The Launch Canada - Initial Design Proposal
DETechnologies
Memorial University of Newfoundland and Labrador

Miri, Shakib
`smiri@mun.ca`

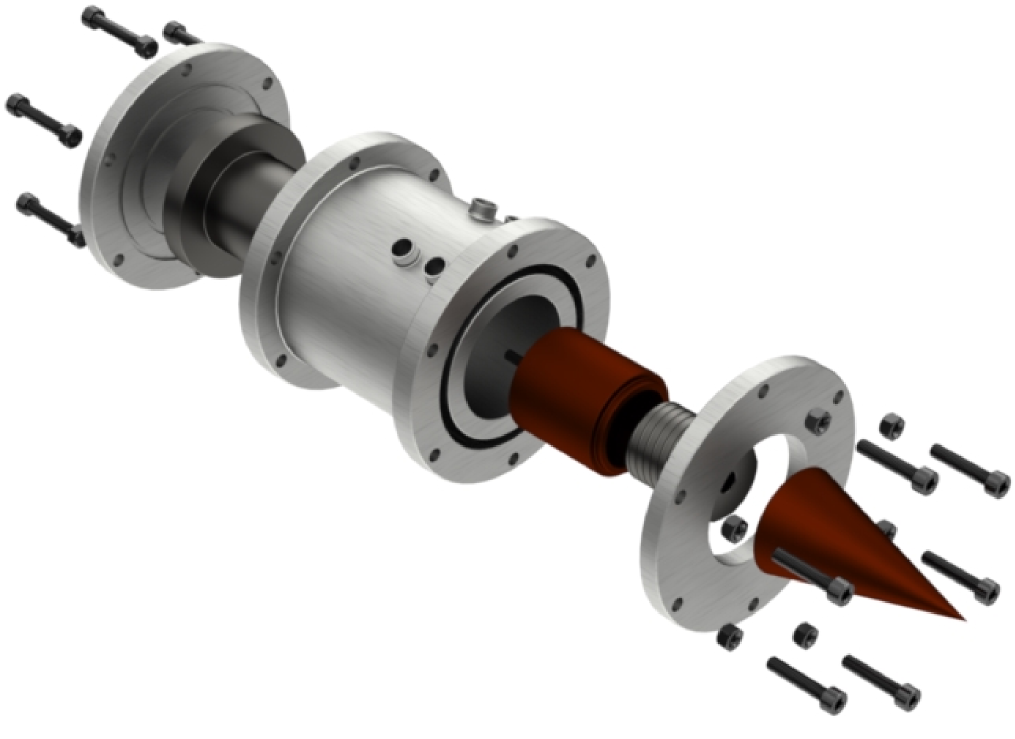
Palmer, Logan
`lrpalmer@mun.ca`

Clark, Aidan
`amhclark@mun.ca`

Cleary, Patrick
`pcleary@mun.ca`

Ryan, Nicholas
`nryan19@mun.ca`

November 2023



Contents

1 Introduction - Overview of the Team 4
1.1 Team History & Accomplishments . . . 4
1.1.1 Team Structure . . . 4
1.2 Outreach Activities . . . 5

2 Summary of Planned Project 6
2.1 Project Context . . . 6
2.2 Overview of Mission and CONOPS . . . 6

3 Design Specifications 8
3.1 Overview . . . 8
3.2 Combustion Chamber Design . . . 8
3.3 Detonation-to-Deflagration Tube Design . . . 9
3.4 Propellant Feed System Design . . . 9
3.5 Engine Cooling Design . . . 9
3.6 Simulation Design . . . 10
3.6.1 Computational Fluid Dynamics Simulations . . . 10
3.6.2 Finite Element Analysis Simulations . . . 10

4 Testing Plan 11
4.1 Deflagration-to-Detonation Transition Tube . . . 11
4.2 Injection Plate . . . 12
4.3 Pressurization . . . 12
4.4 Emergency Shutoff . . . 12
4.5 Propellant Feeding . . . 12
4.6 Coolant Loop . . . 12
4.7 Engine Hot-Firing . . . 13

