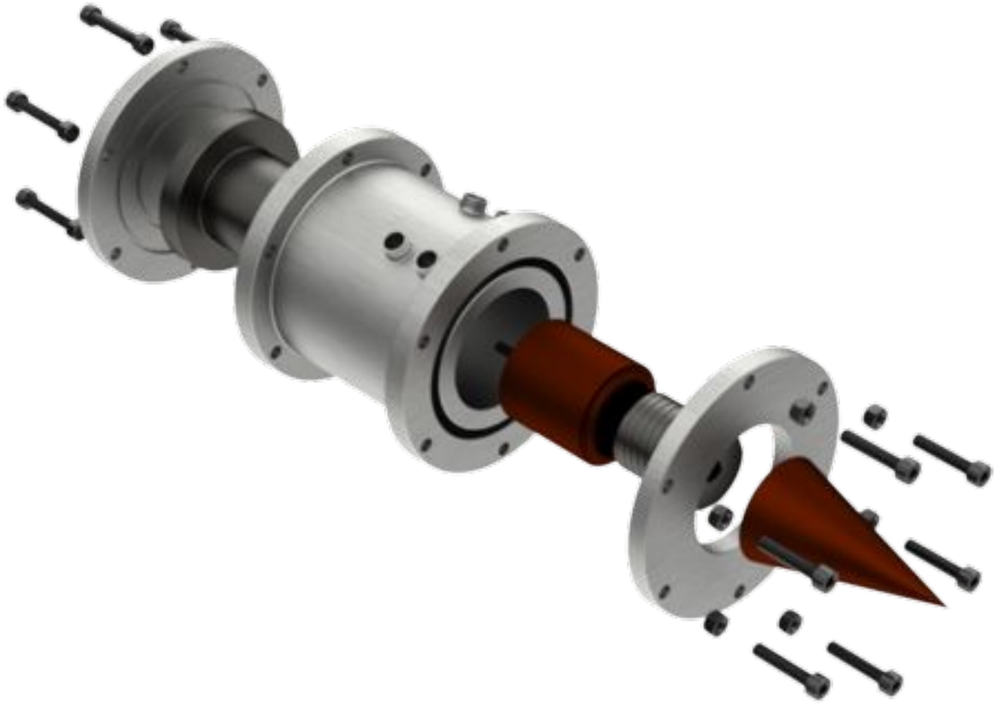


Figure: Exploded view of early preliminary design.

Topic Introduction: What is a RDE?

Rotating Detonation Engines (RDEs) are propulsion systems that operate on the principle of Detonation, meaning supersonic combustion, rather than Deflagration; the typical combustion process, being subsonic combustion [1]. RDEs are not at a technology readiness level for commercial use, however RDE research is a very active research field at many academic and research institutions [1-4].

RDREs have theoretical applications as [5].

- Satellite Thrusters
- Launch Vehicle Propulsion
- Defense System Propulsion

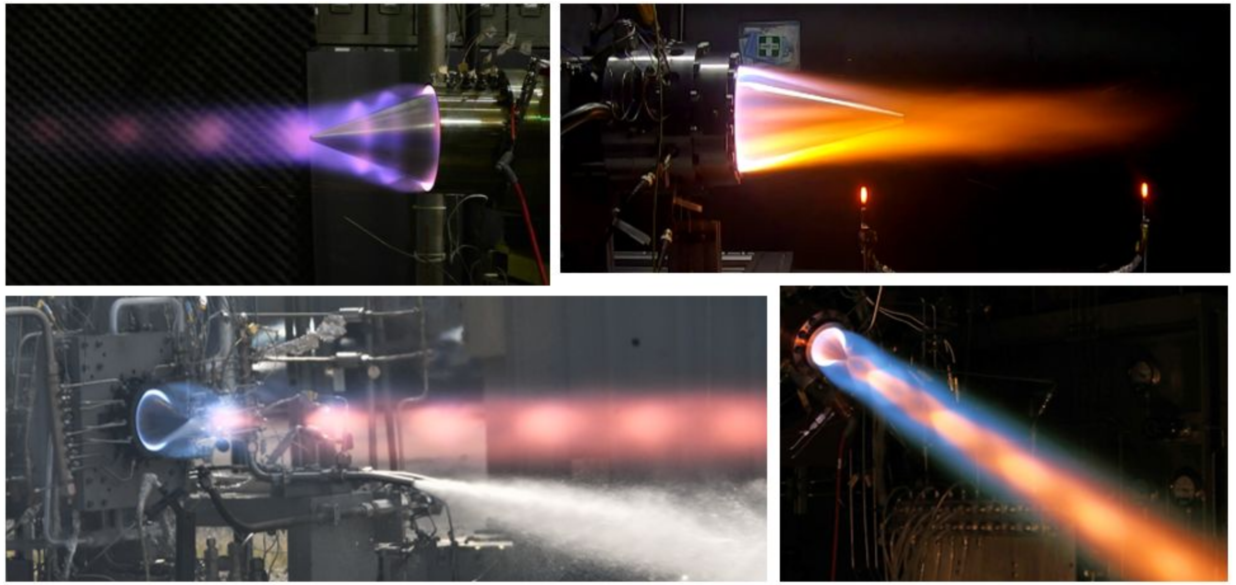


Figure: Experimental RDEs: Zucrow Laboratories (Purdue University) [2], DefenTex [3], NASA Marshall [4], AFRL [5].

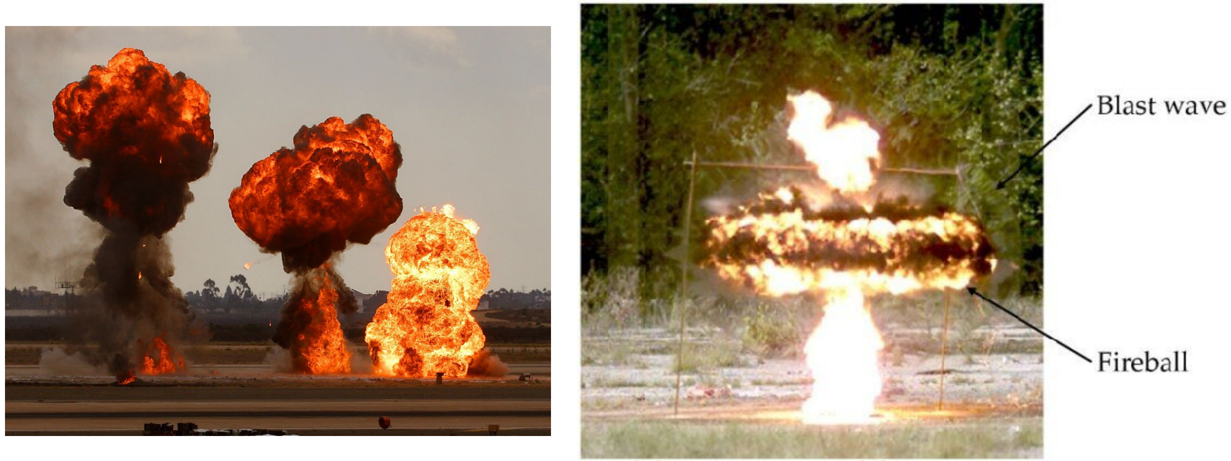


Figure: Deflagration Combustion Right [6], Detonation Left [7]

