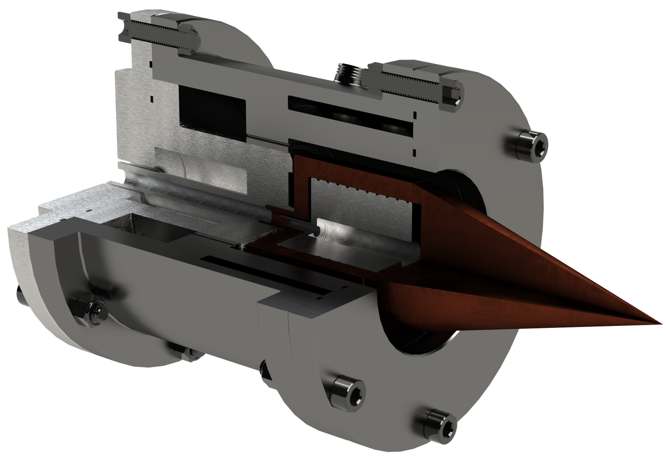
# Memorial University of Newfoundland

# Faculty of Engineering and Applied Science



Report Three: Final Term Report

ME 7704

**Rotating Detonation Engine**


**Put forward by:**

*DETechnologies*

| | |
|---|---|
| Shakib Miri | 201848900 |
| Logan Palmer | 201906765 |
| Patrick Cleary | 201901261 |
| Aidan Clark | 201919990 |


**Submitted for review by:**

Professor Mihiran Galagedarage Don

Dr. Nakhla

**Submitted on:**

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# Abstract

The DETechnologies (Detonation Engine Technologies, DET) team has successfully completed the first phase of this project, which involved conducting an in-depth literature review on detonation theory, combustion thermodynamics, injector design, wave stability analysis, and detonation control theory in order to develop and deliver an initial defined engine geometry, that could then be iterated over using computational fluid dynamics (CFD). In addition to initial engine geometry, a simulation model that yields convergence when solving was also identified as an end-of-term deliverable.

To develop the selected initial geometry, the engineering design process steps were employed. The project scope, and problem were identified, then requirements and constraints followed. The first iteration loop subsequently occurred where the analytical model was created. This analytical model is where the basic engine parameters were planned to be generated. Unfortunately, the calculated values from the analytical model aligned poorly with those of the published documentation, therefore rules of thumb and the minimum detonation cell size (1.75 mm) were used to generate the initial engine geometry. Further refinement comes in project phase 2 where CFD simulation will be used as an optimization tool. An input file for a 2-Dimensional "unwrapped" rotating detonation engine model supplied by a sponsor company, Convergent Science,was used as the basis of the simulation model to be employed by DET. This model was checked for convergence upon receival, and it has been determined that using the supplied inputs, a simulation case will converge.

From the rules-of-thumb and minimum detonation cell size, the current major engine diameters are: 115 mm long, 81.2 mm outer body diameter, 40.6 mm center body diameter, 8.4 mm combustion chamber/exhaust duct width, and 0.5 mm propellant injection orifices. This small scale model will also be equipped with exit nozzle features, and internal cooling cavities. It will be mostly modular in nature, allowing for component changing down the road or part inspection after engine hot-firing.

# Table of Contents

# 1.0 | Introduction

The detailed design for the functional Rotating Detonation Engine (RDE) will outline the design work to date for the RDE, which includes the chemical and thermodynamic analyses, input-to-output parameter relation development, injection design, CFD model validation and preliminary engine geometry. This report will begin with a summary of the previous works submitted [1][30], which then leads into the bulk of the report, which discusses the current status of the iterative development of engine geometric parameters through CFD studies.

## 1.1 | Rationale

This project addresses the limitations of traditional rocket engines used in space exploration, specifically their efficiency and specific impulse. Traditional deflagration rocket engines have low efficiency and specific impulse, meaning that a significant amount of propellant mass is not converted into thrust, which limits the capabilities of spacecraft and space missions.

Researchers have been exploring alternative propulsion systems, and one promising technology is the Rotating Detonation Engine (RDE). RDEs operate based on the principle of detonation, a supersonic combustion process that allows for higher thermodynamic efficiencies and specific impulses.

This project aims to aid the research and development ecosystem regarding rotating detonation engine development. By synthesizing published design parameters and operational information, work can be done to build an engine to validate and experiment with theoretical operational parameters.

## 1.2 | Constraints

The biggest constraint for this project involves the dangers of flammable propellants and their respective handling and storage guidelines. The RDE being designed uses Hydrogen gas ($H_2$)

and Oxygen gas ($O_2$) as the propellant mixture, both inherently dangerous gasses. Careful considerations must be used while handling these gasses during testing, and all necessary Safety Operating Procedures (SOPs) will be developed and followed. Additional constraints of this project include financial limitations, as materials, propellant, high-pressure pipe fittings and custom components are expected to be a significant cost.

Time is another major constraint for this project. The topic of RDE development, or even general engine development, is broad and deep, and there is a lot that can be done in the research space. Ensuring there is no scope creep or tunnel vision focus on a particular aspect of the development will be imperative that project deliverables proceed as scheduled. This can be done by having explicitly defined goals and objectives, as well as a proportionally detailed timeline that breaks down the project progression. These time management tools are notwithstanding any unexpected issues or roadblocks that occur during the project.

The last major constraint for the project is budget. As it stands during phase 1, there has only been $5000 CAD secured. The engine fabrication cost will be approximately $15000 CAD, and the testing will be approximately another $15000 CAD, not including any in-kind donations/sponsorships that can be secured from organizations. An extensive plan and outreach campaign will be conducted to attempt to raise the necessary funds, however, if these funds cannot be secured, then the project will have to fall short of its original final deliverable and goal.

# 2.0 | Concept Generation

The following concept generation discussion is based on the preliminary decision to investigate detonation propulsion systems. An RDE is chosen as the starting point because of its ability to generate effectively continuous thrust compared to other types of detonation propulsion engines. This preliminary design realm reduces the project scope according to the team's interests. Working with the baseline of an RDE system, the following morph chart is built to further narrow in on the final concept design.

***Table 1***: *Decision making morphological chart to assist with concept selection with high level sub-function breakdown of an RDE.*

| Feature | Solution 1 | Solution 2 |
|---|---|---|
| *Initiation* | Injection of pre-formed shock wave | Internal sparking |
| *Continuous Detonation* | Circular combustion chamber | Non-circular (curved) combustion chamber |
| *Injection Direction* | Axial | Axial + Radial |
| *Injection Scheme* | Pre-mixed | Non-pre-mixed |
| *Propellant* | Gas | Liquid |
| *Exhaust Outlet* | Blunt | Nozzle |

There are two ways that combustion can be initiated, either directly in the engine's combustion chamber or in a secondary combustion chamber. Given how both ignition methods have been investigated and tested for the application of RDEs, it was deemed necessary to consider both for the design [3][20].

Typically the combustion chamber (and resultant shape) of an RDE is circular; however, some have investigated the validity of non-circular combustion chamber shapes [14]. Since an effective engine that operates is a goal of the project, considering non-traditional geometries could prove advantageous.

A primary objective for propellant injection is to ensure as close to complete mixing as possible for the fuel and oxidizer. Irrespective of the physical space available around the RDE housing, the injection can be achieved by axially feeding fuel and oxidizer [3] or by axially feeding one and radially feeding the other [3].

Along with propellant injection orientation, the way in which propellant is injected is important. Since mixing is a critical factor for achieving efficient combustion, one method to improve the likelihood of achieving efficient combustion is to have the propellant pre-mixed before entering the chamber. Both methods have been successfully employed with research units [3].

