DEVELOPMENT OF A TEST FRAME TO INVESTIGATE THE PROPAGATION OF PRESSURE WAVES GENERATED BY A THUNDERBOLT HAMMER

VOLUME I: DISSERTATION

A dissertation submitted by

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Abstract

This report gives an appreciation into the design and development of the ThunderBurst testing frame undertaken as part of USQ’s research project.

ThunderBurst is a conceptual design for a driver-less machine used in underground mining to destroy large boulders following a designated blast without using explosive material. Russell Mineral Equipment Pty Ltd (RME) first started investigation into the feasibility of the project in 2002. This machine uses RME ThunderBolt hammer technology to impart a high-energy blow to a column of water inside a rock.

The ThunderBolt test frame is designed to provide this high-energy system with a fixed location to impact a water column and conduct the pressure wave analysis of the subsequent shock waves. This consistent position will ensure the accurate calculation the pressure waves and energy values through a column of water during its operation. On-going research project undertaken by RME to increase understanding into future energy requirements of hydro-rock fracture will be achieved with the development of this project. It is hoped that the preliminary research into the pressure wave motion using the test frame will help develop the design of the ThunderBurst energy delivery system and conclusions drawn from the project will form the foundation of continued development of this product.
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1.0 Introduction

1.1 Introduction

The “ThunderBurst” project is a conceptual idea conceived by Russell Mineral Equipment (RME) in their quest to provide increased mining safety with a human-less underground mine.

An underground mining environment is not generally a safe place for human activity. With the action of heavy machinery, the use of explosives, potential shaft collapses, noxious fumes and flyrock by-products of the blasting process, there is great potential for injury or fatality for workers.

After any underground blasting, there is a great potential for roof collapses and the dangers of toxic fumes and fly-rock within the shafts. This prevents humans from entering the mine for long periods of time until it is deemed safe. If there are rocks that were not broken to a suitable size for transportation after blasting, it takes further time for a specialist explosive technician to set up and blast the rock again to the correct size. This secondary rock breakage is both costly and time consuming for the mine and dangerous for the technician.

This chapter outlines the need for the dissertation by providing necessary background information, project aims, methodology and an assessment of effects consequential to the undertaking of the project. A dissertation overview is included to show the structure of the report and give the reader a clearer picture into the layout expected in the following chapters.

1.2 Background Information

Current mining operations are categorised ore close to the surface is mined by open pit techniques and ore bodies contained in rock deeper below the surface need to be exploited by underground mining. Underground mining is an efficient way of collecting and recovering ore from the
underground bedrock formed many thousands of years ago. But this collection of ore is not as easy as it sounds.

The mining method used in an underground mine is adapted to the ore body and conditions, shape, dimensions, strength and stability of surrounding rock for that particular mine. A number of different underground mining techniques are typically used to extract the ore from the earth. These techniques include:

- Room-and-pillar methods,
- Narrow vein mining,
- Vertical crater retreat,
- Sublevel caving,
- Block caving, and
- Stoping methods.

All the techniques involve the use of machinery to enter a tunnel, drill and blast the mixture of ore and rock, and extract the broken fragments of rocks at draw points before delivering it the crusher for refinement and processing. This practice can quite often be very dangerous to employees and a logistical nightmare for supervisors, especially if things go wrong!

Figure 1.1 shows a typical Vertical crater retreat (VCR) method of extracting ore from the ore body. A vehicle travels along the tunnels through and above the ore body, long-bore drilling into the ore body and setting charges. Once a blast occurs the heavy vehicles enter the draw points below and extract the ore/rock mixture to be processed. It is at this point, if the blasted rock is too large or too heavy, and cannot be removed from these tunnels by the machinery, that secondary blasting is required.

Secondary blasting or secondary rock-breakage is a very dangerous and costly activity for a mine. A specialist explosive technician conducts secondary rock breakage but the technician can not enter mine until noxious fumes from the original blasting have dissipated. The dangers for the explosive technician aren't only confined to the noxious fumes. There is the potential for shaft collapse, possible unexploded charges from the previous blast and fly-rock from the secondary blasting that can injure or kill workers in the vicinity of the blast.
The expenses of mine downtime are crucial because excavation of ore ceases until secondary blasting is complete and area deemed safe is for human re entry. This will cost the mine thousands of dollars in lost revenue. Contracting the explosive technicians to come in and conduct the secondary rock-breakage is also quite expensive, due to their high wages incorporating danger pay.

The ThunderBurst project is a conceptual idea conceived by Russell Mineral Equipment Pty Ltd (RME), in conjunction with Julius Kruttschnitt Mineral Research Centre (JKMRC) and University of Queensland (UQ) in their quest to provide increased mining safety in underground mines and introduce explosive-free technology for secondary rock breakage situations.

The proposed ThunderBurst system is a driver-less machine used in underground mining to break rocks without the use of dangerous explosive material. This machine would be used in situations where inspection of the blasted ore reveals rocks that were not disintegrated during initial blasting. After a blast occurs in a mine shaft it takes a long time for the area to be deemed safe for humans to
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enter due to the dangers of toxic fumes and the potential for collapsing shafts. Therefore if there are rocks that were not destroyed in blasting it takes further time for a specialist explosive technician to set up and blast the rock. The ThunderBurst could enter the dangerous area and break apart the rocks quickly and without the safety concerns required for human entry.

The ThunderBurst system would increase the safety of mining staff and also decrease the downtime of the mine waiting for the shafts to be safe for human productivity.

The procedure the ThunderBurst arrangement will use to complete the given task initially involves drilling into a rock above the horizontal axis and filling the rock with an incompressible liquid. Once the liquid is in the rock, a large energy pulse is delivery to the rock along the axis of the liquid by the ThunderBurst. Due to the incompressibility of the liquid, a pressure spike is induced in the liquid that spreads into the weak points and cracks in the rock. The rock will fracture along these cracks and continue to propagate under the pressure loading from the delivery system of the ThunderBurst. Ultimately the rock will break up and mining can continue to proceed.

The induction of a pressure wave through a column of water within a rock is a relatively new concept and thus little research has been conducted into this area.

It is the task of this project to design a testing frame that will enable the capture of the pressure wave data through experimentation as it travels through a column of water. This is to represent an actual situation that would occur at the mine site. From this pressure wave analysis, it could be determined how the waves travel through the incompressible fluid and interact with one another in instances where multiple loads are applied in a short time frame. This will also give an indication on the practical energy values that are experienced during the experiment and help determine what if previous ThunderBurst project work will be suitable to be used in the final design of the device.

The test frame will provide RME with a permanent location to house the ThunderBolt during its research and development phase. By constraining the locations of the impact load and the water column, as well as having a fixed position for the experiment to occur, consistency in the data will be obtained. Adjustment in the frame design will enable slight changes in the experiments to be trialed and will ensure the orientation of the impact will always be vertical in relation to the column.

Further experiments will follow the initial testing with basalt boulders from the Toowoomba quarry to provide a correlation between the data found experimentally using the mock-up steel column and
the rock. This experimentation will also enable the verification of confidential theories brought forward from computer simulations conducted by University of Southern Queensland into the energy required to split a given rock.

1.3 Project Aim

This project will attempt to produce a completed and operational test frame to describe how the pressure waves from an impact load delivered from the ThunderBolt travel through an incompressible fluid. It will also be required to find out if the resulting pressure waves from the impact loads will be constructive or destructive as it travels through the liquid following consecutive impacts.

This will give an indication of the expected energy levels achieved during operation and provide an insight into the adequacy of the current energy delivery system comparing the recorded data with computer simulations of rock fracture. This test frame will be seen as a universal design that encompasses potential energy delivery designs that may be needed in future.

1.4 Project Methodology

The objectives of the project will be achieved using a given method called the project methodology. This is an outline of how the specific objectives are going to be completed and why they are important to the overall success of the project. This is set out in detail within this section.

The researching of the background information and the completion of the literature review required for the dissertation will be conducted using an internet and database search. A thorough internet search of relevant information regarding mining techniques, mine safety, non-explosive mining technology and pressure wave theory is required to gain a complete understanding of the need for the ThunderBurst in industry. A search of published papers on researched and designed structural test frames and on the impact loading of fluids will be conducted using relevant engineering databases. The database search will encompass seeking journal articles from an array of sources available to the author including USQ and other university databases, EBSCO host and American Mechanical Engineering listings to name a few. A number of topics relating to the structural integrity of an impacting frame, the possible methods to conduct the experiments and applications
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of the ThunderBurst project in general have been researched by scanning the databases.

A conceptual design of the test frame will begin with a construction and accumulation of ideas to achieve the desired aim of the project. Using these compiled ideas, a number of different frame designs will be conceived and analysed. The final design will be chosen after analysing the original conceptual designs from the previous step. This will be achieved using a decision matrix approach to award points to various aspects of each design that contribute toward the achievement of the overall aims of the project. The opinions of members from RME’s engineering department and members of USQ’s Engineering and Surveying Faculty will also be considered in the selection of the final design. From this point, further development of the test frame will occur using Finite Element Analysis (FEA) and abiding by Australian Standards.

Following the completion of the design and FEA of the test frame, the next step in the process is the requirement of drafting each fabricated or machined component in the design. The production of these workshop part drawings will give the relevant dimensions and constraints for separate components in the design and show how the manufacture of the structure components should occur. The designer will also produce an assembly drawing to give the user an idea of how to correctly set up the individual portions of the test frame to conduct the experiment as intended. The design office of RME will again be used to complete this step of the project.

Workshop manufacturing processes will now take over the construction of the individual pieces of the design. RME’s fabrication team will undertake this step of the project using the part drawings issued in the previous step. The individual fabricated sections of the test frame will be transferred the RME Works where they will be assembled and preparation for the experimentation will begin.

Experimentation using a water column to simulate fluid situated in a rock will begin in July 2007. The experiments will be conducted to analyse the pressure waves through the incompressible fluid and to calculate the peak energy values of the impact loads. Following the successful testing of the rock-splitter system with the water column, a similar experiment will be conducted to verify the results using a second system. The secondary system uses a known energy source to accurately compare the results between the two separate systems. The two test frame systems will be designed in parallel during this research project. The ThunderBolt test frame will also need to be capable of supporting the rock experiment as well as the water column experiment.

The design of the ThunderBurst testing frame will, however, primarily focus on the use of stress
analysis and Finite Element Analysis (FEA). The test frame will undergo a series of stresses caused by gravitational forces from the weight of the frame and the device transferring the energy to the water column. The dynamic forces that are involved in operation will also need to be considered as part of the frame design. Stability of the frame will be a concern when expecting a large impact load and moment calculations will also need to be conducted to ensure it is fully supported in operation. Other theories to be considered in the design include the conservation of momentum and energy transfer that will occur in loading the water column.

1.5 Assessment of Consequential Effects

The ThunderBurst test frame will be beneficial to the mining industry, as it will attempt to find out how the pressure waves travel through water within a rock following an impact imparted onto the water and provide a measurement of the energy levels seen during the impact. The continuing research into the pressures involved in hydro-rock breakage will help create a greater knowledge base for future work in this area. Using this knowledge of the peak energy value from the modified hydraulic hammer, the development of non-explosive rock extraction using this method can continue once the energy required to split a boulder is known.

The testing frame experiments will also provide a correlation of data for RME into the likely practical energy found during operation of the device, and give an insight into how much energy will be required to split a given boulder. From this information, the development of the energy delivery system to be used in the ThunderBurst project can continue.

This analysis will help in the understanding and development of the energy delivery system of the ThunderBurst. The more efficient this machine is, the less time it will take to split the remaining boulders too heavy for transport. Faster evacuation of this mixture of ore and rock to the mill will mean higher productivity for the mine and more money for the mining company.

A human-less machine working in an underground mine will also dramatically increase the safety of the site. Where in previous days a blast technician has been employed to perform a secondary blast on the oversized blasted rock, there will be no chance injury occurring if the ThunderBurst is in operation. Any risk of exposing the technician to unexploded shells or dangerous fumes will be nullified.
Therefore the ThunderBurst has the potential to positively influence the mining industry by decreasing the downtime suffered by mining companies following a blast and increasing worker safety. The ThunderBolt test frame will help RME to achieve their goal in developing this safe and effective technology through the measurement and analysis of how the pressure waves split the rock during operation of the modified ThunderBolt hammer.

There are no known adverse ethical issues currently arising from the development of the ThunderBurst project or in the ThunderBolt test frame used to analyse the pressure waves through the rock during its operation.

1.6 Dissertation Overview

The structure of the chapters in the dissertation is discussed throughout this section. The dissertation is separated into four distinct sections. A brief overview of the separate sections, along with an individual outline of each chapter of the dissertation is shown in the list below.

Chapters 1 - 4 introduce the requirements for the project and provide relevant information into current mining techniques.

- Chapter 1 provides background information into the dissertation and outlines the aims and methodology of the project.
- Chapter 2 investigates explosive rock-breakage technology currently in use in industry
- Chapter 3 displays the literature review for the design and development of the test frame and other forms of non-explosive technology for use in the research project.
- Chapter 4 looks at the previous ThunderBurst experiment and discusses restrictions on the ThunderBolt test frame assembly used in the research project.

Chapters 5 - 8 investigate the ThunderBolt test frame development from the conceptual phase through to the completed analysed design.

- Chapter 5 brings forth conceptual designs into the ThunderBolt test frame system and selects the most appropriate design for the foundation of future work
- Chapter 6 develops the conceptual design selected from the analysis conducted in Chapter 5. The conceptual design will be evolved to the final solution during the chapter.
- Chapter 7 conducts Finite Element Analysis (FEA) of the major components in the
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design.

- Chapter 8 provides an overview of the final ThunderBolt test frame solution.

Chapters 9 - 11 look at the drop weight test frame development. This includes the design, analysis and testing of the structure.

- Chapter 9 discusses methods of known energy transfer. Conceptual designs for the secondary testing rig to validate the results of the ThunderBolt test frame system are introduced and an appropriate concept is selected.
- Chapter 10 develops the drop weight energy transfer system selected in Chapter 9.
- Chapter 11 discusses the assembly and testing of the drop weight and calibration tube structure. Results are graphically produced and data analysed.

Chapter 12 concludes the dissertation and reveals the future work beyond the research project.

The block diagram (Figure 1.2) gives a visible outline of the four separate sections in the report. The background information and literature review is the first stage, leading onto the two test frame system designs shown as tandem projects. The final section is the conclusions, which wrap up the report.
1.7 Conclusion

RME's ThunderBurst project is expected to be the first driver-less underground machine in operation with the ability to destroy large boulders without the use of explosives. This system uses
a modified LRT ThunderBolt hammer to impact a column of water inside a rock. The ThunderBurst test frame is designed to provide the energy system with a fixed location to conduct the pressure wave analysis within a water column. This consistent position will ensure the accurate calculation the pressure waves and energy values through a column of water during its operation.

A second test frame and energy delivery device is required to validate the results achieved by the LRT. System design is required to produce a simple energy delivery device that simulates the expected energy output of the modified hydraulic hammer. The work on the second frame will run in tandem with the development of the required LRT test rig.

The project aim, objectives and methodology required to successfully complete the ThunderBurst test frame are outlined in the chapter to provide the scope for the remaining work throughout the project.

The proposed ENG4111 project design of the ThunderBurst test frame is part of an on-going research project undertaken by RME. It is hoped that the preliminary research into the pressure wave motion using the test frame will help develop the design of the ThunderBurst energy delivery system and subsequent conclusions drawn from the project proposal will form the foundation of continued development into this product.
Chapter 2

2.0 Background Information

2.1 Introduction

Underground mining is generally an unsafe environment to work in. This is especially apparent during the periods of rock-breakage and extraction from the stopes and drawpoints in the mine.

This chapter introduces background information into current methods of explosive rock breakage currently used in industry. This information is included in this report to provide the reader with a greater appreciation of the need for ThunderBurst in the mining industry.

Section 2.2 will provide detailed information into the current techniques for rock extraction in quarries. It will specifically focus on the drill and blast method effectively used in rock removal at most mine sites around the world. Section 2.3 will address the safety issues that arise from the drill and blast method and give the reader a sense of why non-explosive technologies are need to be developed and used safely.

2.2 Drilling and Blasting Techniques

The mining industry is one of the largest industries in Australia bringing in billions of dollars to the Australian economy and providing thousands of Australians will full-time employment. To keep up with the large export demands of metals and ore within Australia and around the world, billions of tonnes of rock are mined each year and sent to crushing plants and mills for processing (Djordjevic, as cited in confidential report given to RME, 2006). From the processing plants, the ore is refined and formed into usable metal before being exported to buyers around the world.

A safe and efficient method of excavating the mixture of earth and ore from the quarry is necessary to keep up with the current high level of demand for processed metal and ore. The drill
and blast method is the preferred method used today. This method is favoured due to the very fast time it can remove the rock from a given area due to the high energy explosions it creates. However, there are many dangers in using drill and blast in mining, many due to the creation of high energy shock waves into the environment.

This section of the report will discuss the issues of rock breakage, drilling and blasting techniques and theories, secondary blasting, the effects of blasting on the surrounding environment and give a summary of some of the dangers arising from using drill and blast methods.

2.2.1 Rock Breakage

The initial stages of extraction of the ore from the rock involves breaking the rock from the walls and floor of a mine site. Ancient civilisations such as the Israelites (under King Solomon's rule) and men from Claudius' Roman Empire used a method of breaking rock from quarries using wooden wedges and other various techniques such as fire-setting to construct their extraordinary architecture (Polaris, n.d.). This was the original form of drilling and blasting techniques thousands of years before the use of explosives was known in Western culture. Drilling and blasting are therefore interrelated mining techniques currently used in industry to perform the same rock excavation as used by the ancient civilisations, but in a much shorter period of time.

Rock breakage using explosives have been operating since the early days of contemporary mining, beginning with the use of black powder, advancing with developments in blasting methods, detonation and delaying techniques (Hoek, n.d.). Today, numerous different methods of rock extraction are being tested and developed to try to minimise the dependence on blasting methods. The majority of the devices that are challenging drilling and blasting techniques are only in the development stages (Zaitev et al, 2004). However, states that drilling and blasting is still by far the most common technique used in the extraction of rock from the earth.

Zaitev et al (2004), believes blast free technology in mining rock is not being accepted as widely as it could be in the mining community. Possible replacements of blasting technology include cutting rippers, impacting devices, water jet assisted and electrically discharging machines that fragment the rock from the given mining area safely and without creating a seismic disturbance to the surrounding environment. Further research into the development of rock-breakage technologies without the use of explosives will be discussed in Chapter 3 of this report.
2.2.2 Drilling Methods and Techniques

Even though blasting is the most recognisable component in the separation of rock from the quarry walls or floor, it is only seen in the final half of the process. Drilling is the other important segment in the method of rock removal. This application is critical to the mining process, as every process that follows after the drilling is complete, such as blasting, loading, crushing etc, is reliant on how accurate the drilling was performed (Fiscor, 2000).

As the cost concerns of the blast and the subsequent processes are directly related to its performance, it is critical for mining companies to have accurate drilling right at the beginning of the process. An initial up-front cost on the drilling will save the mine operators time and money in dealing with poorly fragmented muck piles that may even require secondary blasting (Fiscor, 2000).

A number of factors relating to the effectiveness of blast design are dependent on the accuracy in the drilling pattern which houses the explosive charges. Accuracy of the pattern is required in a number of different dimensions. The location of the holes, the depth of the blast hole and the path of the blast hole are all important to the final product. If any of these aspects of the design are too far outside the design limits, the resulting fragmentation of the rock will have a vast array of various sizes.

The accuracy of the hole locations is an important factor that drillers must get right in order to maintain the intended burden-spacing ratio. "Today's specialised equipment, such as the laser-profiling systems and sophisticated blast design software packages that are used to determine the best hole locations work well, but are rendered useless if the holes are not drilled in the right location" (Fiscor, 2000, p10). Hole positions can be easily and effectively measured with tools after drilling to ensure the accuracy of the pattern. A typical drilling pattern is shown in Figure 2.1. According to the experts in Fiscor, (2000, p10), accuracy in hole positioning is determined "if the blastholes are within one hole diameter of its desired location."

The drilled depth of the blast holes are also important to the final fragmentation of the rock. This is most commonly seen in holes that are drilled too short into the floor of the pit (Konya, 2000). According to Fiscor (2000, p10), "it is better to overdrill the hole than underdrill the hole."
Although drilling a hole deeper than the intended length causes problems, a shorter hole depth is much more dangerous to workers as it will create a thinner layer of burden and can potentially produce flyrock into the surrounding (Fiscor, 2000). Measures can be taken to avoid a large variation in the depths of blast holes. A simple measurement using a guide rod or tape is sufficient to ensure a constant and correct depth of the hole.

The path the blast hole takes through the rock is also a concern that needs to be addressed by drillers. This inaccuracy can potentially stem from a number of different reasons, however it should be noted that the onus is still on the driller to check, and perhaps even double check, the machinery and geology before the operation begins. Any variation in the path of a blast hole is usually caused in the setting up or in operation of the drill (Fiscor, 2000). Fiscor (2000), lists a number of specific reasons path fluctuation can occur:

- Sharpness of the drill bit,
- Drill pressure,
- Torque and rotation speed of the drill,
- Compressed air delivery system, and
- The driller or drill itself.

The tolerance on the drill patterns used in the blast design is limited, if non-existent, as "Many drill patterns begin out as square and end up staggered" (Fiscor, 2000, p10). Fiscor, (2000, p10) states that "There are still blastholes on a pattern that have 50% less burden than the design, or 50% more." Rock blasted with excessive blasting resulting from poor blasthole drilling will therefore cause damage to the surrounding walls and create a gap between the expected design window and the area of rock that was actually removed. This difference is called overbreak. A blast that uses a well controlled pattern is more likely to have less blast damage and minimal overbreak occurring (National Institute For Occupational Safety and Health, 2007).

2.2.3 Blasting Methods and Techniques

The main purpose of blasting is to excavate rock from the quarry walls if in underground mining, or the quarry floor if in open-cut mining. It is important for the steps immediately following a blast in the ore refinement process, such as loading and material handling, to be smooth and as uneventful as possible.
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Fracture mechanics with the rock is used to explain how an explosion actually separates the mixture of rock and ore from the quarry. It is the opinion of Hoek (n.d.), that "From a practical point of view, it seems reasonable to accept that both the dynamic stresses induced by the detonation and the expanding gases produced by the explosion play important roles in the fragmentation process."

Using this theory, the combination of the expanding gases and stresses created by the explosion produce cracks to occur throughout the rock which spreads quickly through weak points within the earth following the theory of fracture mechanics. Due to the large amount of energy involved, the stresses induced along these cracks causes catastrophic failure of the rock and ultimately separates the rock from the wall or pit.

Blasting theory can be complicated and difficult to understand at times. A list of six general points regarding blast theory and its applications can be seen in Polaris (n.d.). These points can serve as a guide to beginning blasters on what to do and not to do when designing for a blast.

- The strength of the explosive should be proportional to the resistance of the rock.
- The burden should be properly proportioned to the strength of the explosives and the resistance of the rock.
- Blasting of the rock to leave two or more faces will require a smaller quantity of explosives than if only one free face is left by preceding blast.
- It is more economical to break to a system of regular faces and benches than to blast in an irregular manner.
- Where possible, the simultaneous firing of several shots grouped closely together often requires less powder than if shots are fired singly.
- No more explosives should be used than is required to break rock to the proper size and leave it in the best position for handling.

Polaris, (n.d.) also makes mention that the formation of a crater will occur when explosives are detonated inside a drilled hole. Figure 2.1 shows the crater theory of explosion.

It is common knowledge around the mining industry that blasters usually only design the drilling pattern for a blast using the powder factor to calculate the amount of explosives required to remove the given volume for a specific rock material (Konya, 2000). This is not the best method to use, as solely relying on the powder factor to determine the drilling configuration does not consider the burden required to break the grade of rock to an appropriate uniform size, or the possibility or how the rock will separate from the wall or floor of the pit. Konya (2000, p7), makes their concerns very clear by questioning, "If one simply uses the powder factor alone, how would the proper burden and spacing be determined?"
The need to accurately design the blast pattern for the burden and spacing in a particular geology is of higher importance than many people give credit. If this were true, why are there many instances where inaccuracies cause mine downtime and money due to hiring a specialist blasting technician to perform a secondary blast on poorly fragmented muck piles? "To produce uniformly sized material as an end product, there must be consistent drilling and a properly selected burden and spacing" (Konya, 2000, p7). A typical blasting pattern and appropriate charge details are visible in Figure 2.3.

The timing and spacing between the firing of the explosive charges are another crucial aspect of a blast design. A blast must have a firing sequence of the explosives in the blast pattern that selects the optimum number of milliseconds between each blast for the geology of the rock needing extraction (Konya, 2000). The firing sequence of the charges is often conducted row by row separated by millisecond delays between each blast. Any inaccuracies in the delays of the explosives sequencing can cause charges detonating out of given order and produce significant damage to the remaining rock structure and poor fragmentation of the removed material (Hoek, n.d.).

The timing of a firing sequence "must be scaled to the physical dimensions, burden, spacing, hole depth and rock type" (Konya, 2000, p7) otherwise there may be adverse consequences in controlling such factors as "vibration, airblast, flyrock, fragmentation, displacement and floor control" (Konya, 2000, p7) of the blast.
Controlling the accuracy and efficiency of each blast is a constant need within the mining industry and a task many people are trying to accomplish. It is hoped with the introduction of highly technological gadgetry and more computer-aided software will help give the blasters greater information and subsequently allow them to produce the best blast design for a given geology (Konya, 2000). There is also a major need for increased communication on many different levels with blasting specialists. The drill operators, blasting foremen, managers and even owners need to maintain constant communication with the blasters in the field to continuously improve the blasting techniques used in the mine and to ensure the proper execution of the designs are carried out (Hoek, n.d.).

2.2.4 Secondary Blasting

Blasting is a mining process used to remove the ore from the wall or floor of the mine site. This enables machinery to gather the mixture of ore and rock, known as burden, into a muck pile before
loading the burden into trucks for transportation. An examination of the muck pile will often show the blast did not produce rock fragments of equal size and equal distribution. Some blasts will have a high level small particles, while other blasts will show a large array of very large and heavy boulders (Djordjevic, as cited in confidential report given to RME, 2006).

The large boulders left in the muck pile following the initial blast are sometimes too large and heavy for the loading equipment available for underground mining mining to move to the crusher for refinement. National Institute For Occupational Safety and Health (2007) states secondary blasting is "Secondary breaking of oversize rock, manually or by drilling and blasting." It is common for mechanised impact breakage to be used in secondary rock breakage, with drill and blast methods are only used on large boulders (Djordjevic, as cited in confidential report given to RME, 2006). This style of blasting is carried out by an explosive technician specialising in this area.

Secondary blasting is undesirable for mining companies to undertake, as it causes disruption to production and decreases the efficiency of the run due to extra time needed to conduct a second firing to the excessively large boulders.

2.2.5 Effects of Blasting on the Surrounding Environment

A single blast can contain thousands of joules of energy. This one blast creates shock waves that travels through the surrounding environment effecting anything in its path. This amount energy can create an intense shock wave through the ground that has the potential to cause serious damage to infrastructure, vehicles and workers surrounding the blast radius if it is not used correctly (National Institute For Occupational Safety and Health, 2007).

The creation of blast damage to the surrounding excavation has the potential to increase the possibility of walls, or roof collapse in underground mining. This can be minimised if the blast is properly controlled. Figure 2.3 below shows the difference between a controlled and uncontrolled blast in a open-cut quarry.

The way the rock fractures along a wall during a blast can be manipulated using a series of fracture control methods. This technique is often used in tunnel blasting in underground mining where tight control over the spread of the blasting cracks into the surrounding rock structure is critical to the stability. Pre-splitting and smooth blasting techniques are commonly introduced into the rock to
help control the blast damage (Hoek, n.d.), however a conventional drill and blast method can be modified in three ways to achieve the same required accuracy of the blast. This is the process where the rock is pre-split before blasting to guide the cracking of the rock surrounding the tunnel. A clean separation surface between the rock to be blasted and the rock to remain is achieved before the blasting occurs (Hoek, n.d.).

![Figure 2.3: Pre-splitting blast (left) and normal bulk blasting (right)](image)

The method of controlling a blast by converting the original drill and blast technique is given in Barker et al (1978), and is listed below.

- Side notches that extend the length of the borehole are used to control the initiation site for the cracks that produce the fracture plane.
- The pressure in the borehole is maintained between specified limits by using light and cushioned charges.
- Stemming length is increased to avoid venting that could produce premature arrest of the crack that produces the controlled fracture plane.

Using this technique, smooth and accurate underground tunnels can be produced similar to the Victoria hydroelectric project in Sri Lanka (Figure 2.4), that will have a minimal chance of wall or roof collapse (Hoek, n.d.).

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2.3 Mine Safety

An underground mine is a dangerous place to work. There are the constant dangers of working in an enclosed environment, the instability of the surrounding rock walls and the use of heavy machinery and high-energy explosives. The use of explosives as part of the rock extraction process in an underground mine greatly increases the risk of injury to personnel and property. Due to the high energies contained in the explosives and mortars used to blast the mixture of rock and ore from the mine, there are a number of potentially fatal consequences that can arise if things go wrong. These dangers are listed below:

- Introduction of fly-rock,
- Undetonated mortars,
- Creation of toxic fumes, and
- Wall and roof collapse in underground mining.

A brief explanation of these issues are given in Sections 2.3.1 – 2.3.4.

Extraction of the rock in muck pile from drawpoints is also a dangerous activity. Serious injuries and fatalities are common during this extraction. The

Mr M. Knee, Western Australia State Mining Engineer, released a safety bulletin in March 2007
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pertaining to the use of explosives in removing large rocks from drawpoints. Knee (2007) explains a near-miss incident involving the premature firing of a mortar charge during secondary blasting to remove a large boulder jammed in the drawpoint.

This was the result of manufacturer error in the finned tubes surrounding the impact fuse (Knee, 2007). This is not the first time an incident such as this has occurred in the removal of drawpoint hangups using mortars. “A previous incident resulting in a fatality occurred approximately a year ago involving a similar device”

Knee (2007) recommends the discontinuation of the mortars for secondary rock breakage in drawpoints until an inspection of the supplied explosive products is completed by the appropriate supervisor.

2.3.1 Fly Rock

Flyrock is any rock that is propelled with great energy from a blast. Flyrock is extremely dangerous and has the potential to kill or injure (Fiscor, 2000). Excessive flyrock is a result of poor blast patterns or powder factor (Fiscor, 2000). This poor design can greatly increase the fragmentation of the rockface and induce sections of the rock to ‘fly’ out into the surrounding environment. The energy driving the rock through the air is very high and subsequently gives rise to the flyrock travelling at high velocity.

Flyrock has the potential to cause tremendous damage to both people and equipment in the velocity of a blast. Damage also occurs to the surrounding wall structure of the tunnel. Large impact loads from the flyrock on the walls and ceiling can induce cracking in the rockface and destabilise the entire tunnel. The cracks in the surrounding rock can increase the potential for shaft collapse (Konya, 2000).

2.3.2 Undetonated Mortars

A mortar is a long-bore explosive shell used to blast rock external from the rockface. A typical mortar is equipped with a wide base that stands beneath the explosive projectile (Knee, 2000). A 2.2kg impact charge will detonate the mortar, causing a major explosion. This device is shown in Figure 2.5.
A previous incident (Section 2.3) describes the investigation by the Western Australia State Mining Engineer into a premature exploded mortar. It was determined the impact sensitive fuse was acted before the intended time.

![Figure 2.5: Typical mortar design](image)

This premature blast could have been catastrophic if the 2.2kg booster was detonated inside the mortar. Fragments of the steel case surrounding the booster would act as flyrock and be expelled at supersonic speeds in all directions (Knee, 2007). Such an explosion would bring serious injury or death to any personnel in the vicinity of the event.

### 2.3.3 Toxic Gases

The chemicals used in the explosive charges for a blast often contain heavy chemicals. Explosive chemicals such as ANFO and Heavy ANFO produce Nox fumes. The energy released from these chemicals and the concentration of the fumes following a clast are dependent on the strength of the rock (Fiscor, 2000). When exploded, the gases produced are potentially fatal if inhaled. This means the toxic gases resulting from the heavy chemicals need to be cleared before mining staff can enter the blast zone.

There is also a concern regarding the mixing of air to other gases and to form a combustive environment. A definition for an explosive environment is provided by Crown (2007), “‘Explosive atmosphere’ means a mixture, under atmospheric conditions, or air and one or more dangerous substances in the form of gases, vapours, mists or dusts in which, after ignition has occurred,
Crown (2007), continues to explain a dangerous substance does not include the oxidant of materials other than air. Any dangerous gases must be removed from the atmosphere or ensure the concentration of the substance is below the lower flammability limit for the environment to be considered as non-explosive (Crown, 2007). These dangerous substances, similar to the toxic fumes, must be removed from the atmosphere for the environment to be deemed safe for human entry.

### 2.3.4 Wall and Roof Collapse

National Institute For Occupational Safety and Health (2007), states that 43% of the fatalities in underground mining are caused by a form of roof or wall collapse. The Beaconsfield mine collapse in 2006 was a prime example of how easily a collapse can occur. Beaconsfield mine in Tasmania was the centre of the largest recent mine disaster in Australia. Three workers were trapped underground when a tunnel they were working in collapsed. Tragically, only two of these workers were rescued.

As discussed in Section 2.2.5, the collapse is often induced from poor blasting techniques resulting in damage to the surrounding rock in the transportation tunnel. Hoek (n.d.), confirms this theory suggesting that the structural integrity of the underground facility is dependent on the rock surrounding the excavation. A poor blast can give rise to damage that extends several meters into the rock. Tunnel wall and roof collapse can be prevented with the use of fracture control. The difference between a controlled and uncontrolled blast is graphically shown by National Institute For Occupational Safety and Health (2007) in Figure 2.5.