Topic Introduction: Basic Operation Overview

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

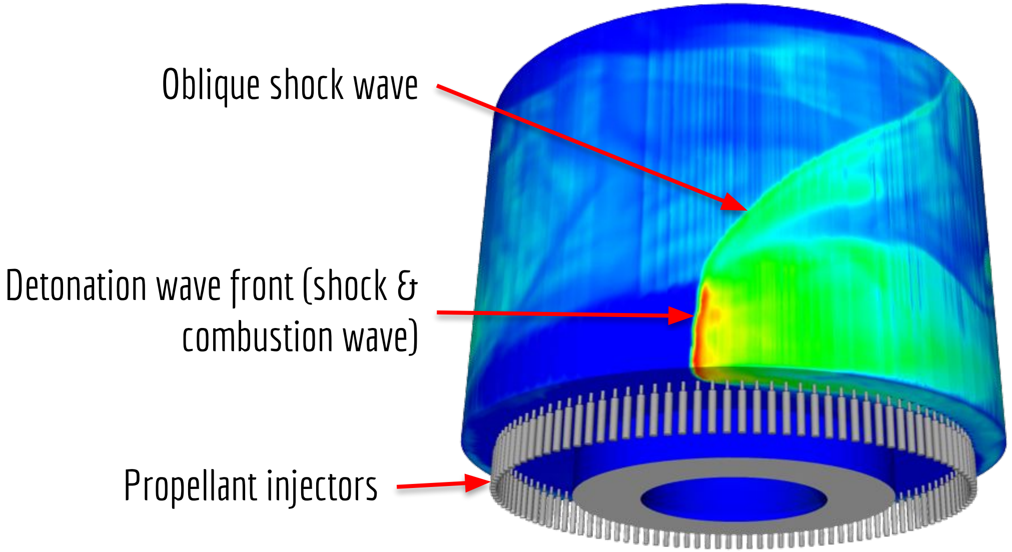
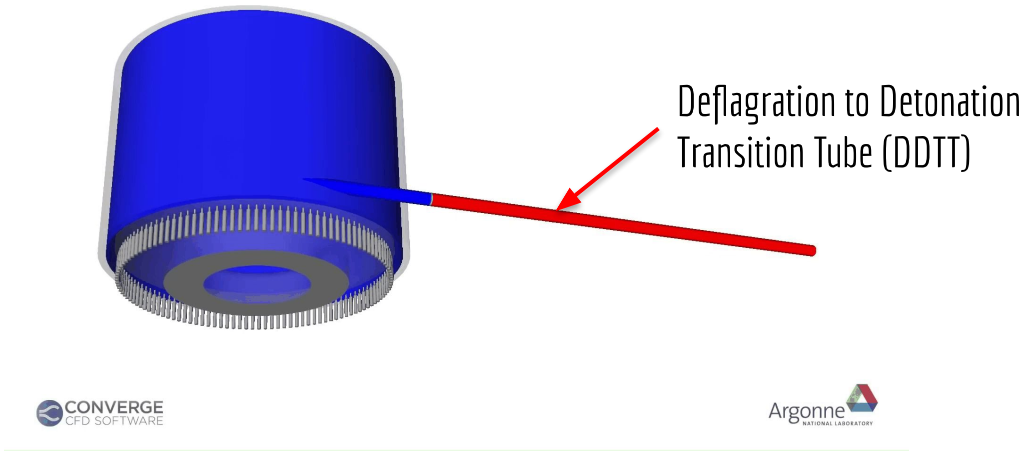


Figure: 3D RDRE CFD Model. Source: ConvergeCFD & Argonne National Laboratory [8][9]



Video: 3D RDRE CFD Model. Source: ConvergeCFD & Argonne National Laboratory [8][9]

Project Formulation

Problem Definition: Very little literature is available that clearly outlines the design process involved in choosing engine sizing for any application.

Alternate RDE Design Approach: Trial and error engine sizing or borrow working experimental design.

Constraints:

Table: Summary of Main Constraints

Technical	Budget	Safety	Time
- No local specialization in combustion, detonation, or compressible fluids research. - Combustion temperature and pressure	- According to Dr. A. Higgins and Dr. C. Kiyanda during a meeting with DET; a baseline propellant supply system will cost between $50-100k [10].	- No combustion testing facilities locally. - GO2 and GH2 handling best practices [11][12][13].	- Only 2 months until graduation.

Detonation Theory

Two primary detonation theories:

- Chapman-Jouguet (CJ) & Zel'dovich-von Neumann-Doring (ZND) theories.
  - Based on conservation equations (Energy/Momentum/Continuity)
  - Utilizes Rankine-Hugoniot Relations.
  - CJ describes detonation changes across detonation wave front, and wave speed.
  - ZND describes the detonation wave structure.