In rocket applications, the most common propellant type is liquid due to the need to contain a large mass of otherwise gaseous material in a confined space [24]. A liquid propellant is much more dangerous, expensive, and regulated than simple compressed gas; however, proper research into the matter would be needed to fully characterize the differences between operating with gas propellant and liquid.

Because the detonation occurring within the RDE is still not fully understood, a nozzle is not yet a feature of research engines under development. Some of these engines simply use a blunt exhaust profile [3] instead of a diverging [14] or converging-diverging nozzle [14]. Nozzle effectiveness is not guaranteed, even though the detonation behaviour is theoretically characterized.

# 3.0 | Evaluation and Selection of Concept Design

At a high level, when deliberating the benefits and deficiencies of the various sub-function options, the options that yielded the highest probability of resulting in a working prototype were selected. Performance is maximized where practical, given manufacturing ability, cost, and time limitations. Safety considerations dictate propellant sourcing, storage and handling, and design challenges are chosen carefully to comply with time constraints. Table 8 below summarizes the final chosen concept.

***Table 2****: Summary of chosen design parameters.*

| | **Concept** |
|---|---|
| *Detonation Initiation* | Injection of pre-formed shock wave |
| *Continuous Detonation* | Circular combustion chamber |
| *Injection Direction* | Axial |
| *Injection Scheme* | Non-pre-mixed |
| *Propellant* | Gas |
| *Exhaust Outlet* | Nozzle |

# 4.0 | Estimated Parameters

This section presents and discusses the aspects of the detailed design that included assumptions and simplifications. These results are not to be considered inaccurate, however, some values will be over-estimations of the results observed from experimentation. In addition, values determined in the following subsections will contribute to determining the baseline operating parameters of the engine.

## 4.1 | Ideal, Complete Combustion Reaction

The ideal complete combustion reaction shown below in equation 1 is assumed to be the reaction occurring in the chamber of the RDE. This assumption is made to simplify the chemical reaction and allow for the system to be analyzed accurately [19]. This simplification reduces the reaction complexity by ignoring the trace amounts of air left in the chamber after a complete oxygen purge, ignoring the various dissociation species or extraneous products from the reaction that would result otherwise. The NASA program; Chemical Equilibrium Applications (CEA) exists and has been used for more realistic chemical analysis which DET has requested, and has been granted access to [4][25]. The only potential consequence of this approximation is that the final combustion reaction will not produce as much energy as predicted. Dissociating species in the products will reduce the propagation velocity as they require energy to dissociate [4]. The energy the reaction produces cannot increase, so there is no potential danger in operating the system.

$$2H_{2(g)} + 10_{2(g)} \rightarrow 2H_20_{(g)} + 483kJ$$

***Equation 1:*** *Ideal Combustion Reaction [19].*

## 4.1.1 | Assumptions related to combustion reaction energy output

The energy released from the combustion reaction is directly related to the products and reactants of the equilibrium equation as per equation 2 below:

$$\Delta h_{rxn} = \sum_{P} n_e(\Delta h_e + h^o_{fe}) - \sum_{R} n_i(\Delta h_i + h^o_{fi})$$

***Equation 2**: Chemical reaction energy formula [19].*

The values of $h^o_{fe}$, and $h^o_{fi}$ are documented values, which were acquired from Moran et al. and verified with Argonne National Laboratory's Active Thermochemical Table for this calculation [19][26]. For this analysis, it was concluded that the formation enthalpy of water vapour must be used, as the engine exhaust temperature will be well above the boiling point of the water [7][9]. Utilizing the tabulated values (e.g. Table A-23 Moran et al.) and equation 2, the value of 483kJ is calculated.

## 4.2 | Theoretical Determination of Equivalent Input Density

For this report, "equivalent input density" refers to the density of the mixed propellant. In other words, given the defined operating equivalence ratio and combustion chamber volume, the combined densities of the fuel and oxidizer yield the equivalent input density.

### 4.2.1 | Partial Densities Method

The original approach to calculating the equivalent input density of the reactants was to calculate the partial densities of the reactants individually, and combine them through summation. This approach is simple to understand at a high level, but becomes very complicated as the calculations progress. On the recommendation of course supervisor Dr. Duan, this approach is abandoned in favor of the Partial Specific Volumes approach discussed in the following section.

### 4.2.2 | Partial Specific Volumes Method

Dr. Duan recommended the team use the application of the Ideal Gas Law in conjunction with Dalton's Law of Partial Pressures (Equations 3 and 4, respectively). The partial pressure component is required for calculating the pressure term in the ideal gas law for each species.

$$P_A \nu_A = M_A R T$$

***Equation 3**: The ideal gas law in terms of specific volume and species molar mass, on a species basis [27].*

$$P_{Tot} = P_A + P_B + \ \dots \ + P_N \ ; \ Where \ P_X = \frac{X_X}{X_{Tot}} P_{Tot}$$

***Equation 4**: Dalton's Law of partial pressures [27].*

Upon completion of calculating $P_{Tot}$, the value of $P_{Tot} = 0.4814 kg/m^3$ is calculated.

## 4.3 | Theoretical Determination of $P_{max}$

$P_{max}$ is determined via a Rankine-Hugoniot and Chapman-Jouguet (CJ) theoretical detonation analysis; the basis of this analysis comes from the respective papers from each of these four scientists [5][6][7][8]. The combined theoretical analysis typically performed for detonation systems is summarized in Kuo's Principles of Combustion, Chapter 4, pp 354-437 [4]. The particular aspect of this analysis related to determining $P_{max}$ is finding the point on the Rankine-Hugoniot plot where the Rayleigh line intersects the shockwave Hugoniot curve (see section 5.2.5 for further calculation detail). As proven by NASA [9], corroborated by numerous literature reviews [3] and lectures at esteemed universities [10],, this model is in close agreement with experimental data for detonation. At worst, this model will overestimate expected results. The findings from the literature review establish that this criterion provides an adequate basis for formulating the structural design of an RDE.

## 4.4 | Theoretical Determination of $T_{max}$

To determine the flame temperature of a combustion reaction, the energy equation at steady state is to be considered.

$$\frac{\dot{Q}_{cv}}{\dot{n}_F} - \frac{\dot{W}_{cv}}{\dot{n}_F} = \sum_P n_e(\bar{h}_f^\circ + \Delta\bar{h})_e - \sum_R n_i(\bar{h}_f^\circ + \Delta\bar{h})_i$$

***Equation 5**: Complete, simplified energy balance equation for an open system [19].*

For an open system undergoing a combustion reaction, the difference in heat and work per mole of fuel equals the difference between enthalpy summations of the products and reactants, respectively (Equation 5). Since the temperature of the reaction comes into play with the $Q$, $W$, and $\Delta h$ terms, if the open system is assumed to do no work and be adiabatic, the flame temperature would be maximized [19]. This idealization is what is known as the Adiabatic Flame Temperature (AFT). This temperature is the theoretical absolute maximum temperature a combustion reactor could achieve. The run time of the engine has to be determined such that the engine housing will not be allowed to reach its melting temperature and cause catastrophic failure. Using an overestimation for the run-time analysis will mean the operating system reaches a higher steady state faster, so the analysis results will ensure the engine is not accidentally run to the point of melting.