![Figure 2.5: Difference between uncontrolled and controlled blasting on surrounding tunnel](image)

Combustion spreads to the entire unburned mixture.”
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2.4 Conclusion

Background information was provided into the current mining methods of rock breakage using explosives. Explosives are incorporated in the most common method of breaking rock is through the use of a drill and blast procedure. A series of holes are drilled into the rock and explosive charges are inserted into the holes. The timing of each charge is critical to produce a suitable tunnel or rock muck. Secondary rock breakage occurs when the rocks in the muck pile are too large for extraction from the draw points. Secondary blasting is the common method of tackling this issue.

The use of explosives as a form of secondary rock breakage in industry creates a number of safety issues. The possibility of injury and fatality to underground mining employees and damage to property is significantly increased by introducing of the secondary blasting. Fly-rock, toxic gases and the potential for tunnel collapse are just some of the many dangers that are introduced by explosive rock-breaking techniques.

Chapter 3 continues to provide background information of the research project for the reader. The following chapter looks to research the specific requirements of both sections of the research project.
Chapter 3

3.0 Literature Review

3.1 Introduction

The ThunderBurst project is a unique concept developed by Russell Mineral Equipment Pty Ltd that takes a number of different ideas and moulds them into a viable design possibility. Due to the originality of the ThunderBurst project, a number of different areas must be adequately researched to understand why the ThunderBurst is needed in industry, how it will operate and what has been achieved in previous RME research into the design.

The dual nature of the project means research must be conducted using a literature review in both areas. The research topics investigating the use of the ThunderBolt hammer as the energy delivering device on a permanent steel test frame will be looked at in Sections 3.2 and 3.3.

Information known to RME regarding the design and development of the ThunderBolt recoilless hammer is provided in Section 3.2. A literature review of the structural analysis of test frames undergoing impact loading is shown in Section 3.3 of the report. Little information was found on this topic, so a discussion on the functionality and applications of a known high-pressure impact test frame housed at the University of Southern Queensland (USQ) was included in Section 3.3.2.

The second phase of the project involves research non-explosive methods of rock breakage and fracture mechanics in rock. This information is included as further background of the report in Sections 3.4 and 3.5. The additional research will provide background into some non-explosive technologies and techniques currently available and give information into the fracture mechanics of material. It is expected that the same theory will be applied to rock and naturally occurring material.
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3.2 RME LRT ThunderBolt

RME’s Liner Removal Tool (LRT) ThunderBolt hammer is a recoilless hydraulic hammer used in the removal of linerbolts from a ball or sag crushing mill. The LRT uses the conservation of momentum theory to transfer hydraulic power through the device to a striking moil which impacts on the linerbolts of the mill. In 1997, the ThunderBolt recoilless hammer won the prestigious BHP Steel Award (Russell Mineral Equipment Pty Ltd, 2006). This machine is used in conjunction with RME’s Mill Reline Machine (MRM) to replace the worn out liners from a mill.

A crushing mill is lined with a number of steel contours, called liners, that protect the inside structure of the mill from damage in the crushing operation and disperse the mixture of ore and rock randomly around the mill. These liners are held on to the walls of the mill using linerbolts. Over time, the liners are worn down due to constant wear and tear of the crushing processes, and require replacement. The linerbolts of these mills were previously removed manually by mine workers using a sledge hammer. Using this method, the average strike for a man is 150J per blow. A series high energy and high momentum strikes on the linerbolt from the ThunderBolt hammer will quickly and easily remove the linerbolts from the mill.

The ThunderBolt hammer comes in three sizes: 450, 750 and 1500. Figure 3.1 shows a 1500 ThunderBolt in action. The size of the hammer represents the energy in joules each strike of the hammer can produce. This means the 450 LRT will impact the linerbolt with 450J of energy each firing of the device, three times harder than a man (Russell Mineral Equipment Pty Ltd, 2006). Therefore the use of RME’s Liner Removal Tools greatly increases the efficiency of the liner replacement process.

A LRT hammer is accompanied by a pneumatic or hydraulic powerpack, which supplies the mechanical power to the device (Figure 3.2). The 450 ThunderBolt relies on pneumatic power supplied by the mine site, while the 750 and 1500 versions are driven by hydraulics. The powerpack also supplies the electrical requirements of the hammer and the power for suspension options that are included in the design (Russell Mineral Equipment Pty Ltd, 2006).
The LRT is suspended via a steel rope from a swiveling jib situated close to the area under maintenance. The jib allows the hammer position to be adjusted in all three directions and allows for the quick manipulation of the hammer between linerbolts. The caster wheels on the frame allow
it to be maneuvered between locations and away from the mill after the liner replacement is completed. The complete jib assembly is shown in Figure 3.3.

The complete jib assembly is shown in Figure 3.3.

The 1500 LRT has the potential to be used in a number of different applications in industry where high impact loads are required. Modifications to the original LRT design are common in the mining industry to help complete common tasks without the need to submit their workers to demanding physical work. This is shown at Mt Tom Price mine in Western Australia, where a modified LRT hammer is used to remove the mantle nut from a mill. This technology can be also used in construction, naval and automotive industries where repetition of high energy impacts is required.

It is this flexibility of the LRT hammer that enabled the modification of its design to incorporate the striking moil used in the ThunderBurst rock breaking device.

3.2.1 Further 1500 LRT Hammer Development

The first experiments of ThunderBurst were conducted by simply hanging the 1500 LRT vertically from a forklift above the boulder. This was achieved by suspending the hammer from the forklift tynes using a thick synthetic strap shown in Figure 2.4 below. This arrangement was not ideal for continuous use due to safety concerns and the need of a forklift to position the LRT vertically.
The orientation of the LRT was not directly vertical in relation to the path of the drilled hole in the rock. Having the energy loading askew from running parallel to the centre of the hole could have impacted the results received from the past experiments. The forces exerted on both the rock and the ThunderBurst during firing caused the device to sway. The swaying of the ThunderBolt hammer following a fire could potentially swing around and injure the operator or nearby spectators if the rock was split and the hammer was left free to move. These concerns seen in conducting the previous experiments have led to the need for a specific test frame to be used in further research of the project.

![Figure 3.4: Slinging of the ThunderBurst project from a forklift during operation](image)

The test frame designed as part of this research project will provide a more permanent frame to safely house the ThunderBurst energy system while research into the pressure waves and energies are being conducted.

Since the initial development of ThunderBurst in 2002, Russell Mineral Equipment Pty Ltd has
developed a permanent method of mounting a LRT ThunderBolt vertically. This method is currently being used at the Robe River mine in Western Australia, to chip away encrusted ore from the bolts of a grinding mill shown in Figure 3.5 and Figure 3.6.

The vertically orientated LRT ThunderBolt is held from the winch jib using a steel rope connected to a spring damper attached to a pivoting arm on the ThunderBolt. The introduction of the spring damper makes handling of the LRT easier by helping to reduce the vertical recoil experienced during firing. This means the operators handling the device will not experience the forces involved in the operation or be pushed back due to the reaction forces when the moil of the hammer pushes on (and is pushed back by) the bolt to be removed.

The pivoting attachment arm of the vertical LRT gives the operator flexibility to change the angle of the moil depending on the orientation of the impact area. A bush is positioned in the connection of the pivoting arm and the hammer to give smooth movement of up to 90° between orientations. Two different operating positions of the vertical LRT at Robe River are show in Figures 3.5 and 3.6. Extra handles were also included in the design to assist the operator to maneuver and hold the hammer in the correct position.

Figure 3.5: Robe River 1500 LRT ThunderBolt Hammer in operation positioned at a 45° angle
A second vertically mounted LRT ThunderBolt is operational in the Holden machine plant in Melbourne. This hammer does not remove linerbolts from a mill; however the LRT is used as part of the manufacturing process to vertically impart a high amount of energy onto a portion of the frame. The Holden ThunderBolt hammer shows one of the applications RME's range of Liner Removal Tools can be used in industry other than for the removal of linerbolts.

The use of RME's vertical attachment for the ThunderBolt hammer is suggested by members of RME's research and development department in the test frame if possible. This would allow for a more accurate mounting of the energy delivery system above the column of water. As there will be vertical movement and potentially some swinging motion laterally of the LRT ThunderBolt after each strike, the vertical mounting will also provide greater safety for those who are operating the system.

By combining the experiences of previous ThunderBurst work with new concepts for RME's LRT
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Hammers, it is expected that the test frame produced as part of this research project will be capable of successfully analysing the pressure waves through the given fluid.

3.3 Structural Frames For Impact Loading Devices

A literature review into the design of structural frames that house a device which impart an impact load to another object was conducted. There was limited information on this topic, however related topics dealing with axial and dynamic loading of steel columns, frames and structures were found and detailed in Section 3.3.1 of this report.

3.3.1 Literature Review

A literature review was conducted into the structural analysis of a steel frame to house a device that delivers a dynamic load. A report prepared by David Buttsworth (2006) gives an analysis of the Vertical Gas Gun facility located at the University of Southern Queensland. The facility uses a series of framework to house pressure vessel and fast acting pressure value, with a guiding tube to send a projectile down to a water column housed in a separate hollow steel cylinder. This device is discussed in detail in Section 3.3.2 and subsequent topic headings due to the similarity between the Vertical Gas Gun and the intended ThunderBurst test frame experiments.

Rotter (1998) reviews the current position of metal silo structures under the draft European standard Eurocode 3 Part 4.1. Included in the paper is a review of the strength regulations for silos under the new draft for cylindrical walls, roof structure, conical hoppers and ring beams. The rules relating to the strength of the cylindrical walls to prevent rupture and buckling include the stiffened and corrugated walls under axial loading or external pressure, and the non-uniform axial compression occurring from patch loading. The investigation of buckling of metal shells was also completed by Edlund (2007). This paper gives an overview of the buckling and post-buckling behaviour of metal shells with thin walls. It was found that the buckling strength of a steel shell from experimentation is much lower than using classical mathematical modelling. This is due to the relationship between the geometric thickness of the wall (t) and the radius of the shell (R). As the wall thickness decreases, the experimental results show a faster rate of decrease of buckling stress than the ratio t/R. Using classical modelling, it is expected however that the buckling stress should decrease proportional to t/R. This analysis of shell structures will help in choosing the arrangement of the
test frame for the ThunderBurst project.

The consequences of axial loading of steel members are discussed in Horvath et al (2004). An insight into the axial loading of tapered steel pipes, called Tapertube at John F. Kennedy International Airport is given by Horvath et al (2004). The determination of pile capacity was determined following the completion of a number of tests including a static load test, quasi-static load test and dynamic load test. Using the results of these experiments, the calculation of the capacity of tapertube can be conducted.

Zeinoddini et al. (1998) investigates the behaviour of axially pre-loaded tubular steel members damaged by dynamic impact loads. The steel members are positioned offshore and were subjected to impact damage from an on-coming shipping vessel. The effects of axial pre-loading was found to change the dynamic characteristics on the steel structure quite dramatically in some cases, while it had no significant effect on others. This will help in the sizes and material properties selected for the test frame structure to support the modified LRT and in the thickness of the steel tubing used to house the water.

Dynamic loading of steel columns are analysed in detail by Hsu (2005), Yabuki (2005) and Tarigopula (2004). Tarigopula (2004) explains how high strength steel thin-walled square sections were tested using quasi-static and dynamic axial crushing. Dynamic axial loading using projectiles was conducted in order to assess the crushing behaviour, deformation and the energy absorption of square steel sections. A number of velocities up to 15m/s and an impacting mass of 600kg were used in the experiments. Hsu (2005) uses a similar theory to Tarigopula (2004) by performing quasi-static and dynamic crushing experiments on circular thin-walled sections. The experiments were conducted on three materials: 304 stainless steel, aluminium alloy 6063-T6, and mild steel. Yabuki (2005) discusses the instability of steel columns under a dynamic load in concrete. This paper shows different methods to assess the performance of strength in structures. From the analysis, a comparison between the behaviour of a elastic and inelastic columns at the instability condition was discovered to be different.

Steel frames undergoing dynamic loading are discussed in papers by Rakicevic et al. (2005), Maneetes (2003) and Kim (2005). Rakicevic describes the analysis of a five story structure with and without the Vibration Base Control System (BCS) under the influence of a biaxial shaking table. The experimentation of dynamic vibration with the BCS shows a reduction of the inertia forces along the top of the structure, than when the BCS is not used. Kim (2005) investigates the
use of a numerical procedure to analyse 3-D steel frames under dynamic loading. This is achieved through the inclusion of stability functions in framed stiffness matrix formulation and the average acceleration method to solve the equation of motion for a framed structure using computer programming. Research into lateral bracing of curved steel bridges due to free vibration is contained in Maneetes (2003). Studies of experimental curved bridge systems using finite element models were conducted to study how cross-frame and lateral bracing parameters are influenced the free vibration response of the structure. The issues arising from these papers will be considered in the steel frame design of the ThunderBurst energy delivery system.

3.3.2 USQ Vertical Gas Gun Facility

The Vertical Gas Gun is a testing device which uses a fast acting pressure release valve to shoot a projectile down a finely machined shaft into a tube filled with water. This device was originally designed and used by University of Queensland (UQ) Mechanical Engineering Department to compact powder using dynamic loading. Queensland Institute of Technology (QUT) acquired the gas gun following the completion of the powder compaction experiments at UQ. The University of Southern Queensland (USQ) purchased the facility and shock tube from QUT in 2002, and was used to experiment the effect of shock loading in the destruction of bacteria in dairy products under the guidance of Dr David Buttsworth (Buttsworth, 2006).

It is still located in the Thermodynamics and Water Technologies Laboratory at USQ. Figure 3.7 shows the Vertical Gas Gun in its present location at USQ.
A detailed examination of the structure, functionality and applications of the Vertical Gas Gun housed at USQ is given in the following sections of the report.

3.3.2 (i) Vertical Gas Gun Structure

Buttsworth (2006) outlines the arrangement used in the Vertical Gas Gun, separating it into five individual components. Figures 3.8 – 3.11 show these separate components of the vertical gas gun. These components include:

- Pressure reservoir which stores the compressed air used to force the piston down the barrel into the water column.
- Fast-acting valve that releases the high pressure from the reservoir in a very short space of time.
- Piston varying in weights to transfer the kinetic energy from the release of pressure to the water.
- Barrel that guides the piston down to the tube filled with water.
- Water-filled tube which undergoes a dynamic load from the piston.

Figure 3.8: Pressure vessel and fast-acting pressure release valve

Figure 3.9: Piston used to shoot down the barrel of the facility
Also included in the facility are two individual sets of electrical sensors and instruments (Figure 3.12). Optical sources and detectors are positioned along the barrel of the facility to record the velocity of the piston as it travels down the barrel. The pressure changes in the water following the impact of the projectile are sensed by PCB pressure transducers evenly spaced in the steel tube down the water column.
Using these individual components, the vertical gas gun is effectively used to analyse the effects of shock waves in water following an impact.

3.3.2 (ii) Operation of the Facility

The vertical gas gun facility is prepared for operation by ensuring the pressure reservoir is emptied to atmospheric pressure conditions and the fast-acting value to open. The piston is then loaded into the barrel and forced upwards to a locked position for firing using a flexible garden hose. The pressure release valve is then closed and the reservoir is compressed to the required pressure ready for operation. This was discussed in the 2006 report 'Vertical Gas Gun Facility at USQ' supplied by Dr David Buttsworth.

Once the facility is loaded, firing occurs by opening a value that releases the fast-acting pressure valve. The loaded piston is forced down the barrel of the facility by the high pressure being released from the pressure reservoir. The piston then travels from the barrel into the steel column containing the water.
Chapter 3 - Literature Review

Buttsworth (2006) also outlines the method of recording the data from experiments. The electrical signals from the optical detectors and the PCB pressure sensors are transferred to a digital storage oscilloscopes. The data recorded by the oscilloscopes is sent to a computer using a serial communications port.

3.3.2 (iii) Mathematical Models

The experiments conducted by Dr Buttsworth used two different mathematical models to explain the results acquired into the destruction of bacteria from dairy.

The constant acceleration model uses Equation 3.1 to infer the initial impact velocity of the piston under constant acceleration where $m_p$ is the mass of the piston, $A$ is the cross-sectional area of the piston, the maximum displacement of the piston travel is shown as $S$, and the coefficient $C$ is incorporated to account for inconsistency in the differences of pressure readings. This constant acceleration is found by deriving the constant pressure difference along the piston.

\[
v_0 = C \sqrt{2SA \frac{\Delta p}{m_p}}
\]

(3.1)

Where

- $v_0 = \text{initial velocity}$
- $S = \text{Maximum displacement of the piston travel}$
- $A = \text{Cross-sectional area of the piston}$
- $C = \text{Account for inconsistent differences in pressure readings}$
- $\Delta p = \text{Change in pressure}$
- $m_p = \text{Mass of piston}$

The results from the experiments into the bacteria destruction analysis shows that the piston velocity found at the exit of the barrel is always higher than the velocity calculated from the constant acceleration modelling. Errors in the constant acceleration modelling is around 10% for lower piston speeds (at around 80m/s), and up to 25% for speeds higher (David Buttsworth, 2006).

A lumped piston mass uses acoustic theory to calculate the velocity of a particle within water that follows a shock wave. The relationship between the piston velocity ($v$) and the initial impact velocity ($v_0$) is shown in Equation 3.2. Equation 3.3 is based on a number of variables where $\rho_w$ is
the water density, $c_w$ is the speed of sound in water, $A$ is the cross-sectional area of the piston, $m_p$ is shown as the mass of the piston, and $t$ represents the time taken.

$$\frac{v}{v_0} = e^{-\frac{\rho_w c_w A}{m_p} t}$$

(3.2)

Where $v_0 = $ Initial velocity

$v = $ Velocity

$c_w = $ Speed of sound in water

$A = $ Cross-sectional area of the piston

$m_p = $ Mass of piston

$\rho_w = $ Water density

$t = $ Time

Using Equation 3.2, the pressure ($P$) following an acoustic wave can be determined. Similar to variables required in Equation 3.2, Equation 3.3 uses the water density, speed of sound in water, the cross-sectional area and mass of the piston, time and initial impact velocity to calculate the pressure.

$$P = \rho_w c_w v_0 e^{-\frac{\rho_w c_w A}{m_p} t}$$

(3.3)

Where $v_0 = $ Initial velocity

$c_w = $ Speed of sound in water

$A = $ Cross-sectional area of the piston

$m_p = $ Mass of piston

$\rho_w = $ Water density

$t = $ Time

$p = $ Pressure

The derivation of Equations 3.2 and 3.3 are found in Section 4.2 of David Buttsworth's 'Vertical Gas Gun Facility at USQ'.

Using the mathematical models shown above, the initial piston velocity on impact, and the relationship between the initial impact velocity and the piston velocity can be calculated and
designed against.

3.3.2 (iv) Applications of the Vertical Gas Gun

The vertical gas gun has been used previously to research into the compaction of powder by UQ and the destruction of bacteria in dairy products at USQ. Varying applications can be seen for future use of the gas gun facility where a high velocity impact is present. Such applications the facility can be used is to model natural situations such as the effects of hail on roofing tiles or vehicles.

Modification of the facility can be incorporated to test the impact loading of materials or equipment needing research or development. This would only mean replacing the water column from the facility with the appropriate device to be tested below the end of the barrel.

3.4 Non-Explosive Technology

Non-explosive technology is critical to be developed to improve the safety levels of a mining environment. The use of explosives in the extraction of ore from the earth creates many dangers to the miners, equipment and the surrounding environment.

Djordjevic (2006, as cited in a confidential report provided to RME), investigated the use of non-explosive mining technology as a substitute for blasting in the removal of boulders in drawpoint hangups. In this report, Djordjevic (2006) explains various technologies that may be implemented in the future to increase the safety in and around drawpoints.

A number of the non-explosive rock-breaking technologies researched in the report are listed below:

- Electrical discharging,
- Water-jet assisted fracture,
- Impact-induced fracture,
- Rock-cutting,
- Shock tube loading,
- Bursting diaphragms,
Chapter 3 - Literature Review

- Hydraulic systems,
- Thermal induced
- Propellant induced loading, and
- Foam injections.

Due to the closeness of RME to impact loading and hydraulic systems, these areas will be a major focus of the further attention.

3.4.1 Impact Induced Technology

Djordjevic (2006, as cited in a confidential report provided to RME), introduces the use of impacting rock surfaces with high-velocity projectiles. Systems such as REAM (Rapid Excavation and Mining) and RAMAX use projectiles to break the unwanted rock. The RAMAX Tunneller meets the need in industry to produce non-explosive underground technology (Djordjevic, 2006, as cited in a confidential report provided to RME). The shock tube loading using the Vertical Gas Gun (Section 3.4.2) is also classed as an impact induced technology.

3.4.2 Shock Tube/Bursting Diaphragm

The application of shock tube loading on a water column is discussed in Buttsworth (2006). The application of the shock tube encasing a water column will have many similarities to RME’s proposed ThunderBurst system (Djordjevic, 2006, as cited in a confidential report provided to RME). Section 3.3.2 of this report outlines the Vertical Gas Gun structure in detail.

3.4.3 Hydraulic Systems

The use of hydraulic hammers have become more popular over the last twenty years to help in the crushing of oversized rocks (Zaitsev et. al., 2004). The hydraulic hammers, similar to RME’s ThunderBolt hammer, can be used in industry to bust sections of rock apart along fractures in the material. Hydraulic jackhammers and drills are common in underground environments to chip portions of the rock away piece by piece. Hydraulic fracturing systems such as the Atlas Copco rock breaking method are outlined in Djordjevic (2006, as cited in a confidential report provided to RME).
3.4.4 Propellant Induced

Propellant induced rock-breaking uses a disposable cartridge as the prime energy source. The RoBust™ system breaks rock in secondary rock-breakage situations using the disposable cartridges (Djordjevic, 2006, as cited in a confidential report provided to RME). Djordjevic’s report (2006), also investigates the ‘Rock Splitter’ produced with the help of Boart Longyear. This device uses two cartridges to break through the solid in-situ rock with the introduction of a pressure wave. The rock-splitter uses a similar idea as the ThunderBurst, except with the use of air between the charges instead of a water column.

3.4.5 Rippers

Zaitsev et. al. (2004) explains the difference between a number of ripper machinery. The use of hydraulic hammers have become more popular over the last twenty years to help in the crushing of oversized rocks. Bulldozer rippers are the main source of blast-free mining technology. Other forms of rippers include cutter-loaders, bucket-wheel excavators and drag-lines.

Djordjevic (2006, as cited in a confidential report provided to RME), brings forth the design of a special rock-cutting machine called the Oscillating Disk Cutter (ODC). This device uses four different techniques to cut through the rock.

3.5 Fracture Mechanics

This section discusses general information on fracture mechanics that could resemble the cracking of rock. This will specifically refer to the fracture mechanics of the material.

Askeland (2003, p264), refers to fracture mechanics as “the discipline concerned with the behaviour of materials containing cracks or other small flaws.” The fracture toughness of the material refers to the ability of the material to withstand the applied load. The stress intensity of a material directly relates to the fracture toughness (K). The critical stress intensity of a material is found using a factor, $K_c$. If $K < K_c$, then the microcracks that exist in the grain of the material will not propagate under the applied load.
Juvinall (2000), explains the crack formation in a thick steel plate. This could be assumed to resemble the thick sections of rock. The crack formation usually begins at the surface of the face and takes an elliptical motion through the material.

### 3.6 Conclusion

This chapter shows literature reviews conducted into the structural analysis of devices that are used to impart high energy impact loads on material. Various papers were shown in the report outlining the impact of axial and dynamic loading of structural material. However, there was limited information available for a test frame to support the high energy delivery device. A report on USQ's vertical gas gun was found to be very similar to the requirements of the ThunderBurst test frame. The details of the vertical gas gun facility were presented in the report due to the close relationship between the facility and the required testing of RME’s ThunderBurst energy delivery system. Research into non-explosive technology and fracture mechanics are shown as a literature in the chapter also.

Chapter 4 looks into the previous rock-splitting experimentation conducted in 2002, and the expectations of RME for the ThunderBolt test frame system. It also outlines the restrictions of the research project.
Chapter 4

4.0 RME Research Project Requirements

4.1 Introduction

There is a need to identify the specified aims identified by RME for the design and operation of the test frame to ensure the successful completion of the project. Section 4.1 will give background into the origins and development of ThunderBurst and identify previous ThunderBurst design work undertaken in 2002. The information gathered from RME employees Mr Peter Rubie, Mr Mick Henderson and Dr Rick Coker into RME’s need for the design of the test frame are situated in Section 4.2 below.

An outline of the restrictions placed on the testing of the Thunderbolt test frame is discussed in sections 4.3 and 4.4 respectively. This chapter also begins to investigate the need for a simulation of the Thunderbolt energy delivery. Performing the same test with a known energy value will allow for a direct comparison between the two systems.

4.2 Russell Mineral Equipment’s ThunderBurst Project

4.2.1 Expectations of ThunderBurst

RME's ThunderBurst project is expected to be the first driver-less underground machine in operation with the ability to destroy large boulders without the use of explosives. It is hoped the ThunderBurst will contain a boring arm to drill into a given boulder, and a device to deliver the required splitting energy through the boulder. Both devices are expected to attach to a maneuverable machine to move about the mine site and in between blast areas.

It is the expectation of Russell Mineral Equipment Pty Ltd that a machine such as the ThunderBurst will be successfully sold and be highly sought in the resources sector. The ThunderBurst will
provide industry with a tool that greatly increases safety in mine sites and saves the mining company money as downtimes experienced from waiting for dangerous fumes to dissipate following a blast will be greatly decreased.

No timeframe has been given to the scheduling of the project beyond the testing of the pressure waves through water in the simulated experiments for this USQ research project in 2007.

4.2.2 Use of Previous ThunderBurst Work

The ThunderBurst project was an RME initiative to investigate the ability to split boulders using a modified RME LRT to impact a column of water within the rock. RME Chief Engineer, Peter Rubie undertook the project in 2002, with University of Southern Queensland mechanical engineering undergraduate, Simon Strong.

A ThunderBolt hammer is a recoilless hydraulic hammer designed by RME to assist a mill relining machine in the removal of liners from the inside of a mill. Section 3.2 provides an outline of RME’s Linerbolt Removal Tool technology.

This device was modified by incorporating a reusable striking device, called a moil, encased in a steel cylinder. The energy is transferred through the length of the cylinder by a number of components to the moil and into the column of water in the rock. Seals are positioned at the interacting face between the moil and the rock to prevent water from ejecting outwards from the column following the impact of the ThunderBolt. Due to the porosity of the rock, the water in the hole will be absorbed and distributed throughout the rock. This means the water will require constant refilling during its operation. To counter this, the cylinder also doubles as a container to hold excess water and as a fill point for the water column.

The modified 1500 LRT is shown with Simon Strong in Figure 4.1.
This project was deemed a success with a sandstone boulder split in a number of different locations during the experiments in 2002 shown in Figure 4.2. From this initial work into the viability of the ThunderBurst concept, a number of conclusions were drawn. These are listed below:

A RME 1500 LRT hammer can be successfully modified to attach the rock splitter moil required to break the rock.

- An impact load imparted onto a column of water will split a boulder.
- The hydraulic power supplied to the modified LRT is only enough to split the boulder in two pieces. A bigger system would be required to break the rock into multiple sections.
- A more permanent structure is required to safely house the system.
- This experiment can be successfully repeated in rocks of varying geological properties.
- More research is required to determine an optimum balance between the energy required to break the rock into multiple sections and the size of the energy delivery device.

The success of the investigation into the viability of the ThunderBurst project has opened the path for further expansion on the idea of using explosive-free technology in underground mining in the future.
Further research into how the impact load of the water in the boulder causes the fracturing of the rock will be explained. RME's initial work on the ThunderBurst project in 2002 will form the basis of the experiments conducted in this research project.

RME has suggested the use of the same modified 1500 LRT Hammer from past ThunderBurst project work, if possible, to limit the time taken before the experimentation into the pressure wave analysis begins. If this retrofitting of the 2002 ThunderBurst is not possible, another means to induce the pressure wave through the fluid is required, all before the graphical analysis of the pressure wave using the test frame can start.

4.2.3 Previous Water Pressure Readings

Observations of the previous rock-breaking experiment showed the hammer moil travel between 30 and 40mm into the water under impact loading. This occurred from the compression of water during the loading. Compressibility of liquids is stated by Nave (2005), in “Compressibility of Liquids” as the “fractional change in volume per unit increase in pressure.” Water is considered to be an incompressible fluid, however it will compress under large loads although it will only be a small amount. The compressibility of water, k, is equal to 4.58 x 10^{-11} Pa^{-1}.

Bulk modulus (B), is the reciprocal value of the compressibility from “Bulk Elastic Properties” (Nave, 2005). It describes bulk modulus to be the change in fluid pressure divided by the volume
compression of the fluid or the amount of compression experienced on a material from an external pressure source. This is shown in Equation 4.1.

\[ B = \frac{\Delta P}{\Delta V/V} \]  

Where \( B \) = bulk modulus, 
\( \Delta P \) = change in pressure (Pa), 
\( \Delta V \) = change in volume (m\(^3\)), and 
\( V \) = volume (m\(^3\)).

From the deflections of moil in water during previous LRT experiment in 2002, the pressure in the system can be calculated using Equation 4.1. It is assumed the highest deflection, 40mm, is used in the calculations. Equation 4.1 therefore gives a pressure valve of 110 MPa on all faces of the tube. This is an equivalent of a 222 951N axial load on the bottom face of the hole.

The hoop stress, \( \sigma_h \) and axial stress \( \sigma_a \) are also important to check the thickness of the material surrounding the water column. Equations 4.2 and 4.3 show the hoop stress and axial stress respectively.

\[ \sigma_h = \frac{pr}{t} \]  

Where \( \sigma_h \) = hoop stress (Pa), 
\( p \) = pressure (Pa), 
\( r \) = inner radius of vessel (m), and 
\( t \) = wall thickness (m).

\[ \sigma_a = \frac{pr}{2t} \]  

Where \( \sigma_a \) = Axial stress (Pa) 
\( p \) = pressure (Pa) 
\( r \) = inner radius of vessel (m) 
\( t \) = wall thickness (m)

Hoop stress is twice as large as the axial stress. This will give way to the material thickness being
twice as big as that required for the axial stress. Assuming a CS1020 steel tube is used to house the water column, the required thickness of the tube needs to be at least 14mm to prevent damage from occurring during the testing.

4.3 ThunderBolt Test Rig

The ThunderBurst uses a theory of a pressure wave being induced through a rock via an impact shock load onto a vertical column of water within the rock. Although breaking and splitting rock using impact loads has been around since the Stone Ages, the theory of transferring an impact load through an incompressible fluid is relatively new.

Due to the uncertainty surrounding the practical implications of the energy and pressure transferred through the fluid to rock, more testing of this theory must be explored to help with future development of this technology. The practical testing of the wave theory used in the ThunderBurst project is the main focus of this research project via a testing frame.

Recording and graphically displaying the pressure wave and peak values through the incompressible fluid following an impact load is the main focus of the ThunderBurst experiments. This will allow for a comparison to be drawn regarding the theoretical values from computer simulations and the practical values from the experiments. It will also be interesting to experiment with how the pressure wave travels through the fluid and interacts with a second wave induced within the system while the first is still present in the fluid.

The ThunderBolt test frame is required to be designed, built and operational before July 2008. The expected test process is likely to occur in three sections. This will include an initial run of the machine, redesign and final experimentation. The initial experiment will occur following construction to ensure the correct working of all components. It is likely that the first run of the ThunderBurst will occur without the electrical pressure sensing and recording devices to prevent any damage occurring to the electrical components if failure of the test frame happens. The structure will then be assessed, and modified if required, before the energy delivery and pressure wave analysis will occur.

The test frame will use a hollow steel cylinder to simulate the original rock experiment in 2002. The cylinder will be orientated vertically and positioned directly below the modified LRT hammer.
Chapter 4 - RME Research Project Requirements

The internal diameter of the cylinder will house the incompressible fluid. An appropriate material will be selected for the design of the cylinder that does not deform during testing.

![Figure 4.3: Steel pressure tube welded onto square steel base](image)

The above hand sketch (Figure 4.3) shows the hollow steel cylinder that would be used to house the water column. The base plate could be welded or threaded to the bottom of steel tube and bolted down to the floor during operation. It is likely different size cylinder diameters are tested to find an optimum sized drilled hole for the ThunderBolt energy.

A series of electric pressure sensors positioned periodically along the length of the tube will record the changes in pressure of the water following the impact and send the results to a data logger. The data logger will process the results and graphically display the pressure readings as a wave to be used in further development of the ThunderBurst energy delivery.

Once the pressure wave theory is tested using the test frame, experimentation with boulders will be conducted to see if similar pressure wave results are present in the fluid. Similarly to the steel tube experiment, the boulder will be vertically drilled, filled with water and impacted with the modified LRT on the same test frame. Electric sensors will be positioned along the drilled hole and cemented into place with a concrete-like material possessing similar properties to rock. This will allow for a comparison to be drawn between the two situations, and help RME to prepare an initial design for the energy delivery system for use in the ThunderBurst autonomous machine.

4.4 Needs of ThunderBurst Test Frame

The ThunderBolt test frame is designed to provide the energy system with a fixed location to conduct the pressure wave analysis within a water column. This consistent position will ensure the
accurate calculation the pressure waves and energy values through a column of water during its
operation. This is achieved by mounting the energy delivery system on the test frame in a position
vertically above a steel tube filled with water and firing the device. The test frame will also need to
record the resulting pressure values that arise from the impact loading of the water column using
piezoelectric sensors. Resulting pressures are sent from the sensors to a data logger, where
computer software will give an accurate display of the wave as it travels through the column.

However, apart from the ultimate aim of the test frame, there are a number of needs that RME have
specified which are required to be adhered to in order to properly control the experiment and
achieve the desired results efficiently and effectively.

