Executive Summary

The Queen's Engineering Rocket Team (QRET) has ordered a stand to be created that will help test the accuracy of their rocket motor, which produces a thrust equal to 10g's or roughly 981 N. They have asked that the stand be able to sustain this force for 6 seconds. The stand must be able to withstand a maximum force of 5000 N without any damage done to the structure. This measurement is not relative to time, only accounting for the maximum force exerted.

Based on the research of force sensors, ideal testing conditions, materials, coding, and proper securing of the stand, three designs were proposed. Design 1 used a vertical, static approach. Designs 2 and 3 used a horizontal, dynamic approach to testing. The big difference between the two horizontal designs were the use of materials and the effectiveness of the proposed structure. All designs used steel, which was determined to be the strongest material. The three designs were compared using an evaluation matrix that isolated the most important aspects, such as safety. From this, a final design was created using the best of all three designs.

Alternate solutions were considered for the final design. One solution included mounting the rocket to sliding rails to allow for a more dynamic design, however, there was a possibility that the rocket would bounce off the back plate and result in spikes of the data. Another addition to the final solution included removable back braces to prevent the model from tipping over due to the rocket's thrust.

The final solution was a horizontal stand with 3 mounting rings to secure the rocket, with the motor's thrust pushing forwards into a steel plate embedded with a piezoresistive force sensor. The force sensor records the force produced by the motor and the data is analyzed using a coded load cell to determine the engine's performance.

The model was tested using SolidWorks and mathematical modelling to determine the forces that the stand experienced. This included modelling the expected 5000 N load on the structure, determining how it would react, and an analysis of how the heat from the engine's exhaust would affect the structure. Results from the mathematical and CAD modelling concluded that the stand withstands the static force of 5000 N with no issues in the structural or material integrity. The dynamic test of 981 N for 6 seconds was inconclusive due to issues running SolidWorks studies, however, the fatigue study passed. Overall, the model scored 17/20 when marked based on the evaluation rubric (**Error! Reference source not found.**) which exceeded the passing score of 16 to be built.

The complete cost of the test stand is $361.32 and includes a square steel tubing and steel sheet metal frame, saddle mounting rings to secure the rocket, and a piezoresistive load cell to measure the thrust produced during testing.

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1 Key Information for Clients

1.1 Problem Statement and Scope Definition

The Queen's Rocket Engineering Team (QRET) requires a stand to hold their rocket motor in place while being tested. A design must be created to fit all the functional requirements and attributes seen below. Additionally, a device must be coded and attached to the design to measure the accuracy of the model and the force applied to the system.

1.1.1 Functional Requirements and Attributes

1. The stand must hold the rocket engine either horizontally or vertically.
2. Withstand at least 5000 N of force from the rocket's thrust.
3. Hold the rocket in place for at least 6 seconds while experiencing 10 g's of force during testing.
4. A device is needed to measure the force exerted on the structure by the motor.
5. Must have a shelf life of at least 5 years.
6. Must pass an evaluation using the Evaluation Rubric with a 16/20 or higher.

1.1.2 Project Scope

To develop a solution to the problem presented, numerous factors were considered to adequately address the needs of the client. Due to public health guidelines, the availability of resources and group participation is limited, therefore building a prototype is not feasible. To compensate, modeling the stand through SolidWorks and other computer-aided design (CAD) software will be completed to fulfill the client's requirements. All licenses to computer software programs were given by Queens University, and therefore all costs associated with these programs are negligible. Through client feedback, the team had determined that there are no financial constraints associated with designing the model, however, all costs associated with the design must be listed. An outline of key milestones and tasks to be completed were created to address all necessary components of the project for the creation of a detailed plan of the model.

1.1.3 Constraints

Some restrictions were acknowledged in the creation of the project scope above. The design had to meet the design requirements set by the clients, but it also had to be created within the listed constraints:

1. Limited supplies: the design may not be achievable with the materials available.
2. Limited knowledge on how to approach this problem, extensive research must be done.
3. Time is a constraint. There will be deadlines with tasks that must be completed along the way.
4. Different ground types and the location of where the structure will be used; how these might affect the design.
5. Existing systems: rocket motor dimensions.
6. Hands-on project done online without necessary equipment and resources.

To evaluate how the design would affect members of QRET and other parties, a list of stakeholders was created. The main stakeholder of the project is QRET. As the client, their needs and interests take top priority and dictate the requirements of the project and other stakeholders. Since the project needs are set by QRET and fulfilled by the design project team, there is a direct correlation between these two stakeholders. Since the group is dependent on the needs of the client, there is the potential for conflict if one party feels their needs are not adequately addressed by the other. The Project Manager Matthew Green is a stakeholder and takes on the mediator role representing both party's needs. If clarification is needed, Matthew serves as the bridge between the client and team. If QRET decides to build this model, all the necessary materials, parts and construction-specific requirements will be specified to build the structure. To build and decommission the structure, QRET will need the use of the Queen's workshop and local recycling companies once the project is complete. Members of the Queen's workshop that will help construct the design and recycling companies who will discard of the structure after use are additional stakeholders.

1.2 Background Information

1.2.1 Orientation of the Rocket Motor

While designing the rocket engine test stand, two possible orientations were considered. In a vertical rocket test stand configuration, the rocket engine is generally oriented downwards, and the rocket nose is pointed upwards. A rocket that is launched from a vertical test stand will most often perform with the greatest efficiency. However, this configuration requires many anchoring devices to ensure that the test stand remains anchored and supports the total force exerted by a rocket pointed upwards. A vertical orientation, therefore, makes it difficult to maintain the safety and security of the rocket's liftoff [1]. Although rockets are carefully designed and tested, the rocket may still exert more thrust than expected, so the stand must account for these unexpected forces. Some disadvantages are that it is difficult to design the stand to allow the rocket to remain free-floating for a dynamic test and the structure requires extensive engineering to accommodate the hot exhaust upon propulsion. A horizontal rocket engine test stand is often easier to design and can accommodate accessory features, unlike the vertical rocket test stand. It is often very difficult to orient the thrust in the horizontal plane and have the rocket remain mounted to the stand while the stand is mounted to the ground [2]. Having the rocket properly mounted on the stand and the stand properly mounted on the ground is essential for safety during operation, but it is also required to reduce strain and motion on the frame that could potentially interfere with the optimal flight of the rocket.

1.2.2 Types of Load Cells to Calculate Thrust Produced

A key diagnostic in evaluating the performance of a rocket is the thrust force it produces. To accurately monitor the force on the rocket, a device called a force sensor is needed. Force sensors are responsible for measuring both tensile and pressure forces as well as elastic deformations. The desired measuring range and expected accuracy are primary criteria to determine the right force sensor suited for the specific application. A load cell is a type of force sensor (or force transducer) which converts a given thrust to an electrical signal that can be acquired, stored, and further analyzed. The magnitude of the electrical signal generated by the load cell is directly proportional to the amount of thrust applied to its measurement element. As force is applied and passed through a measurement element, the elastic body of the load cell is compressed, slightly increasing its diameter. This increase induces a measurable change in resistance, which is then acquired and analyzed [3].

Three types of load cells will be considered: piezoresistive, hydraulic, and strain gauge. Piezoresistive force sensors measure the tensile or compressive force along a single axis. These sensors are more suitable for dynamic loads, such as those that are oscillatory. Hydraulic load cells are loaded with a liquid and measure the force applied based on the change in pressure. They are utilized to measure the compression forces within a structure. In any rocket engine test stand, the strain gauge load cell remains a strongly regarded choice to measure thrust, due to the load being generally static. They measure force by determining the strain at each location [4]. In the test stand design, it is crucial to implement the load cells properly. The most important aspect to consider is that the load cells are placed in a way to minimize side loads and moments or parallel load paths [5]. The load cells must be able to accurately handle the maximum possible side loads to manage loads without damage. The most widely used design is to mount the engine on rails that allow a degree of freedom of movement. Once the engine produces thrust, the rails will press against the load cell with the same force that the engine produces. These forces can then be measured and further analyzed.

1.2.3 Materials

The physical and chemical properties of a wide variety of common construction materials were analyzed to determine the ideal material for the stand based on its ability to withstand the heat, thrust oscillations, and force during testing. Common construction materials include steel, aluminum, and concrete. *Materials Science and Engineering* contains a database that helped form the data presented in Table 1 [6]. The table values are important for determining the strongest, most heat resistant, and durable material for the model, as they represent how the material will function under adverse conditions. Some comparisons can also be made when taking the strength coefficients in Table 1 and dividing them by the weight of the product material. This ratio is important in determining which areas in the model require the most weight to support the presented loads. Important things to note are that the coefficient of thermal expansion accounts for the changing in length of a material as a function of how hot it gets, therefore a higher value will cause more expansion for a temperature change. This will be most effective in the vertical stand but will also be used as a factor in the horizontally oriented stand.