Applying the assumptions described above and rearranging the enthalpy summations to isolate for the $\Delta h_{Products}$ term, equation 6 is employed.

$$\sum_P n_e(\Delta\bar{h})_e = \sum_R n_i(\Delta\bar{h})_i + \sum_R n_i\bar{h}_{fi}^\circ - \sum_P n_e\bar{h}_{fe}^\circ$$

***Equation 6**: Simplified and rearranged energy equation for an open system in combustion, isolated for the change in enthalpy of the products [19].*

To solve equation 6, the moles of each product and reactant are taken from the balanced chemical equilibrium equation, and the enthalpy of formations can be read from standardized tables (e.g. Table A-25 of Moran et al. [19]). The $\Delta h$ terms, the reactant states should be known so the specific enthalpies can be acquired from standardized tables (e.g. Table A-23 of Moran et al. [19]). Usually, reactions have more than one product; therefore iteration is required to produce a solution from the AFT. An initial guess is made of the AFT, the corresponding product enthalpies are found, the left and right sides of the equation are calculated, respectively, and their results are compared. The iteration process continues until both sides are equal (within a specified tolerance).The complete ideal combustion reaction being considered for this project only has one product, a non-traditional approach was taken to solve the AFT. The $\Delta h_{Products}$ was explicitly solved for, and then that resultant value was subsequently used to find a corresponding temperature, which would be the AFT. It should be noted that Table-23 of Moran et al. was used for the calculations, and the table did not go up to the magnitude of the calculated $\Delta h_{Products}$, therefore the AFT was found by applying an approximate interpolation based on a pattern observed in the table.

# 5.0 | Detailed Design

This section is broken down into subsections analyzing the steps of the detailed design process that would result in realistic parameters due to a lack of assumptions and equation simplifications. Like Section 4.0, each subsection below is a component of the analytical model that will yield baseline operating parameters to use as the initial design point for further numerical simulation and iterations.

## 5.1 | Analysis Process Summary

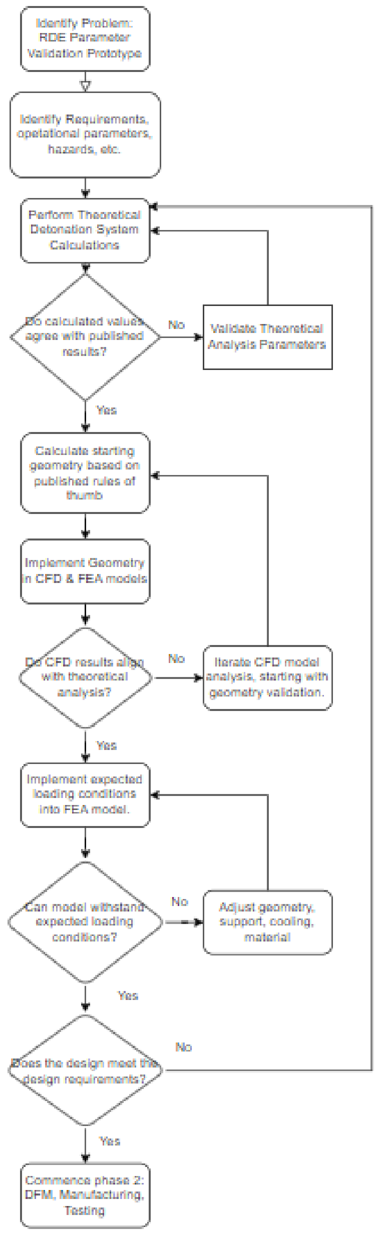


***Figure 1***: *RDE Design Process Flowchart.*

The design process flowchart shown in Figure 1 breaks down the specific steps involved in this design process. The dependencies between each analysis element is shown clearly, reading from top to bottom. There are three main design iteration loops, and one overall iteration loop, as shown by the four decision blocks. Moving beyond each iteration loop is considered a major milestone in terms of design progress.

Completing analytical model calculations is the first iteration loop. This loop ensures reasonable agreement between analytical calculations and published calculations.

The second iteration loop is the completion of the CFD numerical analysis. This loop finalizes the working parameters of this engine; primarily the combustion chamber thickness, engine length, flow rates, pressures, and DDTT initiation.

The third iteration loop is the completion of FEA modelling. This loop determines structural parameters such as required hoop strength. The parameters optimized in this phase are to support the engine and ensure longevity. These parameters do not affect the functionality of the engine.

Finally, a validation check is done to ensure that the chosen design does indeed meet the initial design requirements of this engine, before moving into the manufacturing phase.

## 5.2 | Analysis Process Breakdown

### 5.2.1 | Implementation of Rankine-Hugoniot, and Chapman-Jouguet analysis

Considering the level of complexity of the formulation of the Hugoniot lines, several different variations of the same formulae are plotted against one another to confirm that no analytical implementation mistakes are made. Rearranging the Rankine-Hugoniot ([4][16][20]) relation by hand was the initial method to determine an explicit expression for graphing. This formulation was then validated using an equation presented in Kuo's text [4]; methods 0 and 1 respectively.

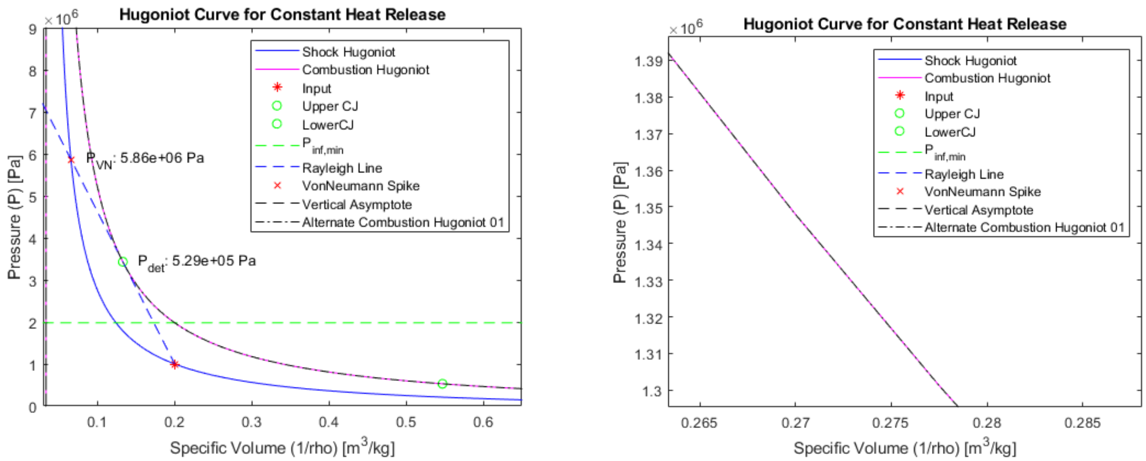


***Figure 2:*** *Hugoniot Plotting Validation. Note: other input parameters have changed since this graph was generated.*

### 5.2.2 | Equivalent Specific Heat Ratio

The equivalent specific heat ratio of the system, $\gamma$ is approximated to be 1.4, as the specific heat ratios of Oxygen and Hydrogen are 1.40 and 1.41, respectively [13]. In addition, the product-specific heat ratio (water vapour) is 1.33 [21]. Varying the specific heat ratio in the equations for calculating the pressure Hugoniot lines between 1.40 and 1.41 has a negligible effect on the calculated pressure for $P_{D, Max}$ and $P_{VN, Max}$.

### 5.2.3 | Identifying Chapman-Jouguet points

From a fundamental standpoint, the Chapman-Jouguet (CJ) points are the only two points on the combustion Hugoniot whose tangential line extends through the initial input point on the shock Hugoniot. The upper CJ (UCJ) point is defined as the CJ point with higher pressure; conversely, the lower CJ (LCJ) point is the lower pressure.