This experiment is hoped to be repeated at a later stage within an actual boulder and the pressure
wave through this practical situation also recorded. A correlation of the data will enable the RME
engineers to find the optimum energy to regularly produce a pressure wave that will split any given
boulder in half. To achieve this, the pressure waves will need to be recorded using electrical
sensors and reproduced in a graphical form to easily display the variation seen in different sections
of the column.

The research and development department at Russell Mineral Equipment has asked for the test
frame to accomplish a number of specific tasks, along with the main proposal stated above. This set
of tasks required by the ThunderBurst test frame to achieve is the minimum prerequisites expected
by Russell Mineral Equipment to successfully complete the pressure wave analysis. These
expectations for the research project are summarised in the list below:

4.4.1 Use of Previous ThunderBurst Work

The test frame will be able to hold the modified 1500 LRT Hammer used in previous ThunderBurst
experiments. This is to try to keep a constant correlation of the data collected from the Simon
Strong’s previous experiments in the boulders and the new experiments in the water column. If the
use of the modified 1500 LRT ThunderBolt Hammer is possible it will greatly reduce the time
before the experiments can begin, otherwise a new method of energy transfer will also be required
to be developed.
4.4.2 Transportation of the Test Frame

It is expected that the test frame will be portable by both an overhead crane and a forklift. By allowing for both possible methods of transport in the design, it will have the potential to be moved quickly around the specified testing area without being solely reliant on one machine being free for use. While the overhead crane will be preferred to the forklift within the workshop due to the crane's larger lifting capacity, the use of a forklift will also allow for the test area to be situated outside if there are safety or space concerns within the workshop. Therefore both methods of transportation are required to allow for flexibility in where and how the experiments will be conducted.

4.4.3 Vertical Orientation of the Experiment

To most accurately simulate the live situation in the field, the test frame must allow the given energy method to strike column of water in the vertical direction. If the column was at an angle, the pressure wave results might not accurately give the maximum energy resulting from the impact load. It is also much more practical for the water column to be close to vertical in orientation, otherwise a large amount of fluid will be required to continually keep the column at the level necessary for operation. The closer the column is to horizontal, the easier it will be for the fluid to spill out of the hole due to gravity.

4.4.4 Data Collection and Display

Recording the data following the impact load imparted on the water column and producing an output relevant for the project engineers is one of the primary functions for the ThunderBurst experiments. The output from the sensors will need to be recorded in a digital data logger and downloaded into a computer that will show the results graphically. Displaying the results in this form will most clearly show how the pressure wave propagates through the fluid.

4.4.5 Variation in Experiments

The ThunderBurst test frame is to experiment with a range of column heights and hole sizes to see if there are any differences in the resulting pressure waves and energy values. This data will
provide RME will parallel research to the pressure wave analysis and verify common knowledge that a larger hole size will require a larger energy value to split the boulder. Therefore the test frame must be capable of interfacing with a number of different sized pipes and heights to compare this data.

4.4.6 Correlation of Data

The data collected from the experiments with the water column is to be correlated with experiments conducted in rocks. This will enable a direct comparison between the theoretical values conducted in the water column experiments and actual values from the rock. For this reason, the test frame must also be able to accommodate an experiment with actual boulders, to maintain consistency between the two scenarios.

4.4.7 Expected Outcomes

It is expected that this research project for RME and USQ will be designed, constructed and operational before the end of the 2007/08 financial year. This test frame will accurately map the pressure waves from an impact load traveling through an incompressible fluid such as water. Electrical components such as piezoelectric sensors and data loggers will map the pressure throughout the liquid to verify the results obtained from the ThunderBurst experiments conducted by RME in 2002. It is hoped to find out if the pressure waves will be constructive or destructive as it travels through the liquid and interferes with waves from consecutive blows.

From the completion of the test frame and successful testing of this project, it is expected that the same experiment is conducted with a basalt boulder from Toowoomba quarry, and an attempt will be made to map the pressure wave during operation.

4.5 Validation of ThunderBolt Test Results

RME were still concerned about knowing the exact energy levels expressed in the impact loading of the 1500J ThunderBolt hammer. This could be overcome by introducing a separate system to conduct similar testing with known energy about knowing the exact energy levels expressed in the impact loading of the 1500J ThunderBolt hammer. A secondary test rig would need to simulate the LRT delivery of 1500J per energy strike.
Chapter 4 - RME Research Project Requirements

The introduction of a second system for testing pressure waves in water will validate that the system works successfully, if both tests perform equally well. Comparing results of the pressure wave display of both systems would allow for the hydraulic power of the LRT to be tuned to the same frequency as the secondary system. This would mean the same energy is being used in both situations.

RME will require the production of conceptual designs for the foundation in developing the secondary frame. This is conducted in Chapter 9 of the document.

4.6 Conclusion

The ThunderBurst project is a concept developed by Russell Mineral Equipment to help eliminate many potentially life-threatening situations often seen in the mining industry following an underground blast. Original experimentation into the feasibility of the project saw the modification of a 1500 LRT used to strike a number of boulders that had been drilled and filled with water. It was determined the ThunderBurst project was viable for RME to continue development into this technology.

A test frame is required for the accurate and consistent positioning of the modified LRT in future experiments into the propagation of the pressure wave as it travels through the water within a steel tube. The changes in pressure that occur following a high energy impact on the water column is collected by electric sensors situated along the length of the steel tube and sent to a data logger. The data logger will send the collected information to a computer where software will graphically display these pressure changes in the form of a wave. A number of constraints have been placed on the design of the test frame by RME to ensure the experiments are conducted in the correct fashion.

Verification of the results produced by the ThunderBolt test rig will be achieved by comparing the data with results from a second test rig. This rig will be developed using a known energy value to allow for direct comparison with the ThunderBolt rig and verify the results achieved.

Chapter 5 begins the investigation of system concept designs for the ThunderBolt hammer test rig assembly.
Chapter 5

5.0 Conceptual Design of Experimental Test Frame

5.1 Introduction

It is extremely important in engineering design projects to begin with a strong foundation that will lead to the fulfilment the major objectives of the project. Once the objectives of the design are met, the design features are simplified where possible to optimise its efficiency and performance.

This chapter will bring forth potential conceptual designs of the ThunderBolt test frame using the modified LRT from 2002 experiments. It will begin by discussing the constraints set by Russell Mineral Equipment and provide some initial ideas for the design that will accomplish the expectations of RME. Different concepts will be brought forth as solutions and analyses of each of the conceptual designs using a decision matrix will be conducted. Finally, a selection of the design that will best achieve the required goals is detailed at the end of the process.

The conceptual design phase is the initial stage of any system design process. The evolution of the test frame design will be outlined in Chapter 6 of this dissertation.

5.2 Initial Constraints of Design

The design team at RME involved in the ThunderBurst project has imposed a number of restrictions on the initial design of the ThunderBurst test frame for the analysis of pressure wave profiles in water. Design constraints are required on the project to assure members of RME’s research and development team that the test frame will provide RME with the intended experiment into the resulting pressure waves after a 1500J impact load from the LRT. Years of experience working within the confines of RME facilities gives the design team an insight into where the system would be located, as well as how it will be transported, assembled and stored. Any constraints regarding these areas will be closely followed to ensure the correct and successful function of the system.
As discussed in Chapter 4, a requirement of the test frame is to mount the LRT vertically over the steel hollow cylinder. Only in this orientation will the hydraulic hammer successfully provide the energy to the water column required for the pressure wave analysis. Having the LRT vertically located will entail that the overall height of the structure will be an important aspect of the design. Due to the likelihood of having a tall structure, it is important the design follows AS1418.1-2002 Cranes, hoists & winches Part 1: General requirements, regarding the stability. This stability factor, \( F_s \), must be greater than 1.4 to be classed as stable for a crane in operation, and greater than 1.2 for a crane not operating but subject to wind loads. \( F_s \) is determined using Equation 5.1 below:

\[
F_s = \frac{\sum \text{minimum stability moment}}{\sum \text{maximum overturning moment due to loads and wind force}} > 1.4 \tag{5.1}
\]

This means the ratio of the moment trying to stabilise the structure and the moment trying to overturn the structure must be greater than a value of 1.4. Therefore in simplistic terms, stability refers to the ratio between the height and base frame floor contact area. The large height of the system will mean transportation of the overall test frame system must be suitable for both a forklift and overhead crane.

It is imperative the ThunderBurst experimental test frame be capable of disassembly and storage when not in use. Although the test frame is considered a permanently erect structure, there is the potential for the device to be treated as semi-permanent. The expanding nature of RME’s Mill Relining Machine (MRM) production gives rise to a fight over floor space at current facilities. Changing priorities may result in the dismantlement and storage of the experimental structure for the ThunderBurst project for a period of time. Ease of assembly and disassembly should be considered in the design of the test frame.

Another characteristic to be incorporated into the test frame design is the need for a modular design that can retrofit any possible energy delivery proposals created in future development. This will be difficult as it is impossible to predict the size, shape and function of the final device to be incorporated in the autonomous underground machine. This is expected to be overcome by shaping the attachment position and mounting arrangement non-specifically to the LRT and so it can easily be incorporated into any delivery system concocted by RME. The frame itself therefore must incorporate a degree of adjustability to help account for minor modifications that occur to the delivery device.
The design of the hollow steel cylinder required for repeatable experimentation on the water column is also necessary as an initial factor. The height of the water inside the tube is to be maintained at 1000mm. This height should provide enough volume for the pressure wave to fully develop down the pressure tube. A round number would also increase the ease of pressure and compressibility calculations expected from the results of the testing.

Finally, it is paramount the final design is safe for operator, data recorder and any observers of the project. The production of the design will not proceed unless all safety issues identified in the system have been appropriately removed.

5.3 Initial Design Considerations and Theory

The vertical gas gun located at the Water Laboratory in USQ (Chapter 3) is used as an inspiration for the test frame. The vertical gas gun uses pneumatic power to fire a slug down a cylindrical tube onto a column of water in a separate tube beneath the structure. It is a large welded steel frame fixed in place with a heavy base and supports extending from the frame to an adjacent wall. Following the investigation of the gas gun, it is hoped to also incorporate the water column and pressure tube as part of the overall test frame structure. This will make transportation of the assembly easier if it is connected together as a single unit. Having the water column fixed relative to the LRT will increase the accuracy in the experimental results especially if the frame is moved around to a number of different locations.

The first design is shown in Figure 6.1 below. This design incorporates the use of the modified 1500J LRT. The hammer is positioned vertically above the water column and uses hydraulic power to impart the high energy strikes to the top of the water column. The LRT hammer will be tuned to expend 1500J of energy per strike and can fire every three seconds delivering repetitive, accurate energy blows.

The base of the frame that holds the LRT hammer is designed with the notion of using a forklift to transport the device to its given destination. The water column is bolted to the top of the frame and allows for the unit to be easily maneuvered as a single item rather than separate pieces.
Another starting point for the test frame design was to study how the previous rock-splitting experiments which were conducted in 2002 and look to replicate the hanging of the LRT in the same fashion. Slinging the rock-splitter vertically from a forklift was considered too dangerous for future ThunderBurst experiments and thus, as outlined in Chapter 4, was the reason for developing a permanent structure to accurately mount the LRT above the water. Using the LRT spring damper to reduce the recoil after firing will provide a point to which the rock-splitter can be suspended vertically the energy device from a common location on the frame.

It is hoped to keep the structure as simple as possible. The frame structure is intended to be a welded steel structure to try to keep common fabrication and welding procedures to RME. To keep the machining and fabrication of the test frame as quick and easy as possible, the design will incorporate a number of Rectangular Hollow Sections (RHS) and Flat Mild Steel (FMS) extruded pieces. RHS and FMS are purchased in long lengths and are cut to the correct size once in the factory. Using these materials, there is no need for special shapes to be profile cut out of large steel sheets. This will greatly reduce the time and cost of the fabrication in the project.

Three-dimensional adjustment in the test frame is needed to account for the possibility of design changes to the 2002 rock-splitter. Incorporating height adjustment in the design of the system would be easily achieved through manually varying the cable length using a block and tackle pulley arrangement. Altering the position of the hydraulic hammer in the two lateral dimensions would
prove a more difficult design task. Input from RME design engineers was received to broaden perspectives on possible adjustment techniques. Some of the techniques offered to reposition the moil of the rock-splitter include the use of roller bearings, pneumatic/hydraulic cylinders, electric motors, magnetic forces and manually moving and pinning the device in its final location.

All these ideas were used in the construction of one or more of the conceptual designs shown in section 5.5.

5.4 Modelling Software

The conceptual designs for the ThunderBurst experimental test frame assembly need to be visually displayed to convey the features of each design. Detail drawings provide a two-dimensional display of the design, usually to allow for a physical print out of the drawing for use in manufacture. Three-dimensional modelling software allows the operator to see the final product on the screen in all three dimensions. It also has the capacity to move and rotate the selected component in any fashion necessary to develop the design of the part.

SolidWorks 2007 (currently being used at RME) provides the user the capability of simulating any given part and provide a three-dimensional representation on the computer monitor using parametric relationships. Like most parametric modelling software, this package aids in the design process using three separate design steps. MEC2304 Mechanical Drafting (USQ, 2004) lists the basic steps in computer-aided design and drafting as:

- The creation of individual components (or parts) of the design,
- Placing the parts together in an assembly showing the relative positions of those parts, and
- Creating mechanical drawings based on the information in the parts and the assembly.

5.5 Initial Designs

A number of initial concepts for the test frame were looked into as part of the design process. All these concepts would achieve the given requirements set down by RME. However, only three conceptual designs were included as possible design solutions for the ThunderBolt test frame using the modified 1500J LRT hammer as the method of energy transfer. These three designs are detailed in sections 5.5.1 – 5.5.3 below.
One of the conceptual designs proposed in this section will form the foundation of future development of the permanent test frame. The selection of a conceptual design is the first stage in the design evolution of the frame. Further development will continue to refine the project to the most efficient and cost effective system. This evolution is shown in Chapter 6.

**5.5.1 Conceptual Design #1**

This section describes the first of three conceptual designs for the ThunderBurst experimental test frame. It is a very simplistic design with a small base for easy forklift transport, shown in Figure 5.2. The tynes of the forklift will be able to lift the structure using the hollow section of RHS running from front to back as a lifting point. Outriggers on both sides of the lower frame are included in an attempt to widening the base and to prevent tipping the structure over. Lifting lugs are also included on the lower frame. It is expected that a chain suspended from the overhead crane will be slung on each side of the structure for balance during lifting. Five small feet keep the frame up off the ground.

Manually pulling on a cable running through a block and tackle arrangement will lift the LRT into the given position for operation. A hook welded on the bottom face of the upper frame connects the block and tackle used for lifting, to the frame assembly. The rock-splitter energy source has the recoilless spring damper attachment suspended from a block and tackle beneath the upper frame.

The removable upper section of the frame makes for easy storage and gives extra adjustment for the height. The overhead support runs inside the RHS post of the lower frame and can telescope to the correct height during the set up of the assembly.

The water column sub assembly is located on the base of the lower frame. The base plate of the assembly will sit over the pins extending from the top of the lower frame and held in place with the use of lynch pins. PCB sensors line vertically along the steel cylinder and record the pressure waves following an impact strike from the hydraulic hammer.
The major advantage of Conceptual Design #1 is the simplistic design. It is easy to fabricate and easy to assemble. Little cost of material will be required as there is nothing flash or fancy in the design that would warrant special machining or fabrication procedures. Few individual pieces in all the components would also mean the volume of material purchased would be lower.

The telescoping upper frame provides flexibility in the adjustment of the frame height. This variable height will allow the test system to vary depending on the space available at RME and the length of steel cable available for use in the block and tackle assembly. Both forklift and crane transportation options are both easily accessible through the numerous lifting points on the lower frame.

A number of potential problems are quickly spotted in the system design. This is especially apparent with the issue of lifting the 550kg LRT off-centre gravitational load. This arrangement
using a block and tackle to manually lift the hammer above the water column looks unnecessarily awkward.

Along with the LRT lifting issues, the frame is very high with a small base. This creates problems with stability of the structure addressed in AS1418.1-2002. Conceptual Design #1 therefore has a relatively high potential of overturning during loading. No adjustment in the x-y plane means the design is reliant on the accurate assembly of components to provide the vertical alignment between the moil of the rock splitter and the pressure tube of the water column assembly.

**5.5.2 Conceptual Design #2**

The second design incorporates an A-Frame structure with a removable frame (Figure 5.3), making for easy storage. This design incorporates an overhead I-beam that provides a large contact area for the LRT to move along. This I-beam runs along the centre axis of the frame. The reinforcing arms of the structure are fastened between the lower frame and the overhead I-beam. The side supports are removable to reduce the overall size of the test frame during storage.

It has a wider base for increased stability. The base of the test frame is very large in comparison to the area filled by the water column base. RHS steel sections provide the strength for the out lying portions of the frame to the centre where the energy of the impact loads are transferred through the water column. The through hollow sections running through the centre of the frame can be doubled as the lifting points of the frame. The RHS outriggers act to widen the base structure and increase the stability of the system while in operation.

The design incorporates a block and tackle arrangement for lifting LRT. Similarly to the first design, the block and tackle arrangement will be manually operated. By pulling down on the cable, the LRT will be able to be manoeuvred into position above the steel pressure tube. A roller carriage is included to make adjustment between the device and the water column easy. A roller carriage will slide along atop the I-beam of the A-frame to any position required. The block and tackle is attached to the bottom face of the carriage and manually controls the location of the hydraulic hammer in a vertical direction.
Chapter 5 - Conceptual Design of Experimental Test Frame

Figure 5.3: Test frame Conceptual Design #2 - Isometric view

Conceptual Design #2 displays a number of features that will be advantageous to the mounting of the rock-splitter appropriately over the hollow steel cylinder. It is a stable, symmetrical structure that theoretically should distribute the loads of the system evenly through the frame. The addition of the overhead I-beam provides adjustment along the centre axis of the system. The top of the I-beam provides a large spacious surface over the frame for the easy attachment and lifting with a crane. Another benefit was inherently found in the design. The long supporting arms of the overhead beam provide a physical barrier between the operator and the rock-splitter. Even if only on a sub-conscious level, the operator will feel as though the system is caged and feel safer than if it was open to environment.

However this design has also has a few disadvantages that may prevent it from being selected as the foundation for future test frame development. The price of fabricating a large frame and a large number of individual components will be high. The assembly process of the concept design would be quite methodical. Constructing the test frame will need to follow a set procedure for the correct arrangement to be produced. The carriage assembly will have a number of small components that would need to be completed and attached to the overhead beam before the support arms or rock-
splitter can be included. The large frame is bulky in size and there is a chance it might not fit in the space restrictions currently being experienced at RME.

5.5.3 Conceptual Design #3

A wide base is a feature of Conceptual Design #3 to increase the stability of the frame. A two piece boom system uses hydraulics and its own hydraulic power pack to adjust height and position of LRT relative to the water column. The base is made of a centre section to provide a connection point to fix the water column assembly relative to the LRT. An outrigger is welded to each side of the centre portion of the frame to widen the base and prevent the system falling over when lifting the hammer onto the pressure tube.

The two stage boom is offset from the centre of the frame incorporating the use of hydraulic cylinders to move the rock-splitter anywhere in a two-dimensional plane. One cylinder will vary the angle between the top of the base frame and the lower boom arm. The second cylinder will change the angle of the upper and lower booms. The final position of the block and tackle connection and therefore the energy delivery device is dependent on the combination of these two cylinders.

Pins run through each boom to provide an attachment point for the hydraulic cylinders and acts as a pivot which the cylinder and booms can rotate about. The long pins are retained in a position with lynch pins. Reinforcement is added to the outside of the RHS booms in areas around the pin location where stress through the structure is likely to be high.

A swivelling wrist at base of arm allows for 360° movement manually operated using handles on lower arm of boom. The wrist consists of a flat plate with mounting lugs for the lower boom and lower cylinder. A bush is added around a cylindrical post sitting above the base frame before the wrist is lowered onto the post.

The addition of hydraulic cylinders to the system brings a few disadvantages to Conceptual Design #3. The LRT hydraulic power source may not be able to cope with the added need to handle the pressure required to run two extra hydraulic cylinders. For this reason, the manufacture of a separate hydraulic power pack is required. The cost of constructing the hydraulic tank, and the addition of a submersible pump, electric motor and extra hydraulic fittings could potentially blow the price of the system out of the price range for the research project.
The remote controlled two-piece boom assembly yields a safety risk for the operator. There is a chance the booms can be operated without the knowledge of those surrounding the experiment, causing injury to personnel or property. Another aspect of the system that could potentially cause problems to the selection of Conceptual Design #3 is the lack of support to keep the LRT hanging vertically. The results of the experiment may not be totally accurate if the moil of the LRT is not fired in alignment with the water column.

There are however, a range of advantages in the third concept design. The large base breeds confidence in the safety and stability of the structure during firing of the hydraulic hammer. The adjustment in height and location of the rock-splitter moil through the cylinders and the swivelling wrist increases the functionality of the system. This system will also give a high degree of accuracy through the small increments possible using hydraulics.
Chapter 5 - Conceptual Design of Experimental Test Frame

5.6 Decision Matrix Analysis

A total of three conceptual designs were developed for ThunderBurst experimental test frame in the brainstorming phase of the design. The decision matrix is required to review a number of critical aspects of the design and select the best conceptual design from a range of potential designs. The analysis of the concepts was conducted using seven separate criteria. Sections 5.6.1 – 5.6.7 provides an explanation of the criteria. A score varying between zero and three is marked against each design depending on how well it will relate to that design criteria.

5.6.1 Stability

The frame must be stable according to AS1418.1-2002. This basically means that the ratio of height to base area must be satisfied to ensure the structure is deemed safe. The dynamic loading imparted on the column may result in the LRT bouncing out of the pressure tube. If this happens, the tension in the spring damper will loosen, leaving the LRT assembly free to swing. This swinging weight may be enough in itself to overbalance the frame and cause damage to the component equipment. The larger and heavier that the base of the frame is the more stable the structure is considered to be.

5.6.2 Adjustability

The test frame must incorporate adjustability to account for errors in design, production or assembly. It is important to make the frame adjustable in all three dimensions to account for the possibility of any error in the design. A solid and safe method of lifting or lowering the LRT into its final position must be included in the test frame system. A large amount of variation between the alignment of the impact moil and the water column in the pressure tube is also to allow for the possibility of future design changes to the delivery system.

5.6.3 Practicality

Practicality of the test frame is also a major design feature that requires analysis using the design matrix. This section includes a general overview of the practicality incorporated in the entire assembly. More specific areas such as the practicality transporting the frame; and how easily the system is assembled and disassembled are detailed in further categories. Space requirements including base size, frame height and overall physical dimensions fall under this heading, as well as
5.6.4 Cost

The cost of the test frame assembly is paramount in the initial design phase. The cost of a research and development project could be the difference between a company undertaking the project or not. The potential cost includes all aspects of the project. Cost of purchasing stock items, material costs, fabrication costs and the labour required to assemble the design are all considered in the analysis.

5.6.5 Safety

Many dangers exist in the operation of a hydraulic hammer suspended vertically over a steel pressure tube filled with expensive electrical equipment. These dangers have the potential to cause serious injury to operators, employees and on-lookers, as well as serious damage to RME property. The safety features in each conceptual design to prevent harm to people and property are analysed and given a rating using the decision matrix.

5.6.6 Ease of Assembly/Disassembly

It is a requirement of the test frame to be disassembled and placed in storage on a semi-permanent basis when not in use. How easily this happens is dependant on the size, weight and connection points of the components in the assembly. The number of components or sub assemblies in the system required to be disassembled will also influence the score given to the conceptual design in this category.

5.6.7 Manoeuvrability

The final aspect of the decision matrix analysis to be considered is the level of freedom in the movement of the frame between various locations around the facility. Space restrictions may force RME to vary the testing location within the facility and even dismantle the structure at times. Lifting point and designated contact areas are required in the design to ease the transportation and assembly process. Forklift manoeuvrability is a must for all conceptual designs as this will be the main form of positioning and relocation of both individual components and the overall structure. It is expected that the structure will be housed and tested undercover, therefore the use of an overhead crane can also be expected.
The conceptual designs for the ThunderBurst permanent test frame are all judged using the seven points previously discussed using a decision matrix. The design matrix helps the engineer to select the optimum design by showing how well each design compares to the others. The rating system used in the decision matrix analysis calculates the optimum design for the selected parameters by tabulating the results. The designs were given a rating for each of the seven criteria and totals displayed at the bottom of each column. The point system is shown as follows:

3: Good
2: Satisfactory
1: Poor
0: Very Poor

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<tr>
<th>Table 5.1: Decision Matrix</th>
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<tr>
<td>1. Stability</td>
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<td>2. Adjustability</td>
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<td>3. Practicality</td>
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<td>5. Safety</td>
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<td>6. Ease of Assembly</td>
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<td>7. Manoeuvrability</td>
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<td>Total</td>
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The decision matrix clearly shows Conceptual Design #2 to be the best style system to use in the experimentation of the pressure wave propagation in water due to an impact load created by the modified ThunderBolt hammer. Design #2 has a large base for stability and an overhead I-beam for adjusting the location of the LRT relative to the fixed water column assembly.

Design #2 scored consistently across all the decision matrix facets. These reasons show why the stability of the frame in Design #2 scored higher in this area relative to the other two designs. The large structural base and large water column base gives a lot of stability to the system. The A-frame design of the test frame and the overhead I-beam also concentrates the gravitational loads in the middle of the structure. This means the centre of gravity (COG) of the assembly is in the centre of
the base frame, meaning it would be extremely difficult to tip over when firing of the hammer during testing.

Although the base frame is large compared to Design #1, it still has the ability to be safely moved by a forklift, provided the COG is maintained between the forklift tynes and not offset too far forward from the front of the vehicle. Lifting lugs atop the I-beam provide the operator with the extra option to transport the structure. This extra mobility option gave Design #2 the highest available scoring points in the matrix.

The final advantage of Design #2 is its level of adjustability. Not only will the block and tackle lift the LRT to the correct height, the horizontal I-beam running along the top of the A-frame provides for horizontal placement as well. This will also be useful in assembly or disassembly or to move the hammer out of the way of the water column to conduct maintenance.

Although not scoring poorly in the other decision matrix criteria, issues such as assembly and practicality were of a concern. The assembly of the structure could be frustrating and uncomfortable for the user due to the number of small pieces comprising of the overhead carriage. The process of connecting all four supports of the A-frame to both the base framework and the I-beam could potentially be a simplistic and tedious. The potential cost to cut and fabricate the required members of the frame will be relatively large. Since there are a high number of individual components, the cost in materials and machining time to complete the production of these components will also be high. Design #2 also scored poorly in the area of practicality. This is due to the large A-frame supports preventing the operator from getting too close to the water column. It would also be difficult to raise and lower the LRT into the correct position by hand.

The simple approach to the design of the first proposed design allowed it to score highly in the area of cost manoeuvrability and in the case of assembly or disassembly of the structure. It was also considered to be the safest of the three designs. The simple and effective block and tackle arrangement and minimal use of moving parts meant there would be limited chance of human injury or fatality when the system is in operation. The stability of the frame is not considered in this scoring area and thus, any safety concerns relating to the overbalancing of the framework is ignored.

Design #1 would be quite unstable during operation and the small number of members in the system gives little adjustment to the overall system. Because of this, the design did score poorly in
the areas. The stability of the design is a major concern. The high frame, with a small base means there is a chance the entire structure could topple over during operation, causing damage to property and/or potentially injuries to staff.

Design #3 was the most flexible of the three concepts in varying the location of the rock-splitting device. The introduction of hydraulic cylinders meant the adjustment of the system would score highly, however it did come with a number of down points in the decision matrix analysis. Not only do the cylinders increase the cost of the overall structure but also make the system more complicated to assemble and disassemble. The addition of an extra hydraulic power pack to source the power for the cylinders would also increase the difficulty of transporting the entire unit at any given time. This is mainly due to the hydraulic hose connections needing to remain connected to power the cylinders. Having the cylinders acting as a remote control the frame would decrease the safety issues of the experiment by removing the operator from needing to be close to the system during this part of the setup. It could be possible, however for an operator or a spectator to be injured by the booms if they were in range of the support structure while the LRT is raised into position or the base swivelled around remotely.

5.7 RME Considerations

RME confirmed all designs would pass, or would pass with minor design modifications, the project requirements for the ThunderBurst experimental test frame as specified in Section 5.2 of the report.

Although Conceptual Design #2 was the selected design using the decision matrix analysis, RME expressed a number of potential flaws in the system. One of these concerns revolved around the size of the base frame. The large frame provides stability to the structure according to AS1418.1-2002 but may be too large for the available space in the undercover facility at RME. A reduction in the frame size and therefore height is needed to maintain the stability factor, $F_s$, greater than 1.4 (Section 5.2). A greater amount of adjustment is also needed in the system to allow for future development of the rock-splitter energy delivery.

It was noticed by the design team that first design is the simplest and most efficient concept of the three suggestions. Because of its simplistic overall configuration, there is the most potential for the development and construction of the components to be completed in the timeframe of the research project. The decision matrix showed this design would have scored higher than the other concepts
Chapter 5 - Conceptual Design of Experimental Test Frame

if the base frame of the structure incorporated a larger and more stable base, and if greater lateral adjustment between the hammer and water column was developed.

It was decided the time and work required developing the first conceptual design was less than that of Conceptual Design #2. The design team at RME recommended the use of Conceptual Design #1 for this reason.

5.8 Chosen Conceptual Design

The sponsorship of RME into this project means the opinions expressed by the design team are highly valued. For this reason, RME's recommendation to select Conceptual Design #1 as the foundation for the future development of the test frame was followed. This would mean the final results determined by the decision matrix are disregarded. This selection was based on the simplistic arrangement of the required components and the projection of a short development and production time on the overall assembly.

Conceptual Design #1 is an uncomplicated arrangement of suspending the modified ThunderBolt from an overhanging frame. The test frame structure separates into a lower frame and an upper frame. The lower frame provides a base for the system and mounts the steel cylinder and water column assembly in position. The upper frame encompasses the hydraulic hammer and a manually driven block and tackle assembly. Transportation of the frame can be achieved using a forklift or an overhead crane.

5.9 Potential Design Implications

The disadvantages of Conceptual Design #1 have been discussed previously in Section 5.5.1 and analysed using the decision matrix (Section 5.6). The inadequacies of the selected concept need to be addressed during the design process to prevent trouble occurring during testing of the pressure waves.

It is important that the issue of increasing stability to ensure the stability factor of the structure is above 1.4 according to AS1418.1-2002 Clause 6.2. The best method of changing the overall dimensions of the test frame design will require some thought to maintain the easy transportation of
the test frame between various locations around RME's facilities. The frame manoeuvrability was a major feature of Conceptual Design #1 and is expected to play an important role in the development of the frame.

Adding lateral adjustment to the assembly without jeopardizing the simplicity of the system will be a major design challenge. The addition of many components to the system will increase the design and production time of the assembly that was saved with the selection of Conceptual Design #1 over Design #2.

The safety issues regarding the chance of the hammer bouncing out of the column after an impact load also need to be addressed. A better method of supporting the LRT is required to prevent the hammer from swinging from the block and tackle and firing out of alignment. A support network surrounding the hammer will also double as a method of maintaining a safe working environment if the hammer moil happens to jump from the steel pressure tube during firing.

5.10 Conclusion

This chapter has introduced conceptual designs for the experimental test frame that will be used in the analysis of the pressure waves through an incompressible fluid. Three concept designs for the ThunderBolt test frame were developed in accordance with constraints imposed from RME. It was imperative the concepts followed these restrictions to ensure the designs will produce acceptable results for future comparison in the research project.

An overhanging frame design was incorporated in Conceptual Design #1 to suspend the modified LRT. It contains a simple suspension arrangement and is vertically adjustable with a block and tackle system. This design was selected as the foundation for the ThunderBolt test frame, although the decision matrix suggested the A-frame style of Conceptual Design #2 would be the optimum design. The selection using the decision matrix was disregarded after discussions with RME, as Conceptual Design #1 has the most potential for improvement. These improvements would take the rating of the design above those calculated for Conceptual Design #2 or Conceptual Design #3 using the decision matrix.

The improvement of the design is also discussed. Safety issues regarding stability of the frame and the alignment of the hammer must be addressed in the future development of the test system.
Incorporating lateral adjustability is another important feature that needs to be reviewed. The ability for this ThunderBolt test frame design to retrofit to new methods of energy transfer is critical to save time and money in future development.

The following chapter will investigate the development of Conceptual Design #1 from the original concept to the final design solution. This is achieved using a series of design iterations to evolve the solution into the most efficient solution for the ThunderBolt test rig.
Chapter 6

6.0 Test Frame Design Process

6.1 Introduction

Every design must undergo a series of design iterations to ultimately provide the most effective and efficient solution to the given problem.

This chapter investigates the design evolution of the ThunderBurst experiment test frame for pressure wave analysis in water. The design process is tracked from the conceptual design selected in Chapter 5 through to the final solution. Initial design thoughts are included to provide background information to the requirements of cranes and hoisting equipment. The final design is capable of addressing all the constraints proposed by RME in Chapter 4 of the report.

The process and reasoning behind the design changes between the design iterations is the focus of this section of the report. Individual items in each iteration of the design are not fully detailed in this chapter.

6.2 Initial Design Thoughts

As shown in the decision matrix analysis of possible permanently erected test frames for the ThunderBurst project (Chapter 5), Conceptual design #1 was selected as the most appropriate foundation for the system. It has been suggested in the design matrix analysis of Conceptual Design #1 for the stability of the structure to be increased (Section 7.5). An increase in the stability needs to occur in both the suspension of the rock-splitter and the base frame.

Section 5.2 briefly detailed AS1418.1-2002 Cranes, hoists & winches Part 1: General requirements, including the general requirements for stability of cranes, hoists and winches. The Australian standard specifies the constraint for the stability of a crane shown in Equation 5.1. This equation
Chapter 6 – Test Frame Design Process

regulates the ratio between the minimum stabilising moment and the maximum overturning moment as per Clause 6.2. The margin of stability must be kept above 1.4 for the structure to be classed as stable.