5 Project Timeline 14
5.1 Overview . . . 14
5.2 Detailed Timeline . . . 14

6 Safety Overview and Project Risks 15

List of Figures

5.1 Full Project Timeline 14

List of Tables

1.1 Roles of Team Members 4

3.1 Design Overview 8
3.2 Thrust Chamber Specifications 8

5.1 Key Milestone Dates 14

Chapter 1

Introduction - Overview of the Team

1.1 Team History & Accomplishments

Detonation Engine Technologies (DETechnologies) was formed in early 2023 by four senior Engineering students at Memorial University of Newfoundland and Labrador (MUNL) as a senior capstone project. The project's focus was, and is to contribute to the global knowledge of Rotating Detonation Rocket Engine (RDRE)'s and their potential applications within the Aerospace and Defence industry. The original capstone team saw an opportunity to expand their work to engage more of the MUNL student body. This was the nucleation of DETechnologies as a student design team. Since this is the team's inaugural year, the primary focus has been on research and prototype development. The research phase of the project involved an in-depth exploration of existing knowledge of RDE's, covering the theoretical underpinnings, potential applications, and latest developments within the research sphere. As DETechnologies transitions into 2024, the team is shifting its focus into prototype development of its first RDRE. While we do not have any historical rocket development accomplishments, we are confident that we will see success in designing a preliminary prototype. The team has a strong background in designing and building functional prototypes as part of student teams at MUNL. This experience includes but is not limited to; Baja SAE off-road vehicle, and various Paradigm Engineering autonomous vehicle competitions. These successful design experiences lend credibility to the team proving that while we are unfamiliar with rocket engine design, are no strangers to approaching new technology in a methodical, scientific way.

1.1.1 Team Structure

Below, Table 1.1, shows a summary of the current team structure. Notably, the team is supervised by Dr. Xili Duan, an associate professor from the MUNL Faculty of Engineering & Applied Science, while the project is led by Shakib Miri, a Senior Mechanical Engineering Student.

Table 1.1: Roles of Team Members

Role	Team Member
Capstone Faculty Supervisor	Dr. Xili Duan
Team Captain	Shakib Miri
Chief Engineer	Logan Palmer
Chief Safety Officer	Nick Ryan
Mechanical Design Engineer	Patrick Cleary
Simulation Engineer	Aidan Clark

1.2 Outreach Activities

Being a brand-new student team at MUNL, DETechnologies has not yet conducted any community outreach. DETechnologies recognizes the importance of community outreach and knowledge sharing and is eager to inspire the next generation of engineers. In the near future, DETechnologies aims to collaborate with other teams, clubs, and societies within local schools and universities to encourage interest in aerospace engineering through open houses, public presentations, or mixers. DETechnologies also plans on participating in local aerospace and defence-related networking events hosted by Atlantic Canada Aerospace and Defense Association (ACADA), and other industry partners in Atlantic Canada.

Through funding discussions with prime defence contractors in Canada, DETechnologies stumbled across several funding avenues of scale exceeding the funding requirements of a student team. This funding was brought to the attention of the MUNL Engineering Faculty, as a potential avenue for expanding the engineering school. This conversation has since expanded to include a number of highly invested local industry partners interested in expanding the reach of MUNL Engineering to include an Aerospace, or Aeronautical engineering program and an aerospace and/or combustion lab. The DETechnologies team is very involved in these discussions.

DETechnologies's involvement in the planning stages of a proposed aerospace engineering program and lab at MUNL is a significant outreach component complimenting our student design team work. Elements of this involvement are still in the works, but there is expected to be a strong component of communication and teamwork with industry partners.

At the end of this academic year, a final presentation and networking event will be hosted by DETechnologies. This will be an event to thank our industry sponsors, connections, and partners for their support, this event will include a full presentation of our design and progress over the past year. Local students will be invited to this event, in order to expose them to the exciting potential of Aerospace Engineering in Newfoundland and Labrador.

Chapter 2

Summary of Planned Project

2.1 Project Context

The rationale behind this project is to address 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. To overcome these limitations, researchers have been exploring alternative propulsion systems, one promising technology is Rotating Detonation Engine or RDE. RDEs operate based on the principle of detonation, a supersonic combustion process that allows for significantly higher thermodynamic efficiencies and specific impulse. Detonation within a cylindrical RDE is a continuous process; the continually rotating shock wave ahead of the combustion wave compresses the injected propellant mixture to sufficiently high pressures and temperatures, resulting in effectively instantaneous and complete combustion at a higher efficiency due to the precompression. Although RDEs are not yet commercially viable on any scale, research is being conducted on small-scale functional prototypes to better understand the detonation phenomenon.