Two methods are employed to calculate and validate the location of both CJ points. The first method is derived from a lecture series by Dr. S. R. Chakravarthy [15]. The final equations derived in this lecture series to calculate the pressures and specific volume of the CJ points, are shown below in Figure 4.

- Subbing (1)/(1.1) into Rankine-Hugoniot relation and solving the quadratic gives: $p_{\infty,\pm} = p_o + (\gamma - 1)q\rho_o\{1 \pm [1 + \frac{2\gamma p_o}{q\rho_o(\gamma^2-1)}]^{1/2}\}$ (2) or

$(\frac{1}{\rho_\infty})_\pm = \frac{1}{\rho_o} + \frac{\gamma-1}{\gamma}\frac{q}{p_o}\{1 \mp [1 + \frac{2\gamma p_o}{q\rho_o(\gamma^2-1)}]^{1/2}\}$ (2.2)

  - Those equations are for the coordinates of the upper (+) and lower (-) CJ points.

***Figure 3****: Equations used to calculate CJ Points [15].*

The second method is developed by the team according to the fundamental principles defining the CJ points. By iteratively selecting each discrete point along the combustion Hugoniot and calculating the tangent slope, along with the slope of a line connecting the input point to that position, a point very close to the CJ points can be identified. These two slopes are compared, and at the locations with minimal difference between them are identified as the two CJ points. Although this method is more computationally taxing, it agrees with the CJ points identified using the explicit method with sufficient accuracy.

### 5.2.4 | Von-Neumann Spike, $P_{VN, Max}$

The Von-Neumann (VN) spike is defined as the maximum pressure observed in a detonation wavefront [4]. This point is produced by the leading shockwave preceding the combustion wave within the detonation wave [4][15]. Regarding the Rankine-Hugoniot plot, the Von-Neumann spike is the pressure on the shock Hugoniot at which the upper Rayleigh line intersects. As per a discussion in Dr. Chakravarthy's lecture series, the observed detonation in real systems will align with that of the CJ condition; therefore, the Rayleigh line will always be the line tangent to the UCJ; therefore, this method relies on the previously established upper CJ point [15]. A graphical Matlab method of finding line intersections determines the intersection point between the

Rayleigh line and the shock Hugoniot. The entire output plot, showing the Rayleigh line and VN spike, is shown in Figure 4 below.

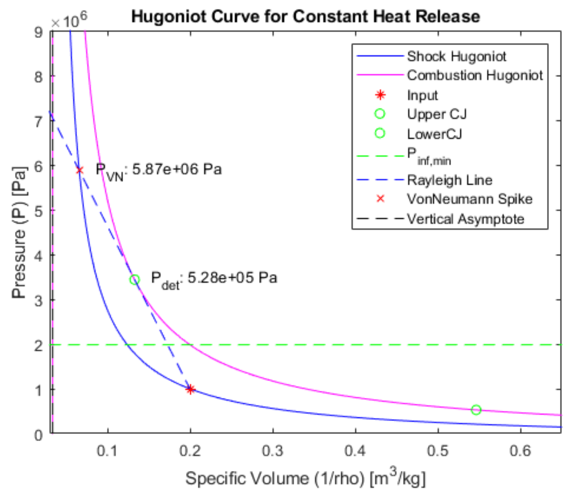


***Figure 4***: *Work In Progress Hugoniot Plot Showing Rayleigh Line and VN Spike ($P_{VN}$).*

## 5.2.5 | Determining Deflagration-to-Detonation Tube Parameters

The Deflagration-to-Detonation Transition Tube (DDTT) geometry must be carefully considered to ensure there is a detonation wave produced at the tube exit. The primary purpose of the DDTT is to accelerate the subsonic deflagration front into a supersonic detonation front (through the mechanism of confining a dense combustive mixture). The resulting detonation wave from the DDTT can be injected into the combustion chamber of the RDE, becoming the self-sustaining rotating wave by feeding on the propellant. The main concern in the DDTT design is the overall length, which is the main factor in ensuring the deflagration to detonation transition can occur.

To design the DDTT to a suitable length, a literature review and simulation using Ansys Fluent has been conducted, leading to a high-confidence DDTT design. The literature review has revealed that, as a general rule, a DDTT length of ten times the tube diameter yields sufficient distance to complete the transition [22].

Another important factor of the DDTT is the propellant mixing within the tube following injection. To assume near-ideal mixing, several internal geometries can be implemented to induce mixing. Commonly, a Shchelkin spiral can be used, which both mixes propellant and accelerates the DDT time. This spiral geometry is generally only implemented for a section of the tube; however, validation of the total spiral length concerning the tube length will be conducted using simulation. In addition to implementing a Shchelkin spiral, several geometries at the propellant inlet can be modified, and different spark timing options can be used to improve transition performance. As per several research studies, these parameters show promising results in simulation models; however, limited experimental evidence supports these results [28][29].

### 5.2.6 | Propellant Injection

Effective injection of the fuel and oxidizer is crucial for the performance and efficiency of the RDE. Injector design is difficult due to the complex relationships between mass flow rates, fuel injection area, injection velocities, specific impulse and thrust, but there have been consistent methods across simulations and real-world models [3]. Figure 6 shows a cross-section of a typical RDE.

The injection system consists of oxidizer feed in the center of the engine and the fuel feed lines further out radially. The fuel and oxidizer are fed axially from supply lines into their respective plenums or manifolds, as labelled in the diagram, and are then mixed in the annular combustion chamber. This injection method will be the basis of the groups RDE and parameters such as the slot width of the oxidizer inlet, injection hole diameter, the number of injection holes area, plenum pressure, flow velocity and mass flow rate will be refined based on the simulated results through Converge CFD of propellant mixing, thrust performance, and operating temperature and pressure. The final design of the injection system is highly dependent on the results from the analysis run through Converge CFD.

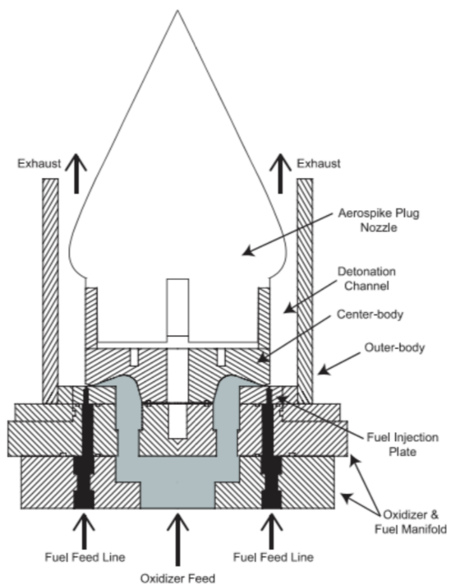


***Figure 6****: Cross section of a typical RDE [16]*

The term "injector" for this RDE strictly refers to the configuration and geometry of the fuel and oxidizer plenums and inlets.

# 6.0 | Mock-Up Development

## 6.1 | Computer Aided Design

The computer aided design (CAD) model was created using SOLIDWORKS. Figure 7 shows a high level drawing of the master assembly outlining the major dimensions and components. The bill of materials (BOM) table in the drawing is only highlighting the major components that comprise the RDE and require custom fabrication. Items such as fasteners, o-ring seals and plumbing (hose/tube fittings/Swageloks) are excluded from this drawing. The components listed are the external housing, aerospike, end cap, plenum body, centre body, coolant cap and centre body cooling tube. The complete drawing package has been submitted to the corresponding course drop box.