Further investigation was conducted into the stability of the test frame system of Conceptual Design #1. Clause 4.5.2.1 investigates the addition of a dead load dynamic factor to the weight of the system. This clause is applied to both the moment that overturning of the system and the moment that prevents overturns the system. A dynamic factor is determined for an overturning moment calculation according to Table 4.5.2.1. The Conceptual Design #1 is made from sprung steel rails continuously welded together. The hoist will lift the ThunderBolt hammer at a velocity below 1m/s. From Table 4.5.2.1, the factor is therefore set at $\Phi_1 = 1.1$. Vibration of the structure is likely to destabilise the frame following a strike. Therefore according to Clause 4.5.2, the dynamic factor for the stabilising moment calculation is $\Phi_1 = 0.9$.

Apart from the off-centre gravitational loading of the test frame from the rock-splitter, additional lateral forces must be incorporated into the calculation of the frame stability. AS1418.1-2002 Clause 4.7.2 states a lateral load of at least 4% of the vertical load must be applied to the system to account for the off-set nature of the vertical loading on the hoist. No wind forces are expected on the frame as the experiments will be conducted indoors. This is confirmed as per Clause 4.6.2.

Inertial loads are inherent in the design when the ThunderBurst rock-splitter assembly is moved in the test frame system. The large weight of the rock-splitter will exert inertial loads on the frame when the device to stops and starts its lifting motion. Clause 4.7.3 explains the determination of the load factor needed for the design. The calculation of the inertial load factor is related to the Equation 9.1 from Clause 4.5.3.3.

$$\Phi_5 = 0.5 \times (1 + \Phi_2)$$  \hspace{1cm} (6.1)

where $\Phi_2$ is calculated from Clause 4.5.3.3.

$\Phi_2$ is referred to as the hoisted load dynamic factor. This factor is dependent on the hoisting velocity. It is unclear at present how fast the weight will be lifted, therefore from Table 4.5.3.3 (B), the worst case scenario is assumed for inclusion into the design to ensure $\Phi_2$ will be covered in any conceptual design. This assumption leads to $\Phi_2 = 2.2$. 

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The assumed value of $\Phi_2$ therefore gives a load factor of $\Phi_5 = 1.6$ (Clause 4.7.3). This means an additional value of 1.6 times the static load will be incorporated in the analysis of test frame components that undergo any form of dynamic loading due to the movement of the ThunderBurst energy delivery system.

Basic calculations were conducted in an attempt to optimise the support post SHS or RHS size required for the expected gravitational loading of rock-splitter. Calculations of deflection and stress were produced according to the lateral and vertical forces of the system. The results were produced in the form of a Microsoft Excel spreadsheet. The spreadsheets and worked calculations are included in Appendix B of the report.

The deflection is deemed to be more of a concern than the stress levels in the RHS of the frame. Deflection for the RHS support post is set at a maximum acceptable value of 5-10mm under load. The design stress of the RHS is determined to be 60% of the material grade. Grade 350 material is common for hollow extruded sections. This means the maximum design stress of the RHS support post is set at 210MPa. A safety factor of 1.6 is added to the gravitational load from the mass of the rock-splitter to account for any errors in the system.

An initial investigation of the data produced by the Microsoft Excel spreadsheet shows the RHS sizes that fulfil the design requirements. The smallest RHS that met both the deflection and stress criteria was selected for the RHS of the telescoping upper frame. A square hollow section, 89x89x6mm, is used as the extruded inside post of the frame. This therefore meant the succeeding 100x100x4mm SHS size will be selected for the support post of the lower frame.

Further discussion of potential problems associated with the selection of Conceptual Design #1 was given in Section 7.8. It was outlined that a lack of support surrounding the hydraulic hammer during operation may influence the alignment of the hammer with the water column. Safety concerns are also frivolent if the hammer were to become detached from its housing in the pressure tube.

These concerns could be designed out of the system with the introduction of slide carriages to stabilise the LRT during firing. This would ease the minds of the design team and solve the issue of potentially having the LRT swinging freely if the hammer moil became loose from the water column. A carriage is best described as a device which carries, cradles or supports an item from one destination to another. In this instance, the carriage will carry the LRT to a desirable location.
A carriage system was used in Conceptual Design #2 to adjust the location of the LRT along an overhead I-beam. A similar system could be incorporated into the design of the ThunderBurst experimental test frame by suspending the I-beam vertically. The carriage would be used to alter the vertical location of the hydraulic hammer relative to the water column assembly.

6.3 Design Process

The design process is an important aspect in developing every design to an optimum solution. If performed correctly, the final design will prove the most effective and efficient solution to any given problem. The solution may undergo a series of design changes depending on time, cost, size or equipment restrictions to present the best available solution for a given problem.

The ThunderBurst experimental test frame is tracked from Conceptual Design #1 (Chapter 5) through to the final solution presented to RME’s design team as the most appropriate method of permanently mounting a modified LRT that applies an axial impact load to a vertical water column. A number of different designs were brought forward during this process. Previous iterations were analysed and evolved into superior designs. A complete overhaul of the overall system to maintain the simplicity of the test frame also occurs from time to time.

The design process for every test frame iteration is outlined and reasons behind the design changes are also specified.

6.4 Design Iteration #1

Design Iteration #1 looked to enhance the features of the selected conceptual design without greatly complicating the system. The design evolution of the system occurred by individually tweaking the design of different sections.

The base of the ThunderBurst test frame was also given a design makeover. The decision matrix analysis on Conceptual Design #1 (Chapter 5) required a redesign to incorporate a larger base and increase the stability of the structure. Longer steel sections were specified and extra RHS pieces
were incorporated into the design to help achieve this goal. The main support post of the structure was moved toward the centre of the base frame and given reinforcement to help prevent beam deflection and reduce the moment incurred under load.

The lower frame still needed to be accessible by forklift. The lifting points for the forklift were widened to its maximum span in an attempt to spread the supports of the frame as far as possible. The supporting framework of the water column was removed and outriggers were positioned a suitable distance in front, and to the side of the water column to balance the gravitational load of the modified LRT.

The separate overhead frame needed a vast amount of design change to include the use of carriages in an effort to stabilise the LRT during firing. Two I-beams are suspended from the upper frame to provide a flat surface slide for the carriage to run along to its desired location. One slide is located on each side of the LRT to balance the weight needed to be raised. This meant the overhanging structure needs to be longer and larger than the conceptual design to allow for the steel slides to hang down in an appropriate position for operation. Extra reinforcing underneath the L-shaped join of the upper frame is required to handle the extra weight of the carriage slides cantilevered from the main support post.

It was important to still keep the upper frame separate from the lower frame to simplify the assembly and disassembly of the system.

The relationship between the lower test frame and water column assembly is changed. The natural elastic deformation of the RHS supporting the base plate of the water column assembly has the potential to absorb a portion of the impact load. This could mean the water column could experience a loss of energy during the rebound of the wave on the base plate and therefore would not be a realistic demonstration of normal operation. The water column assembly is bolted to the floor to ensure the full energy from the axial load delivered by the rock-splitter is transferred through the water. The act of bolting the case plate directly to the concrete floor will avert the potential problems.

The carriage uses roller bearings as wheels for smooth positioning along slide. A solid steel bar runs from both carriages through the spring damper of the LRT providing a solid connection between to two assemblies. The LRT spring damper, discussed in Chapter 2, enhances the stability of a LRT when suspended vertically by reducing the recoil of the hammer following a strike. A
welded lug located at the top of the steel bar gives an attachment point for the lower half of the block and tackle system to connect to the LRT. This therefore allows the whole assembly to be raised or lowered to the appropriate height along the slide.

A network of pulleys is used to guide the steel cable through the structure. The steel cable lifts the LRT into position by running through a block and tackle pulley arrangement. The block and tackle system is an extremely practical device for manually lifting heavy items commonly used in the automotive and shipping industries. The assortment of cable sheaves used in the pulley systems needed to be run along the inside of the lower and upper frame.

Design Iteration #1 is shown in Figure 6.1. The isometric view (Figure 6.1) clearly displays the individual components of the system. This view displays the lack of room available for the steel cable to thread through the carriage reinforcement, and the need for greater spacing between the carriage slides for the block and tackle.

![Figure 6.1: ThunderBurst test frame Design Iteration #1 – Isometric view](image)

A problem was found in assembling the block and tackle system between the carriage slides. There is minimal room for the block and tackle to be suspended vertically above the spring damper and lifting lug. Tight clearances also exist for the steel cable through the reinforcement of the carriage
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slides. This arrangement can be simplified through redesign of the overhead frame.

6.5 Design Iteration #2

The second design iteration only looked at changing the upper frame arrangement to rectify the problems with fitting the block and tackle and pulley system in the correct location between the carriage slides. This was achieved by rotating the slides 90° and locating them outwardly from the upper frame. This means extra reinforcing is required to dissipate the stresses along the supporting cross member at the front of the upper frame.

An extra pulley is now able to be located between the two slides and directly above the LRT. The sheave will provide a point to hold the system vertical, thus keeping the LRT stable. As the carriages have been rotated 90°, the LRT must also rotate the same amount to maintain the relative position with the spring damper.

An isometric view of Design Iteration #2 is displayed in Figure 6.2. The extra reinforcement on the overhead frame and the new arrangement of carriage slides is clearly shown in the picture.

![Figure 6.2: ThunderBurst test frame Design Iteration #2 – Isometric view](image-url)
6.6 Design Iteration #3

Further modification to the upper frame was revealed in Design Iteration #3, shown in Figure 6.3. This design looks to rectify the issue of instability of the LRT during firing by removing the recoilless spring damper from the system and attaching the rock-splitter assembly directly to the carriage.

![Figure 6.3: ThunderBurst test frame Design Iteration #3 – Isometric view](image)

The removal of the spring damper allows the overall height of the frame to be reduced. The carriage slides were lengthened to maintain the same displacement of the LRT relative to the top of the pressure tube. A longer carriage slide means more weight is suspended from the overhanging frame and increased reinforcement is required to stiffen the structure and prevent permanent distortion. A block and tackle would hang below the final sheave of the pulley system and attach to the rear of the hammer to vary the height of the moil.

However, this arrangement still did not suitably address the issue of stabilising the hammer during firing. The two pins extended from the carriage to the side plate of the modified 1500J
ThunderBolt do not fully restrain the motion of the hammer in all three directions. The device still has the potential to rotate around the axis of the pins during an impact. Further design is required to rectify this problem.

### 6.7 Design Iteration #4

Design iteration #4 was the first iteration that had a major revamp to the system. A new concept was investigated. The overhead frame was removed and replaced with a single carriage slide running along the centre axis of the frame. The structure remained in two segments – a lower frame and an upper frame. The lower frame remained similar to the previous iteration, with an end cap added to the top of the support post. The upper frame is reduced to a vertical fabricated slide welded to a RHS located horizontally from the rear of the slide. The upper frame is lowered over the support post of the lower frame and held in position with a number of removable pins. Figure 6.4 shows an isometric view of the improved design.

![Figure 6.4: ThunderBurst test frame Design Iteration #4 – Isometric view](image)

Atop the slide finds a bolt-on plate incorporating an overhead pulley. The sheave is positioned directly above the lifting point of the carriage. Incorporating a cap to the top of the structure opens the slide for the carriage assembly to be lowered down into position on the frame allowing for quick
and easy attachment. A pneumatic winch is located at the rear of the upper frame to minimise the length of cable required. A visual representation of the upper section of the assembly is shown in Figure 6.5.

![Figure 6.5: Upper frame holding ThunderBurst rock-splitter in raised configuration](image)

A series of chemset bolts fasten the frame down to the floor. This will increase the stability of the system, eliminating the problems previously regarding AS1418.1-2002 regulations on the structure stability. Chemset bolts are used to provide a thread from a concrete base. A hole is drilled into a concrete slab and filled with chemical foam provided. The thread is positioned to an appropriate length for the given operation. Once the foam dries, it hardens and increases the strength to approximately the value of the surrounding concrete. This chemical residue holds the bolt firmly in position with an appropriate amount of thread protruding above the base height.

A single slide carriage is incorporated into the system, encasing the front of the hydraulic hammer and engages the LRT via a set of removable pins. Holding the hammer stable in four places fully confines the motion in lateral directions. The internal components of the LRT carriage are displayed in Figure 6.6. Four roller bearings are located on each face of the slide to limit the motion of the LRT due to an induced moment from the offset gravitational loading. The roller bearings act as wheels to vary the position of the hammer along the face. A spring system is included to maintain a constant centre position along the frame and prevent the carriage sliding from side to side during operation.
Two pins are inserted through each side of the hammer and carriage assemblies to hold the system stable. This minimises the effect of shock loading on the LRT from the recoil of the water column. It will also hold the carriage in place and help keep consistent vertical alignment between the rock-splitter moil and the steel pressure tube. Increasing the number of constraint points on the hammer will increase the rigidity of the system relative to the surrounding components. This added stability will ensure the accuracy of multiple tests at the same depth within the water column.

The block and tackle arrangement is removed from the system and replaced with an air winch. An air winch requires a pneumatic power source to lift the LRT and carriage to the required height along the slide. A steel cable is fed by the air winch and runs along a network of pulleys over the slide. The sheave in the pulley assembly needs to have a minimum radius six times the diameter of the cable. The air winch detailed had to compromise on size and power. The winch needs to be strong enough to lift a minimum of 600kg, and yet be as light as possible to prevent cantilever beam deflection on the upper frame.

The design team looked at incorporating the interaction with a rock into the system for future development of the ThunderBurst energy delivery device. Large granite boulders were purchased rocks from Toowoomba Quarry. These rocks vary dramatically in size and shape. It was determined to be easier to move the boulder to the test frame rather than move the test frame to the boulder. The ideal situation is for the same test frame to endure the testing of the pressure waves within rock as well as within the water column assembly. A steel floor plate was introduced to the
design as a raised working surface for the experiments. Lifting the floor plate up above the RHS of the base frame means the size of the given boulder and its orientation between the outriggers would not be a factor.

The floor plate is raised above the top of the outriggers through the connection with a large RHS. The RHS is positioned so the floor plate rests on top of its cross-sectional face. This arrangement was based on the theory that the energy needs to be transferred through the bodies with little elastic deformation. Loading the structure through its cross-section will cause minimal deflection under loading. The RHS is fastened to the concrete floor using chemset bolts and is connected to the floor plate using metric bolts counter-bored into the top face of the plate.

The water column assembly was also investigated in more detail to accommodate the new floor plate into the test frame assembly. Design Iteration #4 looked to use similar base/tube arrangement as previous designs. Adjustment in the system occurs between the base plate of the pressure tube and the large floor plate via an arrangement of slots cut into the plate. This allows the water column to vary relative to the ThunderBolt moil.

6.8 Design Iteration #5

The fifth design change looked at simplifying the base of the lower frame only. The base structure of Design Iteration #4 consists of numerous individual RHS pieces welded together. The time required to fabricate the structure with large amount of welding would be extraordinary. It was therefore important to change the base of the frame to a simpler, sleeker and sexier design. Figure 6.7 shows Design Iteration #5 in a lifted configuration.

The number of cut RHS was drastically reduced to minimise fabrication. Only the most critical pieces were kept in the design. The removal of the forklift RHS provided an opportunity to narrow the entry to the base frame and remove the reinforcement to the outriggers. To maintain stability constraints, the outriggers were angled 30°. This angle also provided enough room for the water column assembly to clear the legs of the base frame. A constant angle between the outriggers allows the RHS centre supports to be cut the same angle, thus simplifying production time.

The same post and upper frame support structure was maintained from Design Iteration #4. The interaction between the water column assembly and the new base frame is displayed in Figure 6.8.
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Figure 6.7: ThunderBurst test frame Design Iteration #5 – Isometric view

Figure 6.8: Floor plate and water column assembly adjustment
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The changes to the frame also included the removal of hollow sections for lifting with a forklift and replaced with saddles. The saddles can be made from simple bent steel plate and welded to the top of the RHS in the base frame. Forklift access is now preferred from the rear of the system. The lifting lugs for the crane were also removed from the lower frame.

6.9 Design Iteration #6

Design Iteration #6 was the second major overhaul of the test frame system. Although it was expected the fifth iteration would be the completed design, another modification was required to simplify the assembly further using engineering design solutions to correct minor problems inherent in the design.

A double-cantilever situation was discovered with the upper frame assembly of the previous iteration. The slide of the upper frame is cantilevered from the support post and the LRT is cantilevered from the carriage. This will put great stresses through both the arms of the carriage and the wheels of the carriage on the slide. It will also endure stresses from the overall gravitational load of the upper frame assembly on the bolts connecting the upper and lower frames. This situation can be simplified to improve the efficiency of the test frame system. An isometric view of Design Iteration #6 is shown in Figure 6.9.

The lower frame underwent a modification to help deal with the simplification of the system. The design plan was to modify the lower frame to help in the removal of the cantilever of the upper frame from the supporting lower frame upright. As the position of the slide was fixed by its vertical alignment to the water column, the upright needed to be angled to finish at the rear of the carriage slide. A mounting plate is welded onto the end of support column to provide a flat surface to connect the upper frame using large bolts, washers and nyloc nuts. Figure 6.10 below best show the position of the upper frame on the lower frame.

The new angle of the upright support means relocating the bottom of the RHS to the rear cross member of the frame. The middle cross-member support now becomes redundant and can be removed from the structure to save on construction costs. Reinforcing side stays are added to support the main post of the lower frame. A lifting lug is added to the spine of the main post above the expected centre of gravity. This is to ensure the safe transportation of the assembly if an overhead crane is used.
The upper frame was also changed. The fabricated slide was replaced with an I-beam to save costs. This change also slimmed the aesthetic upper frame to fall in-line with the sleeker base design discussed in Design #5. The I-beam is lined with reinforcing plates spaced evenly along its length to prevent twisting of the structure when loaded. This will also add extra strength to critical areas.
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of the structure, especially around the lower frame mounting holes and where the carriage is likely to be located during operation. The reinforcing along with the I-beam also provided material for tapped holes to be machined for the removable end cap to be bolted to the frame.

Extra reinforcing either side of the cylinder mounting lug is also required to spread the stresses found in the lug due to the gravitational loading caused by the LRT and carriage assembly found. It is important to position the gussets at the front face of the slide, as the highest stress levels will occur at the undesirable radius of the lug and this will be where the greatest benefit will be. Having side gussets will also provide the strength to prevent the lug from twisting and buckling sideways due to gravitational loading.

A standard hydraulic cylinder that replaced the air winch is held from a mounting lug atop the I-beam. This lug must be shaped to fit the clevis of the hydraulic cylinder and allow the cylinder to hang vertically to the LRT carriage. If it is out of alignment, the cylinder rod could potentially buckle or become jammed from incorrect loading.

The removable plate that was positioned at the top of the fabricated slide is changed to be at the bottom of the I-beam. This means that the connection of the carriage to the structure will need to occur by sliding the carriage up from underneath the I-beam onto the slide surface.

The LRT carriage needed to be changed to suit the modifications of the I-beam and upper frame. The carriage was lengthened to spread the steel roller bearings and will lessen the movement created by the gravitational load of the ThunderBolt hammer. The new carriage assembly was integrated with the sleeker design. Nylon bearing pads were added to the side plates of the carriage to prevent wear on the side of the I-beam of the upper frame. A bolt on bent plate is added to the carriage to provide a surface to lift the carriage to the correct height on the slide using the hydraulic cylinder. The rod of the cylinder will slip through the hole of the lifting plate and a nut fastened on the other side of the bent plate. The plate arrangement and the internal bearings, pads and bolts found in the assembly are visible in Figure 6.11.

It is important to have stable bolted connections that settle square relative to the rear plate upon assembly. The design needed to remove welded joins from carriage to ensure the heating of the profile flame-cut plates does not warp or distort the plate from its original shape during the welding process. Four cam follower bearings were maintained per flange and on each side of the carriage as discussed in Design Iteration #4. The attachment point between the hydraulic cylinder and the
carriage needed to be updated from the threaded eye bolt used with the air winch in Design Iteration
#4.

An overview of the ThunderBurst energy delivery device assembly to the upper frame is detailed. The 1500J modified rock-splitter is connected to the LRT carriage prior to the assembly with the test frame. The bottom cap of the upper frame is removed from the I-beam and the water column assembly is detached from its position beneath the frame. A crane will lower the rock-splitter and carriage into a position for the hydraulic cylinder rod to connect to the carriage. The cylinder raises the hammer and allows the front flange of the I-beam to locate between the roller bearings. Once the eight bearings of the carriage are positioned on the I-beam and the hydraulic cylinder takes the weight of the device, the bottom cap and water column are replaced in position. A side view of the ThunderBurst test frame assembly during this procedure is shown in Figure 6.12.
6.10 Final Design

The final design iteration was the seventh development phase of the ThunderBurst experimental test frame. This iteration was primarily concerned with the development of the water column assembly.

Further discussion with RME’s research and development supervisor Mr. Mick Henderson over the future work of the project involved pressure wave testing with water columns drilled into rock. The use of the permanently erected test frame for both forms of testing has been discussed in preceding design iterations. Although it was previously determined to be easier to lift the boulder onto a raised floor above the legs of the base frame, a review of the new test frame design concluded the opposite should happen. It will be less hassle for the test frame to be lowered above the given rock rather than to move rock onto the raised floor of the frame. The transportation of the test frame is likely to occur using a forklift.

As part of the simplification process, the RHS raised block was removed from the assembly. It would be extremely difficult to lower the test frame over the specified boulder while the floor plate
is designed to overlap the outriggers of the base frame. It would also be hard to position the frame underneath the floor plate using a forklift to nudge the frame from behind the structure. There was therefore now no desire for the rock to be raised above the outrigger of the base frame. It was decided it would be best to keep the same method of adjustment between the water column and moil of the rock-splitter as in the previous design. Removing the raised structure meant the floor plate had to be shrunk to fit between the legs of the lower frame beneath the LRT.

The change to the false floor of the test frame assembly presented an opportunity to review the pressure tube and corresponding assembly. A relief or bleed valve is included in the pressure tube assembly. This valve is required as a fail-safe for the system if the pressure inside the tube increases to a value that would cause damage to the system. The relief would be activated before the pressure reaches this critical level, thus saving more critical components of the system from damage.

A threaded plug is inserted into the bottom of the pressure tube to act as safety valve for the system. The plug consists of a loose fitting external thread running along its outside cylindrical surface and a flat face on the end of the plug. An o-ring seal is located before the thread engagement to prevent water leaking out of the tube. Once the pressure in the tube reaches a critical level, the plug will be forced out of the tube, stripping the thread and releasing the pressure of the tube. A base plate confines the base of the pressure tube and the plug. An external thread on the pressure tube fits into the internal thread of the base plate. If the plug is released from the tube, the base plate will prevent the plug from firing out and potentially endangering the well-being of people around the experiment.

The position of the PCB pressure sensors are changed relative to the new bottom face of the water column. This keeps the bottom sensor 100mm above the reflective surface. Figure 6.13 shows the lower section of the new water column assembly. The base plate and pressure tube are shown as transparent items to reveal the internal components of the assembly.

The lower frame also had a few minor alterations. Added extra reinforcing to the base of the main post supports of the lower frame. This is to make sure the stress is spread out around this area. Internal bosses for fastening the base frame to chemset bolts were removed and replaced with a similar sized boss on external feet found at the ends of the framework. This would increase the access area to the bolts and reduce the amount of machining to the RHS legs. The changes to the lower frame are visible in Figure 6.14.
The final design solution for the test frame to handle the modified 1500J ThunderBolt hydraulic hammer during the experimentation of pressure wave propagation through water is shown in Figures 6.15 (isometric view) and 6.16 (side view).
Figure 6.15: ThunderBurst experimental test frame assembly – Isometric view

Figure 6.16: ThunderBurst experimental test frame assembly – Side view
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The final solution will satisfy all the requirements outlined by RME at the commencement of the research project. The test frame assembly mounts the rock-splitter energy source above a water column for repeatable experimentation of pressure wave propagation in water. The structure is designed for stability according to Australian Standard 1418.1-2002 for cranes and hoists. A high level of adjustment is available to account for wear on the components or assembly and production error. Transportation of the overall system is possible through the use of a forklift or a crane.

6.11 Conclusion

This chapter has discussed the process exercised to progress the ThunderBurst experimental test frame assembly from Conceptual Design #1 to the final solution. An initial discussion was included into the chapter to bring forth possible ideas and problems that existed from the decision matrix analysis of the test frames (Chapter 5). These ideas were addressed and incorporated into the design of the ThunderBurst test frame. A series of seven separate design iterations were outlined in this chapter.

The final solution includes the use of a lower frame, upper frame, hydraulic cylinder, rock-splitter and water column to record the pressure waves through the water. This design will achieve all requirements set by RME and follows the restrictions placed on the system. The modified ThunderBolt hammer is located in a safe fashion above the water column and is expected to successfully transfer the 1500J energy blow to the water.

The major components found in the final design solution will need to be analysed further using Finite Element Analysis (FEA) to ensure the safety of the design under loading. The FEA will be discussed in detailed in Chapter 7 of the report.
Chapter 7

7.0 Finite Element Analysis of ThunderBurst Test Frame

7.1 Introduction

This chapter will discuss the Finite Element Analysis (FEA) of a number of individual components in the ThunderBurst test frame final design. Structural analysis using FEA software is an important aspect of the design process in order to check the mechanical properties of a component and optimise its design. The FEA process for the LRT test rig components are outlined from the manual static calculations through to the interpretation of the FEA results using sound engineering knowledge. Detailed analysis for the LRT carriage is supplied to provide the reader with an in-depth understanding of the FEA procedure for a single component.

It is essential to select the most appropriate modeling and FEA software to investigate the strength and stability of the frame under load conditions. These software packages are used to help detail the linear stress analysis. This form of analysis can be conducted now the final design of the frame has been completed as discussed in Chapter 8 of this report.

7.2 Structural Modelling and Analysis

The structural analysis of the ThunderBurst test frame components is required to assess the integrity of the system. This analysis is critical to the design process and is conducted through the combination of modelling software and the use of a computer integrated FEA package. A three-dimensional computer-aided design program displays to the user a realistic view of how a given design will physically look in the form of a computer model. The model geometry of the part can be transferred to an appropriate software package for FEA to be conducted. A number of analyses can be performed on the test frame to ensure it is safe to use under the expected working conditions. These are listed below:
• Linear displacement,
• Temperature,
• Buckling,
• Fatigue, and
• Modal.

Only the linear displacement analysis is conducted on the test frame. It is not expected that the other forms of analysis will be contributing factors to the failure of the structure as it is only undergoing an offset gravitational load initialised from the rock-splitter. Further investigation of the structure could be conducted using the fatigue and modal analysis to check if the dynamic loading of the water column creates a reaction force on the test frame that induces vibration at the natural frequency of the structure.

The investigation of the linear displacement of the test frame is shown in the following sections. A selection of modelling and FEA packages to conduct the linear analysis is outlined in Sections 7.3 and 7.4.

### 7.3 Modelling Software

The three-dimensional modelling software that was used for the development of the test frame is SolidWorks 2007. As discussed in Chapter 5 of the report, the choice of SolidWorks over other modelling software such as Pro/Engineer or Microsoft Inventor came down to the availability of the software and the knowledge of SolidWorks within RME.

SolidWorks also has the advantage of being compatible with COSMOSWorks. This integration between the programs means the there is no time or data lost trying to convert a file to the correct format for analysis with a separate FEA program.

### 7.4 FEA Software

Finite Element Analysis (FEA) is used to refine the final design by mimicking or simulating the behaviour of a given three-dimensional structure under certain conditions. This is achieved by breaking the large part into very small elements in either two-dimensional or three-dimensional
systems. The elements are made into three or four sided shapes (2-D) or prisms (3-D). Smaller elements that are close to a regular shape or prism tend to produce more accurate results. Analysis of these elements, using a process known as the Finite Element Method (FEM), shows the designer important mechanical information such as Von Mises stress, equivalent strain, pressure and thermal distributions at any place within the system in specific points of time. It is important to remember the relevance of the results received in FEA is dependent on the usefulness of the information entered into the system. Sound engineering judgement should always be applied to the loads and results produced in FEA.

COSMOSWorks is a FEA software package with the capacity to interact with SolidWorks to analyse a given application and optimise the design solution. This software package is based on FEM theory to apply forces to a part in an effort to resemble the working circumstances of the design. Constraints or restriction on the motion of the part are also used to show where the part is fixed in location. A combination of motion and fixation in the model allows COSMOSWorks to predict the part behaviour.

FEA packages such as COSMOSWorks are capable of performing several forms of analysis to investigate the mechanical properties of a given part. Although there are many analysis types that would be relevant to the optimisation of the ThunderBurst test frame assembly, the FEA will focus directly on a linear stress analysis (Section 5.2). It is expected that linear stress will provide all the relevant data needed for the successful design of the components undergoing gravitational loading. The data produced from a linear stress analysis relevant for this research project include:

- Von Mises stress,
- Displacement,
- Equivalent strain, and
- Factor of Safety check.

The FEA conducted on the ThunderBurst experimental test frame is outlined throughout subsequent sections in this chapter.

7.5 Components to be Analysed

Only the major components of the ThunderBurst permanent test frame are chosen to be analysed using FEA. It is not deemed necessary to undertake this system of checking the elemental reaction
of minor parts of the structure as they will not undergo the same level of stresses or be as critical to
the overall function of the device.

The components that have been analysed using FEA are listed below:

- LRT carriage,
- Upper frame,
- Lower frame, and
- Pressure tube.

The ThunderBurst energy delivery system, the modified 1500J LRT, has not been considered for
this form of analysis as it has already designed and analysed previously for preceding experiments.
This design has been used successfully in operation and proved to be dynamically sound. The
hydraulic cylinder has also not been considered for analysis due to being a readily available item
from stores and the material properties of the cylinder are unknown.

The individual analysis of the four components is discussed below. Each section will give an
overview of the FEA subtleties for that component and includes a general review of the results and
conclusions drawn from the results. Only the carriage assembly will be analysed in depth.
COSMOSWorks 2006 features the chance to consider the elemental mesh density and mesh
refinement of the components. These are two of the important aspects of the analysis that will be
looked into in depth for each load case considered for the carriage assembly.

Full details of all components analysed in the FEA are given in Appendix C of the report. Limited
optimisation will occur in the test frame components. For this 'one-off' type of production, it is
preferred to 'over-design' the structure rather than take a chance and remove unnecessary material
from the design. This means it is likely only material will be added to increase the critical areas of
the ThunderBurst test frame design rather than to remove material.

Another important note regarding the FEA results is the value of the design stress for each
component. Under RME standard design practice, the design stress is calculated as 60% of the
yield stress for any given material. This means if the material grade of a component is 350MPa, the
stress should not exceed 60% of 350MPa, or 210MPa.
7.6 Static Analysis of Individual Components

A static analysis manually calculates the loads and reaction forces on each part using free-body diagrams. These loads and reaction forces provide the FEA software with values to run in the program and help predict the behaviour of the part under the given conditions.

The LRT carriage is the beginning of the flow of gravitational forces from the rock-splitter through the test frame system. Loads are applied to the carriage through the support pins on the LRT carriage. These forces are transferred from the carriage into the hydraulic cylinder and upper frame. The connection between the upper and lower frame means the moment induced by the hydraulic hammer is applied through the spine of the lower frame and into the feet of the structure. Only the details of the LRT carriage static analysis are shown in this section.

Figure 7.1 below shows the free-body diagram of the LRT carriage in operation. This arrangement of forces is defined as Load Case One for the carriage. Manual calculations for the applied loads and subsequent reaction forces are also shown in the picture. It is important to note there is no dynamic load factor added to this assembly under loading. The LRT carriage will not take inertial loads of the rock-splitter during operation as the carriage is lowered below a point where the cylinder lock nut supports the hammer.

The carriage takes the gravitational load of the modified ThunderBolt hammer its top two support pins. It is assumed only the top two of the four pins from the carriage assembly undergo shear loading. A reaction force exists on the bottom face of the cylinder lifting plate after fastening the carriage between the cylinder rod and the locknut. This load is equal and opposite to the loading on the support pins. The addition of an offset gravitational load will induce a moment in the system. Loading of the steel roller bearings on the face of the I-beam counteracts this moment. This arrangement of loads will therefore keep the carriage sub-assembly statically balanced under the gravitational load from the LRT.

Free-body diagrams used to determine loads of individual components are shown in Appendix C.
Chapter 7 – Finite Element Analysis of ThunderBurst Test Frame

7.7 LRT Carriage FEA

The carriage of the ThunderBurst test frame is defined as the device that carries the modified RME 1500J LRT hammer along the upper frame until it reaches the position for the ThunderBurst to operate. This device is the first design to be analysed with COSMOSWorks FEA.

7.7.1 Modelling

A difficulty immediately arose in the FEA process of the carriage. The carriage is a sub-assembly of the overall ThunderBurst permanent test frame. FEA is usually conducted on individual parts of an assembly, although a complicated process can be used to analyse an entire assembly.
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To reduce the time required to analyse the carriage sub-assembly, a simplified carriage model replaced the sub-assembly. This replacement carriage is modelled as a single part. The bolted connections are removed and any two adjoining plates are expected to behave as a single item. The friction between the large contact surfaces of two bodies is assumed to behave as one solidly connected part. This allows for the simple linear stress analysis to be performed without complicated COSMOSWorks procedures. This shortcut will not influence the results of the FEA. All material is made from Grade 350 steel and thus, will not jeopardise the analysis due to an incorrect design stress being used in a critical area of the design. The simplified carriage model is shown in Figure 7.2.

The welded section around the support pins of the LRT side plates is assumed to behave similar to that of the surrounding material. No specific processes are used in the simulation of weld joints, however, small chamfers and extruded bodies are occasionally included in the simplified model to resemble external fillet welds. It is expected that the weld strength is the same as the strength of the base material adjoining the weld.

