From Magnetic to Mechanical: Electromagnetically Powered Impact System

Capstone Group: ARL-MLS1
Project Supervisor: Professor Kamran Behdinan
Client: ARL-MLS Lab

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Executive Summary

The ARL-MLS lab at the University of Toronto requires a way of testing lightweight ceramic armour systems. The lab has provided a salvaged machine that can be repurposed to design a new impact test rig. It is standard practice to perform high velocity or ballistic velocity impact tests on ceramic samples; however, due to limited space in the ARL-MLS lab and to ensure students' and operator's safety, this project will not be exploring ballistic or high-velocity impact tests. Instead, the scope of this project will be to design a Technology Readiness Level 4 low-velocity impact testing rig prototype that is capable of causing and measuring an impact on ceramic armour samples.

To reiterate the objectives chosen in the project requirements: the ceramic sample must experience an impact velocity of 5m/s, and the testing rig should sense or calculate the impact force. The project should also cost no more than $500 CAD, and should rank TRL 4. The design must adhere to all safety standards and codes expected of an experiment conducted in an UofT lab and fit into the designated space given by the ARL-MLS Lab (i.e. where the existing machine stands). Beyond this design team and the ARL-MLS lab, the design needs to consider and not impact the individuals accessing the lab in any way.

This document reiterates the background research initially conducted in the project requirements document, the functions, objections, and constraints for this project, and the stakeholders. In addition, the report investigates three preliminary designs and compares their advantages and disadvantages. A final design is chosen based on its scalability, cost, safety, theoretical calculations, and feasibility and it is prototyped for proof of concept. The prototype for the design is explained in detail, tested, and reiterated to produce a final design. The final design is presented at the end of this report along with its 3D-model, engineering drawings, and operational manual. This design's impact on future stakeholders is also briefly considered and discussed. The future work that can be done by the client to scale up this design is suggested at the end of this report so that the design can be used for higher velocity testing in the lab.

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1.0 Introduction

Ceramics have been identified as a favourable material for the development of high protection, lightweight armour systems due to their low densities and high intrinsic strengths [1]. However, ceramics are brittle, which means that they are likely to fracture and crack upon impact [1]. Therefore, to fully explore the potential of ceramic use in armour systems, they must be tested in a controlled environment. This can be done using an impact testing mechanism [2]. Impact can be defined as the force or action of one object hitting another [3]. There are two main categories of impact testing, namely, low-velocity testing and high-velocity testing [4]. Low-velocity testing methods include the charpy and drop weight impact tests. The high-velocity testing method is referred to as ballistic testing [4]. This document details the specific problems, the current state of the art, necessary design requirements, all proposed designs, a final chosen design, all testing done and future work that should be completed. The first six sections have been taken from and revised from this project's Project Requirements document.

2.0 Problem Statement

The ARL-MLS lab has tasked this capstone design team with repurposing pre-existing machinery, shown in Figure 1 below, into an impact testing rig for ceramic armours. The testing rig should be capable of dropping and applying a calibrated force to the projectile, as well as measuring impact velocity and calculating the impact energy.

The impact testing rig must follow all safety guidelines and other physical limitations. Detailed objectives and constraints are discussed in Section 6.0. The design should consider all stakeholders, as well as its design for cost, human factors, safety, and the environment, which are discussed in Section 6.6.

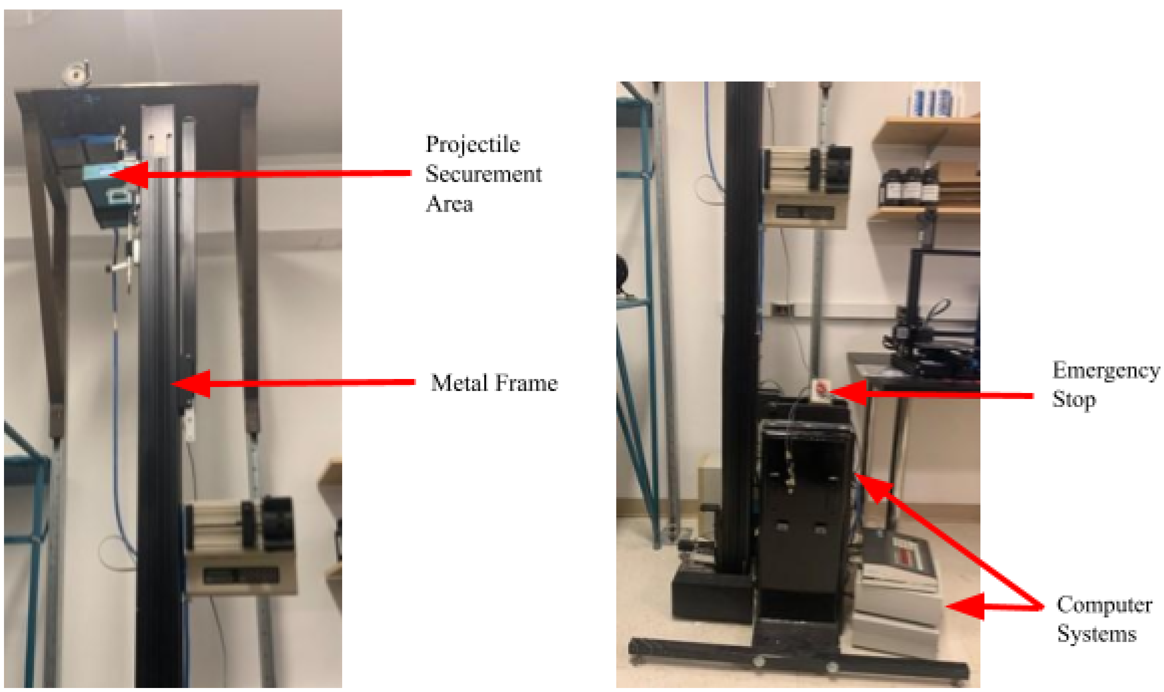


Figure 1: Current Setup of the Drop Test Rig in the ARL-MLS Lab

3.0 Background

This section explores state of the art drop weight testing setups by reviewing experimentation performed within the last 5 years as well as modern testing machines. Drop weight impact tests are used to simulate the expected impact a material would experience in the field [4]. Figure 2 shows the general setup of a drop weight test.

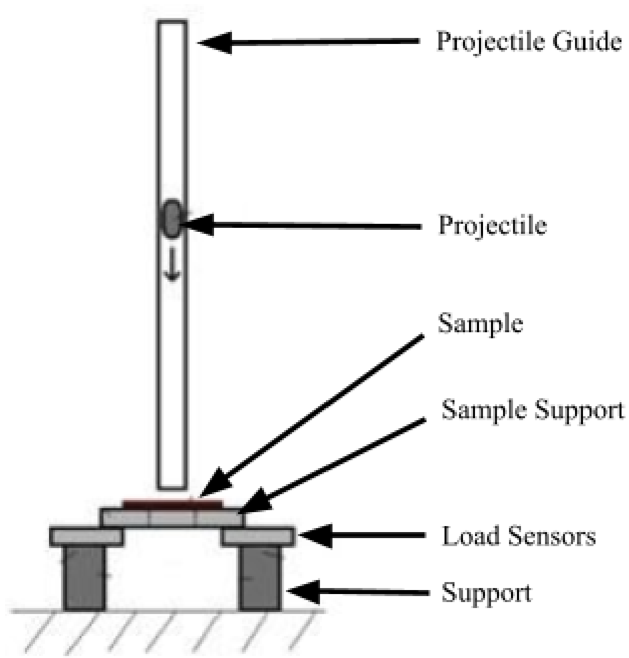


Figure 2: Setup Used to Test 3D Glass Fibre Reinforced Polymer Laminates [5]

The operation of the above test is as follows: a projectile of a specific mass and shape is raised vertically to a predetermined height, released, and impacts a test sample once [4]. The sample itself is typically flat in shape, of a set thickness, and clamped around its edges [4]. The control system involves using sensors together with high speed cameras to measure the impact force, velocity, and the sample response at the instant of impact [5].

Alternatively, rigs can also be designed for repeated impacts [6], [7]. Figure 3 shows the standard testing rig for a multi-impact drop test.

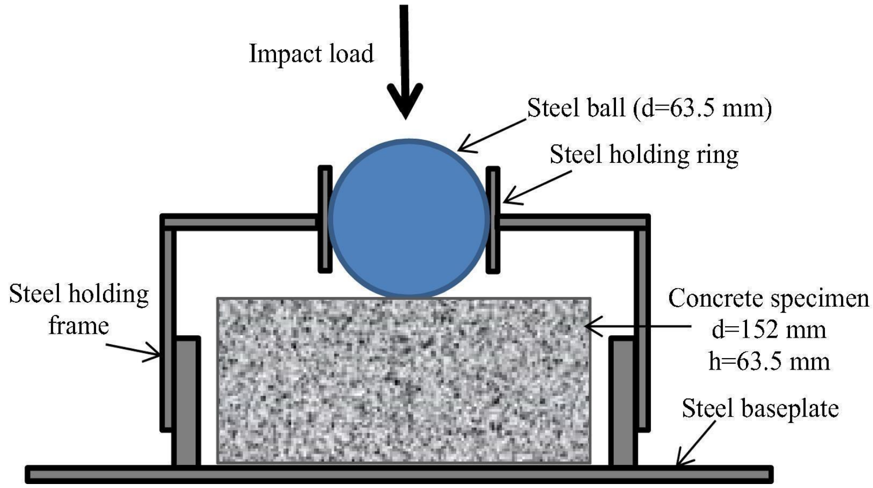


Figure 3: Lower Portion of the ACI 544-2R RBDWI Testing Rig [7]

The operation of the rig is as follows: a steel ball is placed on top of the sample to act as a force distributor and a hammer/weight is then used to repeatedly impact the ball. The number of impacts until the first crack is recorded and used to determine the material properties of the sample.

There are also standardised rigs available for purchase on the market such as the ZwickRoell DWT high-energy drop weight tester [8].

Figure 4: ZwickRoell DWT40 5m HDWT40 5m High-Energy Drop Weight Tester [9]

These machines are computerised, and allow for a wide range of drop weight testing [9].
Using the details in the above figures, the project can be broken down into the following subsystems:

- Controls and Electronics System
- Rig Framing
- Projectile System
- Test Sample

3.1 Controls and Electronic Systems

The controls and electronic subsystem encompass all aspects of the project related to the actuation of the rig, collection of data, calculation of results, and display of results. Typically, impact velocity, force, and energy are the recorded or calculated variables during the experiment.

Theoretically, impact velocity is the velocity of the projectile during its collision with the ceramic sample; experimentally, it is measured just before collision. During impact tests, impact velocities, in both cm/s and m/s ranges, are commonly measured using optical sensors [10], [11]. As seen in Figure 5 below, Kyushu University used a combination of laser diodes and photo-detector units to measure the projectile's velocity [12].

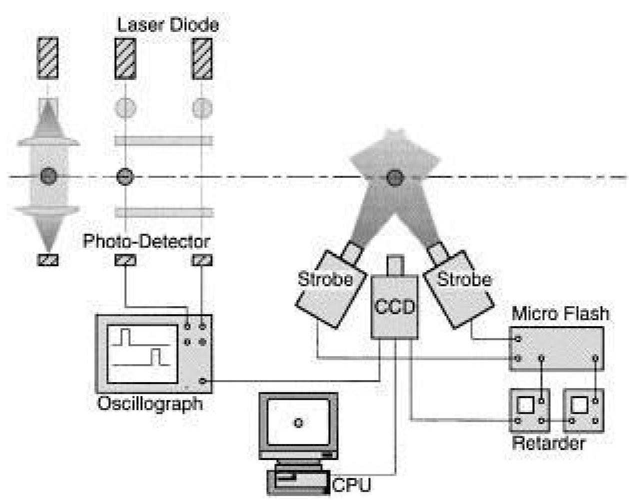


Figure 5: Kyushu University Velocity Measurement Capture System [12]

The AFWAL Materials lab used a combination of phototransistors, light emitting diodes, and 10-MHz counters to measure their impact velocity as seen in Figure 6 below [10].