DETechnologies has identified the final project deliverable to be the prototype RDRE, thrust dynamo-meter, propellant feed system. The prototype will consist of the fuel and oxidizer plenums, the annular combustion chamber, the exhaust duct, the exhaust nozzle, the centre body cooling loop, and the outer body cooling loop. The dynamo-meter will be a steel structure equipped with a load cell(s) in a horizontal configuration parallel to the axis of thrust of the RDRE. The prototype exhaust gas will be pointed away from the dynamo-meter due to the very high exhaust gas temperatures. The axial degree of freedom of the engine will be unrestricted in the dynamo-meter to allow for the load cell to measure the generated thrust, and this will be achieved from the use of a sled equipped with roller sliders. The propellant system will consist of the propellant tanks (fuel and oxidizer respectively), piping and fittings, regulators, valves, and sensors (mass flow, pressure temperature).

For the Launch Canada event, DETechnologies will demonstrate the functionality of our prototype through a hot fire test. A suitable outdoor location will be identified where there is a large clearance of anything flammable 180 degrees around the exhaust surface of the engine and will allow for the dynamo-meter to be bolted down to a solid footing (e.g. concrete slab). Propellant feed and control systems will be set up at a specified safe distance from the operating engine. Propellant feeding and mixture ignition would occur, with the engine operating continuously for the designated safe amount of time.

2.2 Overview of Mission and CONOPS

The project focuses on building a liquid-cooled RDRE generating approximately 500N of thrust using hydrogen and oxygen as the propellant mixture. Efficiency maximization, data collection, and documentation of design choices are key goals. The modular design supports the objective of stimulating future research work through component modifications and design knowledge sharing.

Student involvement in DETechnologies cultivates cross-disciplinary skills, theoretical knowledge, and practical experience in simulation and mechanical design. The timeline allows for project work to span literature review, analytical modeling, Computational Fluid Dynamics (CFD) studying, Design For Manufacturing and Assembly (DFMA), fabrication, testing, and engine refinement.

Chapter 3

Design Specifications

3.1 Overview

DETechnologies' proposed RDRE is being designed as a modular, research engine capable of quickly and cost-effectively having critical geometric parameters modified such that this engine can be used in further advanced research studies. The overarching design for this engine is a gas-gas, non-premixed Hydrogen and Oxygen-fuelled, liquid-cooled RDRE capable of producing $500N$ of thrust. Key design parameters are summarized below in Table 3.1. These design parameters are driving objectives behind the more complex specifications of the proposed RDRE.

Table 3.1: Design Overview

Specification	Value
Thrust Output	500 N
Propellant	H_2
Oxidizer	O_2
Run time	$> 1sec$
Safety Redundancies	3 per system
Maximum Temperature	3900 K
Maximum Pressure	3500 kPa
Back Pressure	101.325 kPA

3.2 Combustion Chamber Design

The combustion chamber is still a work in progress, however, the numbers below, 3.2 show the current working values, subject to change. These values are determined using the custom analytical model developed by the team. The analytical model is based on Cantera and SDToolbox Application Programming Interface (API) available in Matlab [1][2]. These toolboxes provide access to chemical kinetics, thermodynamic databases, and an interface that allows for ease of numerical modeling of Shock and Detonation waves [1][2].

Table 3.2: Thrust Chamber Specifications

Specification	Value
Injection Pressure	1.0 MPa
Injection Temperature	323.15 K
Combustion chamber width	6.83 mm
Combustion chamber outer diameter	113.824
Combustion chamber length	68.23 mm
Detonation Cell Size	2.8 mm