Remodelling the carriage allows for the removal of unnecessary items from the assembly that will not influence the application of the loads or affect the likely areas of stress distribution in the part. Items such as the bearing pads and metric bolts, washers and nuts are removed to maintain the simplicity of the model. Hand calculations are performed on the bolts to ensure the selected
diameter is suitable to bear the shear stress inherent in the design.

7.7.2 Meshing

The breaking down of a large model to smaller elements is known as ‘meshing.’ The size of the mesh used and the density of elements in the model will determine the accuracy of the results produced in the experiment. The FEM analysis is based on the theoretical differentiation of the values between the nodes of the elements. This means as the size of the elements, and therefore distance between the adjacent nodes, approach zero the readings from the analysis become more precise.

However, there is a limit where the difference between the percentage of element refinement and error of given results from the theoretical values does not dramatically change. This is when the results of the FEA begin to converge on a given value. Further mesh refinement therefore, will give a slightly improved value but the time taken to analyse the smaller mesh density will be greatly increased. This balance is important to find to reduce the time taken for the design of the project. It is recommended mesh refinement only occurs in specific locations where a precise value is critical to the judgment of acceptability of the given design. In a linear stress analysis, the critical areas of the design will be the immediate elements surrounding a stress concentration.

Figure 7.3 shows an isometric view of the meshed carriage assembly. An increased mesh density is incorporated into the FEA around the supporting pins of the carriage side plate and on the bent plate in contact with the hydraulic cylinder.

A closer view of the part around the refined portion of the carriage is displayed in Figure 7.4. This clearly shows an increase in the number of elements around the support pins and cylinder lifting face. Having a larger number of smaller elements in these areas will produce better data than if the size of the elements were larger. These areas are expected to show the maximum stress in the carriage assembly due to the engagement of the large applied forces.
Figure 7.3: Final mesh of LRT carriage

Figure 7.4: Close up of support pin and lifting bracket mesh density
7.7.3 Application of Forces and Constraints

Static analysis of the carriage assembly was conducted (Section 7.6) and determined the values of reaction forces on the component. The arrangement of applied forces, reaction forces and constraints using COSMOSWorks 2006 is displayed in Figure 7.5.

![Figure 7.5: Application of forces and constraints on LRT carriage](image)

These forces are applied to the appropriate faces of the LRT carriage to simulate the experimental conditions. Reaction forces are also included in the analysis to make sure the loading is balanced and does not suggest dynamic motion will be present in the system. Restraints exist on three different points of the assembly away from load forces to help calculate the elemental stresses of the carriage.

7.7.4 Finite Element Analysis and Results

The analysis for Load Case One is conducted using COSMOSWorks. A new linear stress study is created for the model of the carriage sub-assembly. The maximum stress on the carriage sub-assembly is found to occur around the underside of the bent plate used to lift the carriage using the hydraulic cylinder. This maximum value of 513MPa is almost twice as large as the design stress of the carriage.
Figure 7.6 shows an iso-clipping of the resulting stress plot for the study. An iso-clipping feature of COSMOSWorks is used to show all the regions that have a value higher than a user-defined number. In the case of the linear analysis of the carriage, the iso-clipping shows where the 210MPa design stress is exceeded.

![Figure 7.6: Von Mises stress plot for carriage Load Case One](image_url)

Only the area surrounding the cylinder lifting bracket is visible. This therefore confirms the stress in the inside radius and underneath the face of the bent cylinder plate is above the limit for operation and will require redesign before the sub-assembly is safe for production.

Another view of Von Mises stress in the carriage sub-assembly is shown below in Figure 7.7. This rear view of the carriage provides another shot of the hydraulic cylinder lifting plate. A close up confirms the magnitude of the problem. The remaining components of the sub-assembly barely exceed a stress of 20MPa during operation. It is therefore only the cylinder lifting bracket that needs further design work before it will be passed as acceptable.
The physical displacement of the experiment is another major aspect of the design that needs to be investigated. Figure 7.8 shows the structural displacement of the carriage under the conditions of Load Case One. This figure shows the part with a deflection scale 51 times what will physically occur to the carriage in operation. A resulting maximum displacement of 1.02mm is shown for the cylinder lifting bracket following the application of the gravitational load. This means the end of the bent plate will deflect 16.7% of the original thickness of the plate. This backs up the Von Mises stress analysis in suggesting the bracket is loaded beyond its capabilities.
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A screenshot showing the relative strain is found in Figure 7.9. Strain is calculated as the ratio between a change in deflection due to loading over the original size of the component. Similarly to the stress plot, the maximum strain occurs in the underside face of the bent steel plate. COSMOSWorks calculates the maximum value to be $1.425 \times 10^{-3}$. The remainder of the carriage assembly does not undergo strain over $10^{-6}$.

![Figure 7.9: Equivalent strain resulting from analysis into carriage Load Case One](image)

A check of the factor of safety (FOS) for the carriage confirms the lifting bracket of the cylinder is the area needing most attention in the design (Figure 7.10). It shows the bracket having a FOS as small as 0.56. This means the bracket is likely to fail in operation. A large FOS, shown in blue, displays the regions where the effects of the applied loads in the design will be limited. Redesign of the bracket must occur to bring the FOS up to a value greater than one.
Chapter 7 – Finite Element Analysis of ThunderBurst Test Frame

Figure 7.10: Design factor of safety check for carriage Load Case One

From the analysis of Load Case One, it is seen that the values of stress and displacement for the bent steel plate holding the hydraulic cylinder is too high for both the design and yield stress of the material. This infers that the bent plate will deform beyond its limitations and fail during operation. The maximum stress of the plate is seen at the underside radius of the plate and at a value of 513MPa, which is far higher than the design stress of 210MPa for this component. This means the bent plate needs to be redesigned to bring the stress level down below 210MPa. A redesign on a simple plate is best to start by increasing the thickness of the plate and increasing the radius of the bend. This will help disperse the stress from the applied pressure from lifting through the assembly.

A secondary analysis of Load Case One looks to optimise the thickness of the bent plate. Increasing the thickness of cylinder lifting bracket from 6mm plate to 10mm plate stiffens the rear of the carriage assembly. The same load case was run and applying all the same loads gave a much different result to the original analysis. The stress plot for the analysis is displayed in Figure 7.11. This time the stress was reduced down to a maximum 209MPa, which is on the design limit but is deemed acceptable. Increasing the plate thickness to 12mm would further decrease the stress in the plate, but it would infer a higher cost in materials. Therefore the 10mm plate is decided to be acceptable for the final thickness for the cylinder lifting bracket.
A second view of the Von Mises plot from the rear of the sub-assembly provides a comparison between the original and secondary analyses of the carriage. Figure 7.12 shows the stress concentrations occur in the same region as previous, but the maximum stress value has more than halved. It is interesting to note the deflection of the carriage side plates is more clearly visible after the increase in plate thickness.

A secondary review of the ultimate displacement of the model is also conducted as part of the analysis (Figure 7.13). The maximum value is still visible at the end of the bent steel plate. This expected deflection has sharply decreased from 1.02mm to 0.347mm from the introduction of a thicker plate. A simple comparison to the original design also reveals the percentage of displacement relative to the plate thickness has reduced to 3.47% from the original 16.7%. The visible deflection scale is a reminder that the geometry shown in Figure 7.13 is 153 times the real bending that will occur during operation. The side plates of the carriage undergo more deflection than in the previous orientation, but the values are still below 0.2mm of movement. This increased level of movement is nothing to be of concern and will not jeopardise the stability of the structure.
The equivalent strain in the carriage assembly is shown in Figure 7.14. The maximum strain in the
assembly exists surrounding the through hole of the bent lifting bracket. A reduction in the maximum is again observed from the FEA data. This maximum is now decreased to approximately 5.0x10^4. A large portion of the model does not see strain values greater than 4.0x10^5. This shows a very safe area under little deflection. Strain is kept to values close to zero surrounding the restraints. This is likely to occur because the restraints are fully restricted in their motion, therefore preventing deflection and finally strain from occurring in these points.

![Figure 7.14: Equivalent strain resulting of secondary analysis into carriage Load Case One](image)

A final check of the system using FOS is conducted (Figure 7.15). The design intent was to raise the minimum FOS reading above one. It is pleasant to see an increase in the area with a very large FOS. The focus of the results again surrounds the lifting bracket of the carriage. This area is still under the and the most likely position for the system to fail. The change to the geometry of the carriage has increased the minimum FOS to 1.68. This therefore achieved the objective set out in conducting the secondary analysis of the carriage.
The LRT carriage sub-assembly is deemed as structurally sound. FEA conducted with the help of COSMOSWorks 2006 has confirmed the stress, relative displacement and equivalent strain of the carriage is within acceptable design limitations. This means production of the individual components in the carriage sub-assembly can begin.

The original model included bolted steel sections to form the carriage assembly. The diameters of the metric bolts were determined using hand calculations to ensure they were capable of handling expected shear stresses from the loading of the LRT. A review of the stress readings in the locations of the fasteners on the carriage sub-assembly, show small or limited stress values present. This confirms that the selected bolt diameters will be sufficient to withstand the LRT loading, as they will not deal with excessive stress not considered in the hand calculations.

The deflections present in the model are very small compared to the contact faces of the adjoining steel plates. This means constant friction between the surfaces is expected to be maintained, thus confirming the assumption that the bolted plates will act similar to a single combined part.
Chapter 7 – Finite Element Analysis of ThunderBurst Test Frame

7.8 Upper Frame FEA

The upper frame is the section of the test frame that the LRT carriage runs along to the desired position for operation. This is also the portion of frame that bolts to the lower frame. The upper frame is loaded in a number of areas. The gravitational load from the suspension of the hydraulic cylinder on the mounting lug and the reaction force from the carriage roller bearings on the I-beam are applied to the model. Reaction forces are suitably positioned at the slotted holes.

Five separate load cases are applied to the upper frame model to simulate different conditions. The first three load cases were included to review the effect of the reinforcement on the twist that will occur in the upper frame under the gravitational load of the components. The remaining cases reveal the elemental behaviour of the upper frame under normal load conditions and with the inclusion of inertial loads. An outline of the five load cases is given below:

- **Load Case One:** Simplified upper frame model is analysed without gussets and reinforcement to check the twist of the I-beam under vertical loading only.
- **Load Case Two:** Additional gussets around the cylinder mounting lug are included to the simplified model used in Load Case One. Only gravitational loading of hydraulic cylinder and dependent items are applied.
- **Load Case Three:** Reinforcement lining the I-beam is included to the model used in Load Case Two. Only gravitational loading of hydraulic cylinder and dependent items are applied.
- **Load Case Four:** Upper frame model is analysed under full working conditions when the rock-splitter and carriage are at the extremity of the I-beam, awaiting assembly or disassembly to the frame.
- **Load Case Five:** Upper frame model is analysed under full working conditions when the rock-splitter and carriage are in the operating position along the I-beam.

The upper frame was firstly analysed as a simplified model to check the amount of twist to the entire frame and to see how much difference the reinforcing down the I-beam had on the results. A gravitational force of 6100N was applied to the cylinder mounting lug only and the opposing reaction force on the attachment to the lower frame. The result was only a stress value of 68MPa on the underside radius of the cylinder lug and an overall deformation of 0.35mm on the entire frame. This is acceptable.
The addition of reinforcement to the cylinder lug in Load Case Two had no effect on the Von Mises stress. In fact by adding the square join to an area close to the stress concentration, the stress increases slightly to 70MPa. The deflection and equivalent strain values did drop slightly. Reinforcing the I-beam in Load Case Three also proved not to affect the Von Mises stress at all. A drop in the final displacement of the upper frame from the twisting of the beam was clearly visible. A reduction from 0.34mm in Load Case Two to 0.22mm in Load Case Three was found.

Load Case Four was the first of two situations simulated under full load conditions. This case was based on the LRT carriage being at the extent of upper frame. This situation will be common during assembly or disassembly of the carriage from the frame and would be a worst case scenario as this will be the maximum moment applied on the I-beam. Analysis of the case produced results of 60MPa for the stress and 0.17mm for the deflection.

During the analysis, the profile of the mounting lug was modified slightly to increase the inside radius and extend the position of the through hole relative to the front face of the I-beam. Reanalysis of the load case was conducted. The maximum stress occurs in the same region, increasing the stress only minimally to 65MPa.

The final load case was based on the LRT carriage position during operation. The resulting stress plot displays similar results to the previous Load Case Four. A difference was seen in the deflection readings due to the change in position of lateral loadings.

Figures 7.16 – 7.18 give a picture of the stress and deflection experienced by the upper frame during the ThunderBurst test frame experiments under Load Case Four.

Figure 7.18 shows the maximum stress location of the part on the underside of the cylinder mounting lug. The highest stress at this point is 60MPa, well below the design stress. It is clear in Figure 7.18 the simplified gusset supporting the mounting lug. By removing the large chamfer from this body, it was able to make the meshing of the component easier especially with a split line function being incorporated in line with the top of the I-beam. The addition of extra material in this region does not influence the critical stress of the upper frame.

Both Load Cases Four and Load Case Five were then reanalysed with the inclusion of a dynamic factor, $\Phi_s = 1.6$, from AS1418.1-2002 Clause 4.7.3. The dynamic factor takes into account the
inertial loading of the modified ThunderBolt during its motion along the upper frame. The stress values rose to approximately 90MPa in both cases. The analysis of both load cases did not show a dramatic increase in the stress or displacement readings to require redesign as a result of adding the dynamic factor to the applied loads.

Figure 7.16: Von Mises Stress for upper frame Load Case Four
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Figure 7.17: Von Mises Stress on rear bolt holes of upper frame Load Case Four

Figure 7.18: Von Mises Stress on cylinder mounting lug of upper frame Load Case Four
Chapter 7 – Finite Element Analysis of ThunderBurst Test Frame

7.9 Lower Frame FEA

The lower frame is the main support structure of the ThunderBurst test frame. It fastens the upper frame in the final location above the water column and is connected to the concrete floor to provide stability in the system. The structure is only affected by gravitational loading on the top two mounting holes of the plate on the end of the support post. Reaction forces are present on the bottom face of the feet fastened to the floor.

Three different load cases are analysed for the lower frame part. The first case investigates the test frame when loaded under normal operating conditions. The remaining two cases analyse a fully laden assembly during transportation both using the forklift saddles and the crane lifting lug on the main RHS spine. The load cases for the lower frame include:

- Load Case One: Analysis of test frame under gravitational loading of upper frame and dependent attachments
- Load Case Two: Analysis of forklift saddles under gravitational loading encompassing entire assembly
- Load Case Three: Analysis of the crane lifting lug under gravitational loading encompassing entire assembly

Load Case One was the first of the lower frame situations that was analysed. From static analysis conducted in Section 7.6, the FEA requires a 6975N load to be applied on the lower frame at the attachment point of the upper frame. The Von Mises stress plot (Figure 7.19) shows the lower frame under normal loading conditions. Maximum stress is visible at the inside radius of the rear frame footing. The value of 212MPa is too high for the material selected in this location. Grade 250 steel was expected to be used for this plate, making the design limit for stress of the part 150MPa. The feet therefore, need to be redesigned.

A check of the deflection of the structure shows a maximum displacement of 3.3mm occurring at the end of the RHS support post. As stated in the initial design phase of the project, the maximum deflection of the RHS will not want to be greater than 10mm (Section 6.2). This means the selection of the RHS for this structure is adequate for the given loading.

The lower frame is changed to beef the material thickness of the feet to account for the reaction forces required to hold the frame in position. Weld detail was added to the structure to fill in the empty spaces between the individual RHS pieces on the lower frame. The welds were ressembled in
the form of small extrudes and chamfers. Load Case One is then reanalysed with this updated model.

The stress plot from FEA shows the maximum stress is still located at the bend radius of the frame feet, but the value has dropped to 135MPa. This is below the design stress of the steel plate grade. The stiffening of the framework with the introduction of welds actually increases the deflection of the RHS spine to 7.2mm.

![Figure 7.19: Von Mises Stress on cylinder mounting lug of upper frame Load Case Four](image)

Load Case Two investigates the linear stress analysis on the lower frame when being transported by a forklift. A worst case scenario is assumed when the forklift lifts the entire frame with the energy delivery system in place. This scenario will be run through FEA to ensure all components will cope with any loading to the structure. Reaction forces will not be applied evenly on the forklift saddles. The COG of the frame is not located between the saddles, thus creating a moment when lifted. The tipping motion of the frame will exert a load on the inside face of one set of saddles and a load on
the top face of the RHS.

Figure 7.20 shows the Von Mises stress plot for the saddles. The majority of the deformation will occur on the inside face of the saddle and around the bend radius of the plate. The maximum stress value is well below the design stress for the Grade 350 material. This current arrangement of forklift transportation is therefore adequate to handle all reasonable operating situations.

![Figure 7.20: Von Mises Stress on forklift saddles of upper frame Load Case Four](image)

The third load case is defined to be when the overhead crane lifts the entire frame with the energy delivery system in place. The gravitational forces of the test frame assembly are applied as a bearing load on the through hole of the lug. As in Load Case Two, a worst case scenario is sort for the FEA to relieve any doubt the structure can handle any reasonable loading expected during the experiment.

The deformation of the RHS spine under this form of loading remains close to the value found in Load Case One. This is expected as the cylinder, carriage and rock-splitter remain suspended from the lower frame. A close up of the lifting lug in Figure 7.21 shows the stress plot resulting from the loading. A maximum stress of 144MPa occurs around the rear edge of the lug. The deformation of
the lug in the figure suggests the RHS will buckle and permanently distort during loading. This large deformation is an exaggerated resemblance of the expected behaviour and is shown in Figure 7.21 at 437 times the actual physical displacement. The stress and deflection in the lower frame from Load Case Three is acceptable for the given operation.

![Figure 7.21: Von Mises Stress on cylinder mounting lug of upper frame Load Case Four](image)

### 7.10 Pressure Tube FEA

The pressure tube is defined as the hollow steel cylinder that encapsulates the 1000mm column of water. This component is part of the water column assembly that includes a floor plate, base plate, pressure transducers, an internal steel plug and an o-ring. Similar to the LRT carriage sub-assembly, it was required for the assembly components to be combined in order to analyse the pressure tube as single item. Only the steel tube and internal plug would be affected by the applied loads and thus, were combined as a single model for FEA.

Previous experiments have determined the maximum pressure of 110MPa will be applied to the inside of the pressure tube from the expansion of the water (Section 4.4.1). This pressure is exerted on the cylindrical face of the tube, and an equivalent axial force applied to the face of the internal
Chapter 7 – Finite Element Analysis of ThunderBurst Test Frame

plug as part of Load Case One. This was the only analysis conducted on the pressure tube.

Figures 7.22 and 7.23 show the pressure tube following a linear analysis. Von Mises stress of 562MPa is displayed in Figure 7.22 on the inside surface of the pressure tube. This figure also displays the deformation of the pressure sensor housings during the axial load.

![Figure 7.22: Von Mises Stress on pressure tube analysis using Load Case One](image)

Figure 7.23 gives a better perspective on the location of the maximum expected stress value. It shows a close up of a sectional cut taken along the axis of the pressure sensor housing. The maximum stress occurs at the front radius of the PCB sensor housing.

The pressure tube is made from extruded hollow bar with a material ultimate tensile strength (UTS) of 750MPa. This material allows for the design stress limit to be increased to 450MPa using 60% of the UTS as the design limit. The expected stress exceeds this limit, however the inclusion of pressure sensors to the assembly will reduce the deformation and stress through the housing. Analysing the tube with the empty housings provides room for the surrounding material to squash into the available space. Further analysis can be conducted using FEA incorporating round extruded sections symbolising the pressure transducers in the housings of the pressure tube. This will confirm the assumptions made that the high stress value around the housing can be downplayed.
7.11 Conclusion

This chapter has discussed the FEA process required for major components of the ThunderBolt test frame design. The results achieved from the FEA show the expected stresses and deflections of the components under gravitational loading of the LRT. No other form of analysis was considered.

The procedure of analysing the LRT carriage was discussed in detail. The initial step involved simplifying the sub-assembly to a single SolidWorks part model. Static analysis was conducted to calculate the reaction forces applied to the assembly. The forces and constraints were added to the model and analysed using CosmoWorks 2006. The FEA showed the stress level experienced in the cylinder lifting plate was too large for the given application. After slight modification to strengthen this plate, the carriage was deemed acceptable.

FEA using various load cases was conducted on the lower frame, upper frame and pressure tube...
was investigated. The design of the lower frame required minor changes to the thickness of the feet of the structure. The FEA of all components were thoroughly reviewed and deemed to be safe for operation.

The Finite Element Analysis was the final design optimisation process of the test frame components. This means the design optimisation of the ThunderBolt test rig is now complete. The components found in the design solution will be further discussed in detail throughout Chapter 8 of the dissertation.
Chapter 8

8.0 Completed Test Frame Design

8.1 Introduction

The evolution of the ThunderBolt test frame has been a long progression from the initial hand sketch in Figure 5.1. The system has undergone conceptual design evolution in Chapter 6 and FEA on the major components in Chapter 7 to reach the completed design solution. This chapter will discuss the final design of the LRT experimental test frame following its completion in Chapter 7 of the dissertation. An outline into the expected assembly procedures and system operation is provided to give the reader a full appreciation of how the test will be conducted.

A complete insight into the individual components of the frame is also displayed. The considerations for each individual component within the LRT test frame are included in this chapter. Each component is discussed in detail and is shown how it is related into the overall design of the test frame.

8.2 Completed Design

The following portion of the report discusses the final design of the experimental test frame. It will delve into the basics of how the frame is assembled and how it is expected to operate. The design evolution of the test frame to reach its final design stage for the permanent test frame to analyse the pressure wave propagation of a shock wave through a water column was discussed in Chapter 6 of the dissertation and displayed in Figure 8.1 below.
As outlined in Chapter 4, the final design of the experimental test frame had to accomplish a number of specific tasks for the analysis of the pressure through the water to be successful. It was expected that the test frame would be able to mount the selected energy delivery device in the experiments. This round of testing will use a modified Russell Mineral Equipment 1500J ThunderBolt recoilless hydraulic hammer vertically suspended on a frame above a hollow cylinder. This is to represent the how the ThunderBurst project will be in operation within the mine.

The frame consists of a number of separate components assembled together. This method was selected to allow for quick and easy assembly or disassembly of the overall system. Being able to strip the system down to individual sub-assemblies grants RME the option of easily storing the test frame assembly between tests or when testing is no longer required.

When in operation, the structure will stand 4.6m high. The large legs of the structure are required to stabilise and prevent tipping of the system. This increases the volume of the system to an envelope of 22.6m$^3$. This is a large volume of space required to permanently house the assembly.

Transportation of the test frame system can be conducted using either a forklift or an overhead crane. Forklift tynes will be used to lift the structure at the steel saddles located on top of the legs of the lower frame. A lifting lug located on the spine of the lower frame is the specified area for the transportation of the assembly via the overhead crane. It is expected both the forklift saddles and
the lifting lug will be capable of handling the stresses incurred by manoeuvring the LRT energy delivery system fully assembled on the test frame.

8.3 System Components

A discussion of the individual components used in the establishment of the permanent test frame is given in this section of the report. All the components have a specific purpose in the design and play an important role in accomplishing the objectives addressed by RME in Chapter 4. The final design incorporates a minimal number of individual parts to keep the structure as simple as possible.

The conceptual design of the test frame is divided into seven separate sections. These components are listed below:

- Modified 1500J LRT mounted vertically as used in 2002 rock-breaking experiments,
- Carriage to hold the LRT in position along the upper frame,
- Electrical components used to collect and organise the data from the experiment,
- Hollow cylinder representing the drilled hole into a boulder,
- Lower frame required to support the entire upper frame assembly,
- Upper frame to hold and position the modified 1500 LRT hammer, and
- Other miscellaneous components which contribute to the final design.

A general outline on how the frame is expected to perform in testing is described in detail below. This includes how all the parts and sub-assemblies are connected in the ThunderBolt experimental test frame to investigate the pressure waves resulting from an impact load on a column of water.

The lower section of the test frame is bolted to the concrete floor. This is to ensure there is no chance of the frame becoming unstable under impact loading by the ThunderBolt hydraulic hammer. An upper frame connects to the lower frame at the top of a support post running through the centre axis of the frame. The upper frame is a simple design consisting only of an I-beam, structural reinforcement and a mounting lug to attach the clevis of an agricultural hydraulic cylinder. The long, flat face of the I-beam gives a perfect surface for the LRT carriage to run along.

The LRT carriage is an arrangement of profile cut steel plates bolted together. A series of cam follower roller bearings are evenly spaced on the carriage. The rod of the hydraulic cylinder runs
Chapter 8 - Completed Test Frame Design

through a hole in a bent plate of the carriage and is fixed from beneath with a gland nut on the thread of the end of the rod. The hydraulic cylinder is used to vary the position of the carriage along the upper frame by extending and retracting the rod length. The gland nut supports the weight of the carriage and LRT while located on the frame. It is important to note the cylinder rod and gland nut is lowered beyond the point where the steel tube of the water column assembly supports the weight during the firing of the hammer. This will ensure no dynamic loading impacts on the plate and nut connection.

The modified 1500J ThunderBolt hammer is located on pins from the side plates of the carriage assembly. This device exerts the axial impact load on the water column. Steel pressure tube houses the water used in the experiment. This tube contains a series of vertically aligned PCB piezoelectric sensors. A steel plug and o-ring seal is threaded into the base of the tube to act as a rebound face for the shock wave in the water. The base of the pressure tube, along with the steel plug, is housed in a base plate. This base plate is fastened to a floor plate, which in turn, is fastened to chemset bolts from the concrete floor. Minor adjustment will occur between the floor plate and the base plate if there is any misalignment of the hammer in relation to the location of the water column.

Information gathered by the pressure transducers in the steel pressure tube is transferred from the sensors to a high-speed oscilloscope where the data is recorded. The data logger also analyses the results and produces a display in the form of a wave. It is this wave that will show the pressure wave propagation of an impact load through water.

8.3.1 ThunderBolt Hammer

The modified 1500J LRT (Figure 8.2) was used in the 2002 rock-splitting experiments at RME. The 1500J hydraulic hammer underwent significant modifications, including changes to the impact moil that distributes the energy through the water column. The 1500J LRT uses hydraulic power and the conservation of momentum theory to produce an impact strike on the water column within the hollow steel cylinder.

The usual impact moil of a Linerbolt Removal Tool is used to strike linerbolts from sacrificial liners inside a grinding mill. As discussed in Chapter 4, this is removed and replaced by the rock-splitting moil. The rock-splitting moil includes a valve to flood the moil, and then the drilled hole with water. This moil also incorporates a spring to limit the recoil from the impact on the water.
To help simulate a real-life mining situation, the LRT is hung vertically from the test frame. Having the water column vertically aligned to the rock-splitter not only helps to contain the liquid at an even level for the impact load, but also helps to ensure repeatability in the experiments by maintaining a consistent level of water in the steel column.

A LRT carriage supports the LRT. This carriage is capable of holding the hydraulic hammer in an upright position. It is used along with an agricultural hydraulic cylinder, to position the LRT into the most suitable location along the upper frame I-beam for operation and storage.

8.3.2 Electrical Components

The electrical devices used in the monitoring and recording of the pressure wave profile through the water column includes pressure transducers and an oscilloscope data logger. Details of both electrical components are given below.

A piezoelectric sensor is composed of a quartz crystal inside the sensor housing that measures the vibration of the surrounding environment. Floyd (2002) states a piezoelectric sensor is a stable feedback oscillator and the most precise crystal-controlled oscillator on the market. This device incorporates a frequency regulation control system through a negative feedback loop. The
piezoelectric effect uses a quartz crystal to measure changes in mechanical pressure. When the crystal experiences a vibration, voltage is produced at the frequency of the mechanical distortion.

When an Alternating Current is routed to the sensor, the crystal will vibrate and record the natural frequency of the electricity (Floyd, 2002). This needs to be noted when reviewing the data produced by the sensors.

A microelectronic amplifier is coupled to the quartz and linked to the electrical connector (PCB Piezotronics, 2004). PCB piezoelectric pressure sensors are used in the ThunderBurst experiments to record changes of pressure within the water column. A change in pressure will lead to a change in the very small oscillations of the water position relative to the sensor. These slight variations are detected by the quartz and sent as Direct Current to a recording device where the results are stored.

PCB Piezotronics (2004) further discusses the pressure sensors selected for the ThunderBurst test frame assembly. The piezoelectric sensors preferred for use in this round of testing are the ICP 109C11 high-pressure sensors. This range of sensors is designed for high-speed pressure wave and acceleration pulses. The ringing effects that can occasionally result from small rise times in the recording of experimental data can be decreased by the very high natural frequencies produced by the ICP sensors.

It is expected that the range of these sensors will be able to compensate for any errors in the signal due to acceleration from the high-pressure values seen in the experiment. It is important for the pressure transducer to undergo special routine calibration when continuously used in testing environments under high-pressure hydrostatic situations (PCB Piezotronics, 2004).

Mounting the pressure transducer in the steel cylinder requires specific dimensions machined into the tube. It can be mounted either flush with the internal surface or recessed away from the pressure source to protect the crystal. To get the most accurate pressure readings through the water column, it is determined that the sensors should be flush mounted. The expected pressure in the test will be lower than the sensor and crystal can handle, so protection of the crystal in this manner is not an issue.

Voltage readings produced by the PCB sensors need to be recorded and presented in a form that can be interpreted by the operator. These readings are sent from the sensor to the data logger via a connection using 10-32 coaxial cables (PCB Piezotronics, 2004). The input data is analysed by the
data logger and displays the resulting wave profile on the oscilloscope screen.

The Hoki 8860 memory hicorder oscilloscope and data logging system has the potential to analyse voltage, current, temperature, pulse and distortion. The data inputted from the PCB sensor is recorded and a display of the resulting values is shown as a wave profile in real time (Hioki E. E. Corporation, 2006).

The information supplied by Hioki E. E. Corporation (2006) explains Hioki 8860 high-speed oscilloscope has the ability to convert the system from the time domain to the frequency domain for easy analysis. It is easy to change the sampling rate to as low as 50µs and can produce results on a time axis of 5µs intervals.

This data logger will be hired by RME for the pressure wave analysis through water. Its ability to separate frequencies and wave profiles from the data provided during a comparison of the results was a major reason behind this selection.

8.3.3 Pressure Tube

The steel pressure tube (Figure 8.3) is a major aspect of the LRT experimental test frame. The pressure tube is a 1200mm tall steel column containing the water necessary for the experiments. It is expected that the water column will only stand 1000mm high within the steel cylinder. This value of 1000mm will help simplify pressure wave and deflection calculations performed on the results of the experiment.

A tapered entry is needed for LRT moil to sit firmly into the tube. The rubber seal of the ThunderBolt hydraulic hammer will fit snugly onto this taper and help to increase the contact area of the sealing surface on the pressure tube. Incorporating a tapered entry for the moil will offer an easier option during the initial setup of the assembly. A taper will also be useful if the recoil bounces the moil of the hammer out of the tube following the strike due to the spring-like nature of the water column.
Pressure sensor housings are spaced evenly down the side of the tube. A total of five sensors were purchased by RME for this experiment. With the overall water height fixed at 1000mm, it was decided to position the sensors evenly at 200mm intervals. Due to a lack of knowledge in where along the column the maximum pressure value will occur and how the profile of the wave will propagate through the column, the sensor locations was decided to begin 100mm from the base. This then means the top sensor will be 100mm from the impact zone.

8.3.4 LRT Carriage

The carriage sub-assembly is made up of a series of separate profile cut steel plates all fastened together with bolts and spring washers. This arrangement, shown in Figure 8.4, was chosen to prevent weakening of the carriage assembly through the addition of welds. The large gravitational loading on the assembly from the LRT will cause stresses to propagate through the material and fracture at the weaker points in the assembly created by welding. It is also expected the main backing plate of the assembly will undergo torsion as a result of the gravitational loading. Distortion of any plates due to the welding process may increase the likelihood of further developing the distortion under load.

The plates required for the carriage assembly includes:

- a central base plate as a connection point for the remaining plates,
- two front plates that act as arms to hold the LRT in place,
Chapter 8 - Completed Test Frame Design

- two side plates which house the components required for the safe transportation of the carriage on the upper frame, and
- A plate that takes the reaction load of the hydraulic cylinder when the carriage is lifted.

Steel roller bearings at the rear of the carriage run along the face of the upper frame. Cam follower roller bearings are selected, as they will provide a strong, round surface to roll the carriage in the desired location on the I-beam. The added advantage of the cam follower in the design is the addition of grease ports to lubricate the bushes on the bearing rod. The bearing also has an off-centre shaft relative to the centreline of the rear shaft of the bearing. This provides an eccentric motion of the roller and external bush that distributes the greases around the bush.

In an attempt to prevent the moment induced by the off-centre loading of the LRT on the carriage assembly, four roller bearings are included on each side of the front section of the I-beam. This minimal gap between the bearing surface and the I-beam will reduce a moment and shear stress on the carriage. This is a result of the moment being influenced by the force and distance between point of interest and location.

![Figure 8.4: Carriage used to position modified LRT along upper frame](image)

The LRT is held via two pins protruding horizontally from the front arms of the carriage, and two separate fastening pins inserted through specified holes in both the LRT and carriage assemblies. It is expected only the top two pins take load and are adequately sized to prevent shear failure of the pins. Nylon bearing pads are located in pockets of the carriage side plates. These pads act as a sacrificial surface and prevent the wear of the plate against the side of the I-beam.
8.3.5 Lower Frame

The lower frame is the foundation of the test frame system. The main RHS spine, which runs along centre axis of the frame, takes the gravitational load from the LRT. Two supports extend between the RHS spine and the base of the frame to provide reinforcement and prevent twisting of the RHS support post under load. A display of the lower frame component is found in figure 8.5.