Equations:
(i) General form of the Rankine-Hugoniot equation [2].
(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) $$\rho_1^2 u_1^2=\frac{p_2-p_1}{\frac{1}{\rho_1}-\frac{1}{\rho_2}}=\dot{m}^2$$

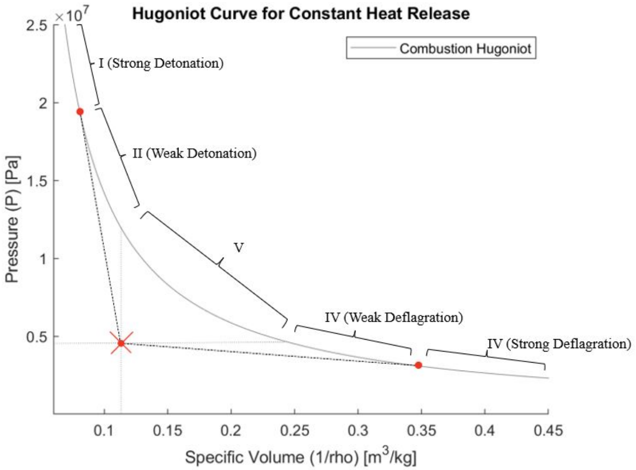


Figure: Rankine-Hugoniot Plot Labelled Regions, adapted from Nordeen and Kuo [14][15]

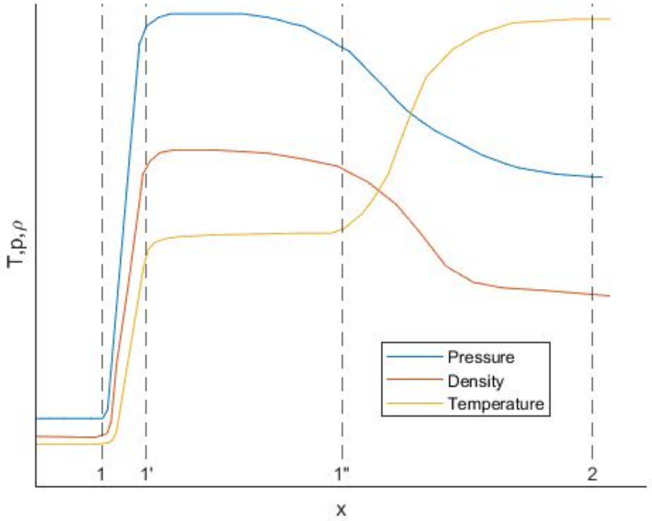
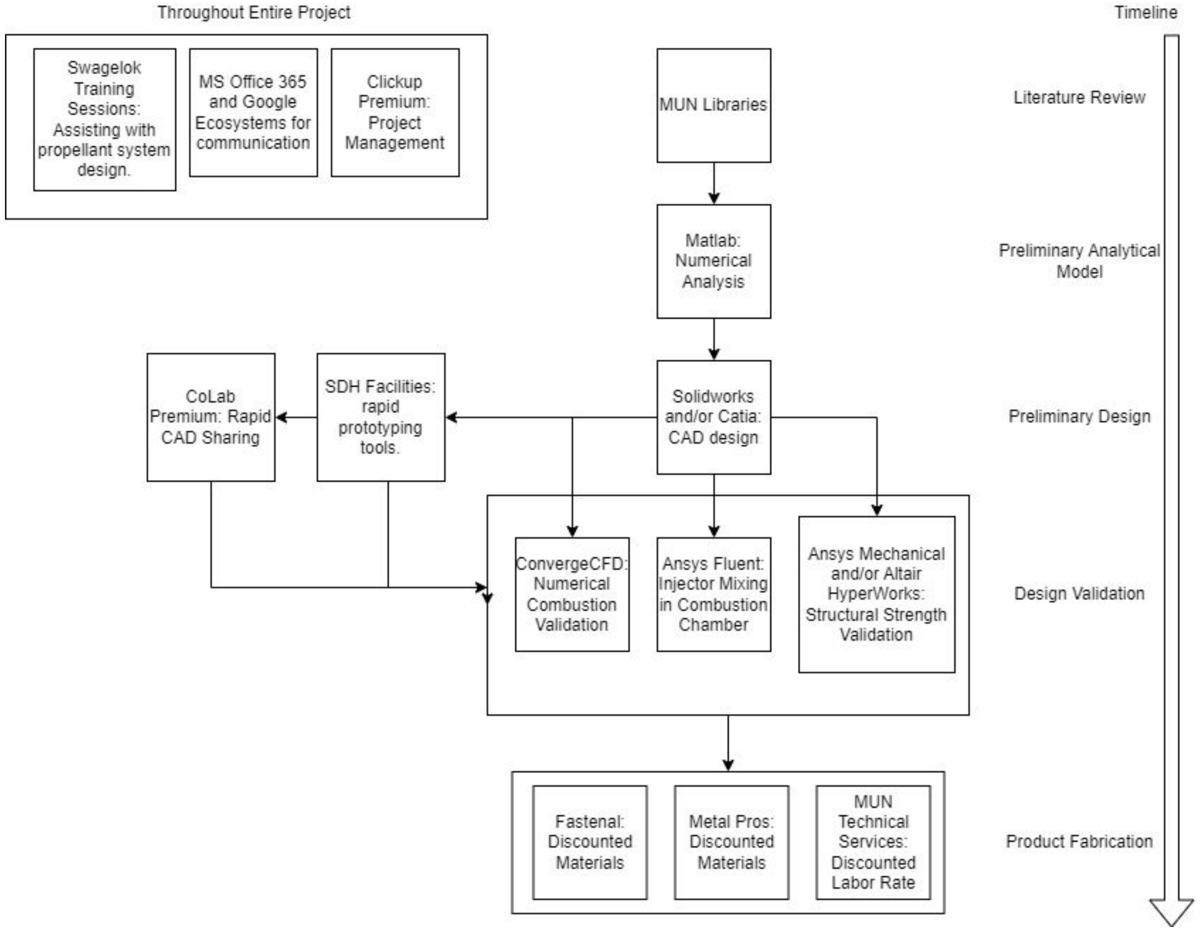


Figure: Temperature, Pressure & Density Across Detonation Wave, adapted from Kuo [15]

Engineering Tools - Design Approach

Immature nature of RDE technology

Our involvement in SDH design teams has given us experience and industry connections which is reflected in the tools/partnerships/access to CAE products.



Throughout Entire Project

Swagelok Training Sessions: Assisting with propellant system design.

MS Office 365 and Google Ecosystems for communication

Clickup Premium: Project Management

MUN Libraries

Matlab: Numerical Analysis

Solidworks and/or Catia: CAD design

SDH Facilities: rapid prototyping tools.

CoLab Premium: Rapid CAD Sharing

ConvergeCFD: Numerical Combustion Validation

Ansys Fluent: Injector Mixing in Combustion Chamber

Ansys Mechanical and/or Altair HyperWorks: Structural Strength Validation

Fastenal: Discounted Materials

Metal Pros: Discounted Materials

MUN Technical Services: Discounted Labor Rate

Timeline

Literature Review

Preliminary Analytical Model

Preliminary Design

Design Validation

Product Fabrication

Figure: Temporal Dependency on various CAE tools, fabrication and materials access, partnerships.