3.3 Detonation-to-Deflagration Tube Design

The DDTT is an integral component to ensure RDRE operation. The DDTT will be a long, slender tube mounted tangentially to the RDRE to which propellant and oxidizer will be injected to a specific pressure and mixture composition. Mixture ignition will yield a deflagration wave that propagates down the tube, transitioning to a detonation wave due to the confinement, before reaching the annular combustion chamber of the RDRE. By using a DDTT as the ignition source, the required helical detonation wave is 95% more likely to initiate and continue its rotation [3]. Without the highest possibility of a (stable) detonation wave, the RDRE will not achieve our design objectives. The final diameter and length of the DDTT have not been determined and one design choice which affects these results is the use of an obstruction within the tube. Schelkin spirals are a type of tube obstruction that has been shown to improve the reliability of deflagration to detonation transition and result in a shorter tube length [3][4][5]. An analytical correlation (lambda/PI) has been determined for the critical tube diameter in which detonation will occur, and this correlation will be the analytical basis for the DDTT diameter [6][7]. To determine the length of the DDTT (analytically), the "demo cv.m" routine provided with the SDToolbox API will be adapted. From the calculated detonation induction length, a minimum DDTT length can be acquired. The onset of detonation depends on a particular pattern of shock fronts created by the accelerating flame front. The pattern generation depends on minute inhomogeneities, therefore Deflagration-to-Detonation Transition is non-reproducible in its detailed sequence of events [**?**]. The analytical DDTT geometry will be verified by a numerical simulation, and then following fabrication will be experimentally tested which will be the only true way to validate the chosen design due to the irregularities explained above.

3.4 Propellant Feed System Design

The RDE will be fed using standard size-44 tanks of hydrogen (fuel) and oxygen (oxidizer). These tanks will be connected to a plumbing system for both precise control and safety. Features of the plumbing system will include back-flow valves, pressure regulators, sensors, and solenoid valves for fluid control. The piping, fittings, and valves will be provided by the Swagelok company, and the team will undergo training regarding fuel and oxidizer handling, necessary plumbing system design, and education about various piping system components. The precise control of propellant mass flow entering the engine's plenums is very important for a sustainable continuous detonation wave because of the speed at which the wave propagates, and the particularity of the chemical combustion reaction. If the mass flow entering the combustion chamber is not fast enough to feed the detonation wave, then the detonation wave will be choked, losing speed and energy, resulting in poor engine performance. In a worst-case scenario, the flow will not being able to sustain the detonation wave at all. If the mass flow exceeds what is required, it would create a more powerful wave, which in part may load the mechanical system to a degree not designed for and could cause premature failure.

3.5 Engine Cooling Design

Due to the inherent nature of RDE operation, high levels of heat exceeding 4000K are expected during operation. One method to avoid catastrophic failure is to limit the engine run time so as to not exceed the engine material melting point. This is the approach used by all RDRE research groups, unfortunately, this results in very short run times. 2D transient heat transfer analyses (analytical and numerical) will be conducted to determine the maximum run time of the engine. The time taken to reach approximately 90% of the melting temperature of the combustion chamber/center body will be set as the maximum engine run time. Through our literature review, DETechnologies has not found examples of research engines being outfitted with cooling jackets, so it was felt this would be a great opportunity to investigate the efficacy of a liquid cooling system for an RDE. For these reasons, a high-performance cooling system will be implemented. The cooling jacket will be featured around the engine's outer body, as well as inside of its center body. The system will be a closed loop featuring a pump and heat exchanger. Depending on the fluid and phase used (e.g. refrigerant or fluid boiling), throttling values and a condenser may be included. From the 2D analyses, the temperatures heat flux' through the combustion chamber and center body can be determined respectively. A combination of liquid-air heat exchanger, fluid, mass flow, and pump parameters (among others) can be varied to determine an ideal and feasible operating point for the cooling loop to result in at least a 10% reduction in temperature.

3.6 Simulation Design

The numerical computer simulation of the RDE will be divided into two main categories, CFD and FEA. These simulations will be used to better understand and validate expected engine performance, safety factors, and possible experiments to be conducted to better understand RDE development.

3.6.1 Computational Fluid Dynamics Simulations

The combustion CFD analysis will be entirely conducted in the CONVERGE CFD software, access provided by our partner, Convergent Science Inc.. This software is used specifically for combustion simulation, and as such, fits the needs of the project perfectly. For other heat transfer and simple fluid flow simulations, ANSYS Fluent will be used as there is software familiarity within the team, and sufficient fidelity can be achieved. Within CONVERGE CFD, two main simulation models will be used; a 2D unrolled RDE model and a 2D DDTT model. As hydrogen combustion simulation is a heavy computational load, it has been decided to keep the models in 2D to limit the amount of high-performance computing power required. To date, a functional 2D unrolled RDE model has been developed and is currently being tuned to meet ideal operating parameters designed to produce the target thrust output. For high-performance computations, Convergent Science has developed a cloud-compute software, Converge Horizon, which will allow us to offload simulations for high fidelity, long run-time modeling.