The RDE is based on the model created by Hansmetzger et al. [38] which utilizes injection slots for the fuel and oxidizer. The injection slots are clearances between the external housing and plenum body for the fuel injection, and the plenum body and centre body for the oxidizer. This makes manufacturing faster and easier because it eliminates drilling and reaming  a large number of small diameter (~1 mm) holes. Unlike the model by Hansmetzger et al., DET's RDE has a cooling system consisting of a continuous flow of coolant, water, glycol or oil. The cooling system consists of two separate flows of coolant through two separate channels. One channel in the external housing to cool the outer walls of the combustion chamber and another through the centre of the engine that cools the centre body and inner combustion chamber walls.

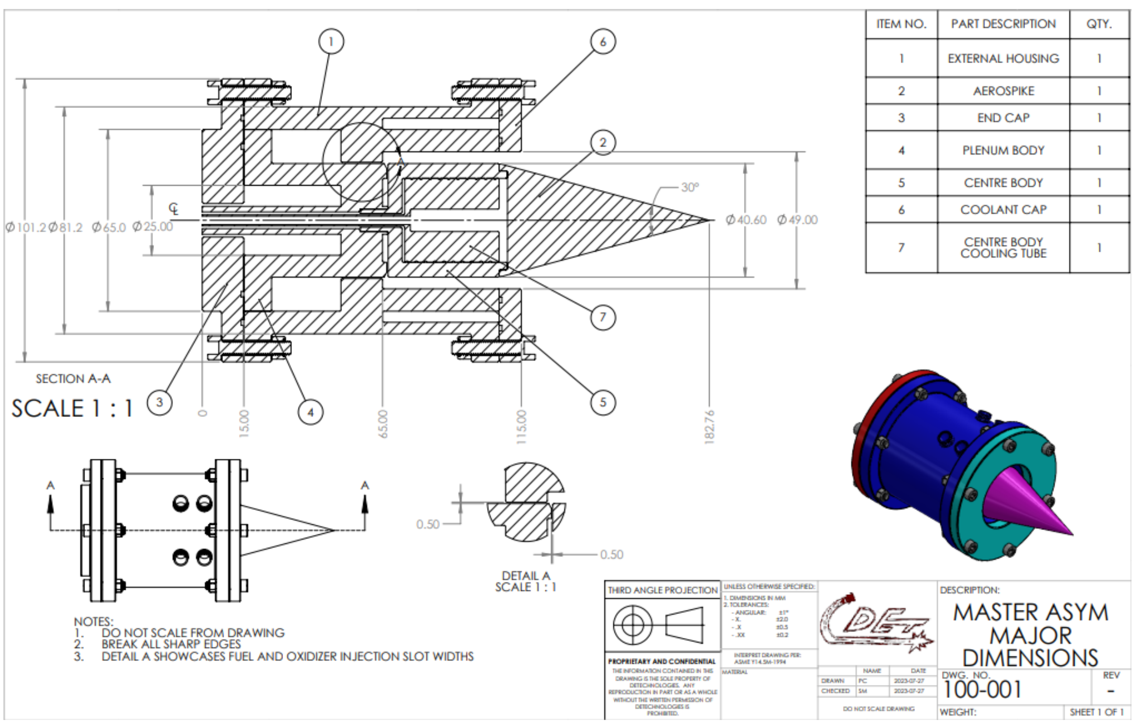


***Figure 7:*** *High-level assembly drawing depicting the major components and dimensions of the initial RDE geometry.*

## 6.2 | Simulation

The RDE and the DDTT simulation is being conducted using Convergent Science's CONVERGE CFD, designed explicitly for combustion simulations. Both models are two-dimensional to ensure solutions can be obtained in a reasonable period of time.

Convergent Science believes that examining residuals for transient simulations does not provide value, therefore this data is not available for analysis [31]. Instead of examining convergence criteria, expected simulation outputs will be examined to ensure a successful model and case setup has been achieved. Although this is only the first model, without any iteration, it is important to note that further refinement will take place so that a better understanding of the engine dynamics can be achieved.

### 6.2.1 | RDE Simulation

The RDE simulation uses a two-dimensional (2-D) model obtained from Convergent Science, which has been altered to meet the operational parameters for the hydrogen-oxygen RDE designed by DET. The below figure shows the simulation setup with each region. This simulation model is designed to simulate a cylindrical geometry which has been flattened into 2-D. To ensure this is an accurate representation, when the detonation wave reaches the far left side of the screen, it will reappear on the right side of the screen.

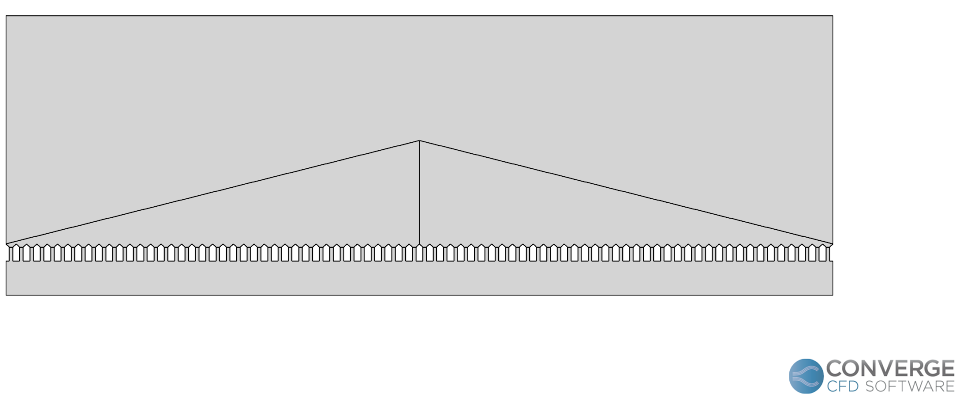


***Figure 8:*** *2-D RDE Simulation Geometry [37].*

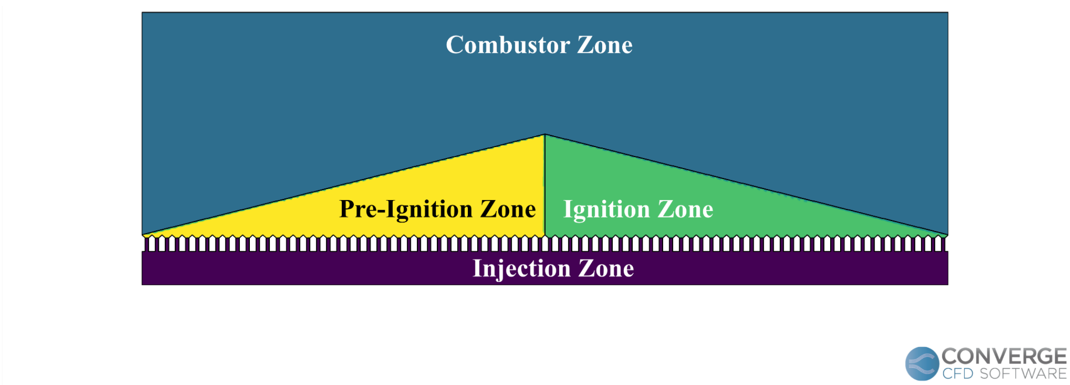


***Figure 9:*** *2-D RDE Simulation Zone Identification [37].*

The geometry of the 2-D RDE is designed to simulate a pre-detonator, therefore, ignition and pre-ignition zones are used to create high and low pressure zones which initiates the wave propagation. Once the wave has been started, it will continue upon continued injection. The additional zones identified above include the combustor zone and the injection zone which are primarily used to ensure the CFD model simulates the desired effects. The combustor zone is at atmospheric pressure, and filled with air. The injection zone is at the desired injection pressure and at ambient temperature.