Table 1: Table of properties important in the comparison of materials being used.

Material	Melting Point (°C)	Linear Coefficient of Thermal Expansion (°C^{-1})	Young's Modulus of Elasticity (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)
Steel	1150-1300	11.7×10^{-6}	200	250	450
Aluminum	660	23.6×10^{-6}	69	276	310
Concrete	~1600	10.0×10^{-6}	35	---	40

Materials can be processed in several ways, including: castability, weldability, and machinability. Steel is rated at fair, excellent, and fair for those three categories. Aluminum is rated as excellent, fair, and good for those categories. Since concrete requires metal rods to hold it in place, concrete does not classify in this category. The three categories address different ways that the structures can be assembled, which will adversely affect the product's final properties and service life [7]. For assembling the product, weldability and machinability will be the biggest factors to consider. Aluminum has the best properties for processing but since its tensile strength and young's modulus are less than those of Steel, Steel is the best option for creating this model.

1.2.4 Stand Mechanics

To understand how testing will occur, the report by The United States Air Force identifying how certain variables are controlled was examined. On a basic level, Figure 1 identifies the main sensors and how those sensors take measurements of a rocket motor during testing [8]. The basic principles in this design can be simulated in a dynamic test using CAD software which will measure forces that would be felt by the structure, while also considering the compensation required for factors such as oscillatory motion.

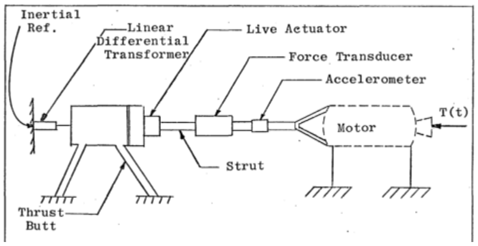

Figure 1: Simple diagram of the testing mechanisms involved in testing the force of a motor.

Dynamic force calibration was completed by The Arnold Engineering development center as a measurement technique for a rocket stand. It was determined that this method, as opposed to static testing, was more efficient and straightforward. Dynamic-force calibration simulates thrust building up over a period. It is a hybrid concept because it incorporates reaction force summation and computer compensation techniques. Due to the electrodynamic actuators, the distortion of the force signals can be virtually eliminated since signal distortions are caused by resonant frequencies. This will lead to the sensors reciprocating natural data from the mechanism [9]. This information helps establish an understanding of how the forces are controlled into the system testing.

1.3 Design Solution

Given the research listed above, 3 test stand designs were created, and one solution was chosen based on the criteria listed in Table 3. The best design was chosen and is described below.

1.3.1 Detailed Design Description

The design was initially chosen based on how it scored in the evaluation matrix (Table 3). After addressing factors such as securing and stability, components were designed to account for these. The design is primarily made of steel, which was used both for the frame and for the base, (1,4,5) in Figure 2. Aligning with the evaluation matrix (Table 3), the horizontal model measures load most effectively in dynamic and static conditions with computer-aided assistance from a piezoresistive force sensor. Originally, the design had the engine secured to a rail in free horizontal motion. Upon further consideration, this rail was deemed to be non-essential for testing and detrimental to the accuracy of the results, as it would bounce off the back plate due to reactionary forces. Instead, 3 clamps (6) were added to hold the engine in place, which are secured to the base (1,2). The engine can still move back and forth, however, by having the clamps secured, the uncertainty due to the oscillations and noise produced by the free-floating rails was eliminated. The stand has been designed to ensure the load pushes against the force sensor (4) that is attached to a sheet of 10-gauge steel (4) welded and screwed into the base (1). Two triangular braces (5) are also secured to the base and the front plate for added protection. The biggest addition from the initial design is the detachable triangular support (8) attached to the front face by a piece of molded steel (9) that acts as a connector for screwing. This truss, constructed with the same steel tubing as the base, allows for the stand to be secured in virtually every condition. The truss acts as a secured point that opposes the force applied on the stand by the rocket. The truss will secure the top portion of the frame using reactionary forces. Since it is detachable, the stand can also be secured by placing it against a sturdy wall, eliminating the need for any other securing mechanisms. Both adaptations act in the same way, making the design versatile.

Bill of Materials	
1	Base Plate
2	Rectangular Base
3	Force Sensor
4	Back Plate
5	Triangular Plates
6	Ring Clamps
7	Truss
8	Truss
9	Truss connector

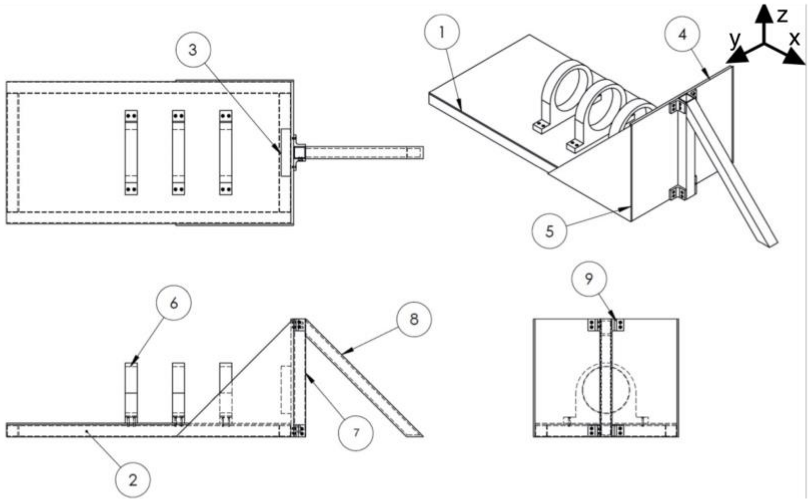

Figure 2: Sketches of completed design including balloons indicating materials and components.

1.3.2 Required Resources

The resources that are needed in the building of the design are as follows. To properly assemble the model, advanced tools are needed such as a welding kit, a metal cutting saw, and metal screw hole cutters, all of which can be found in various labs QRET has access to. Use of the welding kit will secure the flat sheet, metal base, and vertical frame (3,6,7) together. Certain components, such as the truss (2) and base (3,7), require special metal cutting saws to cut down or shape the design using angled cuts. Similar to shaping the structure, normal screws will not naturally penetrate steel, therefore the holes where screws are attaching components, such as where (1) meets (6), and where (4) meets (9), will need to be specially cut.

If QRET does build this design, a workshop would be required. Before commencing construction, 6 hours should be allotted for planning and laying out the required fittings. As seen in Table 2, a detailed description of each part, as well as assembly instructions are given. After the materials are acquired, an estimated 12-16 hours will be spent in the workshop building the design. Most of the time spent will be constructing and welding the frame.

1.3.3 Costs and Benefits of the Design

Benefits

- Materials used can be recycled for future projects or designs.
- Simple and easy to use for testing.
- Easy access to piezoresistive force sensor allows for quick repairs and replacements.
- Design principles can be used to test larger-scale motors in the future.

Costs

- The materials used to create the stand will have varying effects on the environment if not properly disposed of.
- Complex machinery required.
- Possibility that the surroundings will ignite due to the rocket's thrust.

1.3.4 Summary of Costs Associated with the Design Solution

To build the stand, the QRET team will need to purchase an estimated $250.00 of build material and $115.00 for the load cell [10]. A detailed cost breakdown of all materials and dimensions are found in Table 4.

Table 2: Summary of Detailed Cost Breakdown of the final solution.

# [Figure 2]	Material	Qty	Cost ($)	Total ($)
4,5	Steel Sheet	2	40.21	80.42
2	Steel Tube (Frame)	1	36.98	36.98
7	Steel Tube (Back Brace)	1	18.41	18.41
6	Mounting Rings	3	24.30	72.90
9	Truss Connectors	2	4.38	8.76
-	Nuts, Bolts, Washers	~15		15.00+
1	Retractable Sheet	1	13.85	13.85
3	Piezoresistive Load Cell	1	115.00	115.00
	Total:			**361.32**

1.3.5 Assembly of the Stand

Preparation

1. Cut steel tube into dimensions listed in row 1 of Table 4.
2. Cut steel tube for truss at a 45° angle on both ends, with the cut being made on the same face.
3. Cut side triangles with 45° from the steel sheet, dimensions seen in Table 4.
4. Use steel hole drill to place holes as seen in the provided SolidWorks file.