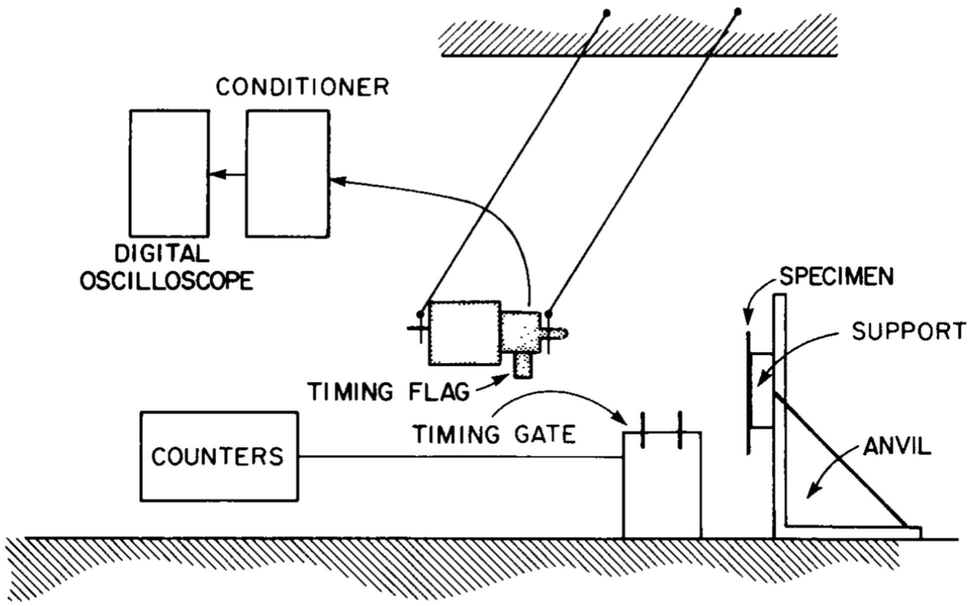


Figure 6: University of Dayton's AFWAL Materials Laboratory Impact Experiment Test Setup [10]

The impact force can be measured using force transducers, a conditioning amplifier, sound card, and MATLAB's Data Acquisition Toolbox. Figure 7 below, shows an example layout for impact force measurement [13].

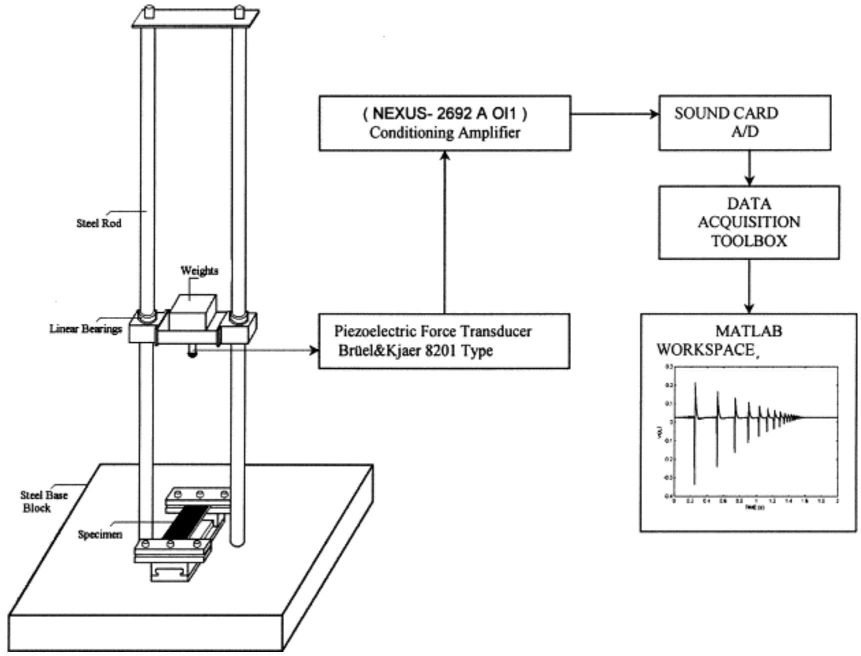


Figure 7: Low-Velocity Drop Test Impact Force Measurement Procedure [13]

As detailed in Section 4.3 below, the impact energy can be calculated through integrating under the load-displacement curve of the sample during impact. In order to generate the load-displacement, strain gauges, or load cells can be used [14].

3.2 Rig Framing

The rig framing is the physical structure of the impact mechanism. The machinery pictured in Figure 1 will be modified into the rig framing. However, the team has observed that the rig framing for a standard state-of-the-art drop test on ceramics exceeds a height of 3m, which exceeds the height of the given machinery [5], [9]. As such, the team must design a ceramic testing rig that differs from the current state-of-the-art.

Further research revealed that drop testing is widely used to test concrete samples [6], [7]. The current standard is the ACI 544-2R RBDWI test [7]. This test involves impacting a concrete sample multiple times using a rig framing that is approximately 0.5m tall. While the testing of concrete is beyond the scope of this project, the principles applied in the ACI 544-2R RBDWI can help the team modify the given machinery.

3.3 Projectile System

The projectile system involves both the projectile itself, as well as a mechanism to hold and release/fire the projectile. Generally, the projectile is spherical in shape, made of metal, and sized smaller than the sample area. For example, a sample of size 145x190mm requires a projectile of diameter 80mm [5].

The hold/release mechanism varies based on the complexity of the drop test system being used. The simplest version of this mechanism involves using a clamp to hold the projectile in place and opening the clamp to release the projectile [5]. A more complex mechanism involves using a series of pulleys to hold, release, and reset the projectile [9]. Another alternative is the use of electromagnets to hold and release the projectile [15].

3.4 Samples

As stated in the introduction, the purpose of the test rig will be to simulate the testing of a lightweight ceramic armour system. Typically, this is done by testing a fixed ceramic sample with a backing layer. Similar impact tests have used the following as samples [16]:

- Ceramic Tile Mosaic + Epoxy Resin (e.g. Alumina (Al_2O_3))
- Ceramic + Metal Backing Layer (e.g. Steel 4340)
- Ceramic + Composite Backing Layer (e.g. Kevlar)

4.0 Equations

This section details the equations required to calculate the impact velocity, impact force, and impact energy associated with a simple drop test. These equations will be used as a starting point for the design of the physical impact testing mechanism. Note that all calculations assume air resistance is negligible.

4.1 Impact Velocity

The impact velocity of a drop test can be found using the law of conservation of energy [17].

Potential Energy, $PE = mgh$

Kinetic Energy, $KE = \frac{1}{2}mv^2$

Law of Conservation of Energy: $PE = KE$

Thus: $mgh = \frac{1}{2}mv^2$

Solving for v gives: $v = \sqrt{2gh}$

Where:
m - mass of projectile
h - drop height
g - acceleration due to gravity
v - impact velocity

4.2 Impact Force

The calculation of impact force involves the work energy principle [17]. This principle states that the work done on a system is equal to the change in kinetic energy of the system [18].

$$W_{net} = \frac{1}{2}mv_{final}^2 - \frac{1}{2}mv_{initial}^2$$

$$F = \frac{W_{net}}{d}$$

W_{net} - net work done

m - mass of projectile

v_{final} - impact energy

$v_{initial}$ - initial velocity (0 m/s)

F - impact force

d - distance travelled after impact

Note that the distance travelled after impact is dependent on the type of collision. For a near perfectly elastic collision, the sample absorbs minimal impact energy and as such, the distance value is small [17] which results in a large impact force. For an inelastic collision, the material absorbs some of the impact energy and as such, the distance value is large [17] which results in a small impact force.

4.3 Impact Energy

The impact or failure energy can be found by integrating the bounded area under the sample's load vs displacement curve [5]. This curve can be drawn using data captured at the moment of impact. Figure 8 displays an example load vs displacement graph.

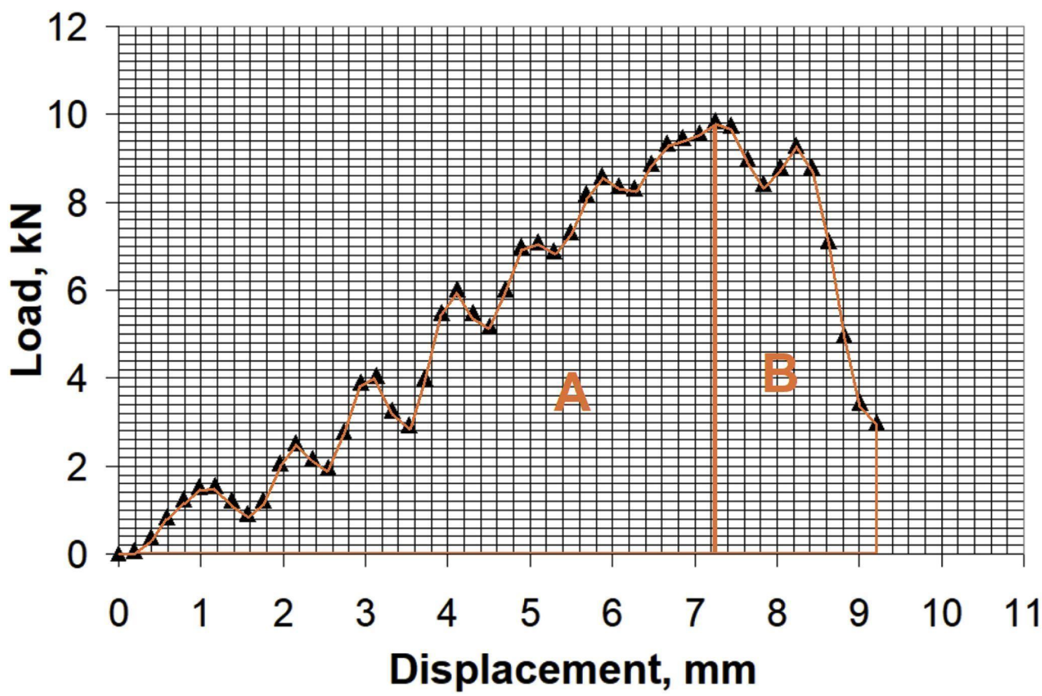


Figure 8: Load vs Displacement Example [5]

Note that the area of the graph is split into parts, A and B. A represents the energy of origin of the major failure process in the material () and B represents the energy of development of the major failure process in the material (). This split allows for the calculation of the sample's deformability index (DI). [5].

5.0 Scope of Work

Due to the size of the ARL-MLS lab and to ensure operator safety, this project will not be exploring ballistic impact tests, rather only low-velocity impact tests. Table 1 shows the scope for each subsystem based on the background research.

Table 1. Scope for Each Subsystem

Subsystems	Scope
Controls & Electrical	<u>Controls:</u> ● Record, calculate, and display: ○ Impact Velocity ○ Impact Force ○ Impact Energy
	<u>Electrical:</u> ● Electrical components required to integrate projectile and control system ● Sensors required to measure results
Projectile	Releasing the projectile such that it achieves a low impact velocity
Rig Framing	To repurpose the existing machinery if possible, elsewise design a new rig framing

As per the client's requirements, the system should be prototyped to a level 4 rank on the Technology Readiness Level (TRL) scale, which requires a complete proof-of-concept work that validates the successful performance of a system and achieves the project requirements [19]. An instruction manual on how to operate the test rig will be provided. In summary, the scope of this project is to design and prototype the projectile, control, and electrical systems of a low-velocity impact testing rig, that is able to cause and measure an impact on ceramic armour samples, to a TRL4 level. This project will be completed over an 8-month period with an allocated budget of $500 CAD. Therefore, while inspiration for this project can be taken from the similar experiments discussed in the background section, space and cost considerations must be made.

6.0 Detailed Requirements

This section highlights the functions, objectives, and constraints that will be considered in the design of the low-velocity drop test rig. Additionally, client-driven and industry-driven parameters such as stakeholders, cost, and safety standards are discussed.

6.1 Functions

The purpose of this project is to design a low-velocity impact testing rig that is capable of testing ceramic samples to assist in ceramic armour research. The primary and secondary functions of the final design outline the actions the test rig will perform, and they are listed below.

Primary Functions:

1. Holds the projectile in a secure starting position
2. Applies a predetermined, calibrated force to the projectile during the launch sequence to achieve a projectile target velocity
3. Launches the projectile vertically to impact the unit under test (UUT)
4. Contains the projectile within the testing rig set-up
5. Produces repeatable and reliable test results

Secondary Functions:

1. Records the impact velocity of the projectile
2. Calculates the absorbed energy of the UUT
3. Calculates the impact force of the projectile

6.2 Objectives

The low-velocity impact testing rig should abide by client driven and technology driven parameters. Table 2 states the goals for the technology, along with a metric and the reasoning/testing method for each objective. Further justification and calculations behind the reasoning for each objective can be found in Appendix A. The objectives are ranked in order of importance through analysing the project's requirements and client's goals for the design. The vital objectives have their target level highlighted. The goals and levelling systems were determined through researching the current state of the art and understanding the client's expectations.