***Table 3:*** *Key Simulation Input Parameters.*

| | |
|---|---|
| **Equation of State** | Steady State |
| **Turbulence Model** | Large Eddy Simulation (LES) |
| **Simulation Run Time** | 0.0 - 3.0 ms |
| **Time Step** | 1.0 ps |
| **Fuel Mass Fraction** | 10.66 % |
| **Oxidizer Mass Fraction** | 89.34 % |
| **Injection Pressure** | 1.101325 MPa |
| **Injection Velocity** | 800 m/s |

| | |
|---|---|
| **Ambient Temperature** | 300 K |
| **Ignition Temperature** | 2400 K |

To ensure the model has been set up and computed properly, key engine performance indicators will be examined. Obtaining reasonable and expected results from the simulation is a good indicator that the model is correct, and will provide accurate results.

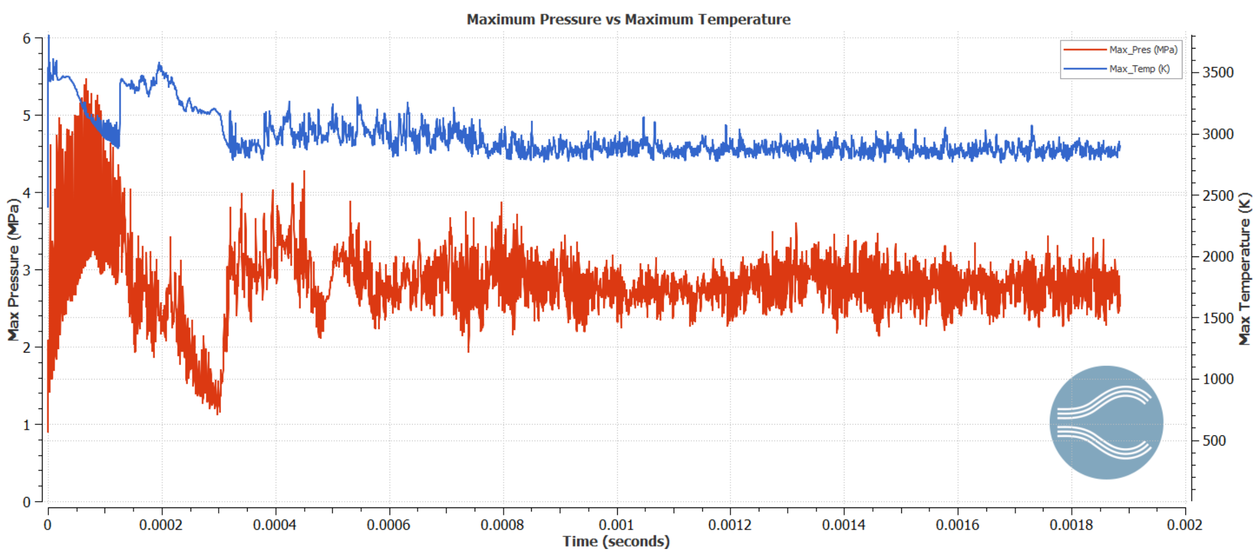


***Figure 10:*** *Maximum Pressure vs Maximum Temperature [37].*

### 6.2.2 | Deflagration to Detonation Simulation

Similar to the RDE simulation, the Deflagration to Detonation (DDTT) simulation will use a simplified 2-D geometry representation. This model will be initialized with an oxidizer and fuel which will be ignited using a high-temperature zone to induce combustion. The key area of interest within the DDTT simulation model will be the wave speed at the end of the tube. For a DDTT to function properly, the wave at the exit must be in supersonic regime [14]. This supersonic wave will ensure that the RDE is operating with a detonation wave - which is required for proper operation.

***Table 4:*** *Key Simulation Input Parameters.*

| | |
|---|---|
| **Simulation Run Time** | 0.0 - 3.0 ms |
| **Time Step** | 1.0 ps |
| **Fuel Mass Fraction** | 10.66 % |
| **Oxidizer Mass Fraction** | 89.34 % |
| **DDT Tube Diameter** | 6 mm |
| **DDT Tube Length (Initial)** | 60 mm |
| **Ambient Temperature** | 300 K |
| **Ignition Temperature** | 2400 K |

It is important to note that although this simulation has been set up, due to current constraints and access to computational resources, this model has not yet been run - therefore, no results will be analyzed in this report.

Following initial simulation setup, the DDTT will undergo a geometry investigation to ensure the length allows for sufficient space to transition from deflagration to detonation. In addition to considering the tube length is sufficient, DDT tubes generally benefit from the addition of obstructions to facilitate the transition in a shorter amount of space.

## 6.3 | Manufacturing Plan

DET will utilize the MUN Engineering Student Machine shop and Technical Services for the bulk of the manufacturing. If the scenario should arise that neither the Student Machine Shop or Technical Services does not have the means to fabricate a part, DET will hire an external fabrication shop for these parts. The members of DET have experience with contracting local private shops for work and have the means to ensure quality and the ability to quality check their work.

The bulk of the parts should be able to be manufactured in the Student Machine Shop with the computer numerically controlled (CNC) milling machine and lathe, as well as the manual milling machine and lathe. The CNC lathe is expected to be up and running at the end of August. The geometries of the parts are all cylindrical and non-complex. With the proper setup and computer aided manufacturing (CAM) procedures the parts can be made efficiently and effectively.

Engine fabrication will begin in October once the iterative design has been completed and enough funding has been secured.

# 7.0 | Funding

Monetary support is a major aspect of this project that has thus far been underreported. The most recent budget estimate is $53,000, tabulated in Table 5 below, a fairly significant amount of money for any project to obtain. To cover the expenses incurred throughout the duration of this project, the team has embarked on several sponsorship outreach activities.

***Table 5:*** *Detailed Budget Breakdown.*

| Category | Description | Cost | Urgency |
|---|---|---|---|
| Engine Design | Software Access to ConvergeCFD<br>(Annual license quoted) | $ 20,000.00 | High |
| Engine Design | Accessing Google Cloud Computing services for 60 hours of simulation run time. | $ 1,000.00 | High |

| | | | |
|---|---|---|---|
| Fabrication | Material Acquisition (excl. propellants) | $ 7,000.00 | Medium |
| Fabrication | Machining time | $ 5,000.00 | Medium |
| Fabrication | Off the shelf components (high-pressure fittings, piping, etc.) | $ 6,000.00 | Medium |
| Fabrication | Electronics (controllers, DAQ, sensors, etc.) | $ 3,000.00 | Medium |
| Testing | Propellant acquisition | $ 5,000.00 | Low |
| Testing | Renting a 20,000 FPS camera | $ 1,000.00 | Low |
| Testing | Renting sufficient location for testing | $ 2,000.00 | Low |
| Testing | Safety Equipment | $ 3,000.00 | Low |
| | **Total:** | **$ 53,000.00** | |

## 7.1 | Funding Materials

In order to appear as professional as possible, the DET team has put effort into preparing various generalized funding materials which can be provided to potential sponsors. These funding materials are designed to give a quick overview of the project and our objectives for the final product. The main funding materials that the team has prepared are;

- Sponsorship Package - shown in Appendix 1
- Professional Logo, draft shown in the upper right hand corner of this document.
- Website (under development): www.detechnologies.ca, similar to www.memorialbaja.ca

- Custom email address requested from MUN: det@mun.ca

Together, these documents will allow the team to present ourselves in a professional manner, instilling confidence in potential sponsors that we are prepared to work diligently and professionally towards our final design.