Legs of the test frame are spread apart to provide sufficient room beneath the energy delivery device for the water column assembly to be fastened to the floor. The wide span of the frame legs also increases the base contact area with the floor and therefore increases the stability of the system. Saddles are incorporated into the design to provide a lifting point for the frame using a forklift. A lug on the RHS spine gives a location for lifting with a crane.

Four feet extend off the ends of the frame legs. The feet are simple bent steel plates that double as end caps for the RHS legs. Chemset bolts protrude through specified holes in the frame feet to fasten the frame down to the floor. The hydraulic hoses used to pump fluid to and from the cylinder are fed through the handles on the side of the RHS spine. These handles will take a portion of the gravitational and axial load exerted by hydraulic fluid in the hoses.

![Figure 8.5: Lower section of supporting test frame for ThunderBurst experiments](image)

8.3.6 Upper Frame
Chapter 8 - Completed Test Frame Design

The upper frame is an integral component of the test frame assembly. The frame incorporates the use of an I-beam and provides a long, smooth surface for the hammer location. LRT slide carriage runs along front face with roller bearings to position the hammer in the desired location. The upper frame is mounted to the lower frame through a set of slotted holes located in the rear face of the I-beam. Figure 8.6 shows the upper frame in an isometric view.

![Figure 8.6: Upper component of the permanent test frame](image)

Reinforcement is spaced along the length of the beam to prevent twisting of the frame from gravitational and dynamic loading of the test frame. The reinforcement is located around points of interest where the stress is likely to be high during operation. This is especially true in the region of the mounting holes in the rear of the I-beam.

A cylinder mounting lug is attached to the top of I-beam. The hydraulic cylinder hangs from the lug on the upper frame and is used to lift the slide carriage along the I-beam. It is important to maintain the rod of the cylinder as straight as possible to prevent buckling of the rod under load. For this reason, the lug was positioned above the front face of the I-beam to ensure a vertical alignment with the lifting plate of the carriage. Reinforcement was added to the front face of the structure to prevent the lug from twisting under the load produced from the hanging cylinder.

**8.3.7 Miscellaneous Components**

The following section discusses some of the lesser components included in the test frame assembly. These components all play an important role in the functionality of the system, although they are
not considered to be the main components requiring vast fabrication or sub-assembly time.

8.3.7 (i) Hydraulic Cylinder

The hydraulic cylinder design is available as a stock standard part many industrial suppliers. Hydraulic fluid from the LRT powerpack will be used as the power source to extend and retract the rod of the cylinder.

The stroke of the rod was the most critical aspect in the selection of a stock cylinder. The large difference between the maximum and the minimum heights of the carriage on the upper frame meant the cylinder stroke also had to be very large. The range of stroke lengths for stock cylinders is limited when the stroke is over 1000mm long. This meant the other dimensions of the cylinder components such as the rod, wall and bore diameters are dependent on the cylinder selected to achieve the stroke required for the project.

The rod size needed to be thick enough to prevent buckling when lifting the carriage and hammer. Euler's equations for buckling are used to ensure the cylinder rod is safe for the loading conditions expected to be experienced during operation. The cylinder with a rod size 1¼” and a stroke 1175mm satisfied both requirements.

8.3.7 (ii) Floor Plate

The floor plate is the component that connects the bottom of water column assembly to the floor. Tapped holes are required for bolted connection with pressure tube base plate into the top face. Slotted holes in the base plate of the water column assembly give a connection point, where the floor and plate will be fastened together with a flat washer and nyloc nut. An isometric view of the plate is shown in Figure 8.7.
Slotted through holes are also cut into the plate, to provide minor positional change relative to the water column assembly in one direction only. This will keep a constant contact surface between the two plates. A thick steel plate is selected as the material for this component to help ensure energy is correctly transferred from the hammer through to the ground.

8.3.7 (iii) Water Column Base Plate

The water column base plate (Figure 8.8) connects the steel pressure tube to the concrete floor through its connection with the floor plate. Slotted holes are cut into the plate, which allow for adjustment between the base plate and the aligning tapered holes in the floor plate. It is important to assemble the floor plate and base plate so the slotted holes are perpendicular to each other. This will allow for minor adjustment in both directions if required. The bottom of the pressure tube will thread into the base plate boss, which sits proud of the base plate. This provides a catchment area for the steel plug to release should the pressure become too great during loading.
8.3.7 (iv) Plug

A stop plug is inserted into the base of the cylinder tube to act as a flat rebound face for the shock wave to reflect from. This plug is incorporated in the design as a relief valve should the pressure in the tube become very large. A relief valve is a device that will activate and release the pressure from a system before it reaches a value that can cause damage to the steel tube or pressure sensors. In this case, the plug is a sacrificial component that can be replaced should it be released and destroyed.

![Figure 8.9: Threaded stop plug and BS o-ring](image)

The plug, shown above in Figure 8.9, contains an external metric thread of long length to give adequate connection with the pressure tube. The thread is undercut so it can be easily stripped should the fail-safe be required. Should it be required, the base plate cylindrical housing will retain the plug from shooting out into the environment if the pressure becomes too great.

A smooth o-ring sealing surface is required on the steel plug to maintain a tight seal between the plug and the tube. If the surface is rough, the o-ring may not seal correctly. Any gaps in the sealing area would result in leaking water from the water column and reduce the static pressure in the tube.

8.4 Detail Mechanical Drawings

Individual part drawings were drafted with the use of SolidWorks 2007 3-D modeling software. The aim of the drawings was to give the workshop at RME adequate dimensions to cut or machine separate portions of the part and to fabricate and build these individual portions into a complete part. Detail design drawings were required for a number of components on the test frame. These
drawings, along with their RME part number are shown in the list below. The detail drawings are also included in Appendix D of this report.

Figure 8.10 shows the top-level assembly drawing for the ThunderBolt test frame assembly.

![ThunderBolt test frame assembly drawing](image)

**Figure 8.10: ThunderBolt test frame assembly drawing**

Assembly drawings have also been produced for this project. An overall assembly drawing is also needed showing the location and connection of sub-assemblies. This type of drawing shows how the individual parts interrelate and connect together to form a sub assembly of parts.

Appendix D also includes assembly drawings of the system. The rock-splitter assembly 10R1905 is not included as the design and assembly of its components was not part of this research project.

### 8.5 Issues Arising From ThunderBolt Test Frame Experimentation

The use of the complete ThunderBolt test frame for the impact load experiments into the pressure wave propagation in water has been affected by a number of issues external to the research project.
Issues such as a lack of physical resources at RME at present due to other company commitments meant the fabrication of test frame components could not be completed by the scheduled date. The time frames laid down by USQ and RME for the Research Project did not coincide. This made it difficult to schedule required fabrication work and assembly labour so it could satisfy the restrictions of the two organisations. Finally a lack of experience with the electrical engineers at RME in working with PCB sensors to electronically generate the pressure wave and data logging equipment continued to cause delays in organising a time frame to conduct the experiment.

The process of physically analysing the integrity of the test frame structure would be lengthy and difficult due to the size and number of components in the assembly. The use of strain gauges supplied by USQ would need to be organised to complete this analysis.

There is still a need to collect and process data into the pressure readings through the water column following an impact load. A simulation of the same energy values provided by the LRT will be created to allow for work into the project to continue.

### 8.6 Conclusion

This chapter has discussed the system operation of the LRT test frame and provided an outline for the various components found in the test frame design. The discussion included detailed explanation of each component and its relationship to the other parts in the assembly. The assembly mechanical detail drawing for the ThunderBolt test frame are included as an appendix for the reader to browse through at his/her own leisure in order to gain a better understanding of the system.

A number of issues external to the research project were present in the manufacturing phase of system design. These issues resulted in the postponement of the component fabrication until 2008. Testing of the ThunderBolt frame will follow shortly after the completion of manufacture.

With the development of the ThunderBolt test frame now at a stand still the development of the secondary test frame to validate the response of the LRT system will be the focus of the project.
Chapter 9

9.0 Determining a Method of Energy Transfer

9.1 Introduction

Due to the inaccuracies of the energy value produced using a 1500J ThunderBolt hammer, a secondary testing rig is required to be designed, constructed and tested as a parallel project to the ThunderBolt test frame system. The second test frame simulation will need to be based on a method of energy transfer that is simple, and easy to calculate. This will allow for the easy prediction of energy values and pressure results from the experiments.

This chapter will bring forth potential conceptual designs for the energy transfer method to be used in the secondary test frame of the pressure wave experiments. Following an initial recap of non-explosive rock breaking technologies, it will delve into the constraints expected of the design, discuss a number of brainstormed ideas into the methods, analyse each of the conceptual designs using a decision matrix and finally select the design that will best achieve the required goals.

9.2 Energy Transfer Methods

Chapter 3 of this report delved into different methods of non-explosive mining and ore removal processes used in the mining industry today. A number of these ideas currently in practice could be used as the basis of the energy for the ThunderBurst system. The success of the 2002 ThunderBurst experimentation means that an impact-induced transfer of energy for hydro-rock fracture will continue to be sort after in this design.

An impact load on the water column within the rock using RME's modified LRT has proved successful in previous experiments, but a simpler design is required for the secondary test rig that can provide a comparison to the results received. It is expected that other methods of delivery could provide similar or a higher standard of efficiency and energy transfer with lower operating costs. From the LRT experiments, it is expected that a fresh look over the potential methods of energy
transfer may result in a more efficient method of experimenting with the impact force on the water column.

From the literature review (Chapter 3), a number of potential methods of applying the impact energy required to the water column are listed below.

- Drop weight on the column,
- Propellant-induced or pressure-induced slug fired onto the water column,
- Slow moving hydraulic-based pressure system pressing on top of water column, and
- Piston and cam arrangement regularly impacting on the water column.

9.3 Initial Constraints of Secondary Test Frame Design

Following discussion with members of RME, a few constraints regarding the selection of the energy method were formatted. These restrictions are put into place to ensure the design is selected according to a suitable standard considered by RME and will allow for the energy delivery system to be tested properly. Most of all, it is important that the system will work as RME intends it to. Prior experiments and subsequent knowledge in this area using RME's modified LRT hammer has meant the considerations imposed by RME on the constraints of the design have been based on the previous testing.

The manufacture and operation of the test equipment would be done in accordance with Occupational Workplace Health and Safety (OH&S) regulations. For this reason it is important for the design to be identified as safe for human operation in all reasonable conditions. Reasonable conditions are determined by the workplace for their employees in which the experiments are to be undertaken. This means it is essential for any safety issues, found in the conceptual designs, to be addressed immediately.

Height and size restrictions may also apply to the design. It is important for the design to fit in the constraints of the housing area specified by RME. The height of the structure must also be considered to ensure the system is able to be housed in the facility. As it is hoped to eventually implement this energy system to the driver-less ThunderBurst underground machine, the size of the system must be able to incorporate this need.

The chosen design or designs must have the approval of RME, taking into account other non-
engineering factors common to business. These other factors include cost, reliability, repeatability, feasibility and how reusable or recyclable the components of the design are. These constraints will be looked at in more detail in the decision matrix analysis of the designs in Section 9.5.

9.4 Initial Designs

This initial concept stage begins with brainstorming different ideas. Hand sketches have been used to convey the fundamentals of the design with a brief overview of how the energy transfer will be applied to the designated impact zone. The impact zone is considered to be a vertical water column, housed within a circular steel tube.

A number of methods were considered for the energy transmittance for ThunderBurst pressure wave analysis. All the energy transfer methods have been designed with an impact load applied vertically. It is ultimately in the method of applying the impact load that the main variations of design occur.

9.4.1 Pressure Tube

All the designs would incorporate a steel tube that houses the water column and rests on a steel base plate. This would allow for repeatability in the experiments over a long period of time. A number of pressure sensors are vertically aligned down the steel column to measure the changes in pressure within the water following the impact from the energy delivery device.

An outline of the pressure tube requirements as part of the test frame design is found in Section 4.3. Figure 4.3 displays a hand sketch of the basic components in the design.

9.4.2 Design 1

The first design incorporates the vertical gas gun housed at USQ. This design is discussed in Section 3.3.2. Some modifications would be required to install the pressure tube in the correct position beneath the exit point of the gas gun. These amendments would occur to the pressure tube or through a separate attachment to maintain the integrity of the vertical gas gun for future experimentation using the device.
The energy transfer system used in the ThunderBurst experiments transfers the energy externally to a separate slug. The vertical gas gun integrates pneumatic power to store pressure within a confined space at the top of the guide tube. A slug is discharged down the hollow tubing under the release of the stored pressure. A simplified sketch of the design is shown in Figure 9.2 below.

**Figure 9.2: Design 1 - USQ’s vertical gas gun with pressure tube**

The top of the steel pressure tube will be detailed to encompass the exit of the guide tube of the gas gun structure. This would allow for a smooth transition for the slug as it passes into the water housed within the pressure tube.

A design including a gun tunnel is dependent on the availability of the structure for testing.

**9.4.3 Design 2**

Design #2 uses a drop weight to deliver the energy to the water housed in the steel tube. A basic hand sketch for this conceptual energy delivery system is shown in Figure 9.3 of the report.

A demountable frame is constructed that includes two legs and a weight that fits between them.
The water column is positioned directly beneath the falling weight. The drop weight would be lifted to the top of the structure awaiting the correct time to be fired. When the weight is, it would run down the legs of the structure under gravity, guided by rolling wheels, and strike the water column with the circular shaped moil.

![Diagram of Design 2](image)

**Figure 9.3: Design 2 – Drop weight experiment with pressure tube and velocity sensors**

The velocity of the drop weight will also be measured at two different places during the experiment to gather information into the energy delivered by the impact load onto the water.

### 9.4.4 Design 3

The third conceptual design uses the theory of delivering a separate item such as a weight or slug vertically onto the water column. This idea was based on the vertical gas gun (Section 3.3.2) situated in the water laboratory at University of Southern Queensland (USQ).

This design will use a series of exploding cartridges to generate a shock wave within an enclosed space above the slug. Following the ignition of the cartridge, the resulting shock wave will force the slug down the guide tube and onto the water within the steel pressure tube. The same slug would then be reloaded in the guide tube before firing again in a similar process. It is hard to predict if the charges will be consistent in each test due to manufacture tolerances on the amount of powder in each cartridge.

Design #3 consists of a steel tube combined with an overhead frame to give the main portion of the
energy delivery system. A combustion chamber is incorporated into the top section of the guide tube. It is here that the ignition of the explosive cartridge occurs and the resulting shock wave will radiate toward the awaiting slug. An automatically dispensing cartridge holder is also used in the conceptual design. This is referred to as the magazine. It can hold a number of cartridges at once and only need to be refilled once the cartridges have been expelled.

A number of velocity sensors are also included to record the speed of the weight as it travels down the guide tube just before impacting on the water column. As discussed previously, the velocity sensors will help in the calculation of an approximate value for the energy transferred to the water. Figure 9.4 shows an outline of Design 3.

![Figure 9.4: Design 3 – Overhanging frame using explosives to fire slug into pressure tube](image)

The sketch shows the conceptual design for the energy delivery system using exploding cartridges. The design does not meet the objective of using non-explosive technology to generate the energy required for the impact load. It will be considered in the conceptual design phase though, as the cartridges will produce a small blast in a confined space. It would be expected that blasts be safely and easily controlled, although it would be unlikely to give repeatably accurate energy levels for each blast.

### 9.4.5 Design 4

The fourth design (Figure 9.5), uses the same thought process as the previous design, only uses
Chapter 9 - Choosing A Method Of Energy Transfer

steam pressure from a boiler to transfer the energy to the slug. Once the pressure in the collection tank at the top of the tube reaches the desired level, the pressure is discharged from the tank toward the slug through a small opening. The slug travels down a tube and subsequently imparts an axial load onto the water column located below.

Design #4’s energy delivery system will therefore require a boiler and associated components for water heating, a collection tank, drop weight and guide tube for the successful regulation of the experiment. Velocity sensors will be employed to determine the speed of the slug as it travels the length of tube to the pressure tube.

This design could also be classed as dangerous. Although it contains non-explosive technology, the use of heating elements and high pressure steam has the potential to cause harm to the operator or surrounding users if the boiler became unstable in operation.

9.4.6 Design 5

The fifth design moves laterally in the thought process. The hand sketch below (Figure 9.6), an
overhanging frame is placed over the water column housed in the reusable pressure tube. A motor, linkage arm and ramming piston are attached to the frame with the piston vertically aligned with the water. In operation, the motor will turn a shaft that is fastened to the linkage arm. The ramming piston will lift and drop continuously as the linkage arm rotates from the motor. A small cylindrical tube housed above the entry of the pressure tube may be required to ensure the piston moves vertically relative to the water column.

The impact loading of the ramming piston will not be very large when compared to other energy devices, but will give a consistent display of if, or how, the superposition of pressure wave reacts to multiple strikes.

![Figure 9.6: Design 5 – Repeatable piston arrangement with pressure tube](image)

### 9.5 Decision Matrix Analysis

The selection of the energy transfer method needs to be analysed in terms of how well it will perform in operation as part of Russell Mineral Equipment's ThunderBurst project. A decision matrix is utilised to weed out a range of potential designs and identify the best conceptual design. The decision matrix is a rating system used to rate conceptual designs for the ThunderBurst energy delivery system created to RME's specifications and constraints, and analysed under a number of criteria. Each criterion is scored with equal weighting within the matrix. A score between zero and three is given for every criteria depending on the potential performance and design functions of the conceptual designs. Six decisive factors were defined to help select the best and most practical
energy delivery system from the seven proposed conceptual designs. The six criteria used in the decision matrix and their potential impacts on the final conceptual design selected are explained in Sections 9.5.1 – 9.5.6 below.

9.5.1 Size

The size of the energy system is a major consideration in the analysis using a decision matrix. As discussed previously in this chapter, the size of the energy system is important as it must fit in the space restrictions set out by RME. The estimated height to create the required energy for the rock breakage must also be considered.

In relation to the energy system attached to the driver-less ThunderBurst system, size is of critical importance. If the energy system is too large, it may become difficult to manoeuvre around the mine. If the energy system is physically too small, it may not produce enough energy to destroy the rock.

9.5.2 Functionality

The ease of use of the machine and energy transfer system is an important aspect of the design that will be analysed with the decision matrix. If the functionality of the energy delivery is too difficult, it will be of little use to the ThunderBurst driver-less machine, or other machines that require this energy source.

9.5.3 Practicality

The selection of the energy transfer method must be practical to the given application. It is hoped to one day incorporate this chosen design into the driver-less ThunderBurst machine, thus can not be excessively large, difficult to manoeuvre or dangerous in operation.

9.5.4 Cost

Like most research and development, the cost of the project is of utmost importance to companies
who sponsor the work. Developing new methods will cost a lot of money in engineering design time and assembly. The total cost of producing the ThunderBolt test frame will include:

- Design cost,
- Fabrication and machining cost,
- Purchasing of bought-in items,
- Assembly time, and
- Testing cost.

The selection of components used in the project will also play a part in the cost analysis. If a design needs the use of specific components or materials that may be hard to source, the cost of the method will be greater than a simpler, more generic design.

### 9.5.5 Safety

The safety of the design is a critical aspect needing extra attention for the energy transfer selection. Depending on the components and technique selected, the safety issues that arise will be unique in comparison to each other. If the conceptual design involves the use of high pressure or tall overhead frames then there will need to be extra safety regulations to ensure the operator and spectators remain safe around the device.

### 9.5.6 Experimental Repeatability

The energy transfer used in operation will need to be one that applies the load in a readily repeatable manner. The ThunderBurst driver-less machine will want to manoeuvre to and destroy each boulder as quickly as possible. From previous experiments, it is unclear how many strikes will be required to break each rock, and therefore multiple strikes could be necessary during operation. For this reason, how quickly each boulder is broken up is a major concern in the design and the repeatability of the energy impacts is important for future designs.
The decision matrix for the energy transfer systems is shown below. Each conceptual design was given a rating using:

3: Good  
2: Satisfactory  
1: Poor  
0: Very Poor

### Table 9.1: Decision Matrix

<table>
<thead>
<tr>
<th>Design 1 Gas Gun</th>
<th>Design 2 Drop Weight</th>
<th>Design 3 Explosives</th>
<th>Design 4 Steam</th>
<th>Design 5 Piston</th>
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<td>1. Size</td>
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<td>2</td>
<td>1</td>
<td>3</td>
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<tr>
<td>2. Functionality</td>
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<td>5. Safety</td>
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<td>0</td>
<td>2</td>
</tr>
<tr>
<td>6. Repeatability</td>
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<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
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<td>8</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

From the decision matrix shown, the conceptual design that is most appropriate for the experiments into the ThunderBurst energy delivery system into the pressure wave analysis is Design #2. This design incorporated the use of drop weights to create the energy required for the impact loading on the system.

This design scored highly in the areas of repeatability and functionality in the experiment. It would also outshine the subsequent designs in practicality as it is most appropriate for the experiments looking to be conducted due to the ease in adjusting the energy values. It was evident that the major advantages of the system are in the ease of adjustment and experimental repeatability as the change of energy levels comes from a variation of either height or weight. It was surprising that the potential cost scored lowly as the design is reasonably simple. The height of the demountable frame and the expectation of long fabrication times were the major reasons behind the low cost score.

Higher scores were expected for Design #1 as it seemed to be the most viable and quickest selection of the energy transfer system. It would also be the quickest to design as it would only require a retrofit of the pressure tube to operate. The height of the structure required to generate the energy for the experiment was a major downfall for this design. A lack of practicality in loading and reloading the slug, as well as waiting for the pressure to reach the desired value between each test
also prevented this concept from scoring higher. The selection of Design #2 over Design #6 shows that there is the potential for more improvement to the energy delivery device used in previous USQ experiments.

Conceptual Design #5 scored surprisingly high considering the simplicity of the final design. It would have a medium potential cost due to the acquisition of an electric motor to drive the ramming piston. This design would be safe and repeatable but was lacking in its functionality and practicality.

Both Design #3 and #4 scored poorly using the decision matrix analysis. Both designs were based on the vertical gas gun and would cost a great deal of time, revisions and money to create a working design from scratch. Safety issues dominated the scores for these designs in a negative fashion and were not considered particularly practical for the use in the ThunderBurst experimentation.

The advantages and disadvantages of conceptual designs were also scrutinised critically to detect potential troubles in the system in either the industry or marketplace. Due to the number of conceptual designs being considered in this analysis, the discussion of the pros and cons of each design will be kept to Design #2.

The ease in which the energy can be calculated and adjusted is a major advantage in using this method of energy transfer. As discussed previously, the height and/or weight of the system can be changed to modify the resulting impact energy. This is due to the relationship in the equation for kinetic energy

\[
\text{Kinetic Energy (J)} = \frac{1}{2} m v^2 \tag{9.1}
\]

Where \( v \) = final velocity (m/s), and
\[ m = \text{object mass (kg)}. \]

The functionality of the design was another major advantage in selecting Design #2 as the energy transfer device. The use of a set mass in the experiments means there will be very close accuracy between the tests performed. This experimental repeatability will give the results much more meaning and show up any errors seen in the results.

There would also be a number of disadvantages by selecting this test rig system. The size, and
especially the height, of the system would be the major concern in the design. Having a very tall system would be problematic when attempting to install the system at RME facilities. This height could be potentially too high to be housed indoors. A large frame to support the drop weight experiment would also give rise to high fabrication and labour costs.

9.6 RME Considerations

Due to time limitations on the experiment, RME has suggested the continued use of modified ThunderBurst hammer. The 1500J ThunderBolt hammer has been previously successful in the 2002 experiments and is still in storage at RME's facilities. This would save a lot of time in constructing the energy transfer device before conducting the experiments into pressure wave propagation. A close approximation of the energy values is known for this system which means a conceptual test frame can be proposed and designed around this knowledge.

The sponsorship of RME into this project means the opinions expressed by the design team are highly valued. For this reason, RME's modified 1500J LRT will be used as the system for energy transfer in the experiments. This would mean disregarding the final results determined by the decision matrix.

The advantages and disadvantages of Design #1 for the modified 1500J ThunderBolt hammer as the ThunderBurst energy source are also looked at in detail. This was to get a proper feel of the system before the 'ThunderBurst' test frame design is undertaken.

The use of the modified 1500J hammer brings a number of positive influences to the 2007 experiments. A permanent structure to hold the 1500J hammer will regulate the experiment and give consistent results. It is expected to have very few safety issues, with the permanent frame alleviating the concerns held from the suspension of hammer from a forklift in the previous ThunderBurst rock-breaking work. The ThunderBolt range of hammers has been proven in the field and is considered to be safe for use in all conditions regarding mill relining around grinding mills.

As seen in the decision matrix, the use of the 1500J ThunderBolt in Design #1 also poses some potential design problems that will need to be overcome. The weight LRT hammer positioned above the water column will need to be adequately supported by the frame. This means the size of
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the structure will need to be large to handle the stress in the frame. The large size of the frame is a major problem in the overall scheme as it makes it difficult to transport and manoeuvre between locations around RME. The cost in fabricating the test frame and the use of the hydraulically driven ThunderBolt system will be above average in comparison with the other designs. Due to the positioning and the average practicality of the LRT during operation, a remote pendant will be required to fire the hammer as it will be unsafe for an operator to stand behind the hammer as in normal activity.

9.7 Chosen Conceptual Design

The selected conceptual design was Design #1. The vertically mounted 1500 LRT will sit above the water column on a permanent frame to minimise the potential for errors due to inaccuracies when striking the water in operation. The LRT would create an impact load on the water column housed in a permanent steel tube and allow for repeatable experiments with a high degree of accuracy.

This selection was determined by Russell Mineral Equipment Pty Ltd, due to the availability of the ThunderBurst energy delivery system designed and built in 2002. This system will give repeatable experiments with high energy blows which are ideal for the analysis into pressure wave propagation and the investigation into the possibility of wave reflections and superposition through the column following multiple strikes.

The decision matrix shows that the drop weight test would be most appropriate mainly due to the accuracy of the energy generated during the experiments. This method was not selected because the influence of RME's design team had greater weighting than the decision matrix analysis. Only one point separated Designs #1 and #2. Thus, the results of the decision matrix were not considered to be a major factor in the selection of the most appropriate system for this round of experimentation.

9.8 Potential Design Implications

As discussed in the disadvantages of the design incorporating the modified 1500J hammer, there will be a number of implications that will be need to be addressed during the design process of the
energy delivery process and pressure wave analysis.

The size of the frame may cause trouble with restrictions on the physical surroundings at the storage facility at RME. The final frame design is going to need a large base to ensure the stability of the structure when assembled with the energy delivery device. The physical restrictions of the testing location will also affect the potential height of the assembly and this will also need to be closely monitored during design process.

The strength of the frame will need to be addressed during the design phase due to the high stresses that will exist through the frame by positioning the LRT vertically. Another issue that will affect the frame design will be preventing the recoil of the hammer and dynamic loading following a fire of the device.

The major concern of the design is in the LRT hammer itself. The inaccuracy of the modified LRT to impart exactly 1500J with each strike will create problems in the design and analysis of the experiments. The LRT hammer is tuned to 'feel' by the fitter, meaning there is no calibrated test on the hydraulic power needed for the hammer to produce 1500J of energy during each strike. This means the hammer could be tuned anywhere between 1250J and 1750J depending on the initial setup of the hydraulic fluids by the fitter. The ability for the LRT to create consistent series of impact strikes is unknown and could create problems in the analysis of the pressure waves during operation. The level of energy losses from the impact on the water column is also unknown from previous experimentation.

9.9 Conclusion

This chapter has introduced possible conceptual designs for the energy transfer system that will be used in the analysis of the pressure waves through the incompressible fluid. A number of possible designs were investigated using a decision matrix to try to determine the most appropriate method for the required method of simulating RME's vertically suspended 1500J ThunderBolt hammer.

A drop weight is selected to supply the experiment with the impact load. This design was selected after all potential prospects were analysed using a scoring system in the decision matrix and taking into account comments from project supervisors and RME engineers.
The drop weight test frame conceptual design is free-standing structure housed over the external surface of the pressure tube. A drop weight falls down the tube onto an impact moil resting in the water. This is achieved using a quick-release mechanism engaging at the top of the tube. The resulting pressure wave travelling through the water is recorded using PCB pressure sensors.

The following chapter will delve into the conceptual design of the test frame to hold the ThunderBurst energy system during the pressure wave experiments.
Chapter 10

10.0 Conceptual Design of ‘Calibration Tube’ and Drop Weight Testing

10.1 Introduction

The introduction of a secondary testing rig is required to be designed and tested in order to validate the results from the testing conducted with the permanent LRT test rig.

With the ThunderBolt test frame unable to be completed before the research project deadline, the drop weight test frame assembly will become the focus of the dissertation.

This chapter will bring forth potential conceptual designs of the drop weight test frame using the conceptual design decided upon in Chapter 9. It will discuss the constraints expected from Russell Mineral Equipment, provide some initial ideas for the design, analyse each of the conceptual designs and finally select the design that will best achieve the required goals.

The selected design will undergo a process of evolution to mold it into the most suitable design for the given load cases.

10.2 Simulation of Experiment

Chapter 9 of the report shows the use drop weight testing was the preferred option for the energy delivery device to compare the pressure readings with the ThunderBolt project. This form of testing is easy to construct, easy to adjust to vary the potential energy of the system, and easy to calculate the potential results using kinetic energy equations. It would be ideal as a simulation of the energy produced by the LRT.

This test will give RME a chance to prove the theory of pressure wave propagation in the water column from an impact strike. An opportunity also arises to check the set up of the system and to refine the operation of the pressure sensors and electrical components for future testing.
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The calibration of a hydraulic hammer to the desired energy value is often done “by feel” and no exact measurements are often recorded. Drop weight testing can be used to tune the LRT to exactly 1500J through a comparison of pressure wave results. An impact of 1500J should give a similar pressure profile reading whether it is conducted using a drop weight or the rock-splitter moil of a hydraulic recoilless hammer. Following the analysis of the two wave profiles, the hydraulic pressure in the LRT powerpack can then be altered until the readings become similar in amplitude.

It could also be possible to predict the size of the pressure wave profile if the LRT hydraulic fluid pressure was increased beyond the value that gives 1500J per strike. Comparing the results of the hammer impact at an unknown energy level to the 1500J strike should be able to be traced back to an appropriate reading.

10.3 Design Constraints

The simulation of the energy produced by the ThunderBolt hammer involves incorporating a 30kg mass falling at a velocity of 10m/s. This was suggested by RME, due to the rough similarity of the mass and velocity values used in the LRT design. From Equation 9.1, the calculation of the kinetic energy in the system would equal a 1500J dynamic blow to the water column.

The time constraint on the project is the major concern of the drop weight experiment. Fabrication and assembly time is critical due to other commitments and deadlines within the company. The design of the experiment must incorporate few components with minimal welding and machining to reduce the time spent in manufacture.

The system will begin with the same water column design produced in the final test frame solution will reduce design time. It is unlikely that this portion of the system will alter with the new energy delivery device affiliated with the ThunderBurst experiments.

RME design team have strongly suggested developing a structure to perform the drop weight testing by allowing the weight to free-fall down a guided “calibration” tube onto a stationary moil positioned in the steel pressure tube. This will negate any possibility of the moil not being correctly aligned with the water column or the drop weight during the test.
10.4 Initial Design Thoughts

As discussed previously, there is the potential for problems to arise if the moil arrangement is sitting above the water column before the drop weight is released. The drop weight could be misaligned relative to the entry of the hollow steel cylinder, and lose energy in the form of frictional forces in the process of repositioning the moil under the loading of the drop weight. This can be overcome by initiating the shaft of the moil in the hole inside the pressure tube and positioning 1000mm above the steel plug located in the base of the tube.

The impact moil positioned in the water column should be treated as a second weight in the system. This impact weight will have the same mass and diameter as the drop weight released from the top of the calibration tube. The drop weight will fall down the calibration tube and strike the second weight located in the water. Theoretically, kinetic energy of the drop weight should be successfully transferred through the weights and into the water with minimal loss in energy through the impact loading according to the conservation of momentum theory. Energy lost in the impact will occur through heat gain and an increase in noise.

The kinetic energy of the falling weight is calculated using Equation 9.1, with the final velocity of the mass is determined by:

\[ v = \sqrt{u^2 + 2as} \]  

(10.1)

where 
\( v \) = final velocity,  
\( u \) = initial velocity,  
\( a \) = acceleration due to gravity, and  
\( s \) = displacement.

To reach the final velocity of 10m/s resulting in a 1500J kinetic energy strike, the displacement of the weight in the tube has to undergo a 5.1m drop. Air resistance is neglected. The overall calibration tube assembly will therefore need to be a minimum of 6.5m high. This is to account for the height of 1.2m for the pressure tube and approximately 200mm for the impact moil resting in the water.

Lifting the 30kg weight to the top of the calibration tube has to be investigated. A 30kg mass is not considered to be overly heavy. This means manually lifting the weight via a pulley system would
not cause problems from the perspective of an Occupational Health and Safety officer. A hand winch or block and tackle arrangement could comfortably handle lifting the small weight 6.5m into the air. Another alternative would be to reinvestigate the use of the pneumatic winch as discussed in a previous iteration of the ThunderBolt test frame assembly design. A similar problem regarding the use of an air compressor to power the device may occur as in the previous design system.

RME have suggested an investigation into the possibility of designing the calibration tube assembly to be retrofitted onto the lower frame of the original test frame assembly of the ThunderBolt pressure wave propagation project. Use of lower frame will not be useful for this research project, as the fabrication the lower frame would need to be completed before the system would be functional. The drop weight testing can be an ideal substitution for the modified 1500J LRT testing should the rock-splitter energy delivery device be indisposed or if a direct comparison is needed between the pressure waves of the delivery device and the known energy values of the drop test.

Nonetheless, a look into retrofitting the calibration tube to the lower frame was performed as an initial concept design. This attachment is quite possible due to the simple connection area made between the lower frame and upper frame in the permanent test frame assembly. Similar to the test frame assembly, slotted holes could be incorporated into a mounting plate of the circular drop tube with bolts fastening the two items in place. This would provide a secure, permanent arrangement for the use of dropping a weight onto the water column.