Welding

1. Weld the cut steel tubes together on all 4 sides so that the base takes a rectangular form.
2. Weld the weldable steel sheet to the base assembled in step 1.
3. Weld the rectangular steel sheet with the two triangular sides. Match the SolidWorks model so that the mates stay consistent.

4. Weld the product of step 3 to the bottom of the base. For reference, everything should be leveled and resting on the ground.
5. Weld the truss together.

Assembly

1. Secure the three clamps in their allotted holes on the weldable steel sheet.
2. Center the force sensor with the middle of the clamps.
3. Secure the truss using the connectors.

1.4 Conclusions

Three preliminary designs were created: one vertical and two horizontal-oriented test stands. The third design was selected based on the evaluation matrix (Table 3) that assessed the cost of materials, feasibility, addressing the needs of the project, ease of manufacturing and the overall thought put into the solution. As said in 1.3.1, the original chosen design had a horizontal orientation and consisted of a sliding rail to which the motor was attached. The motor pushed against a back plate and a force sensor would measure the force exerted. The design was then changed to include support rings instead of rails to prevent the motor from bouncing back off the plate due to reactionary forces.

If QRET were to build the stand, the design would cost approximately $250, not including the force sensor. As mentioned in 1.3.1, the materials for the stand are all available at local hardware stores such as Home Depot, and therefore the cost of shipping is negligible. As stated in 1.3.2, it is estimated that 12-16 hours will be spent in the workshop. Based on the restrictions outlined in 1.1, the use of a workshop by the design team to build the test stand is not possible, and therefore the design was not built, but was simulated using CAD software.

If this project were to be redone, there is room for further change in the design to eliminate any unnecessary materials that could cause price increases, or time wasted in the construction phases. Although these will not be modelled, they will create suggestions for QRET to better the design for their use.

2 Technical Information

2.1 Conceptual Design Solutions

Information gathered in previous phase reports were used to create 3 preliminary designs of the test stand which are explained in further detail below.

2.1.1 Design 1

The first design secures the motor in the vertical orientation as it fires into the ground, with the plume facing upwards. The design incorporates a triangular shape on either side of the motor to add stability while testing, with two horizontal bars which span the width of the concrete base to secure the motor (Figure 6: Isometric view of the motor as it is secured to the frame of Design 1.). A load cell will be placed where the head of the motor meets the concrete base.

Sketches of the Design

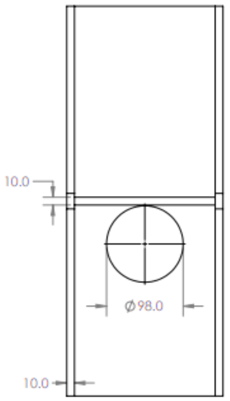

Figure 3: Top view of the motor as it is secured to the frame of Design 1, with dimensions in mm.

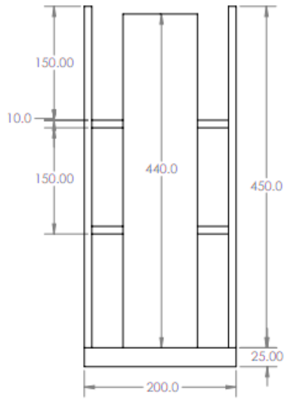

Figure 4: Front view of the motor as it is secured to the frame of Design 1, with dimensions in mm. Concrete base is of dimensions 200 x 25 as seen above.

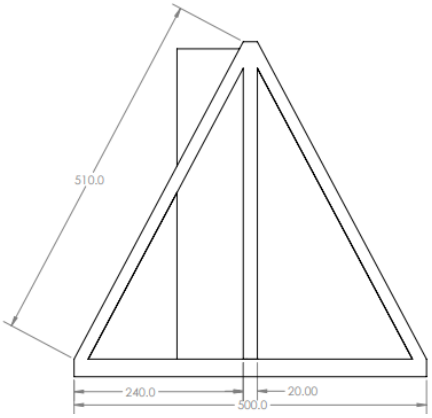

Figure 5: Right Side view of the motor as it is secured to the frame of Design 1, with dimensions in mm. Concrete base is of length 500 as seen above.

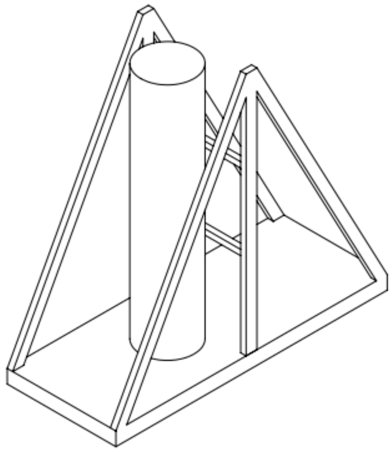

Figure 6: Isometric view of the motor as it is secured to the frame of Design 1.

Reason for Orientation

__Benefits__ – A vertical orientation simulates launch conditions, as all rockets are fired in the vertical direction. It also avoids the need for large fire trenches, as the hot plume on a horizontally mounted engine often ignites the ground it is being tested on, as mentioned by the client. A vertical engine firing downwards is also an advantage as it only needs to be secured to limit side-to-side movement, as all downwards movement is stopped by the strong base. A vertical test provides a single dimension of freedom and will most often perform with the greatest efficiency compared to a horizontally tested motor [1].

__Drawbacks__ – A vertical test stand with the rocket firing downwards requires a strong base that can counteract the rocket's thrust, which results in more material being needed and consequently more expensive than a typical horizontal design. Based on previous research, a disadvantage of a vertical orientation is that it is difficult to keep the motor free-floating, or able to move freely while also being secured to the stand [2]. This results in a static test and is not ideal for load cells that rely on dynamic conditions [3] .

Load Cell Type

The ideal load cell for the vertical test is a hydraulic load cell, as it is best used for compressive forces [5]. Filled with liquid, they measure the force applied based on the change in pressure. Placed at the base of the motor as it fires into the ground, the load cell will record the compressive force due to the thrust. However hydraulic load cells that can withstand the required force of 5000N are expensive, ranging from $150 - $1000 [11].

Securing the Motor to the Stand

Previous research determined saddle clamps are ideal for securing the motor to the stand, however, based on pricing and availability at local hardware stores, the large diameter of the motor and the limited budget, using saddle clamps to fix the motor would not be attainable. The motor, fixed in a vertical direction, will be secured to two horizontal steel tubes. Using the two tubes which can be adjusted for height allows for the motor placement to be calibrated, as necessary. Steel pipe strapping will be used as it is adjustable and can be used for motors of any diameter and shape.

Materials Required and Dimensions

Using prices and material availability from a local hardware store [12], the design will cost an estimated 60-70$, not including the cost for the load cell. Based on previous research, it was found that steel was the best material option, and therefore the design will be constructed of steel tubing and sheets which provide stability and heat resistance.

Given the dimensions of the motor, a 98mm diameter and a 440mm length, preliminary dimensions were developed based on common materials lengths from local hardware stores. The design includes a 200mm width, 450mm height, 500mm length, and two triangles of hypotenuse 510mm. The concrete base supporting the motor will have a thickness of 25mm, which can be placed on a larger concrete surface at the time of testing if necessary.

2.1.2 Design 2

The second test stand design secures the motor in the horizontal direction and is designed to reduce strain and motion on the frame. This design incorporates low friction rails to which the load cells are attached, allowing for the freedom of movement. The test stand ensures a stable system by having a larger horizontal platform to which supplementary components can be attached.

Sketches of the Design

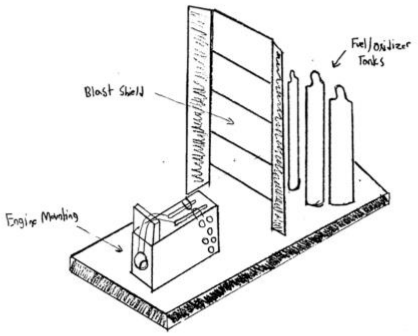

Figure 7: Isometric View of Design 2's test stand (hand drawn).