3.6.2 Finite Element Analysis Simulations

The FEA for this project will be mainly focused on maximum operating pressures and thermal fatigue. The maximum operating pressure simulation will be a validation of the material thicknesses and bolted connections at the plenum, cooling jacket, and combustion chamber will not fail under the pressurization expected. While the current scope of DETechnologies's testing and demonstration sees a small amount of hot-firing of the engine, given the cost and safety concerns of the engine's operation, all modes of failure must be sufficiently analyzed. The engine operation time will bring the combustion chamber material very close to its melting point, and the rapid heating and cooling of engine firing will put the material in thermal fatigue. To ensure that our planned tests will not end in catastrophic failure and that this prototype will be able to serve as a test bed into the future. For the FEA simulation solving, the NASTRAN solver will be used to ensure high-fidelity results balanced with reasonable computation times, as these simulation outputs will aid in guiding standard operating procedures to meet DETechnologies's safety standards.

Chapter 4

Testing Plan

Each component of the RDRE will be tested and performance verified individually (where possible and useful) before integration into the overall systems to ensure possible system failures can be more quickly and easily identified. The subsystem testing breakdowns and final hot-fire test are shown in the following respective sections.

4.1 Deflagration-to-Detonation Transition Tube

The Deflagration-to-Detonation Transition Tube will be tested before mounting to the engine in a controlled, combustion-certified facility. All sensors and ignition sources will be mounted to the DDTT as they will be during the final implementation on the engine. This test's goal is to ensure that the Deflagration-to-Detonation Transition Tube will produce a detonation wave by the exit of the tube, and do so reliably. In addition to the sensor data, Schlieren imaging and/or Soot Foil may be used to visually analyze the results of the DDTT tests, depending on available facility capabilities. To validate design specifications and ensure the highest standard of safety is upheld, the propellant supply to the DDTT will be increased in stages. Due to the very particular nature of the Deflagration-to-Detonation Transition process, it is expected that deflagration combustion will occur for all propellant concentrations below 90%, and should only occur at 100%, but due to the error in measurement of propellant concentration, detonation may be observed within a margin of 100%. The proposed test plan to ensure the safe operation of the DDTT would be:

- Propellant concentration @10% design
- Propellant concentration @20% design
- Propellant concentration @30% design
- ...
- Propellant concentration @90% design
- Propellant concentration @95% design
- Propellant concentration @100% design

Between tests, the DDTT will be stopped, by a Nitrogen purge. Temperature and pressure data will be analyzed to ensure that pressures and temperatures are not exceeding the expected magnitudes. This staggered process of introducing fuel to the DDTT will ensure that the design will be able to handle the high pressures and temperatures that it will be exposed to. At any point during the testing process when the temperatures and pressures exceed the expected values, the test will be terminated and the design will re-evaluated after investigating the results before continuing.

To ensure the DDTT operates as expected, the pressure sensors as mentioned previously will be used to record the speed at which the combustion wave travels down the DDTT. The Data Acquisition (DAQ) system will be the limiting factor of this measurement method, so to ensure that the combustion wave exiting the DDTT is supersonic, Schlieren Image Velocimetry (SIV) will be used to measure the resulting fluid flow velocity.

4.2 Injection Plate

Mixing is a very important factor when trying to create combustion since it can delay the successful feeding of a combustion wave [6]. The Injector plate will be designed such that the best possible mixing time and pattern can be achieved. To verify that the injector plate was machined to the required specifications, a static test for the injector plate is planned such that the inert test gas exiting the plate behaves as expected. The shadow-graph optical visualization technique is the intended way to capture and analyze the results.

4.3 Pressurization

The combustion chamber and propellant supply plenums will be subjected to a hydrostatic pressure test to confirm their adequate sealing. During the test, a temporary plate will seal the engine exit, and distilled water will be used to pressurize the combustion chamber and supply plenums beyond the expected pressure by 50%. This test will be a significant over-pressurization test of the propellant supply plenum, which will never be exposed to this pressure under regular operating conditions. The purpose of the over-pressurization of engine components is to ensure that the engine will be able to be re-used repeatedly as a research tool. The engine body will be inspected for leaks, along with tracking the pressure within the engine to ensure the pressure can be held within a low tolerance for the duration of the test period.