Table 2. Impact Testing Rig Objectives, Metrics, and Reasonings

#	Objective	Objective Levels		Reasoning/Testing Method
1	Projectile should attain low velocities	L1	Less than 1m/s maximum	Reasoning: High-velocity testing is unsafe for U of T students [20]. A slower speed of 10m/s was suggested by the client for safety purposes. Testing method: Velocity can be determined by dividing height over measured time.
		L2	Between 1-5m/s maximum	
		L3	Between 5-10m/s maximum	
		L4	Between 10-20m/s maximum	
		L5	Over 20m/s maximum	
2	Design should hold projectiles of various masses and sizes securely	L1	Holds masses of less than 50g	Reasoning: Projectiles of different masses and sizes should be held firmly in place by the design before testing begins [21]. Testing method: Test the machine by holding projectiles of various masses until failure.
		L2	Holds masses between 50-100g	
		L3	Holds masses between 100-150g	
		L4	Holds masses of 150g or greater	
3	Design should apply a force to the projectile to attain low velocity	L1	Applies up to 0.004N to the projectile to achieve velocities of less than 1m/s	Reasoning: The design will require a mechanism that launches the projectile to impact the unit under test with a low velocity.

		L2	Applies 0.004-0.1N to the projectile to achieve velocities of 1-5m/s	Testing method: Where acceleration can be found using accelerometers or projectile velocity.
		L3	Applies between 0.1-0.4N to the projectile to achieve velocities of 5-10m/s	
		L4	Applies between 0.4-1.6N to the projectile to achieve velocities of 10-20m/s	
		L5	Applies over 1.6N to the projectile to achieve velocities over 20m/s	
4	Design should contain the UUT and projectile within a constrained boundary	L1	Design does not contain the UUT and projectile within the testing set-up	Reasoning: Containing the projectile and any fragments from the impacted unit under test within a certain boundary is critical for operator safety [22]. Testing method: Achieved if an impact test occurs without the projectile or any UUT fragments escaping the containment area.
		L2	Design contains the UUT and projectile within 700x720x570mm (WxDxH)	
		L3	Design contains the UUT and projectile within 490x450x565mm (WxDxH)	

		L4	Design contains the UUT and projectile within 250x150x145mm (WxDxH)	
5	Design should rank Technology Readiness Level 4	L1	TRL 1	Reasoning: The client has requested TRL 4 for the design, which requires prototyping and a final functional product [23]. Testing method: Achieved once a prototype has been built and the design has attained all the other objectives.
		L2	TRL 2	
		L3	TRL 3	
		L4	TRL 4	
		L5	TRL 5+	
6	Design should be affordable	L1	Costs more than $500 to prototype	Reasoning: The design should not be too expensive, as there is a $500 budget given by UofT. Testing method: A complete bill of materials will be kept for the final design with the total calculated cost.
		L2	Costs between $250-$500 to prototype	
		L3	Costs between $100-$250 to prototype	
		L4	Costs less than $100 to prototype	
7	Design should produce multiple impact tests	L1	Design can produce 3 impact tests or less	Reasoning: Successive testing will be required to test the strength of different types of ceramic armour in response to impacts from different projectiles [24].

		L2	Design can produce between 5-10 impact tests	Testing method: The number of successful impact tests (objectives 1 and 3 are achieved each time) will be counted. Achieved if the machine does not fail or break between/during tests.
		L3	Design can produce between 10-20 impact tests	
		L4	Design can produce more than 20 impact tests	
8	Test set-up and duration should be short	L1	Test set-up and duration takes over 20 minutes	Reasoning: The test duration should be kept short to maximise time efficiency and data collection. Testing method: Measure the time duration from setting up the system to when the impact test result displayed. The level will depend on the duration of this interval [24].
		L2	Test set-up and duration takes between 10-20 minutes	
		L3	Test set-up and duration takes between 2-10 minutes	
		L4	Test set-up and duration takes under 2 minutes	

6.3 Final Design Objectives

Table 3 outlines the level the final design will attain for the objectives that are most relevant to the scope of this project. Appendix A Table A2 outlines the reasoning for selecting and levelling these objectives in further detail. These objectives and their levels were selected based on the clients expectations, scope, feasibility, and timeline for this design project.

Table 3. Final Design Objectives and Target Levels

Objective	Target Level	Reasoning
1	L2	The client has stated that 5m/s (L2) would be a safe objective.
3	L2	To achieve speeds of 5m/s, forces between 0.004-0.1N (L2) are required.
4	L2	Current technology that achieves velocities of 5m/s for impact testing use this size containment area for testing and safety, indicating that L2 should be attained [22].
5	L4	The client requires the project to achieve TRL 4 unless safety is compromised.
6	L2	As the team does not plan on using personal funds for the project, a L2 objective is justified.

6.4 Constraints

The client has established various constraints which are conducive to creating an adequate final design. Furthermore, the team has identified additional constraints related to safety and machine precision. The constraints for the design can be found in Table 4 below. For further justification and information, Appendix B provides a detailed reasoning behind each objective.

Table 4. Impact Testing Rig Constraints and Essential Goals

#	Constraint	Reasoning
1	Must drop the specimen from below 1.8m-2.5m.	The client has specified a drop height of 1.8m to 2.5m maximum for the testing rig, as it will be required to fit inside the ARL-MRS lab.
2	Must abide by ISO 45001 safety standards [25].	ISO 45001 outlines the standards for basic safety procedures [25].

3	Differences in calibration of the projectile velocity, UUT weight, and impact energy before and after the test, must be less than 7%.	To ensure consistent test results, the impact test rig must remain calibrated during testing. The guideline for impact testing is that calibrations for the projectile velocity, UUT weight, and impact energy taken before the impact test must be no more than 7% from calibrations taken after the test [24].
4	The projectile must be launched vertically, and accurately impact the unit under test.	The test performed must be a vertical drop test where the projectile accurately impacts the UUT with enough force to test its strength and absorbed energy.

6.5 Stakeholders

The following tables show the internal and external stakeholders, which are individuals or groups of people who are impacted by the design either directly or indirectly.

Table 5. External Stakeholders

Stakeholders	Impact
Client - ARL-MLS Laboratory	The design should fit the client's need to test ceramic armour.
Operators	The design should ensure the safety of the individual operating the machine.
Individuals accessing the building/lab	The design should not affect or cause potential harm to the students or professors accessing the building/lab.
University of Toronto	As the design will be implemented in the Mechanical Engineering Building, UofT holds a certain degree of liability if individuals or buildings were to be impacted.

Table 6. Internal Stakeholders

Stakeholders	Impact
MIE491 Capstone Design Team	The design should be safe to assemble and test to ensure safety of the design team.

6.6 Design for Excellence (Dfx)

This section considers other aspects of the design such as cost, assembly, human factors, and safety. Dfx considerations for manufacturing and environment can be found in Appendix C.

6.6.1 Design for Cost

When sourcing for parts, a cost analysis should be performed to minimise cost. Table 7, breaks down how each subsystem can be designed to minimise cost. Table F2, in Appendix F breaks down existing resources that can be used for design and prototyping.

Table 7. Subsystem Design to Minimise Cost

Subsystem	Considerations
Controls & Electronic System	Repurpose electronic components on the pre-existing machinery if possible
	Source for affordable electronic components (e.g. Digi-Key or Amazon)
	Utilise coding software licences provided by UofT
Frame	Provided by the ARL-MLS lab (can rebuild cost-effective frame if necessary)
Projectile System	Repurpose components on the pre-existing machinery if possible
	Source for affordable mechanical parts (e.g. McMaster-Carr)
	Utilise the free UofT Engineering workspaces (e.g. MakerSpace)

6.6.2 Design for Human Factors

The main use case of this design will be for the member of the capstone team operating the rig, while the secondary use case will be for the member of the ARL-MLS Lab operating it.

Table 8. Subsystem Design for Human Factors

Subsystem	**Considerations**
Controls & Electronic System	A knowledge of programming should not be required to operate the system
	All results and parameters should be clearly displayed
Frame	The user must be able to identify the frame and its components
Projectile System	The area where the projectile is placed must be identifiable
	The area where the sample is placed must be identifiable
	Samples should be labelled for clarity
	Instructions on how to operate the rig will be provided in a manual
Sample	An electronic manual will be given to the lab manager of the ALR-MLS lab

The following table shows the general guidelines for each sub system to ensure a safe design.

Table 9. Subsystem Design for Safety

Subsystem	**Considerations**
Controls & Electronic System	Electrical components should be isolated where possible to account for user error
	The system should confirm that the testing area is clear before operation
	All electronic components should be properly enclosed and grounded following the MIE UG Health and Safety Standard [26]

Frame	Testing area should be clearly marked
Projectile System	A physical barrier should be in place to bar anyone from entering the testing area
	The force generating mechanism should be physically impossible to access.
	The holding mechanism should be accessible only before the test starts if it has moving components
Sample	During testing, the sample needs to be secured such that contact with the projectile will not cause it to escape the testing area
Overall Design	All safety features should be colour coded in red for ease of visibility and to impart a sense of urgency.
	Non-flammable and non-conductive materials should be used when possible to lower the risk of fire
	During testing, the ISO 45001 standard for safety, which outlines the requirements for an occupational health and safety management system, must be followed [25]

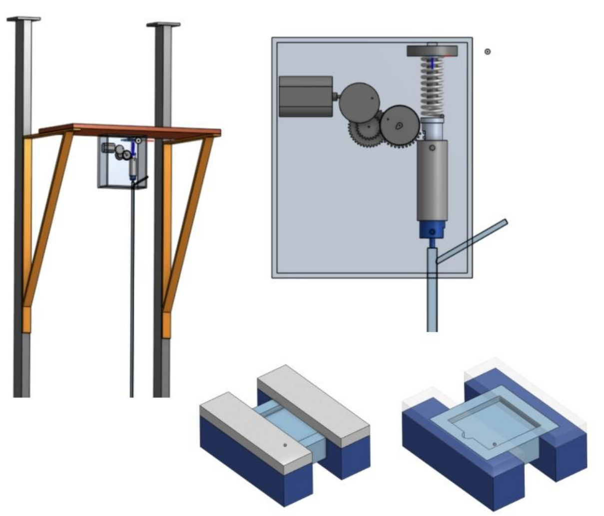
6.7 Service Environment

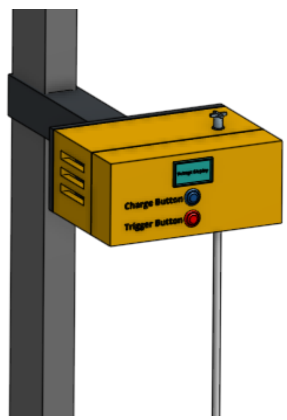
The drop test rig will be operating in the ARL-MLS laboratory therefore, the rig and its method of operation must adhere to all MIE UG Health and Safety Standards [26]. The design must not disturb any ongoing tests in the lab. The environmental conditions of the impact test should be kept at 22˚C, and humidity should also be regulated to ensure no changes to a specimen's physical properties [24].

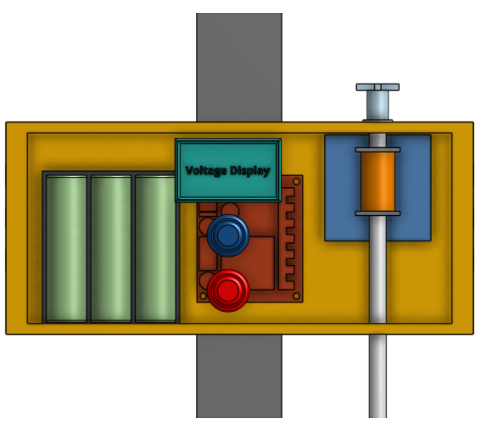
7.0 Design Process

Based on the final design objectives and all factors considered in the previous sections, three potential designs were generated. The first design used a combination of gears, a spring, and a vacuum sealed chamber to propel the projectile. The gears would pull back the spring creating a vacuum within the chamber, and once the chamber was opened to the projectile, the compressed air would instantly escape forcing the projectile and sending it on a downwards trajectory towards the sample. The second design utilized the concept behind electromagnetic coil guns to propel the projectile. Essentially, once voltage was supplied to the coil, a magnetic field would be generated which would linearly actuate and propel the projectile. The third design was the most simple, as there was no linear actuation of the projectile. It relied solely on the force of gravity to achieve the impact velocity by dropping the projectile from a predetermined height. Table 10 below compares the advantages and disadvantages of each design.