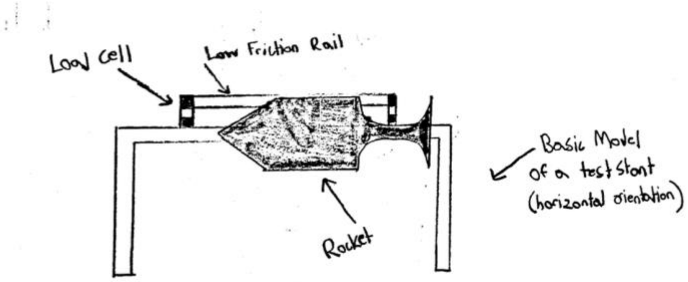

Figure 8: Side view of the low friction rail in relation to the rocket (hand drawn).

Reason for Orientation

Benefits – A horizontally oriented test stand is a very simple, conventional design. One of its benefits is the possibility of designing it with a large horizontal platform to which supplementary components can be attached like fuel and oxidizer tanks. Horizontal test stands commonly require more material to produce, making the test stand a lot heavier. The extra weight will help stabilize the system, making it easier to secure to the ground. The extra weight will also help prevent the system from moving when a large thrust exerted by the rocket is applied. Having a stable system is essential for the safety of the operation and it is also essential to reduce strain and motion on the frame that could potentially interfere with the optimal flight of the rocket. For this specific design, a blast shield component will be attached to the surface of the test stand to help prevent any damages to nearby objects and surfaces.

Drawbacks – The stand requires more materials to produce. This will make the design a lot heavier, and it will be difficult to transport and assemble without having extra support. Careful mountings are required while assembling the test stand to prevent any interferences with the thrust of the engine through unwanted movement on the force sensor.

Load Cell Type

To carefully monitor the force exerted by the thrust of the rocket engine, a force sensor is required. The preferred load cell for this design is a strain gauge load cell. The strain gauge load cell is a very dominant choice if the load is generally static. The placement of the load cell will be in a fixed condition; therefore, this type of load cell will work well with static loading. Multiple, single-axis strain gauge load cells will be mounted along the same plane but in different locations on the test stand to determine the most accurate value of the force exerted by the rocket engine. Some advantages of a single axis load cell are that they are cheaper than multi-axial load cells [2], and they are easy to calibrate. However, they are often easily damaged. This occurs when the side force exerted on the load cell is too large, usually caused by systems that should be modelled to test dynamically. The placement of the load cell is essential if the best possible results are desired. The best place to place the load cell is on rails that will allow freedom of movement, so that once the engine produces a thrust, the freely moving rails will press against the load cell with the same force the engine produces. As explained above, the design will use single axis load cells along one dimension of the low friction freely moving rail to measure the thrust exerted by the engine.

Securing the Motor to the Stand

Steel pipe strapping will be used to securely strap the motor down to the stand. The motor will be fixed in a horizontal direction, and it will be safely secured with flexible steel pipe strapping that are adjustable and that can be used for any specified motor dimension.

Materials Required and Dimensions

The prices estimated for this design are based on price listings from local hardware stores such as Home Depot, Rona, and Lowes. This design will be particularly expensive due to the excess materials needed; however, these materials were deemed necessary to provide stability and security. The design will consist of a concrete base with steel pipe strapping to secure the engine, a slotted steel plate that will be used as the blast shield, aluminum frictionless rails and a strain gauge load cell. This design will cost approximately $170. The strain gauge load cell is the most expensive component to this design, as it costs approximately $100 for one load cell [13].

2.1.3 Design 3

The third design is also horizontally oriented. The stand secures the motor using steel pipe strapping to two axles, connected to two low friction rails, allowing forward and backward motion of the engine. These rails are then secured to a steel frame with a steel sheet covering the top. Finally, three steel sheets arranged in a triangular prism shape is welded to the steel frame at the front of the stand as a point of resistance. During testing, the engine pushes against a metal plate, seen with the blue shading in Figure 9: Orthographic view of the second horizontal design; the motor will push on a plate (blue) to distribute a uniform load to the force sensor. and Figure 10, to apply an equally distributed load to the piezoresistive sensor behind it.

Sketches of the Design

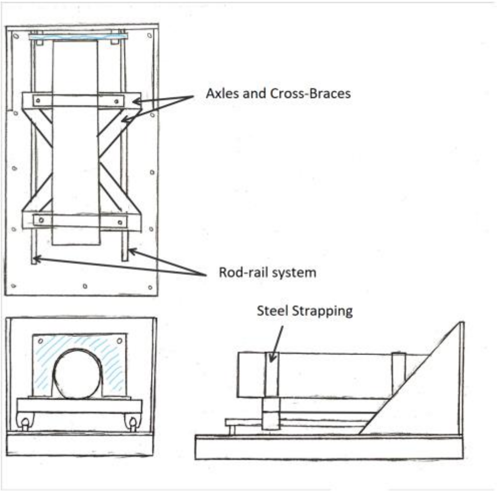

Figure 9: Orthographic view of the second horizontal design; the motor will push on a plate (blue) to distribute a uniform load to the force sensor.

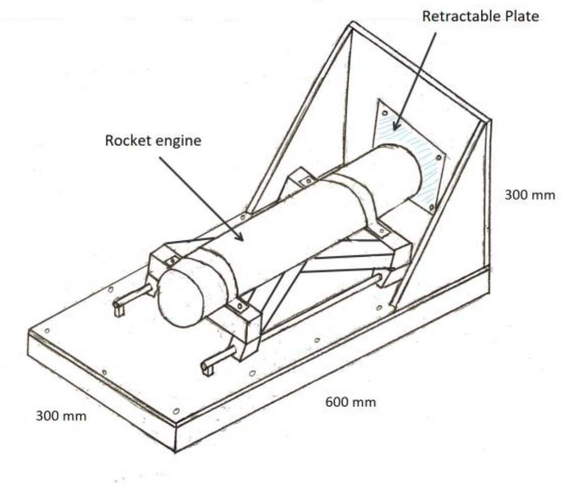

Figure 10: Isometric view of the second horizontal design; held down by saddle clamps, the motor will fire into a reinforced plate.

Reason for Orientation

As preferred by the clients and after thorough review, the horizontal orientation was chosen as stated in Reason for Orientation. In addition to previously made horizontal design arguments, as stated in 2.1.2, this specific design favors the horizontal orientation and allows for easy access to all components while providing a secure and stable platform for the engine.

Load Cell Type

This design incorporates a piezoresistive force sensor due to its dynamic load measuring capabilities, easy to use nature, relatively inexpensive price compared to other types of load cells and its versatility. It is placed between the retractable metal plate, identified in light blue in Figure 9: Orthographic view of the second horizontal design; the motor will push on a plate (blue) to distribute a uniform load to the force sensor. and Figure 10: Isometric view of the second horizontal design; held down by saddle clamps, the motor will fire into a reinforced plate., and the steel sheet at the front of the stand. During testing, the rocket pushes against the retractable plate onto this force sensor to activate the scale for testing.

Securing the Motor to the Stand

For reasons stated in 2.1.1, steel pipe strapping will be used to secure the motor to the axles.

Materials Required and Dimensions

The materials required for the design include the steel frame, axles, and cross braces, which are all constructed from 25.4 mm square tubing with a wall thickness of 1.65 mm. The base and front barrier are composed of 10-gauge steel sheet metal and the retractable plate a 16-gauge sheet. The dowels on which the retractable plate moves along are 12.7 mm diameter steel dowels. Finally, a square piezoresistive load cell for measuring the engine's thrust and a ball bearing linear shaft rail system for the engine to move along. This design can range between 250-350, depending on the metal and load cell provider.

2.2 Decision Making

To choose the best design, an evaluation matrix (Table 3) was created to weigh the three possible designs of the test stand against various criteria. This includes costs associated with the design, feasibility, subsection analysis, manufacturing, and the overall design solution. The design solution that scored the highest was Design 3 and therefore is the chosen option for this project.

Table 3: Weighted Evaluation Matrix used to arrive at final decision.

		Design 1		Design 2		Design 3	
Criteria	Weight /10	Score	Weighted	Score	Weighted	Score	Weighted
Costs associated with design /4	4	3	12	2	8	3	12
Feasibility /4	6	3	18	2	12	2	24
Subsection analysis /4	8	2	16	3	24	4	32
Manufacturing /4	8	3	24	2	16	3	24
Solution /2	10	1	10	1	10	2	10
Total (sum)	/124	80		70		102	

The weighted evaluation matrix provides a framework for which the three proposed design solutions were evaluated. Each category assessed could receive a highest score of 4, with the exception of the solution, which was evaluated out of 2. It was determined that the overall solution must have the highest weighting as this will establish the overall consistency of the design. Within the overall solution, the safety of the design was also considered; however, this was done more thoroughly in the final evaluation of the selected design. The analysis of the subsections and the ability to be manufactured were key weights considered in the analysis. These criteria show that the design is clearly thought out and reasonably complex, but still ensures ease of assembly. Feasibility addresses the overall ability to effectively make use of the materials at hand, ensuring all components of the design are necessary and serve a set purpose. This, along with the costs associated, were weighted the lowest since these are components necessary for improving the efficiency of the design but are not as integral to the design itself.