**10.5 Conceptual Design #1**

As discussed in Section 10.4, this design is produced to verify the potential for future development of the drop weight testing following the fabrication of the lower frame used in the test frame assembly discussed in Chapter 8. This design is not considered as a possible design solution to the drop weight testing and will be disregarded in the selection of the final system. RME wanted a conceptual design of how a drop weight experiment could be conducted using componentry from the test frame assembly. This would provide an ideal backup solution if the rock-splitter LRT is out of commission during future testing of the ThunderBurst project. If future work into the ThunderBurst pressure wave propagation using drop weights is continued, Conceptual Design #1 will provide a starting point for further development.

The lower frame used in the conceptual test frame assembly provides a foundation for Conceptual Design #1. As discussed in Section 10.4, the same water column arrangement provided as a design
solution for the test frame assembly will also be used to save time. The position of the water column relative to the lower frame will need to change due to the removal of the upper frame and rock-splitter from the system. The lower frame and water column assembly have been previously detailed in Chapter 8.

Two weights are employed in the system to transfer the kinetic energy into the water column. An impact moil will rest on the water column. A secondary weight, known as the drop weight, will free-fall down the calibration tube and strike the impact moil. A pneumatic winch discussed in Chapter 6 supplies the lifting force to raise the drop weight to the zenith of the tube. Steel cable is constantly attached to the rear of the drop weight and with the winch changes the vertical position of the weight inside the tube.

The proposed Conceptual Design #1 for the calibration tube and drop weight assembly is shown in Figures 10.1 – 10.3.

![Figure 10.1: Conceptual Design #1 – Isometric View](image-url)
Chapter 10 - Conceptual Design of ‘Calibration Tube’

It is important to note this design is a basic concept and will not be used for the drop weight testing.

### 10.6 Conceptual Design #2

A free-standing cylinder tube is the foundation for the second concept design of the drop weight tests. A modified version of the water column assembly designed in the ThunderBolt test structure houses the water required in the experiment. The drop tube resides over the pressure tube of the
water column assembly with a series of guides helping to maintain vertical alignment between the two cylinders. A hand winch raises the drop weight assembly to the desired height above the impact moil to produce a 1500J energy strike using a steel cable and pulley arrangement. A quick-release mechanism attached to the rear of the drop weight is activated once the final position has been reached. This allows the weight to free-fall inside the tube and impart the energy into the water through an impact moil resting on the water. The quartz crystal inside a pressure transducer senses a variation in water pressure and sends the resulting voltage readings in a waveform to a data logger.

Conceptual Design #2 incorporates parts, which are reasonably simple and easy to fabricate, and assemble. This is to reduce the time taken for production and will allow for testing to occur before the completion of the research project. Figure 10.4 provides an overall appreciation of the design.

The calibration tube is a long cylinder tube situated over the pressure tube and rests on the outside a number of steel blocks extended radially from the water column. Cut outs along the calibration tube are required to help complete various activities of the experiment. There is no welding on the calibration tube. This is to make certain the extruded tube remains straight over its length.

It was suggested to add air relief holes down the calibration tube between the top of the tube and the top of the impact moil. The theory behind the suggestion revolves around the expectation of air within the drop tube being compressed as the weight free-falls toward the impact moil. Air inside the tube will be displaced during the drop. Close clearances between the diameters of the two surfaces mean little air escapes down this avenue. The majority of air is therefore pushed down the tube ahead of the weight. If the air is not released, the pressure of the remaining air will increase and will provide an increased resistance for the weight to push through. As stated in Section 10.4, friction due to air resistance is currently neglected during the fall; however it may be considered as an energy loss if the pressure can not be released.

The idea of adding more holes to the tube was disregarded. The large holes already incorporated into the calibration tube for locating the safety pin, reattaching the quick-release mechanism and viewing the contact between the two weights is likely to provide enough exit space for the air to escape once the weight is released. This will not affect the pressure in the tube.

The water column design remained the same as in the test frame assembly. This design was however, modified slightly to incorporate the new method of energy delivery. The pressure tube
part includes steel blocks or guides located on the outer surface of the steel cylinder to hold the free-standing tube in a concentric position relative to each other. A circular groove is machined into the base plate for the calibration tube to rest in and to help stabilise the free-standing assembly.

Figure 10.4: Conceptual Design #2 – Isometric View
A manual hand winch (Figure 10.5) is chosen to raise the weight to its final position before release. The winch is located a set distance from the point of impact to remove the possibility of injury following the strike. A separate stand is incorporated to provide a stable mounting position for the winch and allow for easy winding of the handle. An overhead pulley system works in conjunction with the hand winch to lift the drop weight assembly to the peak of the tube via a steel cable. This pulley is shown in Figure 10.6.
Once the weight has reached the maximum height of the calibration tube, a quick-release mechanism engages, releasing the drop weight. The quick-release is mounted to the rear of the weight. Beam deflection theory provides a basis for the quick-release system, and allows the weight to fall freely without the restrictions of a steel cable following the weight down the tube.

Figure 10.7 shows the position of the drop weight and impact moil in relation to the pressure tube following the drop test. The location of the viewing windows and reattachment point of the quick-release mechanism are clearly shown. It was determined that any observers and the operator will be interested in watching the impact between the two weights and the difference in height during the compression of the water column using the impact moil. A large hole is required for the reattachment of the quick-release mechanism to the rear of the drop weight. Holes are also cut into the drop tube for the pressure sensors and associated cables to reach the pressure tube. These cutouts allow the air to escape as the weight falls. This will dispel concerns regarding an increase in drag of the weight and compression of air in the tube during the test.

![Figure 10.7: Completed position of weights following drop test](image)

**10.7 Chosen Design**

Due to time restrictions on the project, there was not enough time to fully research and develop a number of different conceptual designs and analyse using a decision matrix. This device is required
Chapter 10 - Conceptual Design of ‘Calibration Tube’

to simulate the 1500J energy strike using kinetic energy produced by dropping weights onto the water column. As Conceptual Design #1 requires the use of the as not yet built ThunderBolt experimental test frame, Conceptual Design #2 was the only choice remaining for the structure used during the drop weight experiments.

Conceptual Design #2 uses a free standing calibration tube assembly to produce kinetic energy from releasing a 30kg weight from the top of the 6.5m tube. The drop tube rests over the outside of the pressure tube, similar in design to the water column assembly from the experimental test frame system. A hand winch and pulley arrangement lifts the drop weight to the pinnacle of the tube. It is here a quick-release mechanism engages, allowing the weight to free-fall down the tube and strike an impact moil resting on the water. Pressure changes are noted by a series of steel pressure transducers lining the pressure tube.

This design will adequately fulfil the original requirements specified on the project by RME in Chapter 1.

Similar problems seen in Conceptual Design #1 are required to be solved in the development of Conceptual Design #2 throughout the design evolution of the calibration tube assembly. Assembling the final design could prove difficult. It will be difficult to locate the impact moil and drop weight inside the calibration tube before being lifted over the pressure tube using a crane. A method of quickly assembling the system without damaging the equipment needs to be developed during the design process of the system.

10.8 Initial Design Considerations and Theory

The overall height of the assembly will introduce an issue relating to the location of the calibration tube during testing. Common facilities in industry vary in ceiling heights between 4.5m and 6m. This will mean the experiment will be conducted in an outside environment. The external environment could influence test results slightly. Factors such as wind loading and corrosion from precipitation may affect the results from testing. The calibration tube will need to incorporate a dynamic factor according to Clause 4.6.2 from AS1418.1-2002. This factor will give a value for the wind loading that is likely to be expected from working outdoors.

Unlike the first design, there will be problems associated with the use of a free-standing drop tube. These problems are limited and will not dramatically change the design of the assembly. It is
unclear at this stage how much stabilising, either at the top of the tube or around the base, will be adequate to hold the structure steady for the experiments. If the tube is not vertically aligned with the water column when the drop weight is released, the weight may rub the sides of the tube and lose a portion of the kinetic energy required for the test.

The rapid release of the drop weight will bring a dynamic load factor to the assembly that needs to be incorporated into the calculation of load values for the final design. This load factor is described in AS1418.1-2002. Clause 4.5.3.4. The term ‘rapid’ infers the weight will fall quickly down the calibration tube once the quick-release is activated. From AS1418.1-2002 Clause 4.3.5.4, a rapid release from a grab holding device requires a dynamic load factor of:

\[ \Phi_3 = 1 - 1.5 \frac{\Delta W}{W} \]  

(10.2)

Where \( W \) = total weight on hoist, and
\( \Delta W \) = drop weight.

This dynamic load is applied to the system described in Clause 4.5.3.2 (6). The rapid release of the weights creates peak intensity of the loads on the calculated using equation 10.3.

\[ P_{rd} = (P_h - P_t) \Phi_3 \]  

(10.3)

Where \( P_{rd} \) = the peak intensity of the loads acting on the hoist as a result of the rapid releasing
\( P_h \) = hoisted load as specified in clause 4.5.3.1
\( P_t \) = the upper estimate of the part of the load being released
\( \Phi_3 \) = rapid load release dynamic factor for rapid load release as given in clause 4.5.3.4

This therefore means the peak intensity of the system following a rapid release of the drop weight is -4.53kg.

The difficulty in raising the 6.5m calibration tube over the pressure tube and into position during assembly will also need to be addressed. This will need to be completed with the help of an external crane. Welding lugs on side of the tube to provide a specific connection point for the crane.
may distort the concentricity of the tube in relation to the drop weight during the weld process. This could again mean the weight will hit the side of the calibration tube and lose energy during the fall.

The interaction between the quick-release mechanism and the drop weight will also need to be refined before the final solution. The discharge device is attached to the rear of the drop weight and allows the weight to fall freely down the tube. It is critical the drop weight is released at the correct height to produce the expected 1500J of energy. As shown in Figure 10.8, the quick-release consists of two flat steel segments located on either side of a tail at the rear of the drop weight.

The quick-release is based on the theory of beam deflection. According to Gedeon (2001), if a vertical load is applied to any beam cantilevered from a fixed site, the distance of the beam deflection (Figure 10.9) at the extent of the beam is calculated using:

\[
\sigma_{\text{max}} = \frac{3 E t}{2 L^2} d
\]  
(10.3)

Where \( \sigma_{\text{max}} \) = maximum stress,
\( E \) = modulus of elasticity,
\( t \) = thickness,
\( L \) = length, and
Chapter 10 - Conceptual Design of ‘Calibration Tube’

\[ d = \text{deflection distance.} \]

![Figure 10.9: Straight cantilever beam deflection](image)

This theory can also be applied to the separation of the two steel plates in the quick-release mechanism. If an equal load was exerted on the long face of the steel plates at the same time, this would resemble two vertical loads on a cantilevered beam discussed in Equation 10.3. It would be difficult to apply this load simultaneously in an outward direction unless a taper exists on the tail of the drop weight. Holding the drop weight in a certain location in the tube, while continuing to pull the quick-release mechanism vertically will force the side steel plate against the taper of the tail. Continuing to lift the quick-release will force the steel plates to slide outwardly along the taper applying an ever-increasing load on the flat face of the plate. This means the plate will undergo beam deflection and will bend until the taper is complete and the weight is able to fall down the tube.

The quick-release wants the steel plates to deflect a distance of 3mm to ensure the drop weight will clear the lifting supports. The maximum design stress for FMS is 180 MPa. The fixed point of the cantilever is assumed to be centre of the bolt hole. Therefore, the critical factors in the theory that can be applied to the quick-release device are the length of the beam and the beam thickness. Standard 5mm FMS was selected for the design of the steel plate due to its availability to RME. A calculation of the quick-release deflections reveals the device needs to be 160mm long to allow for the necessary separation of the supporting plates.

**10.9 Design Process**

The initial design of the calibration tube assembly was based on the selected free-standing concept design. It is up to the designer to now make this assortment of ideas proposed in the conceptual
design a reality. The simplistic design and minimal components required for the drop weight test gives some reprieve from the tight time restrictions that exist on the project.

The calibration tube assembly was refined through the implementation of design solutions in two distinct steps. The first step occurred with the help of the design team from RME. Finally, USQ included other concerns regarding to the project that may increase the efficiency and accuracy of the drop test arrangement.

10.9.1 RME Design Review

A review was conducted on the individual components of the calibration tube assembly with members of RME's research and development team. The goal was to reduce the time required to fabricate and assemble the structure.

Minimal design change was required to the overall assembly. Individual components were refined to simplify the complexity of the assembly. This was to increase the functionality of the arrangement and attempt to reduce the amount of fabrication and assembly time required without jeopardising the simplicity of the design. Modifications to the part designs made during the design process are detailed below.

The calibration tube is a long cylindrical cylinder tube that fits over the outside water column assembly. Changes were made to increase the size of the tube cutouts and their relative locations in the system. The operator viewing window showing the strike of the weights was rotated 180° to protect the operator in case something goes wrong during the impact. The top cutout in the tube was increased in size to help ease the correct attachment the quick-release mechanism to the drop weight. A round steel ring is added to the top of the calibration tube to act as the surface which applies the axial reaction force to the quick-release mechanism. This plate integrates a large hole to the system, allowing the steel cable and quick-release device to safely pass through. The drop weight cannot pass through the hole and provides enough resistance on the system to cause beam deflection quick-release which therefore fires the weight.

The pressure tube assembly is reverted back to the simplistic design seen in the design iterations of the ThunderBolt experimental test frame assembly (Chapter 6). This means the plug, o-ring and base plate were removed from the assembly, and the hollow steel cylinder was welded directly onto the floor plate. A large chamfer was added to the outer edge at the bottom of the pressure tube as
part of the weld preparation process. This chamfer provides room for weld to be added without affecting the location of the calibration tube on the face of the floor plate.

Only minor changes were made to the simplified water column arrangement. Adjustment to account for errors between the alignment of the drop weight and the water column was no longer required in the system due to the calibration tube encompassing the pressure tube and drop weights. A series of guides were added to the outer cylindrical face of the steel pressure tube to help hold the calibration tube in the correct position.

Two high-pressure hydraulic ball valves are used to control the flow of water and air in the system. This therefore controls the pressure flow within the tube. Ports in the side of the steel cylinder to fill and release the fluid were required. It was also determined that milled flat surfaces be added to the outside of the tube to provide a safe mounting face for the shoulder of the ball valve to firmly thread up to.

An internal housing for a rod seal was also needed. This seal locates around the shaft of the impact moil resting in the fluid and incorporated to minimise water leakage from the top of the column. Due to the tight tolerances between the diameters of the moil and the hollow cylinder tube, the housing needed to be machined into the inside surface of the pressure tube. The location of the seal was set to 1000mm above the floor plate to keep the water column set at this value.

The floor plate became a more critical section of the assembly with the removal of the water column base plate. As the steel tube now is fixed directly to the floor plate, the thickness of the plate was increased to 20mm to ensure the pressure loading through the water does not affect the stability of the water column assembly. A groove was also added into the top face of the floor plate around the area of the calibration tube for the tube to rest inside. This will help locate the tube during assembly and hold the base of the tube steady while testing is undertaken.

A problem may arise in the pulley assemblies during the raising of the weight if the sheave were to move from the centreline of the system along the axis of the supporting pins. Spacers were added to the pulley arrangements between the sheave and the sides. This ensures the sheave remains in the centre of the frame and will not create dramatic issues by twisting and loading the cable inappropriately.

The consideration was also floated to have threaded holes in the calibration tube for the housing of
velocity sensors. The sensors will gather and record the velocity of the drop weight as it falls. Both sensors will be located in close proximity to each other near the drop weight impact zone. An average reading of the two velocities will be taken as the final speed the weight fell before the energy transfer. The request for the tapped holes for the velocity sensors was heeded and is shown in the calibration tube assembly.

### 10.9.2 Other Concerns

Further development in the design was required in order to produce the most efficient and effective drop weight test possible under the current project conditions. USQ introduced a number of suggestions to the development and design of the calibration tube arrangement for pressure wave analysis. These considerations from USQ are outlined in the following section of the report.

There is a chance that the guides around the pressure tube will not adequately support the structure when the weight is at the top of the system. This can mean the top of the frame can sway during operation while the bottom remains fixed. This will induce stress through the calibration tube, steel pressure tube and the weld fixing the pressure tube and floor plate. The free-standing tube may therefore require bracing around the top of the tube to prevent oscillations of the frame and to reduce the stress through the system. Failure of the weld surrounding the pressure tube may also be a result of cyclic loading of the frame due to the oscillations. The addition of extra bracing to the top of the frame must be discounted due to the experiment being conducted outside. The supports extending from the calibration tube must connect to another structure, which is currently unavailable at RME's facilities.

There was still a concern regarding the oscillating of the calibration tube assembly. Another potential problem was found in the positioning of the pulley assembly. Having the steel cable run directly from the hand winch stand to the overhead sheave will create a lateral force on the calibration tube from the steel cable pulling on one side of the frame. Winding the winch handle by hand will impart a variable tension in the steel cable, creating a variable load on the calibration tube and changing constantly changing the top position of the tube. Oscillations may cause the tube to vibrate at the natural frequency of the system and result in destructive damage to the frame.

The separate hand winch stand was removed from the system and replaced with an appendage located horizontally from the calibration tube. This support arm is made from extruded steel RHS and provides a mounting arrangement for the hand winch. The height of the support arm is set to
an appropriate position for easy operation. The winch by fastened down to plate for easy removal. The steel cable is run from the winch, through the hollow section of the support arm and around an additional sheave close to the cylinder tube. This second pulley was added to run in line to the overhead pulley system to limit the lateral forces from the steel cable on the tube. It is expected the removal of the lateral loading will prevent the tube from being pulled over and creating oscillations.

The size of the floor plate was reduced with the removal of the hand winch stand. Stability of the system can be retained by fastening the smaller floor plate down to the concrete floor using chemset bolts. This will save time by reducing the effort to transport the large plate from production to the area where the experiments will be conducted.

The number of guide blocks on the outside of the pressure tube was reduced to simplify the fabrication process. The nine separate blocks were replaced with two rings to hold the drop tube in place. The removal of the groove to hold the tube in position during operation meant now more emphasis on the guides is required to hold the structure steady.

The plate used to apply the axial reaction force on the drop weight was removed from the top of the calibration tube to reduce the amount of fabrication on the drop tube. The removal of this plate meant a change was needed to the arrangement and point of release of the drop weight. A new surface was created to oppose the lifting of the drop weight and engagement of the quick-release mechanism. Increasing the height of the pulley arms and adding a second series of flat steel plate provided enough room to add a set of pins to the arrangement. The contact area of the pins will provide enough surface area to prevent the weight from lifting and separate the arms of the quick-release mechanism using beam deflection theory.

A safety device is needed to prevent the drop weight causing injury during operation. There is the possibility the drop weight is released early while being raised up the drop tube. If an operator is working on the calibration tube assembly while the drop weight is raised, the falling weight could shear or crush fingers or hands. A safety pin is added above the impact moil viewing window that will prevent the weight from reaching the operator during a fall. This pin can be removed when all people are a safe distance from the strike zone of the experiment.

**10.10 Final Design**

The final calibration tube and drop weight design was almost the same as Conceptual Design #2.
Only minor modifications were required to reach complete design. This final design took into consideration a number of comments introduced by USQ in conjunction with the research and development team of RME.

The complete assembly is displayed in Figures 10.10. The structure stands almost 7.4m high and weighs nearly 290kg. The design will accomplish the specifications on the project and provide RME with test data into pressure wave propagation following a known axial load on a column of water.

Figure 10.10 displays the lower portion of the drop weight structure. The pressure tube, base plate, hand winch, RHS support arm, impact moil and pressure sensors are visible in the picture. The base plate and pressure tube is fastened to the concrete floor in its final location. An outline of the individual components listed above, as well as others found in the calibration tube assembly is detailed in this section of the report.
Chapter 10 - Conceptual Design of ‘Calibration Tube’

Figure 10.11: Lower section of Calibration Tube Assembly

The calibration tube is a seamless cylinder tube that sits around the outside of the water column assembly. Minimum fabrication on the tube reduces the time and manufacturing processes required to complete the component. An introduction of welded joints or extra steel features along the length of the tube could influence drop weight trajectory relative to the concentricity of the calibration tube during the experiment. For this reason, a seamless tube or pipe was selected as the material for the tube. It is 6.5m in length to ensure the drop weight completes the 5.1m fall in order to transfer 1500J of kinetic energy to the water column.

This item also houses the two weights used to transfer kinetic energy through the water column. A series of rings are located around the top and bottom of the pressure tube that prevent the calibration tube from moving sideways and tipping over during loading. The calibration tube must sit vertically above the pressure tube to avoid influencing the fall of the weight and the energy transfer through the water.

A series of cutouts line the calibration tube. Holes are cut into the tube to allow for the coaxial cables from the pressure transducers to safely run from the pressure tube to the data logger. Viewing windows are also included in the design to allow for spectators to see the collision between the drop weight and the impact moil, and the motion of the impact moil on the water column. The top viewing window also doubles as an attachment point for the quick-release device.
to the drop weight. Housings for the inclusion of velocity sensors are added to the tube. The velocity sensors are located just above the impact zone to accurately record the velocity of the weight during the fall.

The water column assembly houses the 1000mm column of water used in the energy transfer analysis. This assembly simply includes a floor plate and a hollow steel pressure tube. The pressure tube is lined with five PCB pressure sensors detailed in Section 8.3.2 of the report. A housing for the rod seal on the impact moil is machined into the inside face of the pressure tube. This is included to prevent water leakage from the tube when the system is pressurised during operation. Two ports are provided for the involvement of high-pressure valves to vary the water pressure inside the tube.

The pressure tube is welded onto a small floor plate to provide the base of the structure (Figure 10.12). The floor plate of the assembly is fastened to the concrete floor by a series of chemset bolts. Slotted holes in the floor plate allow for minor variations in the fabrication of the plate or in the assembly of the system.

Two weights are included in the calibration tube assembly shown in Figure 10.13. Both weights fit comfortably inside calibration tube and have a total mass of 30kg. One weight, known as the
impact moil, permanently rests in the calibration tube on the water column. A second weight is raised to the pinnacle of the tube and allowed to free-fall down the tube striking the resting weight. This weight is referred to as the drop weight. A large radius is included on the impact face of both weights to ensure an efficient transfer of energy.

The impact moil includes a long shaft that rests in the water column. The shaft of the moil accompanies a rod seal housed in the pressure tube. The seal requires a tapered entry on the front of the shaft and a smooth surface finish. The moil is to rest at a height of 1000mm from the base plate to ensure the column of water remains consistent. A gap of 100mm is expected between the top of the pressure tube and the shoulder of the moil. This is to make certain the shoulder of the weight does not bottom out on the top of the tube after the impact loading. Previous experiments have indicated the moil will compress up to 40mm into the water, therefore a clearance of 100mm will guarantee the shoulder will clear the top of the pressure tube in operation. The majority of the mass in the part is contained in a large cylindrical section and takes the axial load from the drop weight strike.

Figure 10.13 Maximum displacement of impact moil following drop test

The drop weight item contains the main portion of the mass in the front cylinder similar to the impact moil. The quick-release mechanism is attached to the drop weight around a specifically shaped tail. Clearance is required around the tail pin for the lifting system to be attached. The rear
Chapter 10 - Conceptual Design of ‘Calibration Tube’

shoulder of the drop weight is used as a contact face for the quick-release mechanism to deflect under an axial load. A chamfer is added to the underside of the pin head that will encourage the weight to drop from the circular rod it rests on under load.

The drop weight is raised to the top of the drop using a steel cable and hand-driven winch. It is important for the cable not to fall with weight down the tube during the experiment. The potential exists for the cable to influence the fall direction or velocity of the weight. A quick-release mechanism is used in the calibration tube assembly to release the drop weight at correct height along the calibration tube without the connection of the steel cable. The quick-releases will engage at the top of the tube and needs to be reconnected at its resting point after impact.

Belleville spring washers are included in the quick-release device shown in Figure 10.14. Two spring washers are located on the outside of both flat steel plates to add extra flexibility in the sensitivity of the quick-release. The steel cable wraps around the centre spacer of the device and provides an attachment point to lift the weight to the top of the tube.

![Figure 10.14: Reattachment of quick-release to the tail of the drop weight](image)

The negative dynamic load on the lifting assembly calculated in Section 10.8 will have to be factored into the design. A negative dynamic load means the quick-release grapple will move
opposite to the weight following the release. To prevent the quick-release and the attached steel cable from unhooking itself from the pulley arrangement, an extra pin is added to the system just above the sheave. This pin will hold the cable in place within the groove of the sheave and stop the quick-release from flying backwards over the sheave and possibly onto spectators of the experiment. The overhead pulley assembly is shown in Figure 10.15. The pin used to contain the steel cable fixed in the groove of the sheave is also visible.

The specifications of the system require the hand winch to have a drum that is capable to hold over 12m of steel cable. The hand winch does not need to be too large or costly given the drop weight is only 30kg in mass. A Jarrett 8000 series brake winch system provides the assembly both with an
adequate drum size and a relatively small lifting capacity (Figure 10.11).

A large cylindrical pin (Figure 10.16) is inserted into the calibration tube to act as a safety device during operation. The safety pin is located above the impact moil and attachment point of the system as displayed in Figure. This is to ensure the safety of the operator if work is being conducted on a lower section of the assembly while the drop weight is raised. There is a potential for the drop weight to be released early which could shear fingers or hands off if the operator is working through one of the large windows around the impact moil. The circular pin is large enough to withstand shear loading of the weight. A handle is extended from the front of the pin to allow for easy removal.

Figure 10.16: Calibration tube assembly before strike with safety pin in position

Assembly drawings and detail design drawings for the drop weight test frame have been included in Appendix D.

10.11 Further Development

A search conducted by RME's fabrication staff, following design completion found the maximum supplied length of seamless cylinder tube is only 5.5m. The required length of the tube needs to be 6.86m to accurately expect a transfer of 1500J to the water column. This meant to extend the
calibration tube to the required height, two separate sections needed to be welded together. As discussed in Sections 10.3 and 10.7, welding of the tube may cause slight distortion or misalignment that could influence the fall of the drop weight. It is hoped to position one whole extruded tube along the 5.1m fall of the drop weight to ensure the drop is not compromised by a welded seam. The total length of the calibration tube used by the drop weight is 5.43m, giving an opportunity to add a 1.36m section on the lower portion of the drop test. The welded seam will therefore reach a height partway up the impact moil. This is considered acceptable, as the moil is tightly held a concentric relationship with the calibration tube using the rod seal with adequate clearance between the two bodies. This clearance will mean any vertical movement of the impact moil will not be influenced by the distortion of the tube due to welding.

Further problems involving the calibration tube were experienced later in the production phase. The wrong size material was ordered, creating an unexpected series of events to correct the issue. A 5” outside diameter cylinder tube was ordered rather than the 5” inside diameter tube specified by the drawing. This fault was only discovered during a mock assembly of the system at the completion of machining.

Due to the tight time restrictions on the project and long lead times on material and available machining time, it was determined to be easier to change the dimensions of the components interacting with the internal diameter of the calibration tube instead of reordering and remachining the tube. The calibration tube was the final item to be manufactured due to troubles in sourcing the correct material. Seamless cylinder tube was found to have long lead times from the factory commonly used by RME to source extruded material. This therefore meant machining changes were required to already complete components.

The change in the diameter of the cylinder tube meant a change in the outside diameter of the support rings on pressure tube. It was therefore required to go back and remove guide rings from the pressure tubes, remachine to a suitable diameter and correctly reattach in the appropriate location.

The diameter of the drop weight and impact moil also had to be suitably reduced following the change of calibration tube dimensions. The extra machining to remove material from the weights critically reduced the mass from 30kg to approximately 25kg. A change in mass therefore induced a change in potential energy produced by the system. Recalculating the kinetic energy produced by the drop weight now shows a large reduction in energy to 1250J. Although this is not the ideal
energy value intended for the testing, it was deemed suitable for this round of experimentation by RME’s design team. The modified LRT can be adapted to fire at a lower value, thus still allowing for a comparison between the rock-splitter and the drop weight in future testing.

A slight variation to the weights used in the assembly was incorporated during machining of the components. Centres were added to the shaft of the weight to aid in the machining on a lathe. A small centre should not greatly influence the mass or energy transfer of the system.

A quick check of the 3-D models showed the clearance between the quick-release mechanism and the new inside diameter of the calibration tube will not be an issue during operation. The dimensions in the hand winch support arm required changing to suit the new outside tube radius. This could be corrected during the welding process of the support arm to the tube. A single bevel weld is specified in the drawing as the technique to fix the individual items together. This technique requires the boilermaker to grind material from the support arm which will be filled with weld. By grinding a slightly different radius into the support arm during the welding preparation, the difference in the two radii can be overcome without the need for extra machining.

10.12 Conclusion

The conceptual design, selection and evolution of the drop weight test system has been investigated throughout this chapter.

A conceptual design incorporating the use of the ThunderBolt test rig was investigated for future development of the ThunderBurst energy delivery system. This design was neglected as a suitable final design due to the issues revolving around the fabrication of the ThunderBolt support frame.

A secondary drop weight rig using a freestanding calibration tube was selected as the foundation for the design development. Suggestions from both RME and USQ helped mold the final design. This design evolved from a large floor base and separate hand winch stand to an improved pulley arrangement inside a support arm cantilevered from the calibration tube. A quick-release mechanism is used to release the drop weight from the pinnacle of the tube onto an impact moil resting on the pressure tube. Pressure sensors along the water column record the pressure inside the tube following the strike.
The next chapter will provide details of each of the assembly and testing of the drop weight energy system.
Chapter 11

11.0 Drop Weight Testing Results

11.1 Introduction

The assembly, operation and collation of the test results of the drop weight test rig are the last steps in the research project. Using the results from the drop weight and calibration tube experiment, a comparison between the pressure readings of the drop weight experiments and then future testing using the proposed LRT test frame can be drawn. This will greatly assist the future development of the ThunderBurst energy delivery system and provide a foundation for the testing into the required energy levels needed for hydro-rock fracture.

This chapter will focus on the drop weight testing using the calibration tube and the results received from these experiments. It will look into the assembly of the fabricated components and discuss the problems that were encountered during the build process. An overview of the drop testing is given in detail. This also outlines some difficulties that had to be overcome throughout the research into the pressure wave distribution in the water column.

The analysis comprises a complete overview of the test data, the pressure wave plots within the water column using MATLAB computer software, and a look into the average pressure readings in the column across all sensors for a select number of tests. Finally, an initial analysis of the pressure plots through the water column is also included. This analysis is only preliminary and would require further in-depth analysis of the pressure wave propagation.

11.2 Assembly of Calibration Tube

This section discusses the assembly of the individual components of the drop weight experiments and issues that arose during the construction phase.

Overall, the assembly and construction of the drop test experiments went according to plan, without too many hiccups. Due to space restrictions at RME’s indoor facilities, the base plate of the pressure tube was bolted down to an outside concrete slab as a starting point to the assembly. The
connection to the concrete floor is shown in Figure 11.1. This was not ideal as the physical elements could influence the drop test and subsequent result data. The resting weight and rod seal are set up before the calibration tube is located in position.

The drop tube needed to be lifted into position using a crane. This was due to the indented overall height of the test structure to be in excess of seven metres from the concrete floor. The pulley system, drop weight quick-release mechanism and cable are all attached prior to lifting. The drop weight also needed to be inserted into the tube and located in a higher position along the tube relative to the safety pin in the upright position of the tube. The drop tube is then lifted vertically over the pressure tube with all components affixed in their final arrangement. An overall picture of the assembly is found in Figure 11.2. The height of the drop tube relative to the shed is clearly shown.

The fit between the pressure tube and calibration tube was tighter than expected. Slight
manufacture or material error of the two components most likely caused this problem. This situation did not affect the experimentation in any way.

Figure 11.2: Calibration tube assembly in position

The five piezoelectric pressure transducers were inserted into the machined housings in the hollow cylindrical pressure tube. The calibration tube needed to be held in a constant orientation to allow for the ends of the sensors to protrude through the respective cutouts of the tube.

Figure 11.3 shows the coaxial cables running to the pressure sensors. The sensors protrude from the tube through the specified cutouts allowing sufficient room for the connection to be made.

Mr Dean Beliveau from USQ was contracted by RME to run the data logging software and ensure the safe setup of the pressure sensing equipment during the operation of the drop weight tests. This contractual agreement was required due to a lack of experience in this area by the current electrical
engineers at RME. The pressure sensors were connected to the logging equipment using coaxial cables.

![Figure 11.3: PCB pressure sensors protruding through the outside calibration tube](image)

The results of the data logger were transferred and recorded using a portable notebook computer situated close to the calibration tube assembly.

Water was successfully inserted into the pressure tube using town water supply. A close visual inspection of the pressure tube found that there was no fresh water around the base of the assembly from seal leaks. The absence of new water verifies the machining of the PCB pressure sensor housings in the side of the tube and implies that the sealing surface surrounding the sensor is capable of maintaining sufficient pressure for the successful testing of the system. This also confirmed that the welding between the base plate and hollow cylindrical tube was not porous and would be sufficient for the containment of the water column.
A high-pressure hydraulic ball-valve is used to control flow into the water column and to prevent water escaping from the impact of the drop weight. The addition to or subtraction of water from the pressure tube using the ball-valve can alter the pressure within the tube and ultimately change the height of the resting mass situated in the pressure tube. A bleed valve is required to remove air from the tube. As the water fills the steel cylinder from the bottom of the tube, the air is compressed at the top and increases in pressure as the volume of water increases. This pressure will continue to increase unless it is released. It is important to regularly release the air from the water column, as it has the potential to influence the results received from the experiments.

The hydraulic ball-valve and bleed valve used in the drop weight experiment is shown in Figure 11.4 below. The initial height of the resting mass is also shown in this photograph. The height was measured from the top of the pressure tube to the shoulder of the resting mass using a steel rule.