Project Budget

- Two budgets: main scope and stretch scope budgets.
- Ignoring costs associated with in-kind support in this slide. Details on in-kind support in PMP report.

Table: Current Main Scope Budget

Description	Cost Estimate
ClickUp Project Management Software	$ 280.00
Metal Pros - Stock Metal	$ 1,495.00
MUN Technical Services - Machining non-functional prototype.	$ 400.00
Team Clothing	$ 500.00
Overleaf Subscription	$ 50.00
Total	**$ 2,725.00**

Table: Stretch Scope Budget

Budget item	Cost
Computing (Clickup & Horizon)	$ 550.00
Raw Materials	$ 3,000.00
Fabrication	$ 4,000.00
Raw Propellant	$ 2,100.00
Piping, flowmeters, valves	$ 27,000.00
Instrumentation: Sensors (x7)	$ 20,000.00
Testing Facility (assembly, location, etc.)	$ 15,000.00
Safety Equipment	$ 5,000.00
Total	**$ 76,650.00**

Design Progress - At a Glance

T7

Literature Review, Constraints, & Objectives

T7

Basic Design & CJ Theory Exploration

WT

Developed Bulk of Analytical Model

WT

Instrumentation Selection & Propellant Feed System Design

Design Progress - AT8

AT8
Thus Far

- Jan. — Analytical Model Process Paper Drafted
- Jan. — Thick-Walled Pressure Vessel & FE Analyses
- Jan. — Continue Combustion CFD Validation
- Feb. — Begin Detailed CAD Modeling

AT8
Up-Next

- Feb. — Complete Analytical Model Validation & Analyse Flow of Propellant Piping
- Mar. — CFD Analysis of Propellant Mixing
- Mar. — Propellant Feed System and Thrust Stand CAD
- April — DFMA, GD&T, & Dwgs.

Current Work - Analytical Model - Basics

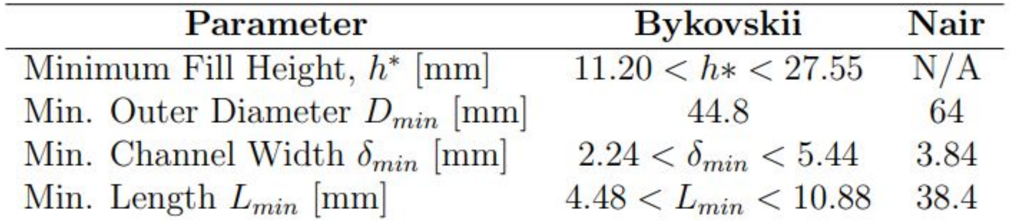
Basic combustion parameters determined using Analytical approach. A range of various geometric parameters are found according to experimentally derived rules of thumb [16][17].

- Detonation cell size predictions could not be implemented as timeline suggested. Detonation cell sizes for P_0=130kPa, found to be λ=1.6mm [18]

Remaining early analytical steps:

- Working towards validating against experimental engines.
- Attempt to retroactively implement cell size predictions.

Table: Tentative Combustion Specific Geometry According to Empirical Rules of Thumb [16][17].



Parameter	Bykovskii	Nair
Minimum Fill Height, h^* [mm]	$11.20 < h* < 27.55$	N/A
Min. Outer Diameter D_{min} [mm]	44.8	64
Min. Channel Width δ_{min} [mm]	$2.24 < \delta_{min} < 5.44$	3.84
Min. Length L_{min} [mm]	$4.48 < L_{min} < 10.88$	38.4

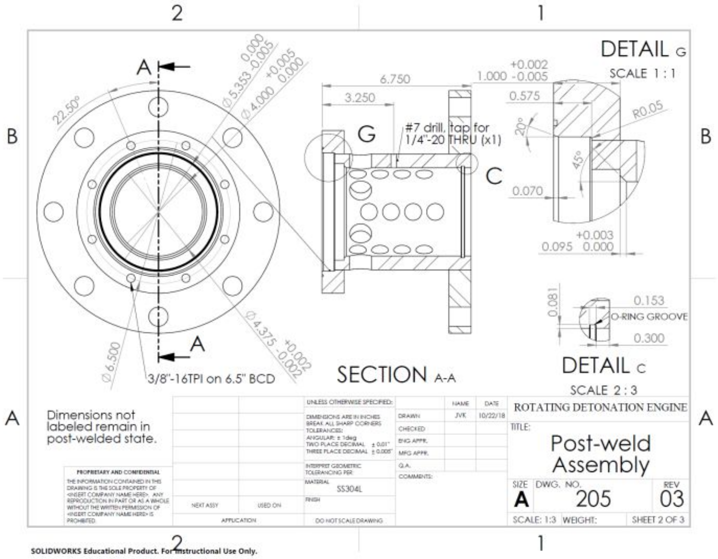


Figure: Similarly Sized RDE from Mundt, compared as results validation [19].

Current Work - Analytical Model - Approach

- Input parameters -> engine geometry/size, expected loads and outputs.
- Relies heavily on adapting scripts from Caltech published SDToolbox Matlab add-in [20]
- Correlations adapted from published literature to expand SDToolbox capabilities to allow for full design and specification of engine. E.g.:
  - Detonation Cell Size/Engine Geometry [17]
  - Mass Flow Rate(s) [21]
    - Fill Volume [22]
  - Thrust [21]
  - Specific Impulse [20]
  - Wave Number [22]