Of the criteria both weighted and assessed, Design 3 scored the highest with a 102 out of 124. Key factors that led to this were the subsection analysis breakdown and the feasibility of the design. Design 3 was especially effective in the orientation category. Situated horizontally, this design ensures stability, as well as the ability to measure loads effectively. While Design 2 was also horizontal, some parts hindered the efficiency of the model, such as the blast shield which would cause extra reaction forces, presents an abundance of unnecessary materials, and pose a potential threat to the safety of others. Design 1 presented issues with the load cell and the structural integrity of the design. The load cell works best under dynamic conditions, therefore if the load is constantly resting on the cell, it causes an error in the testing [9]. Additionally, a static test in the vertical direction would require a stronger base to counteract the reactionary forces of the engine stand. Design 1 and 3 both have efficient uses of their materials but the dynamic testing in the horizontal direction will address more variables than a test in the vertical direction. For these reasons, the final design chosen will be modelled after Design 3.

2.3 Implementation

Once the final design was chosen, changes were considered as stated in 1.3.1 to ensure accurate results were collected. The model was then analyzed using CAD software and mathematical modelling to determine the forces experienced by the stand during testing. A load cell was also coded to measure the rocket's thrust during testing. Detailed descriptions of the modelling processes, as well as coding of the load cell, are listed below.

2.3.1 SolidWorks

During the initial stages of designing a CAD model for the stand, the stand was constructed based on the sketches and dimensions presented in 2.1.3 (Figure 10: Isometric view of the second horizontal design; held down by saddle clamps, the motor will fire into a reinforced plate.). Upon completion, complications arose in two areas that would affect the final solution; there was very little surface area to screw the steel rings that would hold the engine to the rail and there were complications with mating the sliding plate to the rail for the free-floating effect. After consideration of these factors and advice given from the communications assistant that cautioned against the rail due to the oscillatory noise that could interfere with accurate results, the stand was modified. In this new concept, Figure 2, the rings that support the engine restrict motion in the z-axis and y-axis, by directing it through to the force sensor on the x-axis. Since these rings acted only as a restraint, the material was not crucial to functionality which led to a change in material used. Steel clamps were used to save financially and to minimize damage the engine would sustain while rubbing against the metal from the previous clamps [14].

Something that had not been considered was how the design would be secured to the ground during testing. Under instruction by QRET, it was clear the design would be tested outside; however, it was uncertain under what conditions. The only way the stand could have been secured to would be by placing it up against a strong or heavy source that would repel the forces of the engine, such as a concrete wall. It was decided that a new method needed to be developed to secure the stand. Using basic knowledge of reactionary forces and trusses, Figure 11: Hand drawn sketch of the back support brace attached behind the back plate of the final design. was mathematically modeled and built as an add-on in SolidWorks. To secure it, corner braces were made as opposed to welding the truss to the stand to allow the stand to be tested in various ways, either with the brace on, or with the brace off and the stand propped up against a concrete wall.

The original plan was to run simulations for static, dynamic, and fatigue studies. After running into several issues with the design meshing and missing frequencies, an alternative plan was made. The truss would not run in the simulation due to components that were intersecting. Instead of modelling the whole system together, the system was broken into the base model and the truss. The base model was then simulated through CAD and the truss was evaluated mathematically for deflection based on simple mechanics equations seen in 5. This would still yield accurate results since the stand is designed to be tested in multiple conditions. By simulating the stand without the truss, it represents how the stand would react if testing occurred while resting against an immovable object. This same force is being exerted back on the stand when the truss is added since the truss acts with the same reactionary forces.

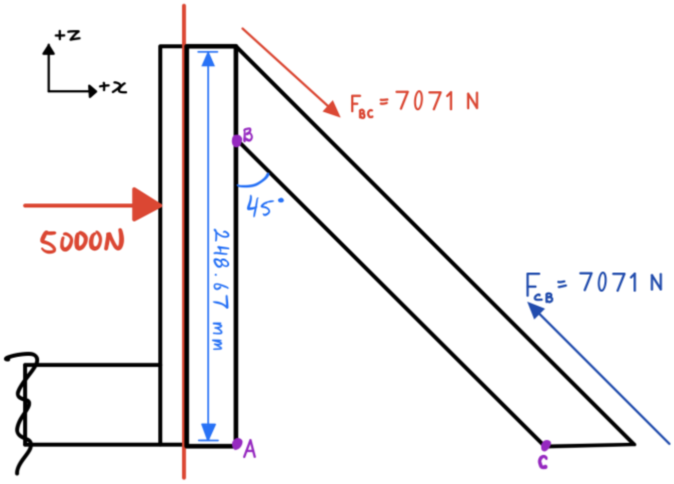

Figure 11: Hand drawn sketch of the back support brace attached behind the back plate of the final design.

The CAD model successfully ran the static test of 5000 N and the fatigue study. The simulation failed to run a dynamic test of 981 N for 6 seconds due to a problem with the initial frequency that could not be established.

2.3.2 Mathematical Modelling

Mathematical modeling was used to analyze the components of the test stand under its expected conditions of 5000N. An understanding of how loads affect members within a structure and how to execute these calculations is important for these models. The values used for these calculations can be found in Table 1: Table of properties important in the comparison of materials being used.

In thermal analysis, the equation:

$$\delta_T = \alpha \Delta T L \tag{1}$$

is used to determine the change in length of a member due to thermal change. The coefficient of thermal expansion, α was found to be 11.7x10^{-6} ($^{o}C^{-1}$) [6], and since the rocket can get as hot as 280 °C [15], the change in temperature ΔT was assumed to be 280 °C. The original length of the member, *L* behind the rocket was 160mm. Using these values, the change in length due to increased temperature was calculated to be 0.5216mm. An analysis of this equation aided in the thermal analysis required to deem the product fit for functioning under the extreme heat produced from the motor. Since the change in length was so small, steel was determined to be sufficient to model the design as it can withstand the expected heat.

It was assumed that the moment of inertia, I, of a hollow square tube would be used, given that all steel available at hardware stores is hollow on the inside. It is also the material that is used for the stand, as seen in 2.4.2. The moment of inertia for a hollow square tube is given by the equation:

$$I = \frac{bh^3}{12} \tag{2}$$

and was used to determine deflection on the structural members of the stand relative to the inertial frame. Since the front sheet is 300mm wide by 300mm high and 3.16mm thick, the base dimension *b* was determined to be 300mm in the x and y directions (separately) and the height *h* was determined to be 3.416mm. Thus, *I* was calculated to be 996 mm^4 in both the x and y directions.

Using moment of inertia, along with the load distribution P, Young's Modulus of Elasticity E, and the length L of the support member, the equation below was used to find the deflection, y_{max} :

$$y_{max} = \frac{PL^3}{48EI} \tag{3}$$

models a beam supported on both ends with an applied load throughout [16]. Since the test stand must withstand at least 5000N of force, *P* was assumed to be 5000N. The Young's Modulus was found to be 2.0x10^{8} kPa (Table 1). These equations determine the best dimensions and structural components to make the stand work. The deflection calculated in both the x and y directions was 14mm. The pressure P on the force sensor was found by dividing the 5000N force, *F* by the cross-sectional area, *A* of the rocket.

$$P = \frac{F}{A} \tag{4}$$

To determine if the 5000N force would permanently damage the structure, the yield strength of steel was compared to the pressure of the designed structure. The yield strength, using literature values, was found to be 2.5x10^{5} kPa (Table 1). This value represents the maximum force that steel can withstand before permanent deformation. The pressure was calculated to be 663 kPa as seen in 5, and since it is less than the yield strength, the front sheet withstands the force without permanent deformation. Finally, basic mechanical modelling was done to determine the internal forces within the truss structure during rocket engine testing. Using the equation:

$$F_c = \frac{F_x}{\cos(45)} \tag{5}$$

where F_c is the compressional force felt on the beam at static equilibrium, Figure 11: Hand drawn sketch of the back support brace attached behind the back plate of the final design. was created to demonstrate the 5000 N force from the engine that creates a reactionary compressional force of 7071N N in the truss to support the stand. All subsequent calculations can be found in 5.