Table 10. Advantages and Disadvantages of Preliminary Designs

Design	**Advantages and Disadvantages**
Proposed Design 1	
	**Advantages:** ● Desired velocity could be changed based on spring stiffness and amount of spring recoiled ● Utilizes existing metal rig in lab ● Requires adding minimal structural parts to the existing lab setup
	Disadvantages: ● Modifying the design to achieve significantly higher or lower velocity could be difficult as complete disassembly of the

<table>
<tr><td></td><td>mechanism would be required
Using the existing setup, in order to change the velocity the gear train would need to be modified to reduce the spring contraction</td></tr>
<tr><th colspan="2">Proposed Design 2</th></tr>
<tr><td rowspan="2">


</td><td>Advantages:
Desired velocity could be changed by changing voltage to the magnetic coil
Utilizes existing metal rig in lab
Requires adding minimal structural parts to the existing lab setup
Modifying the setup to achieve significantly higher or lower velocity would be simple, as electrical components could be easily switched out or an additional set of magnetic coils could be added</td></tr>
<tr><td>Disadvantages:
Requires significant amounts of energy but highly inefficient due to unavoidable energy loss in components</td></tr>
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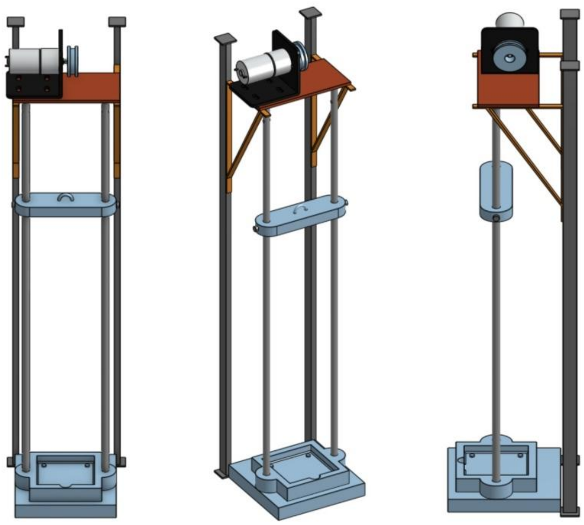
<tr><th colspan="2">Proposed Design 3</th></tr>
<tr><td rowspan="2"></td><td>Advantages:
Desired velocity could be changed by changing drop height
No need to build a custom mechanism to achieve desired velocity
Utilized existing metal rig in lab</td></tr>
<tr><td>Disadvantages:
Maximum achievable velocity is capped at 7.5 m/s due to space constraints in existing lab setup
Requires expensive custom structural components</td></tr>
</table>

As seen in Table 11, a weighted decision matrix was utilized to determine the best proposed design. A weighted decision matrix was used to rank the three conceptual designs and determine the design that best meets the project objectives. The scores range from 0-5, with 0 being the lowest possible score and 5 being the highest. A score of 5 means that the design meets the objective metric defined previously in the project requirements.

Table 11. Preliminary Designs Weighted Decision Matrix

	Attains low velocities (1-5m/s)	Applies force to projectile to attain various velocities (scalability)	Contains projectile and sample within boundary	Ranks TRL 4	Affordable
Design 1	5	3	5	-	-
Design 2	5	5	5	-	-
Design 3	5	0	5	-	-

All designs meet the objectives of attaining low velocities (between 1-5m/s), containing the projectile and sample within a defined space (700x720x570mm), and costing less than $500 to prototype. The TRL of the designs can not be assessed until the design is fully prototyped, which will only be the case for the chosen conceptual design.

As seen in Table 10 and Table 11, the main difference between the three designs is their scalability, or ability to attain various velocities in the future when the design might be altered to either increase or decrease the final impact velocity. Initially, scalability was not part of the project scope, however the client has communicated their interest in future design scalability and velocity control. The first design is scalable, however could possibly require a change in compression of the spring, a new spring, or possibly a more powerful motor (depending on the spring stiffness). Any new parts would have to be reinstalled into the machine to attain higher or lower impact velocities. This was noted in Table 10 and thus in Table 11 the first design was only given a 3, as it is scalable but would require new calculations, new parts, and design modifications. The second design is highly scalable, as it requires either more or less voltage to increase or decrease, respectively, the impact velocity. The PCB for the design will be designed with consideration of the future higher voltages by choosing electrical components with higher voltage/current ratings. Furthermore, if more coil stages needed to be added, all existing components on the PCB and the geometry of the existing coils could be copied. Thus, making it an easy addition to the model. The second design was given a score of 5 for fully meeting the objective and in Table 10, a close up of the PCB and magnetic coil geometry can be seen. The final design is not scalable, as to attain higher velocities the structure must increase in total height, which is restricted by the lab space. Therefore, the third design was given a score of 0, in Table 10 the existing rig in the lab can be seen to be limiting vertical height .

As seen in Table 10 and as shown and calculated in Table 11, Proposed Design 2 is the best option to move forward with and scored the highest in the Weighted Decision Matrix. Therefore Proposed Design 2 is the chosen design.

8.0 Chosen Design

As discussed in Section 7.0, Proposed Design 2 was chosen as the final design. It utilizes an electrically charged magnetic coil to propel the projectile downwards before making impact with the enclosed ceramic sample.

8.1 3D-Model

A 3D-model was created to aid in visualising the design in the current working space of the lab, the placement of the sample stabilizer and the layout of the velocity mechanism (see Figures 9 through 14 below).

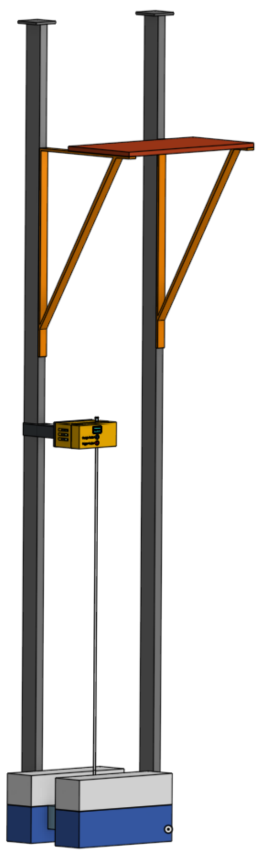


Figure 9: Complete 3D Model of Chosen Design

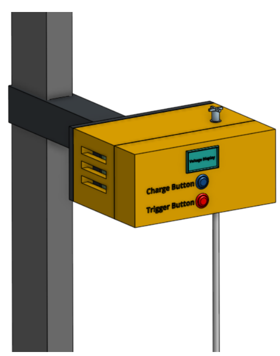


Figure 10: Enclosed Velocity Mechanism Attached to Existing Rig

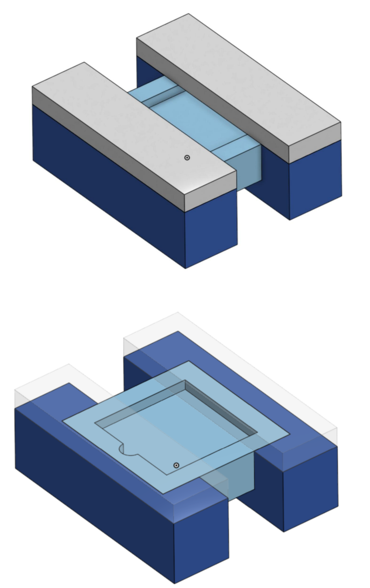


Figure 11: Sample Stabilizer

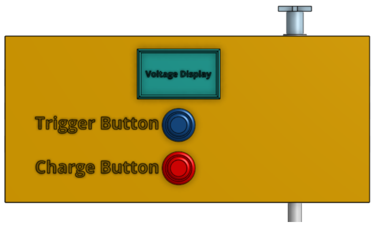


Figure 12: Close-up of Enclosed Velocity Mechanism

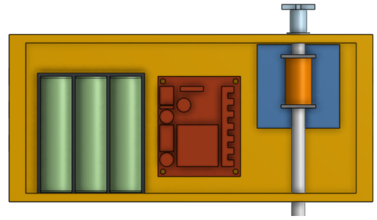


Figure 13: Velocity Mechanism Inner Workings (Left to Right) Batteries, PCB, Magnetic Coil

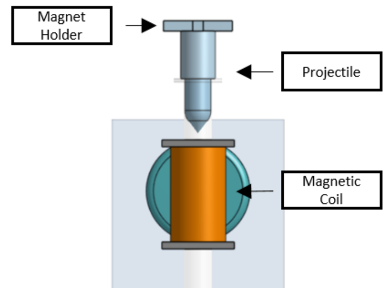


Figure 14: Electromagnetic Coil and Projectile Release System

8.2 Functionality

The chosen design requires some user intervention in order to charge the capacitor and trigger the release of the projectile through charging the coil. Figure 15 shows a flowchart that walks the user through the process of performing an impact test using this system, and highlights the steps where user intervention is required in red.

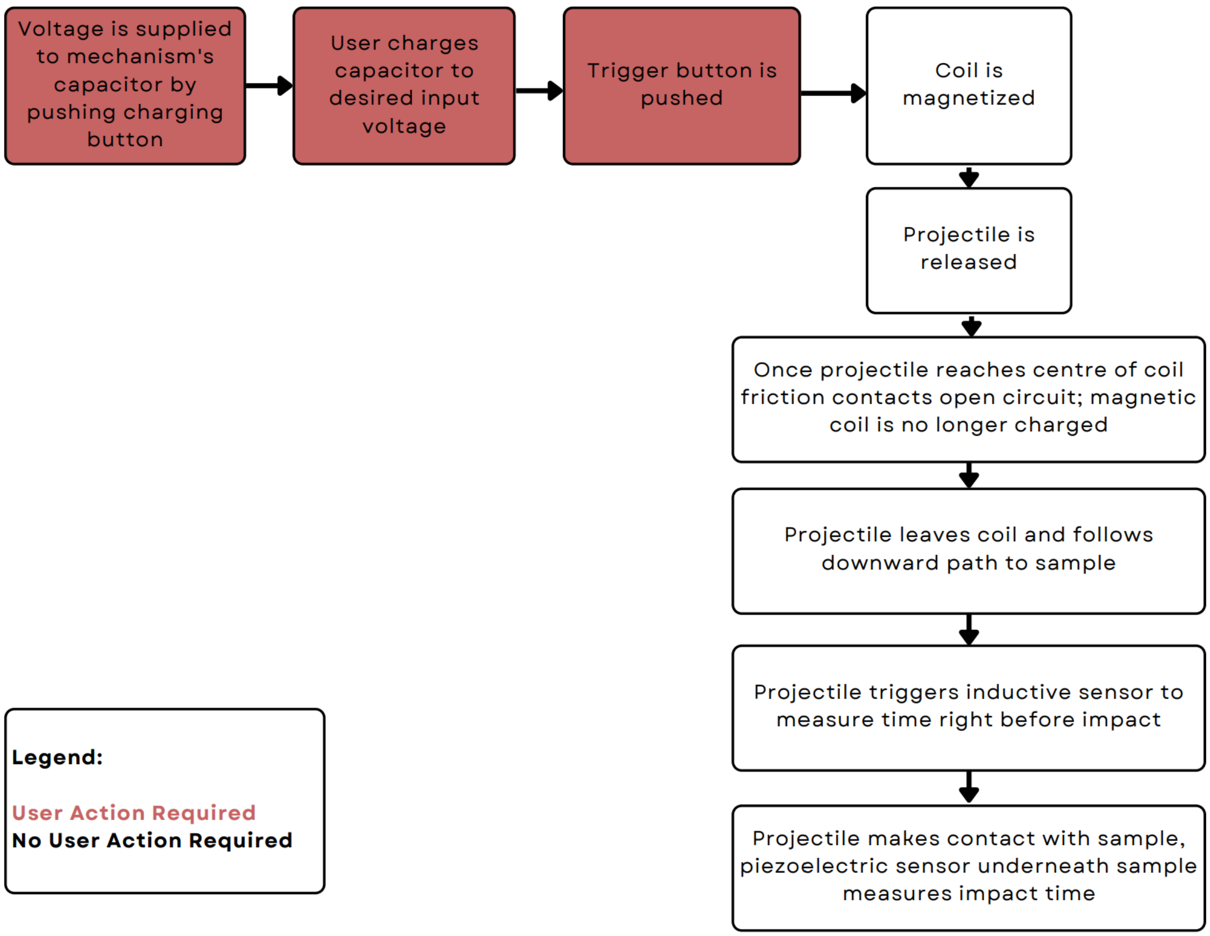


Figure 15: Design Operation Flowchart

As mentioned in Figure 15 above, the design requires the use of friction contacts to open the circuit once the projectile reaches the middle of the coil. This is to prevent oscillation of the projectile within the coil. Figure 16 below shows this in greater detail. The friction contacts open the circuit and also help to hold the projectile before release. However, the projectile is primarily supported by a weak magnet above the coil. When the coil is magnetized, it attracts the projectile into its barrel.