## 7.2 | Closed Funding Opportunities

As of present, the DET team has successfully worked with Convergent Science to obtain a sponsorship in the form of software access to their CONVERGE CFD program. Accessing CONVERGE CFD is an instrumental sponsorship of this project. The Convergent Science team has also agreed to allow us to access their unwrapped RDE model to use as a starting point for our simulations.

Another significant funding source for the team is the A. Bruneau Life Fund, of which the team has submitted a funding proposal, and were awarded a sum of money to use towards continued development of the engine [32]. This funding is generally awarded to student teams working towards a competition, through the supervision of the Student Design Hub (SDH) [32]. In collaboration with Dr. De Silva, and Mr. John Walsh, the DET team has agreed to make an effort towards the end of Term 8 to instill interest in a rocketry based student team, in exchange for continued support by the SDH.

The National Research Council of Canada (NRCC) Oceans, Coasts, and Rivers Engineering (OCRE) Center has been contacted and has generously agreed to support the DET team by providing access to testing equipment. Equipment that will be made available through this agreement include high-speed cameras, DAQ systems and analysis software, and access to knowledgeable researchers and technical staff.

## 7.3 | Open Funding Opportunities

There are several funding sources which the team is currently investigating. The following subsections break down the current status for each funding source under consideration.

### 7.3.1 | Regional Development Fund

The Regional Development Fund (RDF) is a funding program through the Provincial Government of Newfoundland, which is designed to provide non-repayable contributions to organizations for the development and implementation of economic initiatives with respect to regional and sectoral development [33]. The DET team has previously received funding through the RDF program through other Student Team involvements at MUN. After successful discussions with the RDF representatives; there is a high probability of moving forward with a sponsorship through this fund. There is a thorough RDF application process that the DET team is in the process of preparing for submission promptly following the conclusion of Academic Term 7 final exams.

### 7.3.2 | ITB Contractor Collaboration

The Industrial and Technological Benefits (ITB) Policy is a Federal Government policy that requires defense procurement contractors to meet certain obligations geared towards supporting the long term sustainability and growth of Canada's defense sector [34]. There are several contractors with open contracts in Canada, who still have significant ITB obligations to be identified, totaling $8.4bn [35]. Through the ITB policy, contractors are required to spend a portion of the contract value within Canada, and a portion on specifically research and development activities [34]. To entice contractors to support post-secondary research projects, multipliers are built into the ITB policy regulations, which allow contractors to provide funding to research projects, and the contribution amount is 'multiplied' correspondingly, reducing their ITB obligation amount significantly [34]. The DET team is planning on sending a series of emails to a large number of defence contractor contacts immediately following the conclusion of

Academic Term 7 (AT7) final exams to begin rounds of discussions about the possibility of supporting this project. A sponsorship package has been generated, which will be supplied to contractors to instill some interest in the project, this sponsorship package can be found in Appendix A.

### 7.3.3 | ACOA AIF Funding

The Atlantic Canada Opportunities Agency (ACOA) has a fund designed specifically to support projects with a high potential for commercialization, which have a significant R&D component, called the Atlantic Innovation Fund (AIF) [36]. The DET team has been in contact with representatives from the ACOA NL office with regards to this project, with little success thus far. The ACOA team has mentioned that the AIF fund is winding down, and that applications are being directed to other similar funds within ACOA. After the AT7 final exams, the plan is to dive deeper into alternative funding sources within ACOA to hopefully find another that fits our project requirements.

### 7.3.4 | Private Sponsorships

Private sponsors will play a significant role in finalizing funding for this project. The DET team is going to utilize existing relationships with local companies, and past work term employers for monetary support. The sponsorship package shown in Appendix 1 will be used as the primary discussion material for these conversations.

# 8.0 | Discussion

## 8.1 | Analytical Model

As introduced in section 4.2, there were assumptions and challenges when calculating the input density of the propellant mixture. Of the two methods attempted, the results resulted in the solutions the team was not confident in, especially since there was over 100% difference (4.98 kg/m^3 vs. 13.8 kg/m^3) between the two values. Without a finalized input density, the Rankine-Hugoniot curve subsequently cannot be finalized, therefore the baseline operating parameters of maximum pressure, operating pressure, and wave speed cannot be determined. In addition, all other calculations that would be directly or indirectly mathematically linked to those combustion parameters could not be calculated (e.g. thrust geometry, or propellant mass flow).

This derivation setback caused the analytical model work to push past its original deadline by two weeks, at which point it was concluded that further work on the model should be suspended, and focus shifted to getting the converging 2D CFD engine model to an operational status.

In hindsight, once discussion with the project supervisor Dr. Duan had occurred, and it looked as though we were going to unable to come to a final conclusion regarding the density calculation, DET should have reached out to other researchers in the field of RDEs, looking for a discussion session regarding the derivation of propellant density as well as insight to the researcher's analytical calculations in general (where non-proprietary). During the engine iteration phase, DET plans to conduct this outreach with the goals of accelerating final design convergence.

## 8.2 | ME 7704

Unfortunately, another set of challenges faced by DET during phase 1 of the project was with respect to the academic course that this phase fell under. The issues experienced revolved around the deliverables and expectations for the project from a grading standpoint. When the term commenced, there was surprise that a two term mechanical engineering (ME 2T) capstone project was being undertaken. There were no deliverables or objectives tailored to the RDE project, and communication between students, instructors and faculty was unclear (nothing appeared ready for the start of the term). Approximately one month of valuable design time was spent trying to communicate the intent and desires of the students and course instructors to the other party, to then result in a framework that was satisfactory for all parties involved. Throughout the process though, it was unclear to DET who were the stakeholders that had to determine the project's term deliverables and objectives. This was only sorted out by the end of the discussions. It was also made clear that the instructors had no guidance from the faculty regarding the expectations for dealing with such a project. In addition, there was minimal course material or grading rubrics tailored to ME 2T projects. While a satisfactory deliverable scheme was started upon based on some absolute bounds for the course, it was determined those absolute bounds incurred too many deliverables that were not seen as useful to project progression, and took valuable time and energy from proper project progression.

The best was made of the situation, and overall everything turned out well for the project, though in the future it would be great if there was more organization and preparedness for the possibility of ME 2T projects, as well as refining the specific deliverables for the course that are expected.

## 8.3 | Engineering Computer Services

With the sponsorship for CONVERGE CFD from Convergent Science, DET sought out the assistance of engineering computer services (ECS) to set up the software license server as well as install the software on various computers on campus. Unfortunately, even after a month of following up and apparent work being done, there were still no results for the team.

After the month of inaction, DET had identified a suitable computer that could function as a license server and solver. DET subsequently dropped ECS' technical service and consulted with Convergent Science directly to have the identified computer setup as the license server and solver.

# 9.0 | Conclusion

At the time of concluding phase 1, the deliverable goals that have been achieved has been the development of a converging 2D unwrapped RDE simulation, and an initial engine design (geometrically). The analytical model completion effort was unsuccessful at this point, though there may be future efforts to complete it. In terms of non-deliverable goals, DET was able to greatly advance member knowledge on detonation theory and RDE design, which is a massive achievement given how the theory is far beyond what is taught in academic courses.

# 10.0 | Future Work

## 10.1 | Phases 2 & 3

The RDE project has only concluded phase 1 of 3, therefore there is still substantial work to be done to bring the project to completion.

The first stage of continuation in phase two will be to use the design of experiments (DOE) method to generate a path for engine optimization through simulation. Instead of using a very rudimentary and tedious simulation method to iterate over all variations of all parameters to find the most ideal configuration, the statistical tools that make up DOE software will be able to use data points to predict system responses, and allow for a faster focus on parameter values regions that will yield the most ideal configuration of the engine.