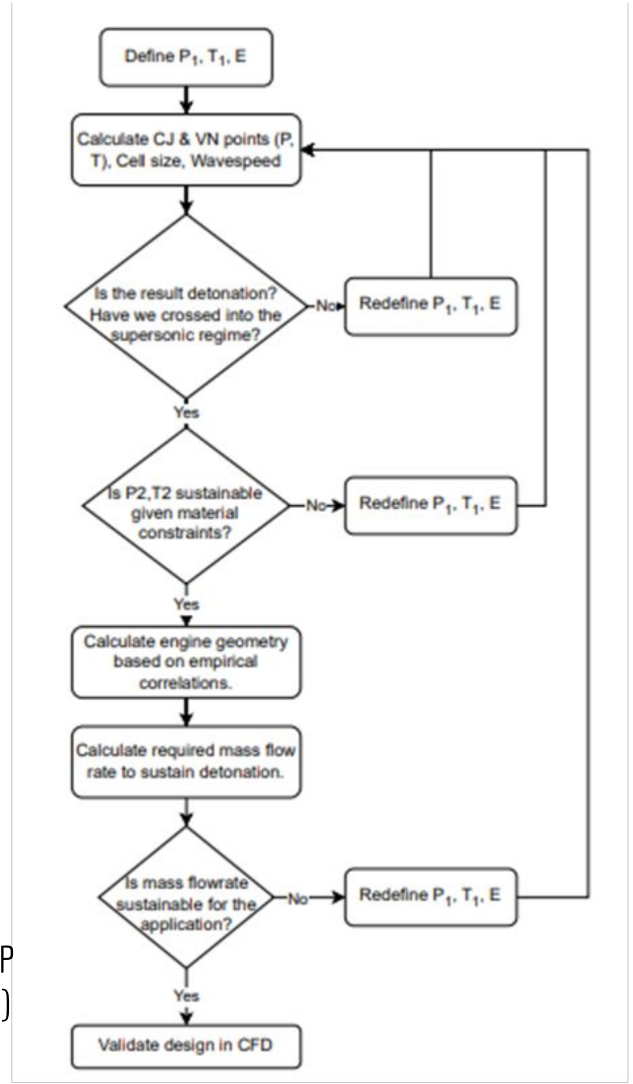
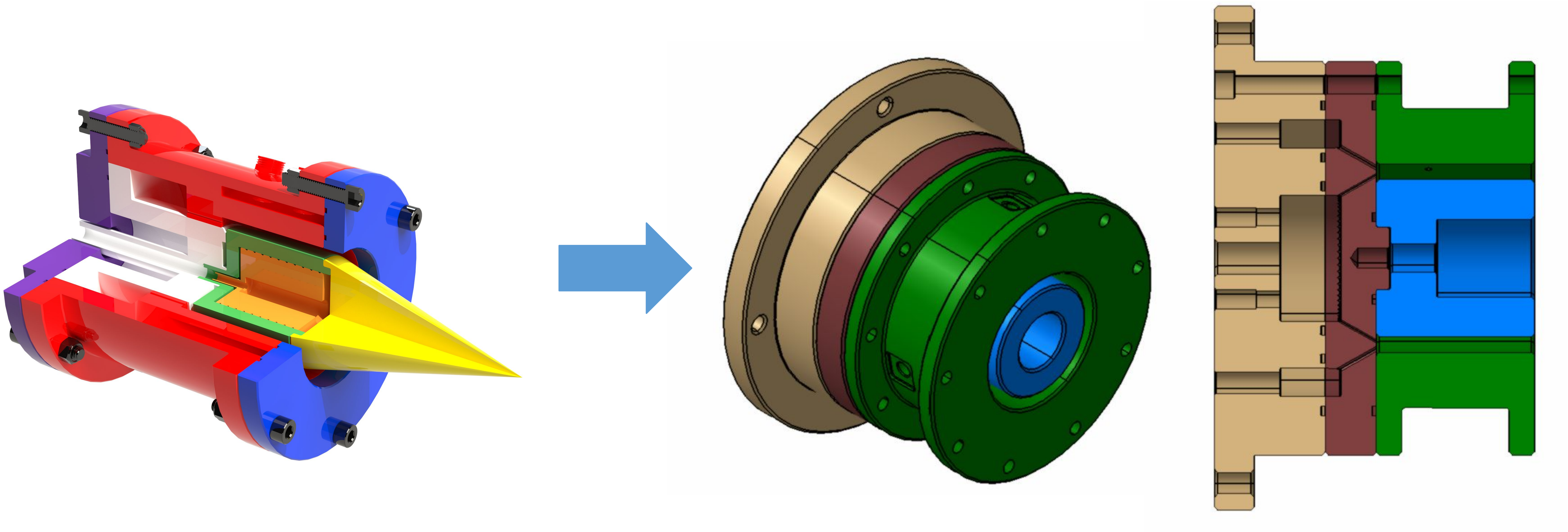


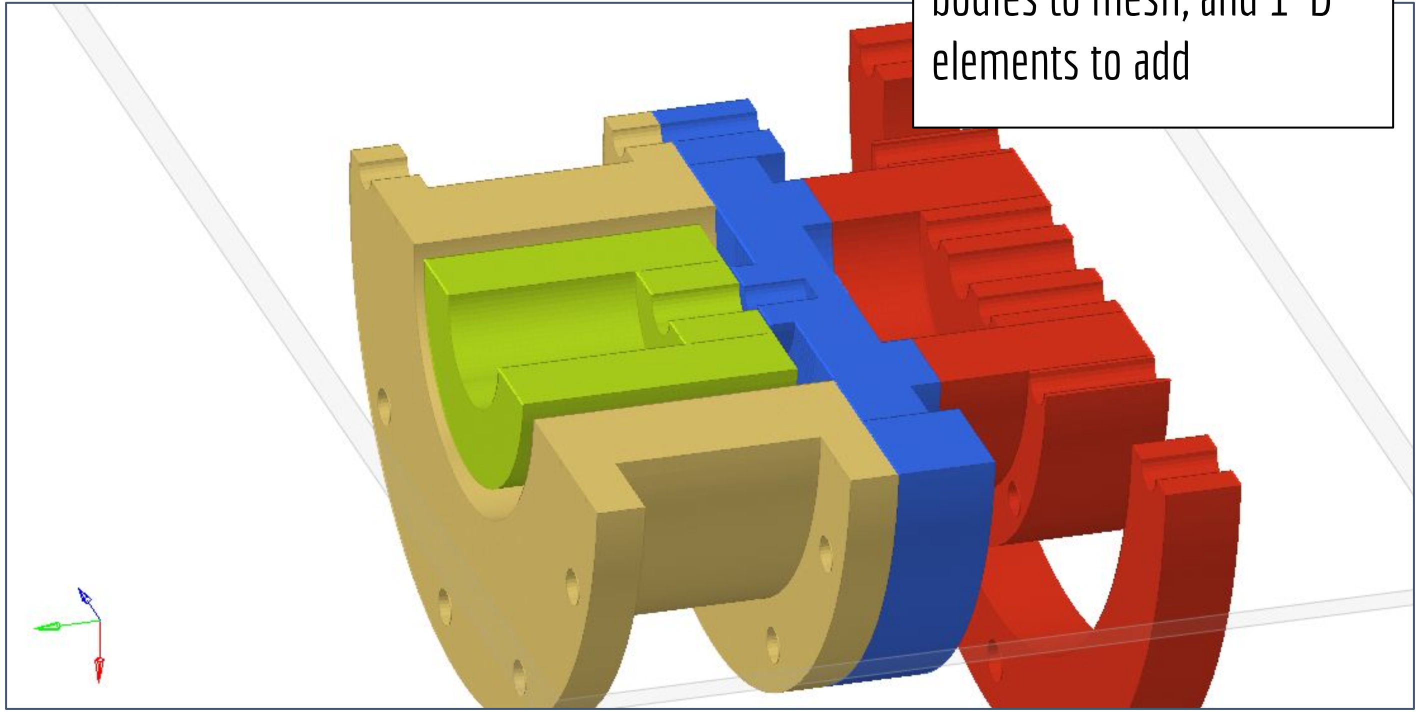
Figure: Proposed sizing methodology Flowchart (P – Pressure, T- Temperature, E – Equivalence Ratio)