2.3.3 Coding

To accurately measure the motor's thrust during testing, a load cell was integrated into the test stand and was coded using an open-source electronics platform called Arduino. The diagram in Figure 14 in 4.1 is a visual representation of how to connect the force sensor to the Arduino board.

To code the force sensor, example codes online that were used for similar applications were used as a reference for this project. The code created can be found in 4. The program was designed in such a way to read out the sensor data from the analog input and display the output in the serial monitor. Once the output is displayed in the serial monitor, the program will then determine the measurement of the applied force and output it as a force in Newtons. If the QRET team decides to use this sensor with a physical prototype, they would use the circuit with a breadboard, jumper wires and a functioning force sensor to transfer the data coded for the model. Once the force sensor is set up properly, a code using the Arduino IDE software will be required to accurately determine and handle the results from the force sensor.

2.4 Financial Analysis

A financial analysis of the final solution was completed. Decommissioning plans for QRET have been provided to ensure the design's materials do not go to waste after use. Though a prototype is not being built, a list of all materials needed, and their associated costs, have been listed; all materials are available at local hardware stores or online for purchase.

2.4.1 Decommissioning Plans

If the materials used to create the stand are not properly decommissioned, the stand will have varying effects on the environment. As seen in Table 4: Detailed Cost Breakdown of the chosen design., the materials utilized support the need of the project, but still ensure environmental sustainability due to the ability to recycle the material after use. If built, scrap pieces of steel can be sold or sent to a metal recycling facility. When deconstructed, larger pieces can be stored for later use if the material is not compromised.

2.4.2 Detailed Cost Breakdown

If a prototype were to be constructed by the design team, the project would have gone over budget, but since a prototype is not being build, it was determined in 1.1 that there is no budget.

Table 4: Detailed Cost Breakdown of the chosen design.

#	Material	Dimensions	Conversion (mm)	Qty	Cost	Placement
[Figure 2: Sketches of completed design including balloons indicating materials						

and components.						
1,4,5	12 x 24-inch 10 Gauge Steel Sheet [12]	12 x 24 x 0.135 in	305 x 610 x 3.5	2	2 x $40.21	One full sheet for base on top of frame, Cut 12” x 12” front sheet, Other 12” x 12” cut diagonally for triangular supports.
2	Paulin 1 x 72 x 0.065-inch Steel Square Tube [12]	2 x 12in, 2 x 24in (tot. 72in)	2 x 305 2 x 610	1	1 x $36.98	Front and back of the stand as the bottom frame (12”), Either side of the stand as the bottom frame (24”).

Table 4 : Cont’d.

# [Figure 2: Sketches of completed design including balloons indicating materials and components.	**Material**	**Dimensions**	**Conversion (mm)**	**Qty**	**Cost**	**Placement**
7,8	Paulin 1 x 36 x 0.065-inch Steel Square Tube [12]	1 x 10in, 1 x 14in	1x 248.67 1x 351.67	1	1 x $18.41	Used to create the back triangular brace.
6	TOTALFLOW Stainless Steel Saddle U-Bolt Exhaust Muffler Clamp-4 Inch [14]	4in diameter	102	3	3 x $24.30	Straps around the motor to secure it to the base
-	Nuts, bolts, washers [12]	N/A	N/A	~15 each	$15.00+	Connecting components together.
9	Everbilt 1-1/2 Inch Zinc Double Wide Corner Brace (2-Pack) [12]	1 x 1 ½ in	N/A	2	2 x $4.38	Corner braces for securing the back triangular rib.

2.5 Evaluation

To model the chosen design against the deliverables of the project, each aspect of modelling and coding was given a score and determined if it was effective in meeting the requirements set out by the client and the design team in 1.1. To be built, the model must have scored a 16/20 on the evaluation rubric However, after complying with the clients request that safety was the highest priority, an added criteria states that the section titled *Overall Strength and Safety* was required to score at least a 3 with a higher score being more ideal.

Table 5: Final evaluation of simulated model based on Table 10: Evaluation Rubric with each category being out of 4.

Overall Strength/Safety	Load Cell Code	CAD Model	Mathematical Model	Accessibility	Final Score/20
3.5	3.5	3	3	4	17

2.5.1 Overall Strength and Safety

Based on evaluations in 2.5.3, the model withstands forces greater than the expected 5000 N while also exceeding the expected number of cycles significantly. This category is important in the decision-making process because the strength of the product along with the durability account for key factors in determining safety. Safety, being a top priority for QRET, must be valued above all else. The stand under computer simulated conditions fits those requirements. However, due to the uncertainty that surrounds the failure to compute the results with the truss attached, this is not ideal. The truss, being the same material, will be affected the same way the stand is. Since the stand and truss are not seamless, there is an error in this that will not fully compute the life cycle of the model.

2.5.2 Load Cell Code

The load cell code developed in Arduino was evaluated and assessed against the key deliverables specified by the client and summarized in the Evaluation. To score a 4, the load cell must accurately read and determine the force exerted by the rocket. The code involved must also have no errors, with properly defined variables and proper indentation. The code developed by group 728D worked very effectively in Arduino simulations (Figure 13) and was able to accurately determine the force exerted on the load cell. However, based on the rubric, the code could have been more concise, with proper code formatting including proper indentation and proper variable definitions. Thus, the load cell and its subsequent code scored a 3.5 on the rubric.

2.5.3 CAD Model

Static Study

The static study analyzed a distributed load of 5000 N across the force sensor to determine the effects of the force on the structure. The results of the static test came in 4 categories: stress, strain, displacement, and factor of safety.

The stress study measured the maximum pressure on the stand. Calculated as part of the mathematical model, the yield strength, which is the most pressure the material can withstand prior to permanent failure, is 2.5×10^5 kN/m^2 or kPa. The maximum value the force sensor and stand feel, seen in Figure 15, is 7.24×10^2 kPa presented by the red colouring. This showed that the pressure the stand feels is significantly less than the maximum pressure it can withstand, proving an effective design.

The strain study showed where the maximum strain is felt on the system. Represented visually in Figure 16, the force from the engine is only felt on the back plate, mainly around the force sensor. This showed that the certain components, such as the base, are negligible in terms of contributing to the system. A recommendation to QRET would be to build the base out of concrete as opposed to metal, since the base is not necessary for the system's success. This will save on material and time due to the elimination of complex welding of the steel frame.

The displacement study, seen in Figure 17, yielded extremely low values for change due to stress, which showed that the system can withstand the given load.

The factor of safety (FOS) study, seen in Figure 18, measures the strength of the system divided by the yield strength, by using results from the stress test. Given that this ratio measures the overall strength with regards to the yield strength, the greater the FOS, the stronger and safer structure. The FOS for the engine test stand presented with values of 2.38×10^2 throughout the entire stand showing that at the weakest points, the stand proves very safe.

Dynamic Study

Many errors occurred during dynamic study testing due to meshing and intersecting parts. Although this test failed, it does not indicate that the system was a failure it just means that it did not pass every criterion. More knowledge of SolidWorks and the design were required for completion. For further studies, research and experimentation need to be conducted on the frequency of oscillatory behavior the engine would pose on the stand.

Fatigue Study

The fatigue study assessed the damage that the system incurs in each cycle to calculate the total life of the product. Since QRET will be testing the motor under given time constraints and for a static load, that is 2 tests needed to be performed. When using experimental data results, no less than 6 tests must be run to assume the trials have produced an accurate range of results. For safe assumptions, 8 trial runs per test with 2 tests means that the testing of the motor to fit both requirements requires the stand to endure 16 cycles. Accounting for failure in the results could double number of cycles needed to be run per year. If 32 studies are needed to be run every year and having a shelf life of 10 years is most successful, the stand must endure 320 cycles. Both the damage per cycle, showing the damage build up over time, and total cycles expected of the stand present much higher than the expected 320 cycles, based on Figure 19 and Figure 20. However, this is only for the stand if it were resting without the truss. If the stand is being operated without the truss, the expected number of cycles that could be run is 1 million before the product will fail. If considering the truss, this number will drastically change due to the forces acting on the truss, the truss connectors, and the screws securing the truss connectors. Due to limited knowledge in SolidWorks, this information could not be modelled. Components of the truss should be monitored yearly to ensure that strength and structural integrity are intact. The number of cycles with the truss should be determined by professionals if implemented but preliminary simulations present results consistent with success over many cycles.