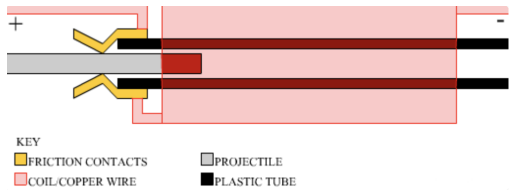


Figure 16: Friction Contact Functional Diagram

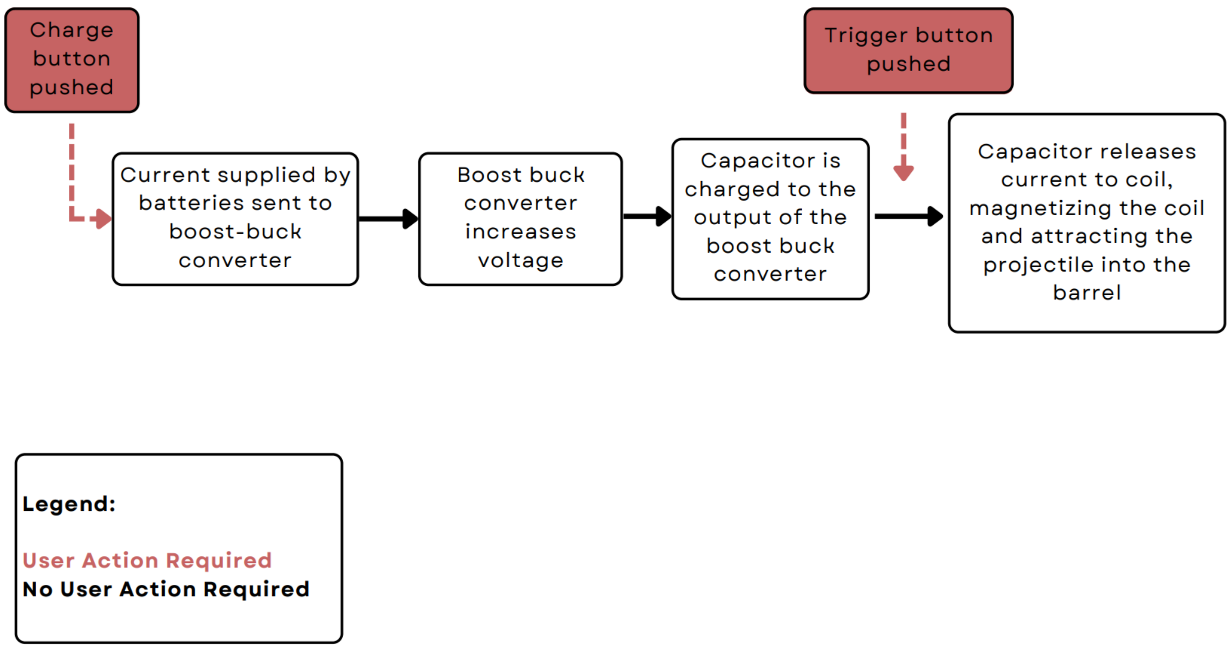


Figure 17: Functional Diagram of Velocity Mechanism Circuit

Figure 17 above, explains in further detail how the velocity mechanism is triggered through the release of current into the coil. This process is controlled by two buttons, the first charges the capacitor while the second releases current into the coil. By releasing current into the coil, the coil becomes magnetized and attracts the projectile into the barrel, thus initiating release. Once in the barrel, the projectile is accelerated by the magnetic field produced by the now magnetic coil.

As mentioned in Figure 15 above, the impact velocity and force data will be collected by a combination of induction and piezoelectric sensors. The induction sensor will be placed close to the bottom of the projectile's guiding tube and the piezoelectric sensor will be placed directly underneath the sample. The induction sensor senses when the magnetic projectile passes it. By placing the induction sensor as close to the sample as possible, this allows an accurate approximation of impact velocity to be measured. This data will be sent to and read by an Arduino, the Arduino will be powered by a PCB. This PCB has a dual purpose of powering both the Arduino and the sensors. Using Visual Studio and C++ as a programming language, the data will be sent to the MQTT servers. Finally, a Grafana dashboard will fetch the data and plot it in various formats so that the data can be easily seen on the user's computer and interpreted by the lab team.

Finally, as seen in Figure 11, the ceramic sample will be stabilized using an aluminum base. This base is independent of the testing rig and will be placed directly underneath the projectile's guiding tube. When the test is running, the sample will be held in place by 2 aluminum blocks to ensure the sample is properly secured. After the test, these blocks can be easily removed and the sample can be removed for further inspection.

8.2.1 Societal Impact

Realizing the future impact this design may have, there are additional stakeholders not included in Section 6.5 that must be considered. As this design will ideally be used to test ceramic armour samples, possible stakeholders include military, law enforcement, and other security officials. It is recommended that the design be scaled up to achieve higher velocities if it is intended to test armour that will be used in the field. Once scaled up, this design would be a breakthrough in methods of testing ceramic armour, as it is inexpensive, consistent, user-friendly, and safe.

8.3 Calculations

The calculations shown below illustrate an example of how the proposed design can reach an exit velocity from the magnetic coil of 8.04 m/s and a final velocity of 10 m/s. These calculations do not account for air resistance once the projectile leaves the magnetic coil and assume that the projectile is launched from a height of 1.81 metres.

The calculations shown in Figure 18 demonstrate how the number of coil turns was determined for this design. Using a current of 25A with the objective of achieving a final velocity of 10m/s, equations for conservation of magnetic, kinetic, and potential energy can help solve for the number of coil turns.

$$\frac{1}{2}mv^2 = mgh + V\mu_o x_m n^2 I^2$$

$$n = \sqrt{\frac{\frac{1}{2}mv^2 - mgh}{V\mu_o x_m I^2}}$$

$$n = \sqrt{\frac{\frac{1}{2}(0.03)(10^2) - (0.03)(9.81)(1.81)}{(3)(10^{-6})(4\pi)(10^{-7})(4999)(25^2)}} = 287\,turns$$

Figure 18: Determining Number of Magnetic Coil Turns

Figure 19 shows the process of determining the length of wire needed to achieve this number of turns, as well as how many layers the design requires to realistically achieve an equivalent of 287 turns.

The length of wire required to achieve 287 turns can be found via:

L = Barrel Circumference x #Turns = 7.66m

By setting the voltage to 5V, the thickness of the wire required can be found using V = IR in combination with R = pL/A.

Thickness = 0.929mm → 19 Gauge Wire

The projectile is 28mm in length and as such, the coil length needs to be 28mm. Using 19 gauge wire, the coil needs to be constructed using 10 layers of 30 turns each.

Figure 19: Determining the Number of Coil Layers and Turns

In order to determine the linear actuation due to the magnetic coil, the velocity upon leaving the magnetic coil was calculated to be 8.04 m/s, this can be seen in Figure 19 below.

$$v = \sqrt{\frac{2}{m} V u_o x_m n^2 I^2}$$

$$v = \sqrt{\frac{2}{0.03}(3)\left(10^{-6}\right)(4\pi)\left(10^{-7}\right)(4999)\left(287^2\right)\left(25^2\right)} = 8.04\, m/s$$

Figure 20: Verifying Barrel Exit Design Velocity

In order to choose a capacitor for the final design, the time at the halfway point in the magnetic coil needed to be calculated. In Figure 21 below, it can be seen that the time to the halfway point is 0.039 seconds.

$$v^2 = v_o^2 + 2a(x - x_o)$$

$$a = \frac{v^2 - v_o^2}{2(x - x_o)} = \frac{(8.04)^2}{2(0.16)} = 202\, m/s^2$$

$$x = x_0 + v_o t + \frac{1}{2} a t^2$$

$$101t^2 - 0.16 = 0$$

$$t = 0.039s$$

Figure 21: Calculating Time to Halfway Point of Magnetic Coil

Then using this halfway point time, the capacitor discharge equation could be used to determine that a 10 uF capacitor rated for 10V in series with a 150kΩ resistor is suitable to achieve an exit velocity of 8.04 m/s.

8.4 Bill of Materials

The bill of materials and the total cost for the chosen design can be seen in Appendix D. The total cost for the entire design was calculated to be $1,947.95 CAD.

9.0 Prototype

This section outlines the design, improvements, and testing of the prototype for the impact test rig. The results from the testing phases are presented as well to demonstrate proof of concept and a technology readiness level of 4.

9.1 Prototype Design

In order to test and prove that the concept of the chosen design was valid, a prototype was developed. Due to safety concerns, the prototype was made to launch the projectile at low velocities no more than 5 m/s. Figure 22 shows the final 3D-model of the prototype design.