Current Work - Preliminary Design



Current Work - FEA

- Structural Analysis to validate safety & engine longevity:
  - Material comparison for maximum stresses & strains
  - Modal Analysis at operating frequency
  - Multi-physics fatigue (pressure and temperature)



Mesh is WIP - nearing completion. Few additional bodies to mesh, and 1-D elements to add

Numerical Analysis - Combustion CFD

- Converge CFD is a purpose built CFD software used for modelling combustion.
- Work has been done on developing a 2D [9] and 3D [8] RDE model with good correlation to empirical results.
- Building an RDE CFD model is not within the scope of an undergraduate research project.
    - Convergent Science sponsorship agreement with DETechnologies provided access to a Hydrogen-Air 2D RDE model.
    - Converting the H2-Air model is one of the non-required project deliverables.

Figure: 2D Unrolled RDE Numerical Simulation in ConvergeCFD [23]

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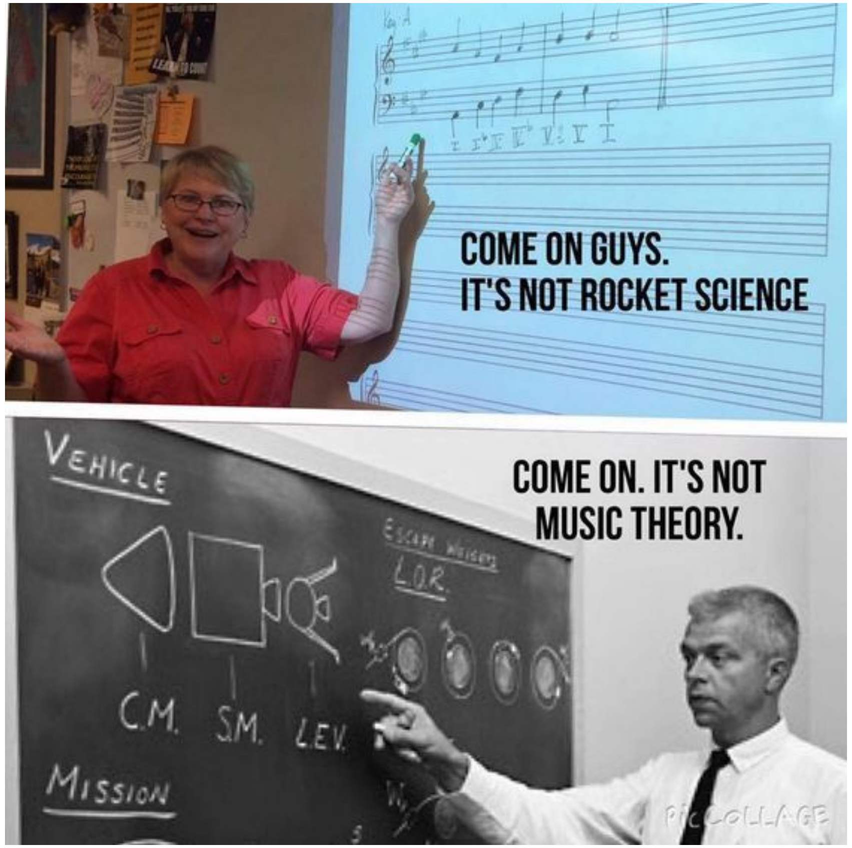

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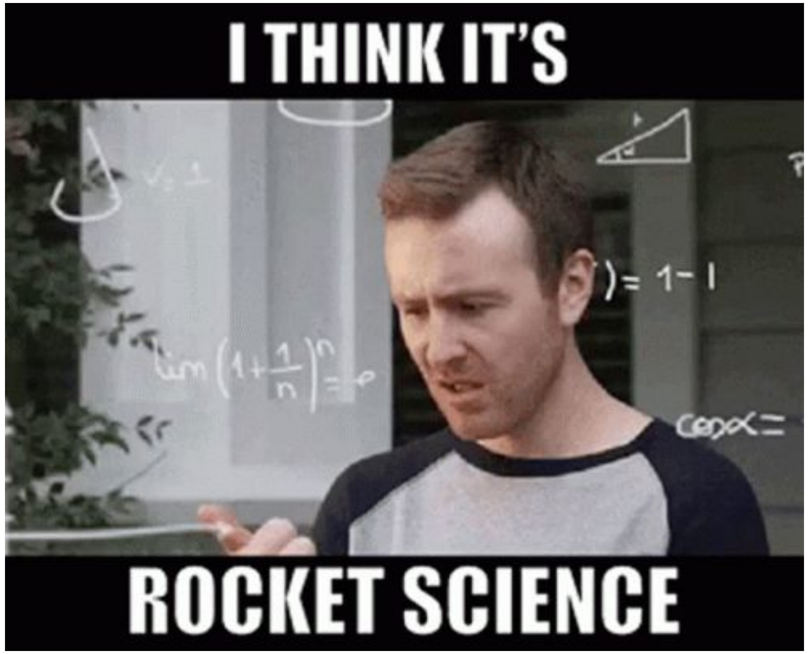

https://tenor.com/view/rocket-science-complicated-difficult-challenging-math-gif-23793443

Appendix:
Reference Slides

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).
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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]