2.5.4 Mathematical Model

The mathematical model presented in 2.3 was evaluated and assessed against the key requirements set out in the evaluation rubric. The calculated values of the model were realistic numerically and corresponded to the design overall. The model compared the yield strength in literature to the force per unit area of the designed structure to determine if the 5000N force would permanently deform the structure. Since the force per unit area was found to be 663 kPa and was less than the yield strength of steel, the model concluded that the design could withstand above 5000N of force without permanent deformation. To receive a 4 in the rubric, the deflection calculated must have been less than 10mm. The deflection calculated for 728D's design was just over and was found to be 14mm. Therefore, the mathematical model presented scored a 3 on the rubric.

2.5.5 Accessibility

Ensuring that the model could easily be recreated with widely available materials was also a topic of evaluation for the design. When deliberating between the 3 designs in 2.1, concision and ensuring that every material served a set purpose was also a topic of evaluation on the evaluation matrix. Thus, the choice to use design 3 also implied that the model would be widely accessible. All changes to the design were made to ensure that the model would not only perform well, but also that it could be easily built and modelled. Further, all materials used can be found at local hardware stores, and therefore are widely available to all. Thus, the model scored a 4 on accessibility.

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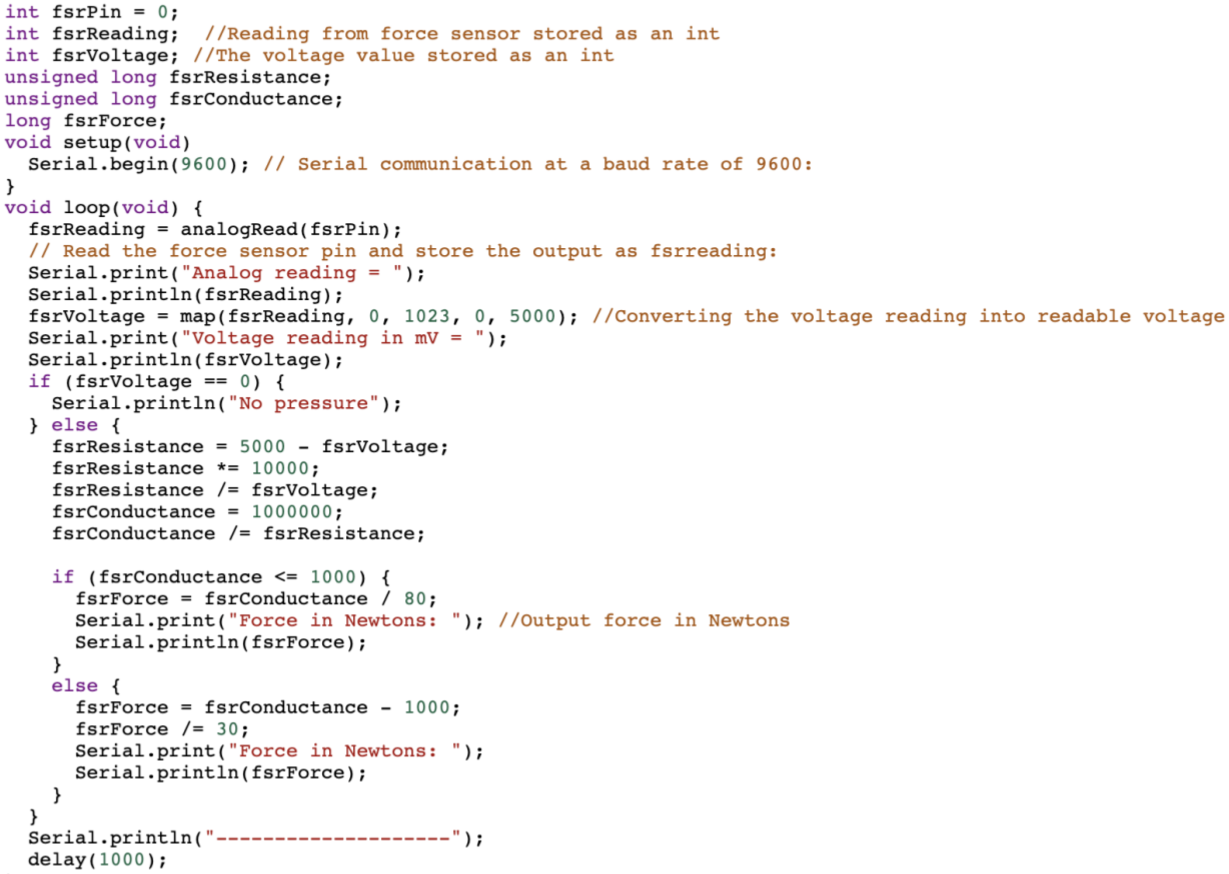
4 Appendix I – Modelling

Below are detailed images of modelling outputs.

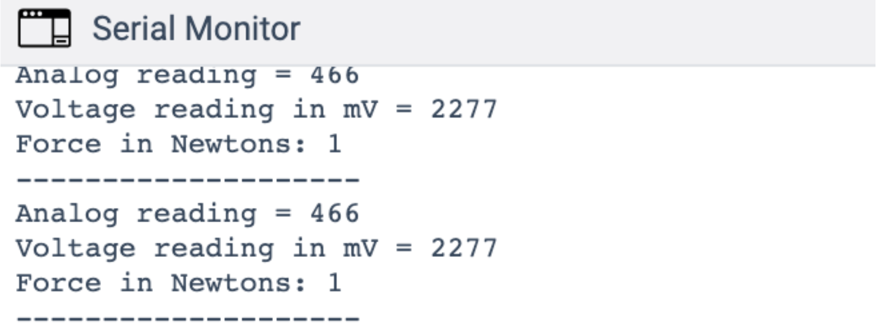
4.1 Force Sensor Code on Arduino IDE



```
int fsrPin = 0;
int fsrReading;  //Reading from force sensor stored as an int
int fsrVoltage; //The voltage value stored as an int
unsigned long fsrResistance;
unsigned long fsrConductance;
long fsrForce;
void setup(void)
  Serial.begin(9600); // Serial communication at a baud rate of 9600:
}
void loop(void) {
  fsrReading = analogRead(fsrPin);
  // Read the force sensor pin and store the output as fsrreading:
  Serial.print("Analog reading = ");
  Serial.println(fsrReading);
  fsrVoltage = map(fsrReading, 0, 1023, 0, 5000); //Converting the voltage reading into readable voltage
  Serial.print("Voltage reading in mV = ");
  Serial.println(fsrVoltage);
  if (fsrVoltage == 0) {
    Serial.println("No pressure");
  } else {
    fsrResistance = 5000 - fsrVoltage;
    fsrResistance *= 10000;
    fsrResistance /= fsrVoltage;
    fsrConductance = 1000000;
    fsrConductance /= fsrResistance;

    if (fsrConductance <= 1000) {
      fsrForce = fsrConductance / 80;
      Serial.print("Force in Newtons: "); //Output force in Newtons
      Serial.println(fsrForce);
    }
    else {
      fsrForce = fsrConductance - 1000;
      fsrForce /= 30;
      Serial.print("Force in Newtons: ");
      Serial.println(fsrForce);
    }
  }
  Serial.println("--------------------");
  delay(1000);
```

Figure 12: Code used to measure and analyze forces produced by the rocket on the force sensor.



```
Analog reading = 466
Voltage reading in mV = 2277
Force in Newtons: 1
--------------------
Analog reading = 466
Voltage reading in mV = 2277
Force in Newtons: 1
--------------------
```

Figure 13: Reading of the forces produced by the rocket's thrust.

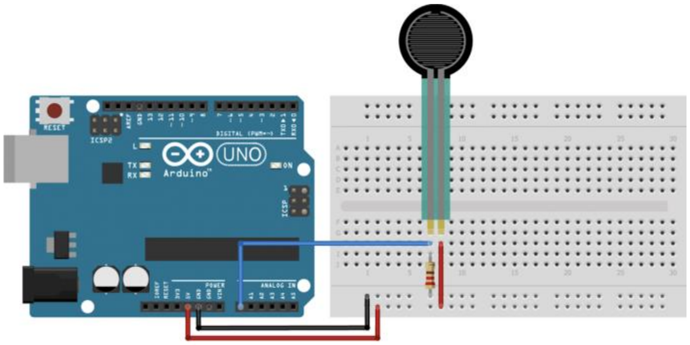


Figure 14:Diagram of a force sensor connected to an Arduino board.