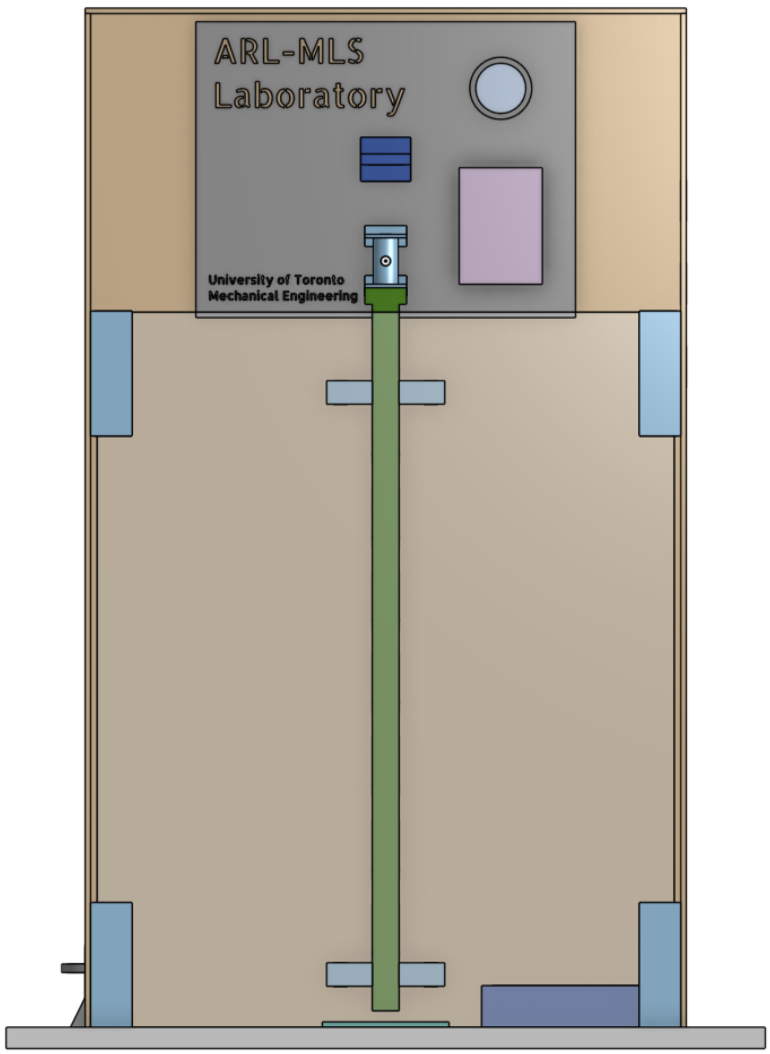


Figure 22: 3D-Model of Final Prototype Design

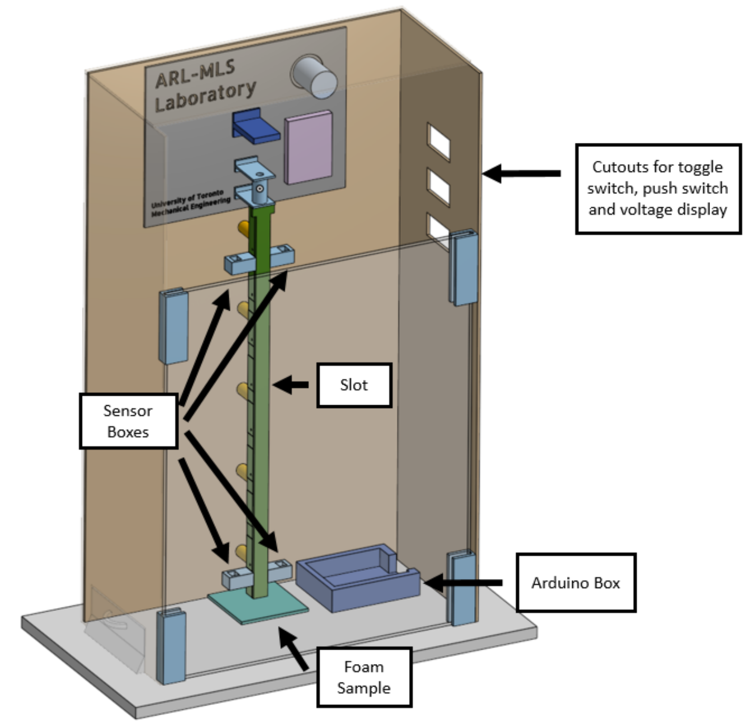


Figure 23: Labelled 3D-Model of Prototype

As seen in Figures 22 and 23, the housing of the prototype was constructed out of wood with an acrylic panel on the front to allow viewing of the design in action. The circuit was controlled by two switches on the side of the enclosure. A toggle switch was used to charge the capacitor while a push switch was used to trigger the release of the projectile. A voltage display was used to determine when the capacitor was sufficiently charged.

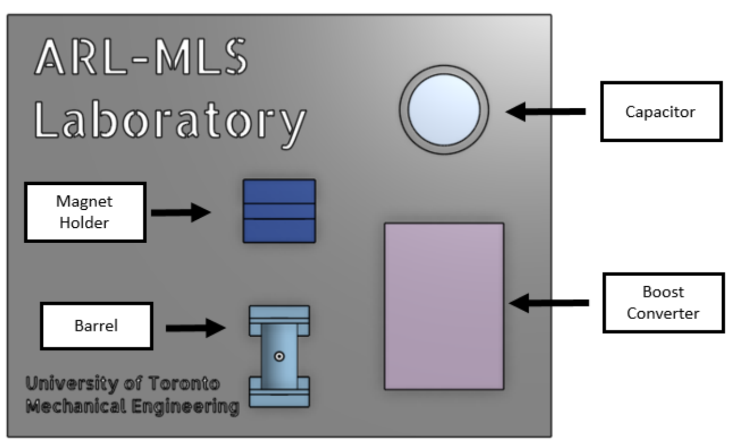


Figure 24: Labelled 3D Model of Prototype Circuit Board

An iron nail was used as the projectile for this setup, and it was grinded down such that it was a suitable size and had no sharp edges. This projectile was suspended above the coil through a magnet. The magnet was held at a fixed distance directly above the barrel as seen in Figure 24. The length of the coil was 28mm with 10 layers of 20 gage copper wrapped around the barrel seen in Figure 24.

The purpose of this prototype was to provide proof of concept for the chosen design. Due to cost constraints and safety concerns the prototype could not be an exact replica of the chosen design. Table 12 below, details deviations from the chosen design as well as the reasoning behind these deviations.

Table 12: Comparing and justifying changes made in prototyping the chosen design

Chosen Design	Prototype Design	Justification for Change
Projectile travels 1.81m vertically	Projectile travels 44.475 cm vertically	● Allows prototype to be portable ● Limitations in material and equipment at Myhal's Fabrication Facility
Velocity mechanism is supplied with 25A and 3V	Velocity mechanism is supplied with and 0.1A 50V	● Time and budget prevented purchase of high current/voltage-rated components ● Myhal Facility's power supply was limited to 30V, which boost converter increased to 50V for capacitor
Velocity mechanism uses a 10 uF, 10V capacitor	Velocity mechanism uses a 10, 000 uF, 50V capacitor	● Required more supplied energy for sufficient power due to capacitor efficiency losses ● Energy of a capacitor is given by $W = V^2 * \frac{C}{2}$. Where W is energy, V is capacitor voltage and C the capacitance. Increasing capacitance and voltage to 10,000 uF and 50V increases projectile speed.

Friction contacts used to prevent projectile oscillation in coil	No friction contacts used	● 10,000 uF capacitor discharges quickly, eliminating the need for friction contacts
Induction and piezoelectric sensors measure impact velocity	IR sensors measure average velocity	● Induction and piezoelectric sensors were not sensitive enough to measure impact velocity ● By using 2 pairs of IR sensors, 2 values of time can be recorded by the Arduino and used in the equation: $v = d/\Delta t$ to get average velocity. Note: v - velocity, d - distance pairs of IR sensors and Δt - time difference between triggering of sensors.
Impact force is measured using piezoelectric sensors	Impact force is calculated after testing if needed	● Chosen piezoelectric sensor (budget restrictions) not able to detect lightweight projectile
Test results are displayed using a Grafana dashboard	Test results are displayed using Arduino Serial Monitor	● Grafana connects to MQTT servers which require WiFi, and Myhal Arduinos are not WiFi compatible
Projectile is shot at a ceramic sample	Projectile is shot at a foam board	● Project cost constraints limit team to using a reusable or cheap sample for testing ● Safety concerns and cost constraints limited building a portable test area with a safe blast radius

The prototype was able to consistently produce an impact on a sample, measure the average velocity, and contain the projectile within safe bounds. This prototype was able to:

- Achieve a final velocity between 1-5m/s
- Apply a magnetic force to the projectile to achieve low velocities
- Contain the projectile within a predetermined and safe space
- Cost less than $500
- Achieve a TRL4 due to successful prototyping and proof of concept (and have developed detailed 3D models of the design)

Therefore, this prototype has met the final design objectives defined in Section 6.3 with the changes highlighted in Table 12, and successfully provides proof of concept for the chosen design.

9.2 Prototype Testing and Results

As discussed above, the prototype was able to successfully provide proof of concept for the chosen design. This proof of concept required multiple tests using the prototype design, and the procedure for these tests is provided below.

Testing Procedure:

1. Set up the power supply in the following manner:
    a. Adjust one channel to 10V and 0.1A (Channel A).
    b. Adjust a second channel to 10V and 0.02A (Channel B).
2. Set up the Arduino and the sensors by connecting the Arduino to a laptop and uploading the code that runs the sensors. This code can be found in Appendix E.
3. Open the serial monitor of the Arduino software to observe the sensor results.
4. Connect channel B to the power lines of the voltmeter, turn this channel on, and ensure the lights of the voltmeter turn on.
5. Connect channel A to the power lines of the boost converter and adjust the converter until the output is 50V.
6. Load the sample area with a sample (if desired).
7. Turn on channel A – the circuit is now fully powered.
8. Use the projectile holder to load the coil with the projectile.

9. Turn the toggle switch on to connect the circuit to the capacitor and allow it to charge.
10. Allow the capacitor to charge to the user's desired voltage (typically within a range of 30-50V). Pay attention to the voltmeter when charging the capacitor, as it displays the capacitor's current voltage.
11. Once the capacitor is charged, switch off the toggle switch to disconnect the circuit from the power supply and prevent the capacitor from charging any further.
12. Press and release the push button quickly to send the current to the coil and release the projectile.
13. Check the sensor data produced by the IR sensors. The Arduino software will output the average velocity of the projectile.

The test procedure listed above was used to test the prototype and prove that accurate and consistent results could be acquired, thus proving that the chosen design could do the same. Furthermore, the scalability of the concept was proven by supplying the prototype with different input voltages and measuring the subsequent average velocity. These results can be seen in Figure 25, as the input voltage increases the average velocity of the projectile increases. As proportionality between the supplied voltage and average projectile velocity was proven, if the design is scaled up and higher voltages are used, the projectile will achieve higher velocities. If the same setup is reproduced, the average velocity could be calculated as a function of input voltage from the equation of the trendline.

$$Average\ Velocity \ = \ 2.34 \cdot \ (Input\ Voltage)^{0.15}$$

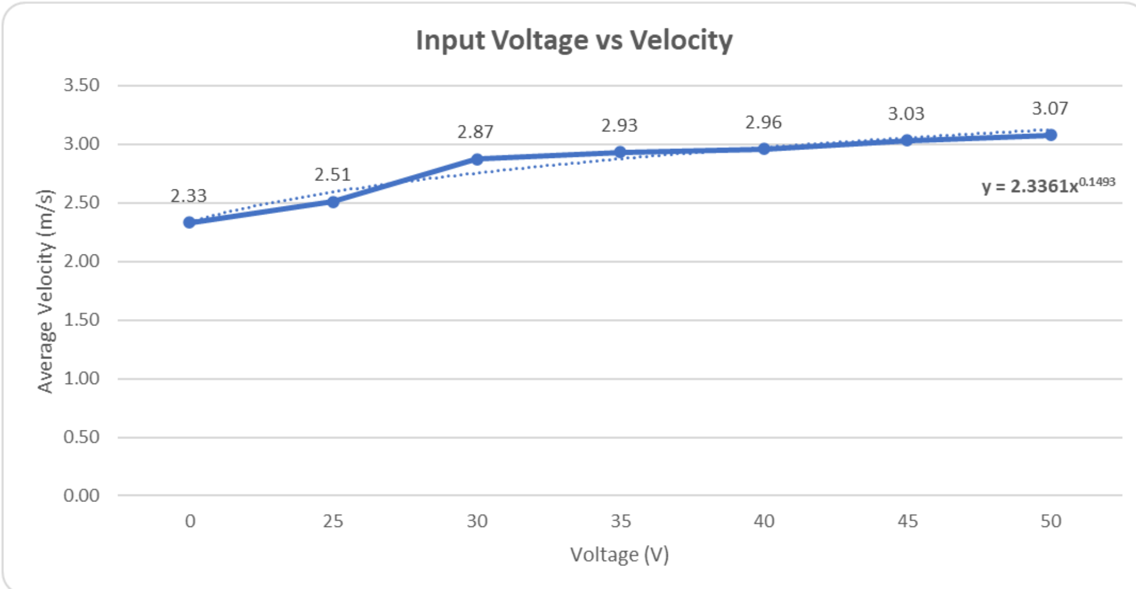


Figure 25: Input Voltage Versus Average Velocity

By looking at Figure 17 and 19, the relationship between velocity and voltage are found to be:

$$Velocity \; = \; \sqrt{\frac{2}{m}(Voltage)\mu_o x_m n^2 I^2}$$

The relationship between velocity and voltage are seen to be:

$$Velocity \; = \; \sqrt{Constant} \cdot \sqrt{Voltage}$$

Therefore the expected behaviour of the trendline in Figure 25 is a power function. The discrepancy in the power of the theoretical vs exponential predictive equations can be attributed to real world factors such as interference with the projectile in the barrel, resistance due to air, heat loss in the electric components, etc.

This proof of concept justifies why this design has the potential to be used for high-velocity impact lab tests in the future.

10.0 Potential Iterations for Chosen Design

Table 13 explains the recommended changes for the chosen design based on what the team has observed through prototyping.

Table 13: Recommend changes for the chosen design

Iteration Number	Lessons Learned from Prototype Testing	Recommended Changes
1	Using induction sensors to measure velocity is theoretically possible, however the level of sensitivity required to accurately measure velocity using a magnetic projectile requires sensors that are out of budget.	Use infrared sensors to measure velocity.
2	Friction contacts were omitted for the prototype, however to increase the efficiency of the system, the timing of when the power switches off is important.	Implement the friction contact system and switch out the mechanical switch to a MOSFET for more control over when power is turned off.
3	Magnetic coils are extremely inefficient due to the nature of capacitors and where the force is strongest in the coil (i.e the centre of the coil).	Testing different geometries of coils can rectify the efficiency issue (i.e. using a conically-shaped barrel).