4.4 Emergency Shutoff

In the event that the engine operation will need to be terminated, there will be an automated emergency stop system implemented within the engine controls and propellant feeding systems. The main cause for concern is the back flash of combustion into the fuel and oxidizer plenums. Pressure and temperature sensors in the fuel and oxidizer plenums will be used to detect any signs of back flash. Abnormal spikes in pressure and temperature will cause the engine control system to undergo an emergency shutdown procedure.

The controls implemented emergency shutdown procedure will close the fast-actuating valves to the fuel and oxidizer supply as well as simultaneously open the fast-actuating valve to a high-pressure nitrogen tank to purge the propellant supply lines and plenums of flammable propellant. All three valves will be specified to have a feedback signal to indicate valve position. The two propellant supply valves will default to the closed position, while the Nitrogen supply valve will default to the open position. All gas supplies will be equipped with manual valves to ensure safe transportation and working with the engine.

These components along with the controls involved in the emergency shutoff system will be tested individually, as well as in a full system dry test before any propellant is introduced to ensure that all expected shutoff actions occur in any scenario.

4.5 Propellant Feeding

The propellant feed pipes will need to be hydrostatically pressurized to ensure there are no leaks between fittings and connections. The propellant lines would be purged with as before engine operation. All of the fast valves and actuators would have to be verified as working correctly and synced with the control system. Sensors would also have to be checked to ensure communication with the DAQ. An overall system test will occur checking to make sure each of the system operations occur when and how they are supposed to. To do this system test, inert gas(es) will be used.

4.6 Coolant Loop

The cooling circuit will need to be hydrostatically pressurized to check for leaks at all of the fittings. The pump will need to be tested to ensure that the necessary coolant flow rate and head pressure can be achieved, in addition to verifying the sensors are integrated into the DAQ properly with data being collected, as the test fluid is being circulated.

4.7 Engine Hot-Firing

The final engine testing will be conducted in a private quarry. The engine will be mounted to the test frame, and the test frame bolted securely to a concrete slab. The entire setup will be surrounded by a thick rubber tarp made from recycled tires. Similar tarps are used in mining applications to keep shrapnel and flying debris down. The propellant supply cylinders and electronics will be kept outside of the rubber tarp.

The control base will be set up a sufficiently safe distance away from the test apparatus, behind a cinder block safety structure where all team members and on-site personnel will be residing. Live camera feeds of the quarry and surrounding areas will be available from the control base such that if any unwanted people or animals approach the test setup, the engine can be shut down.

Chapter 5

Project Timeline

5.1 Overview

A high-level overview of the milestone dates for this project can be seen below, in Table 5.1. These dates are subject to change, however, they have been carefully reviewed and committed to by all team members. The timeline is intentionally aggressive to ensure that the most progress is made as possible.

Table 5.1: Key Milestone Dates

Milestone	Date of Completion
Literature Review	May. 2023
Finishing Analytical Model	Aug. 2023
Detailed Engine Design	Nov. 2023
Prototype Fabrication	Dec. 2023
Testing and Validation	Mar. 2024
Troubleshooting and Academic Paper Publishing	Jun. 2024
Final Launch Canada Preparations	Jul. 2024
Launch Canada Competition	Aug. 2024

5.2 Detailed Timeline

The following Gantt chart in Figure 5.1 shows a detailed timeline breakdown of the research and development of DETechnologies' RDRE. This timeline shows a breakdown of subsystem progress and expected completion dates. System inter-dependencies on one another are shown by this timeline, giving more insight into the progress of DETechnologies.