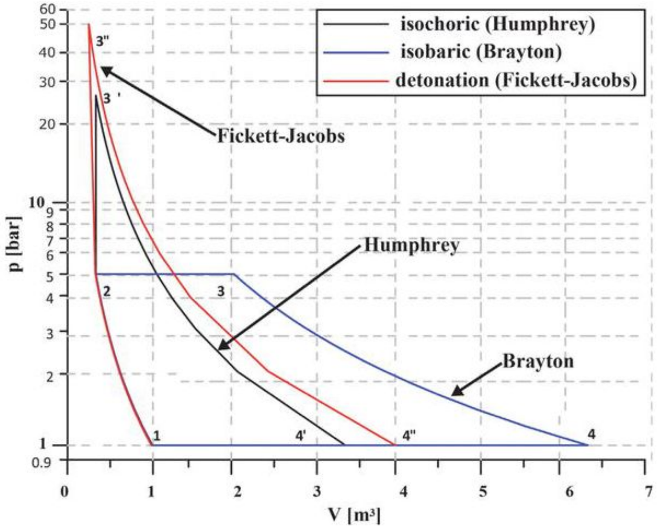

Figure: PV Diagram Comparing Brayton, Humphrey and Fickett-Jacobs Cycles [1].

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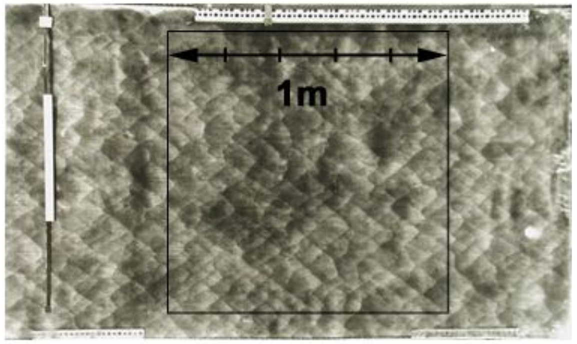
Technical Overview - Theory

- Detonation Cell Size very important parameter for achieving detonation.
  - Geometry too small, detonation structure cannot form

    i- **$D_{critical} = \lambda/\pi$** [5]

- 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 [3]



Original sooted foil
The square limit indicates the cropped region used to compute the cell size.

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

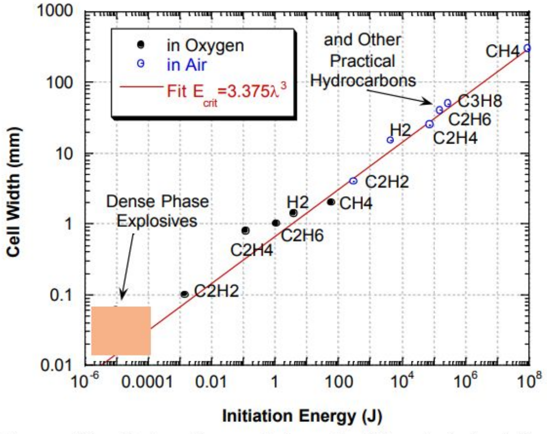


Figure: Plot of Cell Width and Initiation Energy [4]

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Technical Overview - Design Specifications

Thrust Class: **1350N**

Fuel: **Hydrogen (gaseous)**

Oxidizer: **Oxygen (gaseous)**

Hot-Fire Run-Time: **⩾ 1 second**

Injection Type: **Non-premixed**

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

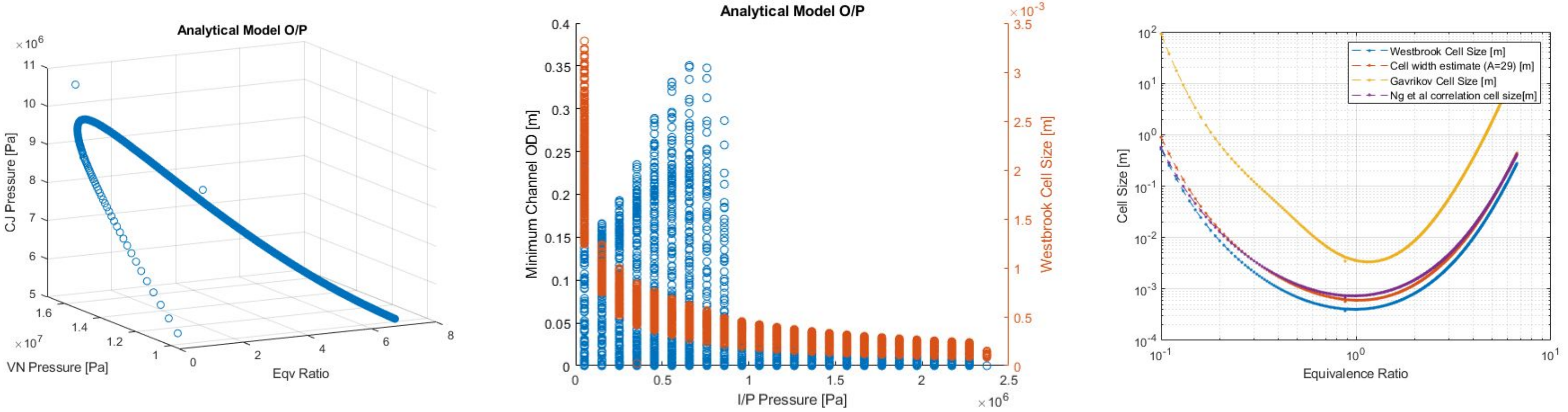
Maximum Expected Temperature: **3900K**

Maximum Expected Pressure: **4 MPa**

Back Pressure: **101.325 kPa**

Analytical Model - Design Optimization

- Analyzing critical operation parameter from a full factorial numerical experiment for a 1350N 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)