11.0 Team Management and Organization

Creating an efficient workflow sequence, maintaining team organization, and consistently communicating are all important factors when working in a team. The team members for this project met every week for a couple hours in first and second semester, had a designated capstone group chat and a second group chat with the project teaching assistant (TA), and met with the teaching assistant every week for progress updates. There were also four additional client meetings where a progress update presentation was given for the client.

Team meetings were held Thursdays in the first semester and Wednesdays in the second semester. These meetings typically lasted between 1-2 hours. During the team meetings, the team would start by recapping the work they had completed throughout the week and make any changes/edits to this work as agreed upon by the team. A brainstorming session would follow to discuss designs, calculations, and concepts for the project. The work would then be divided equally among teammates, and any questions or concerns related to this individual work would be discussed. A final deadline for the assigned work would be agreed upon at the end of the meeting. The team would additionally work on the project individually outside meeting times or meet up to build/design the models as needed in the Myhal Fabrication Facility.

A team group chat was created to announce milestones and check in with other team members during the week. Whenever a team member made progress on a task, it would be communicated to the other team members using the group chat, such that others could make comments and/or suggestions on the work. If any teammate had questions, they could use the group chat to communicate with the team to come up with a solution. The group chat with the TA was used for questions that could not be answered by other team members. The TA would assist the team by explaining client expectations, clarifying due dates, and making report edits/recommendations.

The meetings with the TA were mostly for progress updates to make sure the team was on the right track. The TA would help in areas where the team would be stuck, like for example if the team needed assistance with complex calculations. The TA would also read through any reports and make suggestions for improvements. At the end, the team would discuss their timeline with the TA to ensure the team was making acceptable progress.

The team found that group chats, designated meeting times, and regular TA meetings were all beneficial during the year, as they kept the team on track and ensured that progress was made weekly. The team also found that using the resources provided on campus such as the Myhal Fabrication Facility, was very helpful. The Myhal Fabrication Facility sold electrical and mechanical parts at lower prices compared to McMaster Carr and DigiKey. However, the team had some setbacks when it came to the Myhal Fabrication Facility, as it closes at 9pm every day, thus the team could not make any mechanical/electrical design progress after this time.

Appendix E shows the final design specification report contribution table for this project, however it does not consider the work put into building the final prototypes. Some team members made a considerable contribution towards the prototype designs while others worked on the report, and this needs to be taken into account when considering the contribution table in Appendix E. Table 12 shows the prototype design contribution table, which encompasses designing, building, and testing the impact test rig prototypes. There were a total of three prototypes, the first comprising the sensor and coil launching system. The second prototype built off the first by adding a larger capacitor, a boost converter, more voltage/current displays, a projectile barrel guide, and a new sensor system. The final prototype is similar to the second, however has a large enclosure to cover all the electrical components and overall has a more organized structure.

Table 14. Prototype Design Contribution Table

Section	Student Names			
	Nathalie	Kevon	Jasmine	Victoria
Prototype 1	X	X	X	X
Prototype 2 3D-model				X
Prototype 2		X	X	
Prototype 3		X	X	
Prototype 3 3D-model				X

12.0 Conclusion and Future Work

The ARL-MLS team has provided the lab with a method of testing ceramic armour samples and met all of the objectives and constraints defined previously in the project requirements report. The design has additionally proven its potential for future scalability to achieve higher velocities, and a working design has been provided to the client. The team contribution table can be found in Appendix F. The operational manual containing all the safety information is also provided in Appendix G.

As a recommendation for future work, it is suggested that the client look into scaling up the design so that it may achieve higher velocities. To achieve this, the lab would require specialized power supplies that could supply greater than 15A to the test rig, and the components in the test rig would need to be resized accordingly to accept higher currents and voltages. In addition to increasing the power supply, more stages of coils could be added to further accelerate the projectile and reach a more impactful speed. As mentioned previously in Table 13, one of the major disadvantages of a coil gun is its inefficiency, thus further research should be done to improve this. While revision of certain parts in the overall design could be made to improve the impact velocity and the accuracy of the sensor system, the results show that the chosen design provides a solid foundation to build off of in the future.

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14.0 Appendix

Appendix A - Objectives

Table A1. Detailed Objective Reasoning Descriptions

#	Objective	Reasoning
1	Projectile should attain low velocities	Some high-velocity impact test rigs can achieve speeds of up to 200m/s [20], however these are dangerously high speeds that could result in injuring the University of Toronto students using the testing rig in the future. As students are more inexperienced with this machinery, a slower speed of 10m/s was suggested by the client for safety purposes.
2	Design should hold projectiles of various masses and sizes securely	Modern bullets such as the 150-grain round nose, can weigh up to 10g [21]. If the bullet is held at one end and the tip is vertically facing downwards, a normal force of at least 0.0981N (F=0.01*9.81) should be applied to the other end to hold the bullet securely in the machine.
3	Design should apply a force to the projectile to attain low velocity	Assuming a projectile of 10g as in objective number 2 and a drop height of maximum 2.5m as per the client constraints, one can find the required force () to achieve the desired projectile final velocities.
4	Design should contain the UUT and projectile within a constrained boundary	By investigating other drop impact testing machines, we can gather the test area dimensions of machines that can launch the projectile between 0.77-4.65m/s. As these speeds are within the objectives, similar test containment areas should be used for this design [22]. Containing the projectile and unit under test within a certain boundary is critical for operator safety.

5	Design should rank Technology Readiness Level 4	TRL level 4 requires that the basic components of the system be integrated together to establish proper mechanical function [23]. The client has requested prototyping and a final functional product, thus a TRL level 4 was assigned as the project objective by the client.
6	Design should be affordable	The University of Toronto MIE491 capstone course has provided a budget of up to $500 for capstone projects. The cost can go beyond this limit, but the university will not fund the additional expenses.
7	Design should produce multiple impact tests	Constraint number 3 outlines the calibration requirements for the design. Design repeatability will be closely related to differences in calibration. The design should achieve the same impact velocity and impact area (within plus or minus 7% [24]) when calibrated correctly. A design that can achieve successive testing will ensure more reliable results, which are critical when using the results to test the strength of different types of ceramic armour.
8	Test set-up and duration should be short	When transferring the specimen from its pre-conditioning environment to the drop test rig, the conditions might differ, in which case the test-set up and duration must occur quickly enough to ensure consistent physical properties [24]. Impact should occur at most 2 minutes after the sample has been removed from a conditioning environment [24].

Table A2. Detailed Final Design Objectives Reasoning

Objective	Target Level	Reasoning
1	L2	The client has stated that velocities above 10m/s are dangerous to attain, and that 5m/s (L2) would be a safer objective. This test should attain low velocities to meet the client’s requirements.
3	L2	To achieve speeds of 5m/s, forces between 0.004-0.1N (level 2) are required. As the client expects speeds of 5m/s, this objective was selected for further design development.
4	L2	Current state-of-the-art achieving velocities of 5m/s for impact testing use this size containment area for testing, indicating that level 2 should be attained [22]. This objective relates to safety, which is crucial when designing an impact test, explaining why this objective was selected.
5	L4	The client requires the project to achieve TRL 4 unless safety is compromised. This objective was selected due to the emphasis the client has put on attaining a TRL 4 project.
6	L2	Personal funds should not be used for the project, a level 2 objective is justified. This objective was selected as cost will be a limiting factor when deciding the final design.

Appendix B - Constraints

Table B1. Detailed Constraint Reasoning Descriptions

#	Constraint	Reasoning
1	Must drop the specimen from below 1.8m-2.5m.	The current test rig that can be found in the ARL-MRS lab is around 2 metres tall. If this machinery is repurposed for this project, the constraint of a drop height of 1.8m-2.5m will be attained. Otherwise, the client has specified a drop height of 1.8m-2.5m for this capstone project. The drop test rig will be required to fit inside the ARL-MRS lab for University of Toronto research purposes, further justifying a maximum height of 2.5m.
2	Must abide by ISO 45001 safety standards [25].	ISO 45001 outlines the occupational healthy and safety standards by the International Organisation for Standardisation [25]. These standards include basic safety procedures to reduce workplace risk and create safe working conditions. As University of Toronto students will be using this equipment in the future, it is important that the machinery abides by legal safety standards.
3	Differences when calibrating the projectile velocity, UUT weight, and impact energy before and after the test, must be less than 7%.	The International Systems of Unit (SI) are the physical units based on the metre, kilogram, second, ampere, kelvin, candela, and mole used to measure the design impact energy, projectile velocity, and unit weight. To ensure consistent test results, the impact test rig must remain calibrated during testing. The guideline for impact testing is that calibrations of any form of SI units taken before the impact test must be no more than plus or minus 7% from the calibrations taken after the test [24]. Elsewise, the test must be performed again, as the machine was not properly calibrated and the test results are inaccurate.

4	The projectile must be launched vertically, and accurately impact the unit under test.	The launching mechanism of the design should provide enough power to the projectile for it to travel at low velocities when it is launched from a specific height. This velocity should be high enough such that the projectile successfully impacts the unit under test with enough force.

Appendix C - Design for Excellence

Design for Environment

The project is limited geographically to the ARL-MLS Laboratory. The main effect on the environment would come from the energy consumption required to build the rig and the materials used and purchased to create the design. Table C1 outlines the potential effect on the environment for each subsystem.

Table C1. Subsystems Potential Effect on the Environment

Subsystem	Considerations
Controls and Electronic System	The energy consumption of operating the rig should be minimised by minimising the time it takes to to initialise and perform the test and calculate and display the results
Frame	The frame can be repurposed from the existing structure in the ARL-MLS lab thus negating the need for additional materials to be consumed
Projectile System	The energy required to create the materials cannot be controlled
	In order to minimise energy consumption, the time and energy required for the chosen manufacturing process should be considered
	The energy required to create the materials cannot be controlled
Overall Design	When possible, when sourcing materials, one shipment order should be placed to reduce the unnecessary energy consumption associated with shipping in parts

Design for Manufacturing and Assembly

As the project is scoped to creating a TRL-4 prototype, it is not necessary to consider the manufacturing and assembly processes for the market.

Appendix D - Final Design Bill of Materials

Table D1. Bill of Materials for the Chosen Design

Part	Qty	Cost (CAD)
20 Gauge Copper Wire Roll	1	$20.00
10uF, 10V Capacitor	1	$19.64
Battery Pack	1	$0.88
Batteries	3	$1.83
Clear Acrylic Tube	1	$2.30
DC-DC Buck Converter	1	$5.65
Soft Iron Projectile Rod	1ft	$8.67
Voltage Display Meter	1	$48.44
Arduino	1	$46.95
Inductive Sensor	1	$6.93
Piezoelectric Sensor	1	$0.95
Force Sensor	1	$50.29
Aluminum Base System: - 350 x 350 x 100 mm block - 550.2 x 150 x 157.5 mm block - 550.2 x 150 x 50 mm block	1	$1,735.42
Total Cost		**$1,947.95**

Appendix E - Prototype Sensor Code

```
/* Code for IR Sensors that measure average velocity of projectile fired
  fired from magnetic coil.*/

#define LEDPIN 13
#define SENSORPIN1 4

// variables will change:
int sensorState2 = 0;         // variable for reading the pushbutton status
float timeFirstSensor;
float timeSecondSensor;
float delta_T;
float velocity;

int flag = 0;
bool lastSensor1 = false, lastSensor2 = false;

#define SENSORPIN2 6
int sensorState1 = 0;

void setup() {
  // initialize the LED pin as an output:
  pinMode(LEDPIN, OUTPUT);
  // initialize the sensor pin as an input:
  pinMode(SENSORPIN1, INPUT);
  digitalWrite(SENSORPIN1, HIGH); // turn on the pullup
  pinMode(SENSORPIN2, INPUT);
  digitalWrite(SENSORPIN2, HIGH);

  Serial.begin(9600);

}

```

```
void loop(){
  // read the state of the pushbutton value:
  sensorState2 = digitalRead(SENSORPIN2);
  sensorState1 = digitalRead(SENSORPIN1);

  // check if the sensor beam is broken
  // if it is, the sensor state is LOW:
  if (sensorState2 == LOW) {
    // turn LED on:
    digitalWrite(LEDPIN, HIGH);
  }
  else {
    // turn LED off:
    digitalWrite(LEDPIN, LOW);
  }
  if (sensorState1 == LOW) {
    // turn LED on:
    digitalWrite(LEDPIN, HIGH);
  }
  else {
    // turn LED off:
    digitalWrite(LEDPIN, LOW);
  }

  //code for ensuring sensors are functional, commented out when ready to measure velocity
  /*if (sensorState2 ) {
    Serial.println("Sensor 2 Unbroken");
  }
  if (sensorState1){
    Serial.println("Sensor 1 Unbroken");
  }*/
```

```
  if (!sensorState1){
    Serial.println("sensor 1 Broken");
    timeFirstSensor = micros();
    lastSensor1 = true;
    Serial.println(timeFirstSensor);
    //delay();
  }
  if (!sensorState2) {
    Serial.println("sensor 2 Broken");
    timeSecondSensor = micros();
    lastSensor2 = true;
    Serial.println(timeSecondSensor);

    delta_T = (timeSecondSensor - timeFirstSensor);
    velocity = (0.4/delta_T)*(pow(10,6));
    Serial.println("delta T:");
    Serial.println(delta_T, 5);
    Serial.println("velocity:");
    Serial.println(velocity, 5);
    lastSensor1 = false;
    lastSensor2 = false;
    delay(500);
  }
}
```

Appendix F - Project Management

Project Title: Impact Mechanism for Testing Lightweight Ceramic Armour Systems

Supervisor: Professor Kamran Behdinan

Document Name: Final Design Specification

Date: March 21st, 2023

This form must be filled out and signed for each team-written document. The completed form must be attached to the document, though not included as part of the document (not included in the table of contents, page numbers, or word count limits). It should accurately reflect each team member's contribution to the document and in what way they contributed.