Once the final design point of the engine has been identified, the next step will be to proceed to design for manufacturing. Individual component drawings will be made for fabrication purposes, and assembly drawings will be made to assist with engine assembly, along with the assembly process plan which will outline the sequential assembly procedure. The fabrication process with these drawings is expected to be completed internally using the Faculty of Engineering & Applied Science's (FEAS) student machine shop and Technical Services. Outsourcing will be done for work that cannot be completed using the tooling available in-house.

In the final phase of this project, individual component evaluation test plans will be developed to ensure that each functional part works as intended. If components fail to meet performance expectations, the cause of failure will be identified, and an evaluation of the standing project timeline will occur to determine the best course of action to meet the testing timeline. Following the component evaluation results, the engine will be assembled and the full test plan and safety operating procedures (SOPs) will be created. These documents will ensure the test experiment can safely proceed and all required data can be collected. Due to the inherent danger of a hydrogen-oxygen combustion reaction, strict safety protocols and advanced test equipment will be required to ensure safety at all times. Phase three will be concluded with the post processing of the engine's experimental test data, collected after the test apparatus has been set up in the test location and the hot-fire test performed.

Securing adequate funding is another imperative task that lies ahead. The team is actively exploring various funding opportunities, including government grants, private investors, and research partnerships, to acquire the necessary resources for building a functional prototype. Collaboration with industry partners and specialized manufacturers will be crucial during the fabrication phase to ensure the accurate realization of the design.

## 10.2 | Lessons Learned

While the entire project has not concluded, there have still been a number of lessons learned identified from completing the first phase. These lessons learned can be considered useful information for other groups that would consider taking on an advanced design project, whether that be engines like na RDE or not.

With respect to the analytical model, two main lessons learned came out of the model development attempt. The first notable lesson is regarding learning. The DET team had to greatly expand and refresh their understanding of RDEs, combustion, chemistry and thermodynamics in order to begin dissecting the problem and develop mathematical models. Learning began with published expensive literature reviews, and research papers. These documents provided an excellent foundation on the state of the RDE technology, and gave an idea of what kind of physics is needed to analytically model an engine, but it was challenging to find a starting point for the mathematics. Eventually, certain textbooks and YouTUbe lectures regarding rocketry design, combustion, and thermodynamics were found and these resources became invaluable sources of formulations. It is highly recommended that reading textbooks, and watching recorded lectures (when appropriately useful ones have been identified) be made a priority in the early literature review.

Continuing with the analytical model, as identified in Section 8, outside sources of technical knowledge (technical experts) should be contacted for possible assistance soon after roadblocks have been faced. It may increase the likelihood of removing the roadblock and learning other valuable information related to the project.

Due to the experience the DET team had with ECS, it is recommended that information technology (IT) resources (e.g. software and licenses) be handled internally by the team on internally held assets where possible, seeking assistance where necessary.

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# 12.0 | Appendix - Sponsorship Package

# DETechnologies

Fifth Year Mechanical Engineering Capstone Project

*Memorial University of Newfoundland Faculty of Engineering and Applied Science*

## Overview

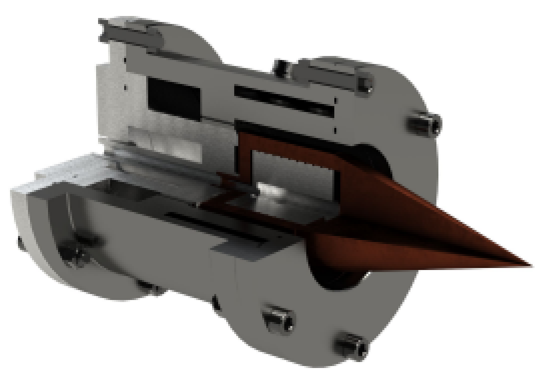
This project aims to contribute to the global research space regarding Rotating Detonation Engine (RDE) development. RDEs have prospective applications as orbital maneuvering thrusters, staged launch vehicle booster engines, missile engines, gas turbine combustors, and supersonic aircraft engines. The goal of this project is to build a modular, liquid cooled, RDE capable of thrust output on the order of 500N.

Our operational objectives are to maximize efficiency, collect comprehensive empirical data, and meticulously document design relations to expected results during the iterative development process. The engine will be designed to be as modular as possible, facilitating future research and development work by students and faculty researchers. Our ultimate aim is to have our work published in full, serving as a valuable reference roadmap for the design, construction, and rigorous testing of Rotating Detonation Engines (RDEs) in research environments.

## Scope & Project Objective

Design, Build and Test a Rotating Detonation Engine

- Gas-Gas, non-premixed, orbital thruster
- Liquid cooled
- Modular
- Design focus on engine structure geometry
- Maximize thrust

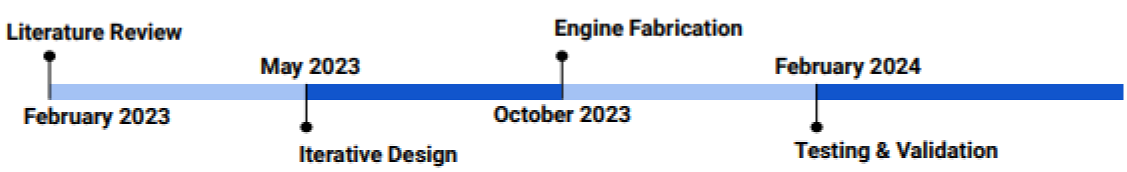


## Areas Requiring Support

Seeking support in the following areas;

- Testing Equipment/Laboratory Space
- Computational Resources for Simulations
- Manufacturing Support
- Financial Support

## Project Timeline



# DETechnologies

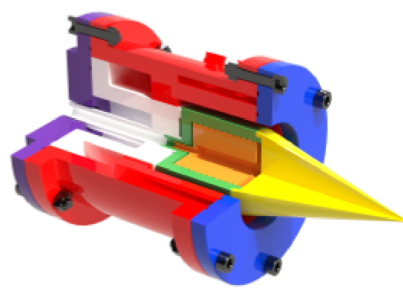
Fifth Year Mechanical Engineering Capstone Project

*Memorial University of Newfoundland Faculty of Engineering and Applied Science*

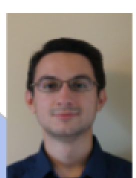
## Sponsorship Levels

| | Platinum<br>$20,000+ | Gold<br>$15,000 | Silver<br>$5,000 | Bronze<br>$1,000 |
|---|---|---|---|---|
| Commemorative 3D Printed Model | ✓ | ✓ | | |
| Investor Event | ✓ | ✓ | ✓ | ✓ |
| Logo Size on Team Gear | Large | Medium | Small | Extra-Small |
| Logo on Website | Large | Medium | Small | Extra-Small |
| Logo Size on Engine | Large | Medium | Small | |
| Framed Thank-You Photo | ✓ | ✓ | ✓ | ✓ |

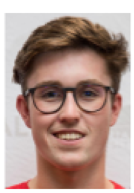
**Contact Us**
det@mun.ca
www.detechnologies.ca



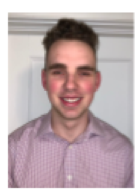
## Meet the Team

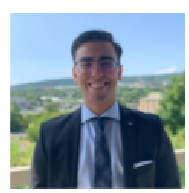
**Shakib Miri**
smiri@mun.ca



**Logan Palmer**
lrpalmer@mun.ca



**Aidan Clark**
amhclark@mun.ca



**Patrick Cleary**
pcleary@mun.ca