P&ID

- Size 44 compressed gas cylinders
- Swagelok plumbing feeds the engine and DDTT

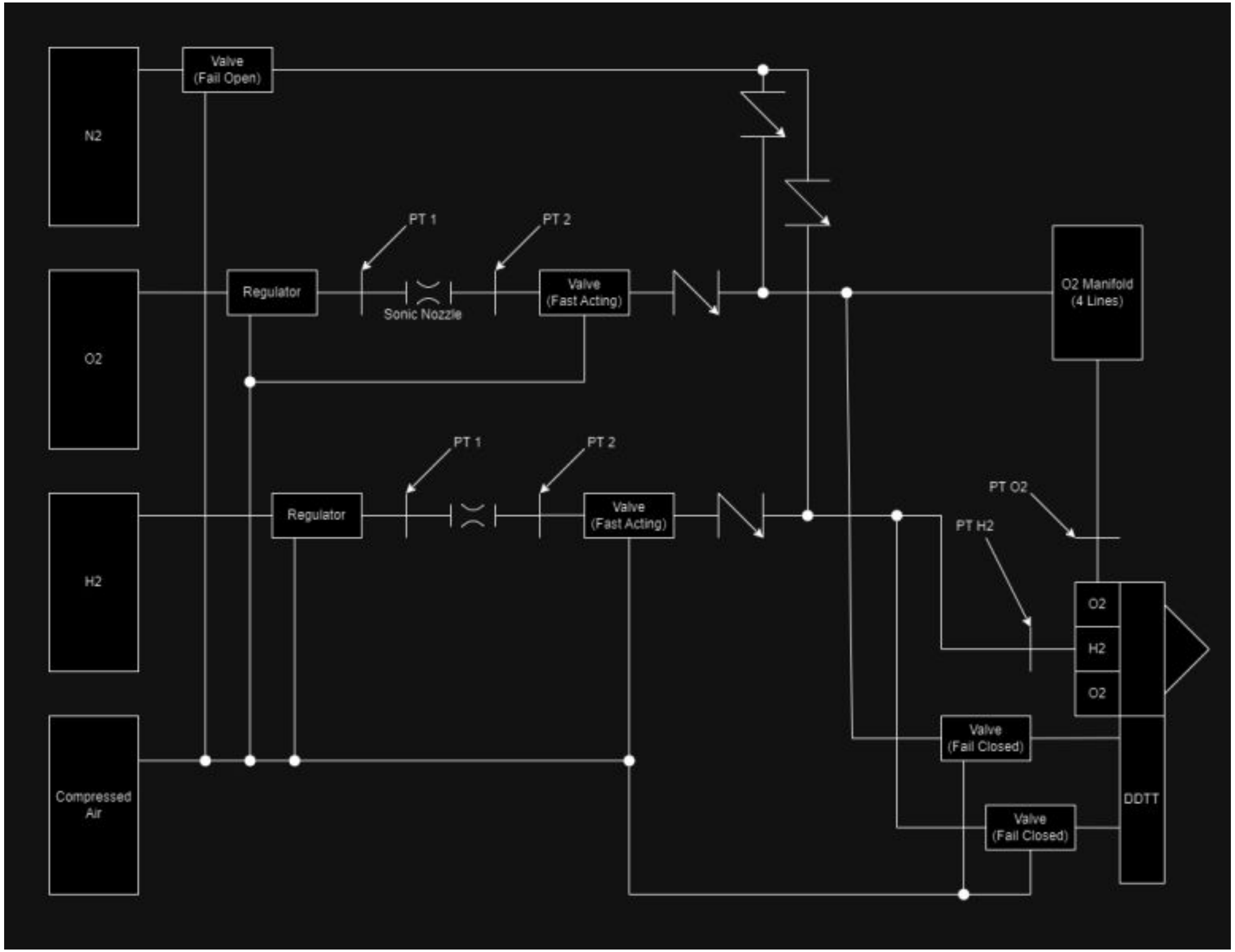


Figure: *Current conceptual P&ID*

Safety Measures

- Propellant supply/injection systems
  - 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.
  - Piping system, propellant tanks, and thrust stand are all grounded [12].
  - Piping will be purged before and after all propellant feeding [12].
  - Piping and fittings must cleaned to remove all burrs or surface defects [12].
- Hands-free engine operation
  - Fast acting, fail closed valves selected for propellant and fast-acting fail open valve selected for Nitrogen supply line [12].
  - 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 [12].
- 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.
  - Forced ventilation through test-stand container [12].
  - Spark proof tools will be used [12].
  - Electrical and flame producing systems banned from operating in active test zone [12].

Current RDRE Technology Limitations

Current Research focus

- 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).

Limitations

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

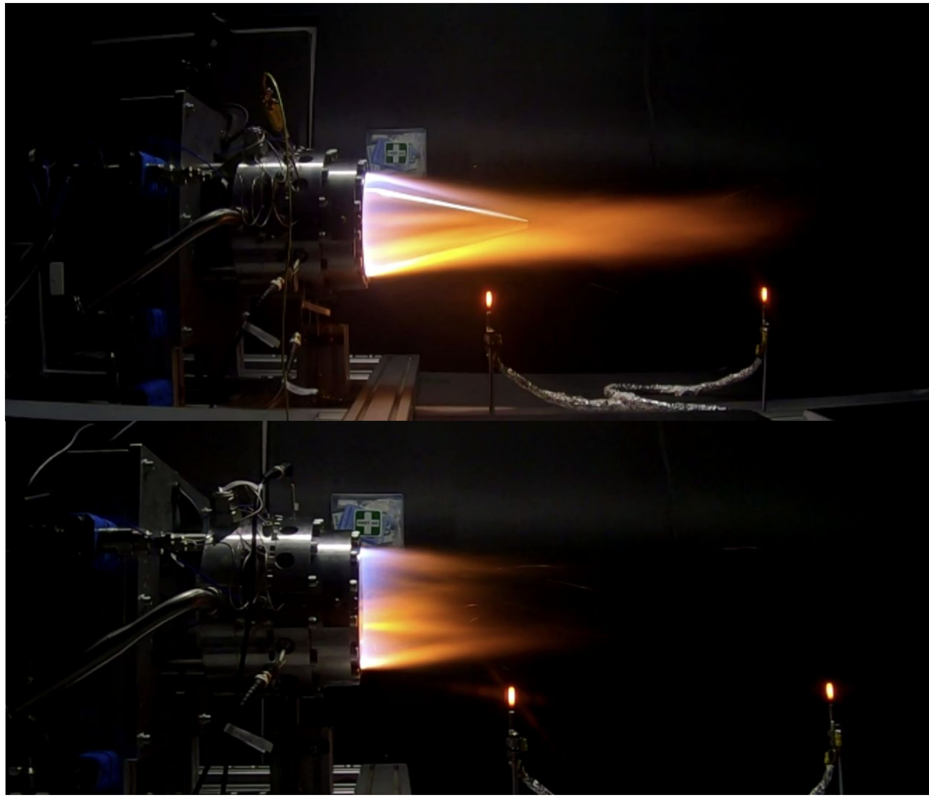


Figure: DefendTex RDRE with and without Aerospike [1].

[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.).