If there are irreconcilable differences that are preventing all team members from signing the attribution table, then each team member must write a letter (max 800 words) explaining their position on the difference and suggest a solution.

Making fraudulent claims in an attribution table displays intent to deceive and is a serious academic offence.

Table F1. Team Contribution Table

Section	Student Names			
	Nathalie	Kevon	Jasmine	Victoria
PR report parts	RD, ET, FP	FP	FP	FP
Executive Summary	RD, ET, FP	FP	FP	FP
Design Process	RD, ET, FP	FP, RS, CM, ET	FP	MR, FP
Prototype Design	RD, ET, FP	FP, RS, CM, ET	FP,ET	MR, FP
Prototype Testing	RD, ET, FP	FP, RS, CM, ET	FP,ET	MR, FP
Final Design	RD, ET, FP	FP	FP	MR, FP
Conclusion and	RD, ET, FP	FP	FP, ET, RS	FP

Future Work				
Operational Manual	RD, ET, FP	FP	FP	

Fill in abbreviations for roles for each of the required content elements. You do not have to fill in every cell. The "all" row refers to the complete report and should indicate who was responsible for the final compilation and final read through of the completed document.

RS – research

RD – wrote first draft

MR – major revision

ET – edited for grammar and spelling

FP – final read through of complete document for flow and consistency

CM – responsible for compiling the elements into the complete document

OR – other

By signing below, you verify that you have:

- Read the attribution table and agree that it accurately reflects your contribution to the associated document.
- Written the sections of the document attributed to you and that they are entirely original.
- Accurately cited and referenced any ideas or expressions of ideas taken from other sources according to an accepted standard.
- Read the University of Toronto Code of Behaviour on Academic Matters and understand the definition of academic offense includes (but is not limited to) all forms of plagiarism. Additionally, you understand that if you provide another student with any part of your own or your team's work, for whatever reason, and the student having received the work uses it for the purposes of committing an academic offence, then you are considered an equal party in the offence and will be subject to academic sanctions.

Print Name: Nathalie Cristofaro Signature: NCristofaro

Print Name: Kevon Seechan Signature: Kevon Seechan

Print Name: Jasmine Chen Signature: Yu-Tung Chen

Print Name: Victoria Velikonja Signature: Victoria Velikonja

Table F2. Resource Allocation Table

Resource	Explanation
Rig Frame	The frame for the rig has been provided by the client, the ARL-MLS Lab
Lab Space	Our client, the ARL-MLS Lab have granted us access to their space to work and repurpose the frame
Complete DeWalt Mechanical Toolbox	Any tools needed to repurpose the frame have been provided by the client, the ARL-MLS Lab
$500 CAD	The University of Engineering office will reimburse up to $500 CAD for any resources needed for this project
University of Toronto Mechanical Engineering Machine Shop	As everyone on the team has undergone the George Brown Basic Machining training and are full time Mechanical Engineering students, access to the machine shop is permitted and covered by the Mechanical Engineering Chair's Office.
University of Toronto Makerspace	As University of Toronto Engineering student's, access is permitted to UofT's Makerspace, with resources such as 3D printing are available

Appendix G - Operation Manual

OPERATION MANUAL

ARL-MLS IMPACT TEST RIG

The ARL-MLS Impact Test Rig can become dangerous to personnel when improperly operated or poorly maintained.

All employees operating and maintaining lab equipment should be familiar with its operation and should be thoroughly trained and instructed on safety.

Most accidents are preventable through safety awareness.

It is the responsibility of the customer to ensure that all personnel who will be expected to operate or maintain the equipment participate in training and instruction sessions and become trained operators.

All personnel operating, inspecting, servicing or cleaning this equipment must be properly trained in operation and machine safety. BEFORE operating this equipment, read the operating instructions in the following manual. Become thoroughly familiar with the machinery and its controls.

Training

Before operating the ARL-MLS impact test rig, training sessions led by the lab director/manager are recommended. These sessions will ensure that you can operate the machinery in a safe manner and minimise any machine-related hazards that may occur.

Your training will be conducted by [NUMBER] of our trainers over [NUMBER] of total sessions that will last from [TIME] to [TIME] on [DAYS]. Training sessions will be comprised of both activities and lectures that will touch upon the following subjects:

- General safety
- Machine components overview
- Machine operation
- Troubleshooting

These subjects are described in detail in the manual sections following the training contract. Please read all these sections before operating the ARL-MLS impact test rig machinery.

Training contract

This Training Contract (the "Contract") states the terms and conditions that govern the contractual agreement between [TRAINER] having its principal place of business at [TRAINER ADDRESS] (the "Trainer"), and [CLIENT] (the "Client") who agrees to be bound by this Contract.

WHEREAS, the Trainer holds significant expertise in high-velocity impact testing and offers training services in high-velocity impact testing for which the Client would like to engage the Trainer according to the terms and conditions herein.

NOW, THEREFORE, In consideration of the mutual covenants and promises made by the parties within this Contract, the Trainer and the Client (individually, each a “Party” and collectively, the “Parties”) covenant and agree as follows:

1. TRAINING

The Trainer shall conduct training in high-velocity impact testing in accordance with the schedule attached hereto as Exhibit A.

2. CANCELLING THE TRAINING SESSIONS

The Client agrees and acknowledges that a change in the schedule may present a significant burden for the Trainer and thus the Client shall cancel the training services within [NUMBER] days of the date on which the training services are to be scheduled.

3. PUBLICITY AND MARKETING

The Client authorizes the Trainer to utilize the Client’s logo and associated trademarks as well as any media, photos, or footage from the any training session solely for the purpose of marketing the Trainer’s services.

4. NO MODIFICATION UNLESS IN WRITING

No modification of this Contract shall be valid unless in writing and agreed upon by both Parties.

5. APPLICABLE LAW

This Contract and the interpretation of its terms shall be governed by and construed in accordance with the laws of Ontario and subject to the exclusive jurisdiction of the federal and provincial courts located in Ontario.

IN WITNESS WHEREOF, each of the Parties has executed this Contract, both Parties by its duly authorized officer, as of the day and year set forth below.

General Safety

- Ensure that all power sources are turned off when the machine is not in use. This includes electrical and pneumatic power. Unplug the machine before inspecting, maintaining, servicing or cleaning the equipment to help prevent anyone from accidentally injuring themselves.
- Read the manual for any special operational instructions for each piece of equipment.
- Know how the equipment functions and understand the operating processes.
- Know how to shut down the equipment.
- Understand the equipment safety labels and heed them.
- Wear the appropriate personal protective equipment for the job to be performed (EX: eye protection, hearing protection, gloves, safety shoes, hard hat). Ensure that nothing you are wearing could get caught in the machinery.
- Do NOT touch any of the wiring on the machine other than the main power plug. The wires used in this machine can carry high currents which can be lethal to humans.
- Do NOT attempt to fix any components of the machine yourself. Contact the lab manager if you suspect that the machine is faulty or damaged.
- When working on or around all equipment, avoid wearing loose clothing, jewellery, unrestrained long hair, or any loose ties, belts, scarves or articles that may be caught in moving parts. Keep all extremities away from moving parts. Entanglement can cause death or severe injury.

- For new equipment, check plant voltage with the voltage specified on the machine. Electrical specifications for your machine are printed on the machine serial number tag. A properly grounded electrical receptacle is required for safe operation regardless of voltage requirements.
- Treat this equipment with the respect its power and speed demand. Use it only for its intended purpose.
- Keep the operating zone free of obstacles that could cause a person to trip or fall toward an operating machine. Keep fingers, hands or any part of the body out of the machine and away from moving parts when the machine is operating.
- Any machine with moving parts and/or electrical components can be potentially dangerous no matter how many safety features it contains. Stay alert and think clearly while operating or servicing the equipment. Be aware of operations and personnel in your surroundings. Be attentive to indicator lights, warning lights and/or operator interface screens displayed on the machine and know how to respond.
- Do not operate machinery if you are fatigued, emotionally distressed or under the influence of drugs or alcohol.
- Know where FIRE EXTINGUISHING EQUIPMENT is located.
- Know where the FIRST AID SAFETY STATION is located.
- “Horseplay” around machinery at any time is dangerous and unacceptable.
- Never sit or stand on the machine or on anything that might cause you to fall against the machine.
- Rotating and moving parts are dangerous. Keep clear of the operating area. Never put any foreign object into the operating area.

- Use proper lifting and transporting devices for heavy equipment. Some types of equipment can be extremely heavy. An appropriate lifting device should be used.
- Use caution when moving portable equipment. In some cases the machinery can be heavy and/or may be top heavy if loaded. Portable equipment can gain momentum during transporting and must be controlled at all times.

Machine Components Overview

The following list outlines the parts that can be found on the outside of the test rig. These are parts that are safe to touch/use by the machine operator.

Main enclosure - provides an enclosure around the electrical components of the machine such that they are not directly accessible by the operator.

Capacitor charge switch - a switch to charge the capacitor which discharges to the coil.

Coil trigger button - a button to send the charge from the capacitor to the coil to begin the test.

Sample loading area - the location where the sample to be tested is placed and locked in.

Projectile guiding tube - a long tube that guides the projectile to the sample to ensure operator safety.

Main power cable - plugs into a power supply or wall and powers the impact test rig.

Machine Operation

The following procedure outlines the general steps to follow when conducting a high-velocity impact test using the ARL-MLS impact test rig. To ensure your safety, do NOT skip any of the steps outlined in the procedure below.

General Procedure:

1. Ensure you are wearing the appropriate safety equipment outlined in the first section of this manual.
2. Secure the sample in the sample loading area.
3. Plug in the ARL-MLS impact test rig.
4. Wait for the LCD screen to display “Ready”.
5. Charge the capacitor by switching on the toggle switch.
6. Wait for the LCD screen to display “Charged”.
7. Press the coil trigger button to charge the coil and release the projectile.
8. Wait for the LCD screen to display the final velocity and record this data.
9. Unplug the machine.
10. Collect the projectile and sample from the machine.
11. Reload the projectile into the machine.

Troubleshooting

The following list identifies some of the common issues you may experience when operating the machine. If your issue is not described in the list below, do NOT attempt to fix the machine yourself, instead call the lab manager.

Inaccurate velocity readings:

- The IR sensors might not be properly aligned. Use a level to make sure the sensors are aligned.
- If the issue still persists, replace the IR sensors with new ones with the lab manager.

Capacitor is not charging:

- Make sure the current/voltage you are supplying to the capacitor is high enough. You can use a multimeter (under supervision from the lab manager) to test the wires leading into the capacitor to make sure they are reaching your expected voltage.
- Check the wiring of the components inside the enclosure (under supervision from the lab manager).

Projectile is not achieving a high velocity:

- Supply a higher current/voltage to the capacitor and ensure this current/voltage has the correct reading at the capacitor using a multimeter (under supervision from the lab manager).

For other issues, call the lab manager.

Proof of Training Completion

[COMPANY]

[NAME], [TITLE] DATE

[CLIENT]

[NAME], [TITLE] DATE