4.2 CAD Model

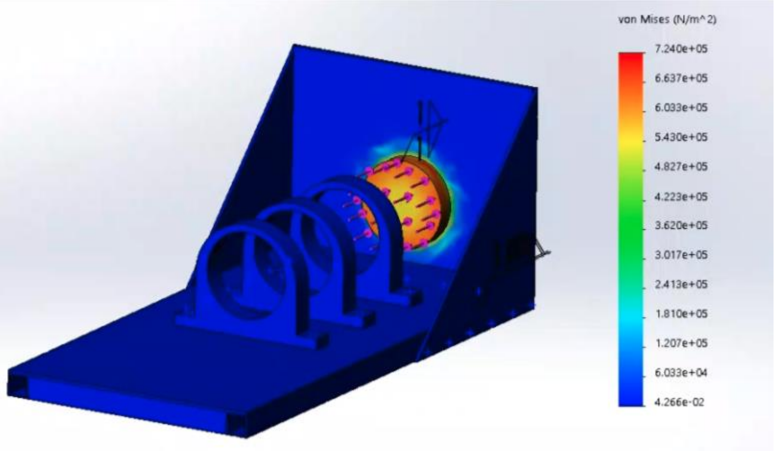


Figure 15: Von Mises Stress Study

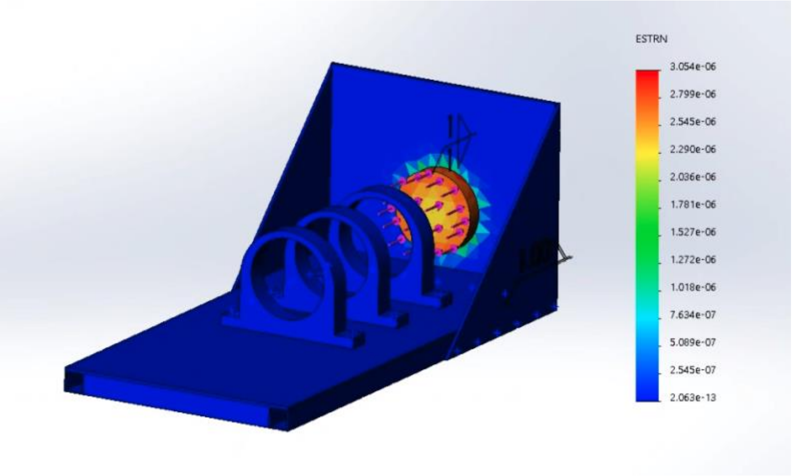


Figure 16: CAD Strain Study

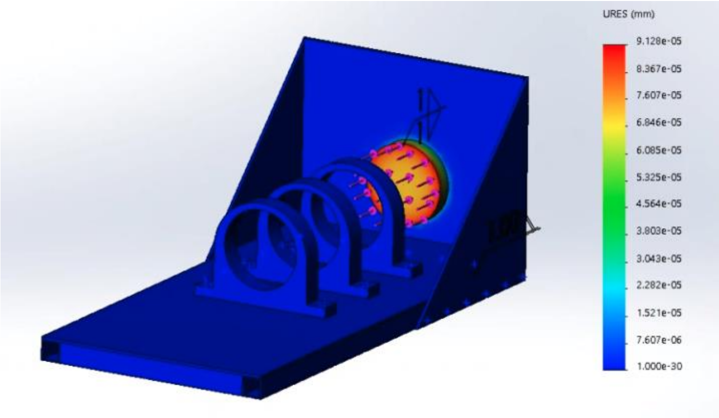


Figure 17: CAD displacement study

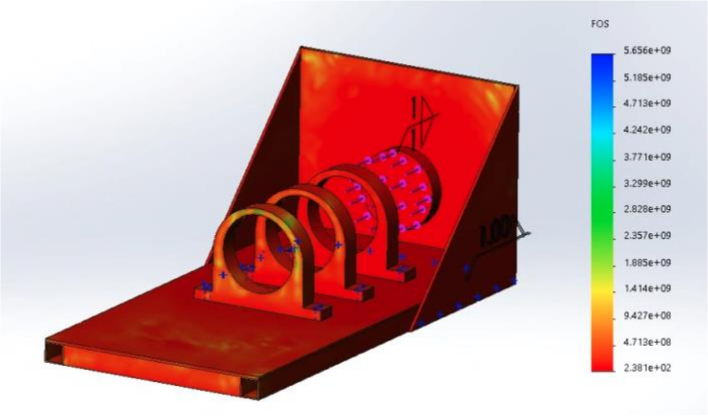


Figure 18: Factor of Safety Simulation

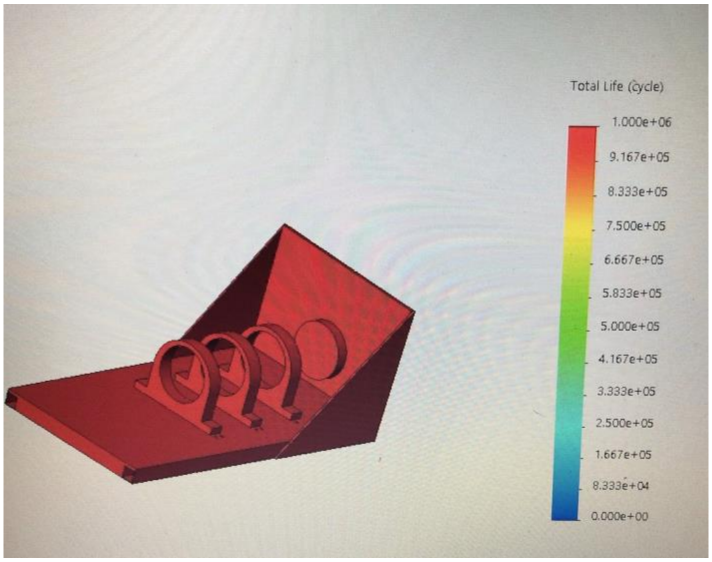


Figure 19: Life Cycle Analysis

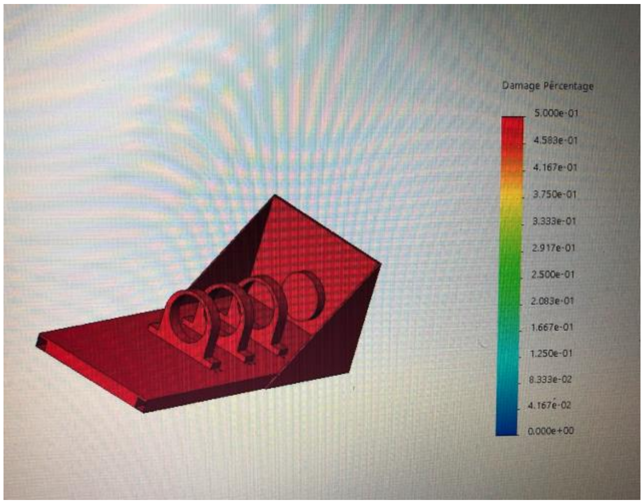


Figure 20: Damage Percentage per Cycle

5 Appendix II– Calculations

Table 6: Table of calculations performed to test the final model.

$$\delta_T = \alpha \Delta T L \tag{1}$$

$$\delta_T = (11.7 \times 10^{-6}\ ^{\circ}\mathrm{C}^{-1})(280\ ^{\circ}\mathrm{C})(0.16\ m)$$

$$\delta_T = 0.5mm$$

$$I = \frac{bh^3}{12} \tag{2}$$

$$I = \frac{(0.3m)(0.3m)^3}{12}$$

$$I = 9.97 \times 10^{-10}\ m^4$$

$$y_{max} = \frac{PL^3}{48EI} \tag{3}$$

$$y_{max} = \frac{(5000N)(0.3m)^3}{48(200000000000\ Pa)(9.97 \times 10^{-10}\ m^4)}$$

$$y_{max} = 14mm$$

$$P = \frac{F}{A} \tag{4}$$

$$P = \frac{5000N}{\pi(0.049m)^2}$$

$$P \cong 663kPa$$

$$0 = \sum F_x \tag{5}$$

$$0 = F_c \cos(45) - F_x$$

$$F_c = \frac{F_x}{\cos(45)}$$

$$F_c = \frac{5000}{\cos(45)}$$

$$F_c = 7071N$$