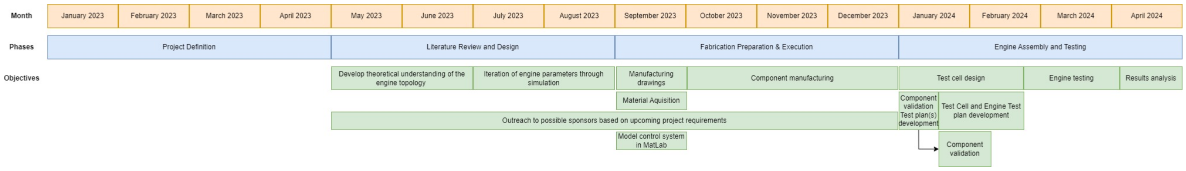


Figure 5.1: Full Project Timeline

Chapter 6

Safety Overview and Project Risks

At DETechnologies, safe construction, design, and testing are very important to us. All design and testing choices are made with safety as our number one priority. As part of our in-house safety measures, every member of our team will be required to follow our stringent rules and regulations. Our preparations include the use of flame-retardant materials and coatings to mitigate combustion and fire hazards. In addition to the number of safety redundancies built into our propellant supply system. Controlled points of failure will also be designed into certain parts of the engine. As an example, the prototype will utilize bolts at the flanged connections that have been specified to fail at the designated safety factor pressure (maximum operating pressure) of the engine. In the event of overpressure in the plenums or cooling jacket(s), bolt failure will eject the engine components tied to the respective flange off of the fixed portion of the stand. In the lead-up to the Launch Canada event, we plan to conduct a series of comprehensive tests in a controlled environment to ensure the performance and safety of our engine under secure conditions.

The biggest project risk associated with testing a high-performance novel rocket engine is user safety in the event of an unplanned emergency. An unplanned emergency could consist of a back flash event or a rapid over-pressurization event in the cooling system. Both of these systems have built-in design choices to ensure that a failure would leave the engine intact and ready to test again. In the event of an unplanned and unforeseen failure, the engine will be surrounded by a thick tarp of recycled tires. Any projectiles leaving the engine will be stopped by this tarp, and all testing personnel will be safely residing in the testing bunker a safe distance away.

After testing is complete, no personnel shall approach the engine without prior visual, and control feedback that automatic valves are shut. This safety check will be conducted from the control bunker. If both of these safety checking avenues are unavailable, the team will be instructed to remain in position until both propellant supply tanks are empty: a simple calculation based on the current flow rate.

Acronyms

2D Two-Dimensional. 10

ACADA Atlantic Canada Aerospace and Defense Association. 5
API Application Programming Interface. 8, 9

CFD Computational Fluid Dynamics. 7, 10

DAQ Data Acquisition. 11
DDT Deflagration-to-Detonation Transition. 9, 11
DDTT Deflagration-to-Detonation Transition Tube. 1, 9–11
DETechnologies Detonation Engine Technologies. 4–6, 8–10, 14, 15
DFMA Design For Manufacturing and Assembly. 7

FEA Finite Element Analysis. 10

MUNL Memorial University of Newfoundland and Labrador. 4, 5

NASTRAN NASA STRuctural ANalysis. 10

RDE Rotating Detonation Engine. 4, 6, 9, 10
RDRE Rotating Detonation Rocket Engine. 4, 6, 8, 9, 11, 14

SIV Schlieren Image Velocimetry. 11

Bibliography

[1] D. G. Goodwin, H. K. Moffat, I. Schoegl, R. L. Speth, and B. W. Weber, "Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes." `https://www.cantera.org`, 2023. Version 3.0.0.

[2] S. Browne, J. Ziegler, N. Bitter, B. Schmidt, J. Lawson, and J. Shepherd, "Sdtoolbox: Numerical tools for shock and detonation wave modeling," *GALCIT Report No. FM2018*, vol. 1, 2018.

[3] I. J. Shaw, J. A. Kildare, M. J. Evans, A. Chinnici, C. A. Sparks, S. N. Rubaiyat, R. C. Chin, and P. R. Medwell, "A theoretical review of rotating detonation engines," *Direct Numerical Simulations-An Introduction and Applications*, 2019.

[4] Z.-J. Xia, Z.-H. Sheng, D.-W. Shen, and J.-P. Wang, "Numerical investigation of pre-detonator in rotating detonation engine," *International Journal of Hydrogen Energy*, vol. 46, no. 61, pp. 31428–31438, 2021.

[5] S.-J. Liu, Z.-Y. Lin, W.-D. Liu, W. Lin, and M.-B. Sun, "Experimental and three-dimensional numerical investigations on h2/air continuous rotating detonation wave," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 227, no. 2, pp. 326–341, 2013.

[6] I. Q. Andrus, "A premixed rotating detonation engine: Design and experimentation," *AIR FORCE INSTITUTE OF TECHNOLOGY WRIGHT-PATTERSON AFB OH WRIGHT-PATTERSON*, 2016.

[7] A. P. Nair, A. R. Keller, N. Q. Minesi, D. I. Pineda, and R. M. Spearrin, "Detonation cell size of liquid hypergolic propellants: Estimation from a non-premixed combustor," *Proceedings of the Combustion Institute*, vol. 39, no. 3, pp. 2757–2765, 2023.