Figure 11.4: Hydraulic pressure ball valve and air bleed nozzle
Height of the resting mass had to be manually jacked up to the required position and held in place with a crowbar until water pressure and buoyancy forces of the water within the tube take effect. This would then hold the gravitational load exerted by the resting weight and ensure it maintained its location.

The erection of the calibration tube experiment did not go exactly to plan. A number of problems were experienced during the initial setup and had to be overcome before the experiments began. The town water pressure could not lift the weight to the desired 100mm starting height. The maximum gap between the top of the pressure tube and the shoulder of the resting weight was only 75mm. Another problem arose involving the resting moil with the ordering of the wrong size rod seal. A replacement BS o-ring was found that could fit within the specified groove and around the shaft of the moil. This form of seal was adequate for the testing performed.

A minimum sampling rate of the pressure sensors was required to be specified for the data logging equipment. Previous rock-breaking experiments have shown the impact time of the ThunderBolt hammer was 0.00678s. It is expected in this time that the pressure wave will travelled through the column and reached the moil again. This therefore means an expected time of 0.0034s is set for the pressure wave to travel through the water and the frequency is set at 300 samples per second.

Using the Nyquist theorem, it is expected a sampling rate twice the frequency is imposed on the data logging. However, it is common for the sampling rate to be up to ten times the frequency to achieve an appropriate wave profile. This gives a minimum sampling rate of 3000 samples every second.

The hand winch specified in the assembly drawings could not be ordered by the time testing was to be conducted. A replacement boat winch handy to an employee of RME was incorporated into the design in its place (Figure 11.5). This new winch was physically smaller than the original, but could easily handle the rope length required and can cope with a lifting capacity of 25kg. The length of cable specified was too short to provide comfortable operation of the system. To reattach quick release after the initial drop, the whole mechanism had to be lowered down to where the drop was resting atop the impact weight before being able to re-clip the mechanism into position again. This was made difficult because the cable length shorter than intended and meant the lower pulley had to be removed to the give extra cable length needed to reach the drop weight.
There was also the real danger of accidentally destroying the piezoelectric sensors operating the drop tests. As the sensors protrude through the drop tube from the pressure tube, there is potential for the sensors to be sheared off if the drop tube is twisted around too far. There are no stops or shoulders preventing the spinning motion of the outer tube and this should be looked into if the same testing is conducted again in the future.

**11.3 Drop Weight Testing**

The drop weight experiments generally performed as discussed in Chapter 10 and were successful in giving pressure readings through the water column using the PCB transducers. The drop weight was able to be quickly and easily lifted to the maximum height of the calibration tube. At the very top of the tube, the quick release mechanism engages, and smoothly releases the drop weight. The
weight falls freely down the calibration tube until it strikes the impact weight resting in position in the pressure tube. The kinetic energy is transferred through the weight into the water column. Pressure variations were taken by the sensors and recorded using data-logging software and a nearby laptop.

One observation that was not foreseen or accounted for was the rebound of the drop weight on the resting weight following the initial strike of the drop weight. The incompressibility of water and its subsequent spring-like nature forced the drop weight back up the drop tube before gravity again brought the mass onto the water column.

The structure was held stable around the base plate of the pressure tube. Gusty winds did cause some gentle swaying of the top of the calibration tube although this did not seem to influence the dropping of the weight. As discussed in Chapter 13, any sway in the drop tube may cause the weight to fall out of alignment with the water and lose energy by striking the walls of the tube. The use of a hand winch to raise the drop weight into position also tended to cause oscillations of the tube. These frequencies were expected to occur and tried to be overcome but slowing the winding speed of the winch down when the quick release neared the pinnacle of the tube.

The major reason behind the successful testing and positive experiment results was relatively easy assembly due to the accurate fabrication of individual components in the design. There were however, some problems that were experienced in the testing process. These problems hindered the experiments and sometimes were the factors behind the poor test results.

The major problem found from the experiments involved the sensitivity of the quick release mechanism. This device worked too well for the application of simply releasing the weight at the pinnacle of the tube. The mechanism was too sensitive for the rough nature of the experiment and the use of the hand winch to lift the weight. Any small knock of the frame or to the drop weight inside the tube would release the weight early. Simply having the cable bounce during winding or rolling the cable around the winch would cause the weight to fall before intended. This may have been corrected by tightening the nut and increasing the tension between the Belleville washers on the quick release assembly.

The length of data logging needed to be exceedingly long to account for the likelihood of an early drop of the weight. Although this is not a major design fault, it does create extremely large data files that contain excessive amounts of irrelevant data. The data files needed to be trimmed down to
remove some of the irrelevant recording and allow for a closer analysis around the areas of interest.

The air in the pressure tube needed to be released at the end each run. This was a little unexpected, but from observation it seemed to dramatically increase the rebound height of the drop weight on the resting moil in the pressure tube. A simple check of the plot results between test number two (air not released) and three (air released) showed a vast difference in the size of the initial spike. This confirmed the thought that any air pressure in the tube needs to be released before the beginning of each test.

11.4 Results

A total of seventeen tests were conducted. Not all the tests were successful with the quick release mechanism acting before it was intended. All the data was recorded and inserted into a table. Apart from the values recorded by the sensors, the start and finish height of the resting mass are also measured. This is determined using a steel rule to measure the distance between the top of the pressure tube and the shoulder of the impact moil. From this data, the energy produced by the drop weights, the pressure on the water column, the volume of water lost and the pressure lost from the tube can be calculated.

It can be seen from attached Table 14.1 that a number of values changed as the tests progressed. An increase in the impact energy and therefore the pressure exerted on the water column has occurred because the starting height of the impact mass varied slightly between tests. The velocity of the falling weight is calculated using Equation 7.1. As the initial velocity and acceleration are constant for all the tests, it is the distance travelled by the drop weight that varies and gives different energy readings.

An overall summary of the drop weight and calibration tube experiments is given in the table below.
Table 11.1: Drop Test Results and Pressure Analysis

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The first five columns in Table 11.1 show the measured values taken during the test session. Data in the remaining columns were calculated from the measured data with help from the extra information provided as a subset to Table 11.1. Items such as initial volume of water (mm³) and bulk modulus (N/mm²) are used in the table to help calculate the pressure within the water column. The calculation of the water volume lost and therefore calculation of the pressure lost, is dependent on the accurate recording of data of the start and finishing heights of the impact moil. The data could have been improved by using a more accurate measuring device.

It can be seen that the initial impact test released an extra amount of water compared to subsequent tests. This could be due to the release of extra air left in the column possibly from an incorrect setup of the water pressure initially. Air pressure contained at the top of the pressure tube was not released following the first few drop tests. Air was released after Drop Test #3 in preparation of Drop Test #4. Two false starts occurred in Drop Test #4 where the weight discharging before reaching the zenith. The air pressure was not released following these minor drops and therefore the test was not considered successful. Air was methodically vacated from the pressure tube for all remaining tests.

The physical test data for the drops that were considered unsuccessful were also included. This is stated clearly in the ‘Successful Test’ column. A total of nine tests were deemed successful. As the weight did not fall from the maximum height in these tests, the applied energy was not considered to be the same as the ‘successful tests.’ This therefore influenced the subsequent impact pressure and pressure lost from the column calculations.
The difference in the height of the resting mass was large, approximately 5mm, at the beginning of the sample. This decreased however, as the testing continued. The difference in resting mass height reduced to 1-2mm toward the end of the testing sample. This could be due to the end of the moil nearing the minimum height for the water column. If the moil was raised during the test sample and filled with water to increase the pressure inside the tube, the original 5mm height changes may have again resulted.

The data received from the five pressure sensors were recorded by the data loggers organised by Mr. Beliveau with permission from USQ. The software in the form of a text file output the data. The file contained five columns of pressure readings, one for each sensor at each time interval. MATLAB computer code was written to load the data into a matrix and plot the resulting voltages versus time scale. Each graph was customised to most accurately display the results immediately before and after the strikes of the drop weight on the column. Due to the abnormal amount of irrelevant data before the initial drop, the clarity of the results is not acceptable when viewed over the length of recording. A simplified version of the overall data plot which zooms in on the impact strikes on the water column is also included in the results.

![Voltage Vs Time plot for Drop Test #1](image)

**Figure 11.8: Voltage Vs Time plot for Drop Test #1**

A plot of Voltage Vs Time over the entire recording of Drop Test #1 is shown above in Figure 14.8. The five coloured lines display the voltage readings for all five PCB pressure transducers at any instant in time. It is obvious from the plot a pressure spike occurs above the regular noise levels at approximately 3.85s and a secondary spike at 5.05s.
As discussed earlier, Figure 14.9 is also included to clarify the plot of the two pressure spikes in Drop Test #1. This figure shows the values of voltage readings more accurately compared to the original graph. The graph was zoomed in to a time period of 3.75s to 5.45s.

A Microsoft Excel graph of the average water column pressure across the five sensors at every time interval is also included for Drop Test #1. This analysis of the average valves over a specific time frame is used to define the pressure through the water at any time. The graph clearly shows the pressure spike recorded as a result of the falling weight and the secondary spike from the rebound. It is hoped the collection an average voltage reading across all the sensors will display a distinct variation of the wave during the spike.
A complete overview of the data recorded by each pressure sensor during Drop Test #1 was required to gauge a better understanding of the data produced by the experiment. This was to distinguish if all the pressure sensors reacted in a common manner. It was also an appropriate check to confirm if all the sensors were functioning correctly. The individual Voltage Vs Time plots for pressure sensors 1 to 5 are shown in the five figures below.

**Figure 11.11: Pressure Sensor #1 Voltage Vs Time plot for Drop Test #1**

**Figure 11.12: Pressure Sensor #2 Voltage Vs Time plot for Drop Test #1**
Figure 11.13: Pressure Sensor #3 Voltage Vs Time plot for Drop Test #1

Figure 11.14: Pressure Sensor #4 Voltage Vs Time plot for Drop Test #1
Figures 11.11 – 11.15 all show pressure readings similar to one another. All pressure sensors also follow the average wave propagation shown in Figure 11.10. This confirms the sensors are working correctly and all are performing as anticipated. The peaks and troughs of the wave profile vary slightly between the five sensors. This was expected, as the front of the shock wave will be changing its position relative to each sensor as it travels through the water column. Therefore, slightly different readings between the sensors will be expected for the same time. It is interesting to note the highest value of voltage produced was at pressure sensor #5, located toward the bottom of the water column.

The MATLAB coding for each drop test is shown in Appendix E of this report.

The Voltage Vs Time plots for the drop tests containing significant data results or particular test conditions are shown in Figures 11.16 to 11.29 below. Remaining drop test data plots not shown in this section are displayed in Appendix F. Both an overall and simplified plot of the results have been included in the report as performed for Drop Test #1. A simplified plot basically means the graph is zoomed in on the area of interest around the data spikes. The data could not be recorded for the Drop Test #8. This was due to the weight falling before the data logger was ready to begin recording. There is therefore no pressure wave plot for this test.
Drop Test #2 was considered to be unsuccessful, as the air pressure was not released from the pressure tube before the test was conducted. The lower voltage reading of the initial spike in comparison with Drop Test #1 could be a result of air in the pressure tube having a negative influence on the size of the pressure wave through the water.

Figure 11.17 definitely shows three peaks in the pressure profile. This would be due to the bouncing of the drop weight on the resting mass positioned in the water column. It is also interesting to note the cyclic nature of the peaks of the pressure wave profile between the strikes.
A glance over the plot of Figure 11.18 gives the impression of four major rises in the wave profile. A total of three spikes in the data are clearly seen in Figure 11.19. The notion of a fourth spike was given because the drop in the general noise levels was on at a low point and gave the impression of a further high point in the data once the cycle of the voltage wave rose again.
Initial spikes shown as red and blue lines in Figure 11.20 are the result of two previous drop tests that were released early. These weights did not reach halfway up the drop tube almost immediately after the safety pin was removed. The results received from these initial drops were neglected. Two spikes occur at the very end of the drop test. This is the actual drop weight experiment released from the top of the calibration tube and are the results taken for the fourth test.

The two pressure spikes are displayed very clearly in Figure 11.21. It is curious that there are two distinct rises in the wave profile as a result of the pressure exerted on the water from the drop weight, but there are no third or fourth pressure spikes in the wave profile that would be expected from such a clear secondary spike. This may have occurred if the weight rebounded at an awkward angle and lost energy by running along the inside of the tube.
A large negative spike is seen in the wave profile of Drop Test #6 before the impact of the drop weight. A negative maximum value of the spike does not necessarily mean negative voltage was produced. The voltage produced is relative to the average centre line of the wave profile. If the voltage spike rises above the average centre line, the quartz crystal in the piezoelectric pressure sensor has moved away from the centre of the tube. This is because the pressure inside the tube expands, pushing everything outward. It is this form of spike that is expected in the drop weight testing as the energy delivered to the water column from the drop weight increases the water pressure in the tube. If the quartz crystal moves inward toward the centre of the pressure tube, the water pressure must be undergoing compression. This is displayed by the drop of the voltage readings below the average voltage reading in the wave profiles.

The magnitude of the compression spike shown in Figure 11.22 is very large. This could be have happened if a large impact occurred on the pressure tube or individual pressure sensors that caused the sensing crystal to vibrate toward the inside of the water column, rather than away from the water as expected in the impact tests. A change in the pressure within the water column could also have drawn the sensor into the centre of the water column, producing the compression spike. Such a reduction in tube pressure may have resulted in a release of water from the column by a knock to the system that moved the o-ring seal around the impact moil and allow air to sneak into the system.
The release of the excess air atop the water in the steel column continues to make a difference to the magnitude of the voltage readings in the data spikes. A maximum voltage of 0.82 Volts was recorded in this experiment. This is again much higher than the previous maximum of tests where the air was not bled prior to the drop. Drop Test #2 produced the highest value in these tests at maximum of only 0.76 Volts.

Figure 11.24 shows the plot of the results of unsuccessful Drop Test #7. The quick release activated before the weight reached the designated height of the drop tube. This meant the weight fell with a lower kinetic energy than needed for the drop weight experiments. Data had only begun...
being recorded by the notebook when the weight struck the pressure tube. Results of the experiment are therefore neglected.

![Figure 11.25: Simplified Voltage Vs Time plot for Drop Test #7](image)

Although the drop weight was released from a point below the height necessary to produce the intended energy strike on the pressure tube, it is still evident of three voltage peaks higher than the general resonance of the pressure sensors.

![Figure 11.26: Voltage Vs Time plot for Drop Test #14](image)

An outlying voltage reading is present in Drop Test #14. This voltage reading has transpired a number of times now in the test samples. As only one sensor has recorded the smaller voltage, this
could be a result of a glitch in the sensor data or a bump to the system that produced a compression of the water pressure in the tube.

Figure 11.27: Simplified Voltage Vs Time plot for Drop Test #14

![Graph](image1.png)

Figure 11.28: Voltage Vs Time plot for Drop Test #15

![Graph](image2.png)

The recent run of early drops of the weight meant the recording of the test data began when the drop weight was lifted up the calibration tube. Almost 90 seconds of extra data was recorded to ensure the pressure spike was recorded if the quick-release mechanism engaged before the top of the tube.
11.5 Results Analysis

The following is an initial analysis into the results of the drop weight experiments. From a glance at the Voltage Vs Time plots there is a clear spike in the results that is caused from the initial strike. A secondary spike and then occasionally a third spike will have caused by the rebound strikes. Drop Tests #2 and #3 were conducted before it was realised air was entering the pressure tube during the impact loading. Air is sucked into the water column when the moil is pushed down into the water. At this time, the o-ring seal slides along the surface of the impact weight allowing air into the system. As the water column is essentially a vacuum, the large difference in air pressure between the steel tube and outside environment means a large intake of air to the available volume in the column. Data received from these tests can not be considered to be as accurate as those performed in a vacuum. The results received from Drop Test #4 could also not be considered as successful because the air pressure was not released following two minor drops prior to the next successful test.

The majority of the data produced in the graphs is irrelevant to the experiment. The simplified plots that focus in on the region surrounding the sharp rises in data due to the impact load provide more relevant information into the change of water deflection, and therefore the change in voltage and finally pressure, in the water than the plots showing the entire data range. Information displayed by the full data plots do however show a consistency in the resonating of the structure well before and after the drop test is conducted.
All the five pressure sensors have provided values at approximately the same level and there is generally no outlying data seen in the sixteen tests that were recorded. Some unexplained peaks and troughs in the wave profile are assumed to be caused by the experiment process affecting the data recording and not from the direct impact of the drop weight. This can be confirmed as the outlying results occur before the weight is dropped onto the column. The greatest deflection on the steel pressure tube, and therefore the highest voltage readings, seemed to occur toward the base of the water column. It is unclear if environmental conditions including the weld surrounding the contact area between the hollow steel cylinder and the base plate made have influenced the results. It is however, likely to be due to the slight compression of the water in the column. Although water is considered incompressible, it will squash very slightly under load. As the shock wave progresses further down the pressure tube, the water remaining in the column will increase in pressure. The less water remaining, the higher the pressure will become. This small variation in pressure readings potentially is a result of the compression of water ahead of the front of the shock wave in the water column.

The pressure sensors also recorded general noise and system vibration levels that occur during the experiments. These values are displayed by the negative sine wave is clearly visible in the average test data for Drop Test #1. The rough nature of the oscillating wave is likely to be caused by combining the wave profiles of both the noise and vibration using superposition. Values for the interference usually resonate between 0.25 and 0.4 Volts. Only the impact load of the drop weight manages to break the wave out of the oscillations recorded by the transducers. Any spike that transpires above 0.5 Volts is considered to have resulted from a shock load on the water column.

It is interesting to note the change in the amplitude of the sine wave values increase as the test sample increases. A closer inspection of the amplitude in Drop Test #1 clearly shows the range of general noise wave profile varying from approximately 0.26 to 0.42 Volts. By Drop Test #11 the amplitude has increased to 0.2Volts with the values roughly ranging between 0.23 and 0.44 Volts. An increase in the amplitude is seen after Drop Test #10. In the final drop test, the resonating range is between 0.17 and 0.42 Volts. It is unclear at this stage what has caused this change in amplitude.

An analysis of the pressure profile in the vicinity of the spikes is also conducted. Figures 14.30 and 14.32 below show the values of the voltage for the initial and secondary spike for Drop Test #1 using MATLAB data plotting. Microsoft Excel software provided a comparison for the Drop Test #1 result showing the average voltage plots displayed in Figures 14.31 and 14.33. It is obvious for all sensors the voltages rise, fall slightly, before rising again sharply to its peak value. A similar
situation occurs as the voltage levels begin to fall to regular values. It would be interesting to investigate the range of the rise and falls within the pressure spike further.

Figure 11.30: Voltage Vs Time plot for Drop Test #1 focused on initial spike

Figure 11.31: Average Voltage Vs Time plot for Drop Test #1 focused on initial spike

A comparison is also shown for the secondary voltage spike due to the rebound of the drop on the water column.
It is clear from Figures 11.30 and 11.32 that the values of the voltages within the pressure spike for each pressure transducer are variable. There are distinctive rises and falls of the individual pressure sensor recording through the voltage spike caused by the impact load. It is unlikely that the shock wave propagated along the entire length of the pressure tube in 0.00057s causing two oscillations of the piezoelectric pressure sensor. Similar variations in the voltage wave occur naturally due to the vibration of the quartz crystal from the electrical current.

The variation is not as visible in the average voltage graphs. This lack of variation was expected as the voltage throughout the entire tube is recorded and the average value is taken. The small changes in the average voltage profile in the pressure tube could be explained if the head of the pressure wave travelling through the water is physically located between the pressure sensors when
the data is recorded. The minor peaks and troughs in the pressure spike shown in the graph of average values can therefore be neglected. The high voltage value of the trough in the wave profile immediately following the secondary strike in Figure 11.33 could be triggered by kinetic energy from the impact still being present in the column. The following wave peak is not dramatically higher than the surrounding peaks that could be a sign that the energy dissipates before the front of the shock wave reaches the top of the tube a second time.

Future work is required with a higher sampling rate to more closely investigate the wave propagation immediately following the impact due to the conflicting data provided in Figure 11.33. As discussed previously, there is no clear evidence of any drastic rebound of the shock wave through the water column. If a higher sampling rate of the data is used, it should give a more detailed view of any rise or fall immediately after a strike on the water column. Another possible solution could be to insert more pressure transducers down the steel column to reduce the physical distance between the recordings. This would illustrate if there are consecutive waves within the water column behind the impact load.

The data received could also be replotted using different software able to isolate the pressure spike from the natural vibrations of the sensors. This would give another indication of the actual value of voltage produced by the impact loading of the water column above the voltage produced by the local power source.

11.6 Conclusion

The drop weight testing conducted with the calibration tube assembly is shown in this chapter. It used the drop weight arrangement, discussed in Chapter 10 of this report, to produce a simulation of the energy levels expected from the 1500J ThunderBolt recoilless hammer.

Testing and assembly of the structure proceeded relatively smoothly. Minor errors in sourcing equipment were experienced, but quickly these problems were ratified without major hold ups to the testing timeframe. Design concerns regarding the oscillations of the drop tube and the safety of the quick-release mechanism did not prove to be a factor in the results of the experiment.

It was noticed that relieving the air pressure from the pressure tube following each experiment dramatically altered the pressure wave results. It is likely air is sucked into the top of the tube when the shaft of the moil slides past the rod seal in the pressure tube. This additional air may affect the
pressure of the water in the steel column.

The drop weight pressure wave analysis produced adequate results of the pressure spike in the water column. All the pressure sensors were active and functioning as expected. The majority of the plotted results showed only the vibration of the sensors in the form of a sine wave acting at the natural frequency of the electric current. A rapid jump in the data is seen following the original impact of the drop weight on the resting moil, often followed by a second, third, and occasionally fourth subsequent spikes in the data where the drop weight rebounds until eventually coming to rest.

Only a few outlying data spikes were experienced during the testing. This unaccounted data is usually caused by a drop in pressure, rather than an increase. It has been assumed that a slight impact or jolt to the structure could have caused a result such as this.

The results obtained from the testing will provide a comparison for future testing with the ThunderBolt test frame system. It is expected the energy readings on the LRT can be altered to match the pressure wave profile of the drop weight tests.

The final chapter will summarise the details of the research project and look forward to future work still to accomplish with the ThunderBurst autonomous vehicle through RME.
12.0 Conclusions

12.1 Introduction

Chapter 12 is dedicated as a final summation of the research project. This chapter looks at all aspects of the project discussed throughout the research project and those topics of future work for RME that were not yet covered in the project.

12.2 Project Objectives Achieved

The research project was deemed to be a success in that two detail designs of testing frames for energy delivery devices were produced. A permanently erected test frame was designed and developed for the ThunderBolt experiments to investigate the pressure wave propagation through a water column housed in a steel hollow cylinder. A drop weight testing system was also designed for the research project as a comparison to the ThunderBolt testing rig.

The conceptual test frame using the ThunderBolt 1500J hydraulic hammer was analysed and detailed, but external circumstances prevented further construction and development on this design. The drop weight test rig was designed and successfully tested to graphically display the pressure waves as the shock wave travelled through the water column.

The objectives set out in the Project Specification, shown in Appendix A, were met in the course of the research project. Current mining methods were researched, non-explosive alternatives into rock breakage were investigated, and these concepts were implemented into conceptual designs for the ThunderBolt and drop weight energy delivery device.

The additional objectives discussed in the Project Specification were not reached in the time frame given by USQ. The initial design and development process of the ThunderBurst energy delivery
system and the investigation of a suitable vehicle as a foundation for the autonomous vehicle are two developments now intended for future research projects. An attachment device for the energy delivery system to connect to the vehicle will also need to be implemented. Future work into these issues will need to be explored in later projects with the assistance of RME.

12.3 Summary of Outcomes

This section will provide a detailed summary of the individual requirements set out in the Project Specification. Requirements such as the investigation of current mining practices and the need for non-explosive technology in underground mining were conducted in a literature review. The design, development and analysis of the ThunderBolt test frame was conducted, but was unable to be tested in practice. The selection of an appropriate energy transfer method for a suitable secondary experimental test frame was also achieved. Physical testing using drop weights was successful and plots displaying the variation in voltage within the water column collated by the pressure sensors were recorded.

As previously discussed, the extra objectives of the research project were not reached due to circumstances out of our control. It is expected these objectives will be met by RME in their continued development of the ThunderBurst system.

12.3.1 The Need For ThunderBurst

Secondary rock breakage is conducted by a specialist explosive technician when large boulders get caught in the drawpoint access of the stopes. Secondary blasting is a crucial activity in the ore extraction process because mine downtime is affected while this process is underway. There are also inherent hazards with the use of high-powered explosives that put workers in danger of being injured or killed. Safer and more effective methods of secondary rock-breakage are needed. The “ThunderBurst” system is one option being considered using hydro-rock fracture.

12.3.2 Test Frame Development

The aim of the project was to design and develop a permanently erected test frame to conduct pressure wave testing within a water column using Linerbolt Removal Tool. Following on from
past experiments into hydro-rock fracture conducted by RME in 2002, these experiments required an impact load created by a suspended vertically 1500J Liner Bolt Removal Tool from a forklift. RME imposed a number of constraints on the conceptual designs of the ThunderBolt test frame by to ensure the final design will produce the intended results in the experiments. After careful consideration of these restrictions, three different designs were developed. The conceptual designs are described as follows:

1. Simplified overhanging frame
2. A-frame with overhead rail
3. Hydraulic cylinder-driven structure

After conducting a decision matrix analysis on the test frame conceptual designs, the A-frame design was chosen as the best structure to begin the design optimization process. However, RME's design team saw more potential in using the simpler overhanging frame design. Using this conceptual design as a foundation for the final design, the test frame underwent a number of drastic changes before the optimum solution was reached. The final design incorporates a lower frame, an upper frame, a hydraulic cylinder and a carriage which is fastened to the modified 1500J rock-splitter. This energy delivery is aligned to the water column positioned below the test frame.

Finite Element Analysis (FEA) was conducted on a number of major components in the assembly. This was firstly conducted to check if the material in the structure will endure the stress and deflection values likely to occur in normal operating conditions. The FEA also provided an opportunity to optimise the components of the test frame and reduce unnecessary weight and material from the design.

Unfortunately there were some external issues that arose regarding the completion of the test frame. A lack of physical resources at RME to fabricate individual components of the test frame and in working with PCB pressure sensors to generate the pressure profile caused delays in organising a time frame to conduct the experiment. The resulting time frame did not coincide with those required by USQ as part of the research project.

12.3.3 Drop Weight Testing

The second major portion of the research project was to produce a conceptual design of a second test frame system. This system was required to have a confirmed impact energy value that was able
to compare the energy values in the LRT test frame to a second system with a. The conceptual design process brainstormed fresh ideas into methods of delivering energy to the water. Five designs proposed for the energy delivery device on the water column are:

1. Dropping weights from a height onto the water
2. Propellant-induced slug fired down a tube onto the water column
3. Steam powered firing of a slug on the column of water
4. Piston and cam arrangement regularly impacting on the water column
5. Pneumatic pressure-induced slug fired on the water column

A decision matrix was used to compare and analyse different features of the conceptual designs for the energy transfer system. From this analysis, it was considered best to select the drop weights as the source of an impact load on the water column. This form of energy delivery would be most appropriate for the range of testing required due to the simplicity of the testing procedure and the ease of calculating and varying the energy values acting on the water column.

A completely free standing calibration tube evolved from a number of conceptual designs. This design was separate to the pressure tube encapsulating the water column and contained a minimum number of fabricated components or mechanisms to ensure quick and easy assembly. This design was proven to be a success. The testing of the PCB pressure sensors as a method of recording the pressure profile through the water was also proved successful using the drop weight experiments. The information was sent from the transducers to the data logging equipment via coaxial cable, and the results were recorded on a portable laptop located nearby.

MATLAB and Microsoft Excel to were used to graph the pressure wave as it passes through the water over a period of time. An initial analysis shows definite pressure spike upon initial impact and then subsequent spikes occurring from a number of rebounds of the weight on water until it came to rest.

12.4 Future Work

This project was only the first stage of the design and development of ThunderBurst autonomous vehicle. Following the successful drop weight testing on the water column and verification the system can accommodate the utilisation of pressure sensors to give precise data of the pressure profile travelling through the water column following an impact load, this project can continue to
progress toward developing an energy system that will be accurately and repeatably tested at RME. The next step in the initial development of the experimental test frame can now be implemented.

The remaining work left to be performed as part of the initial developmental stage of the ThunderBurst project is outlined below.

Fabrication of the test frame incorporating a modified 1500J hydraulic linerbolt hammer detailed in Chapter 8 of the report is required. At this point, further testing involving the recording of pressure profiles in the column due to the impact load created by the hydraulic hammer will enable a comparison between the energy values being produced by the two systems. This will provide confirmation on the accuracy of the tuning of the LRT. Once a 1500J pressure wave is standardised for the LRT, the energy levels can be accurately monitored if the hydraulic power of the system is raised or lowered to a specific value needed to successfully fracture rock.

A comparison between the pressure wave results produced in the pressure tube tests and in a realistic rock-breakage situation is also required. This will be used as a gauge to ensure the It is hoped RME will continue to work closely with USQ to continue development into hydro-rock fracture techniques. The results of FEA conducted by USQ into stress fracture in rock will be necessary to accurately determine the optimum energy requirements to break rock efficiently.

A vague outline of future work required for the ThunderBurst project is also given. As ThunderBurst is only in its conceptual stage, it is currently hard to gauge the exact requirements of the project at this early stage. The following section looks at the potential segments RME’s ThunderBurst project could be divided into for future research projects.

A decision on the method and size required for the impact energy imparted onto the water column will be made depending on the FEA results determined by USQ. The design of the energy delivery device must be capable of producing a large enough strike to fracture rock. It is expected that a magic value of 20 000J is required to fracture the rocks into multiple sections with a single strike. Conceptual designs of energy delivery systems will aim at delivering the final energy value of multiple fracture of rock using hydro-rock splitting techniques. This figure is yet to be confirmed by USQ. This means the development of the conceptual designs can not be initiated until the FEA into rock fracture has been completed.

Another stage in the ThunderBurst design process will be to investigate possible vehicle designs to
successfully transport the rock-breaking energy source around the vast tunnel network of an underground mine. This research would also include the research and implementation of autonomous features into the vehicle design which will allow it to be remotely controlled. A suitable method of attaching the energy source to the vehicle to ensure its correct function will also be an engineering challenge that will need to be investigated in the future.

Individual components in the ThunderBurst such as the placement and function of the water tank will also require detail design and analysis to be performed. The managerial aspect of the project will also need to be considered. Items such as scheduling design tasks, organising fabrication and assembly lead times, conducting safety reviews, ordering critical components and other project management tasks shows another aspect to the ThunderBurst project.

All the sections detailed would be good final year projects to be continued in future years. This would be particularly true for engineering undergraduates interested in mechanical or mechatronic design. Having the support of an industry partner such as Russell Mineral Equipment is a major incentive to strive to produce a high quality solution to the engineering problems currently being faced in the mining industry.

12.5 Conclusion

This chapter has discussed the results of the research project and has brought forward conclusions for each project objectives. The research project was deemed a success, with conceptual designs for the ThunderBolt test frame and the drop weight test frame being produced for RME. The ThunderBolt structure was unable to be tested due to problems external to the project, but the drop weight experiment was successfully tested with an energy load of 1250J.

There is still significant effort required to complete the first phase of the ThunderBurst project. Although the drop test simulation was successful, more testing into the pressure wave propagation through a water column is required firstly using the modified 1500J LRT and subsequently a granite boulder is required. Future work in the ThunderBurst project is pending the results of Finite Element Analysis on typical rock properties undertaken by USQ.

In closing, the success of this project has continued to open doors for Russell Mineral Equipment to further their research and development of the ThunderBurst driverless rock breaking machine. It is
hoped that this project will provide the stepping stones for further research into hydro-rock fracture and encourage RME to continue their support of the ThunderBurst project into the future.
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DEVELOPMENT OF A TEST FRAME TO INVESTIGATE THE PROPAGATION OF PRESSURE WAVES GENERATED BY A THUNDERBOLT HAMMER

VOLUME II: APPENDICIES

A dissertation submitted by

Jeremy Thiess

In fulfillment of the requirements of

ENG4111 and ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Mechanical)

Submitted: November, 2007
Appendix A

University of Southern Queensland
Faculty of Engineering and Surveying

ENG4111/4112 Research Project
Project Specification

For: Jeremy THIESS

Topic: Development of a Test Frame to Investigate the Propagation of Pressure Waves Generated by a ThunderBolt Hammer.

Supervisors: Dr Selvan Pathar (University of Southern Queensland)
Mr Peter Rubie (Russell Mineral Equipment Pty Ltd)
Mr Mick Henderson (Russell Mineral Equipment Pty Ltd)

Sponsorship: Russell Mineral Equipment Pty Ltd

Project Aim: This project seeks to develop a test system to provide for the measurement and analysis of pressure waves in water, generated by a ThunderBolt hammer. The system will be used to validate future designs in the development a ThunderBurst rock breaking system.


1. Research background information in current mining practices and to the safety issues arising from these practices.

2. Compare and analyse various rock-breaking technologies, including methods previously used in research and development of the “ThunderBurst.”

3. Develop conceptual designs for the “ThunderBolt” energy delivery system for use in the test rig.

4. Develop a “drop-weight” test rig to conduct initial test for the measurement of pressure waves in a column of water.

5. Critically analyse the design produced in (3) & (4).

6. Produce a detailed design of the “ThunderBolt” and “drop-weight” test rigs. This will include FEA analysis of critical components of the design.

7. Conduct trial test on the drop-weight system. Evaluate the test rig and conduct preliminary analysis of the test data.

As time and resources permit:

9. Construct the "ThunderBoil" test rig and conduct trials.

10. Evaluate this system and compare results with the drop-weight tests.

11. Undertake any modification to the system to improve accuracy and effectiveness of the test rigs.

Agreed: ________________ (student)  __________________ (supervisor)  

Date: __/__/2007  Date: 27/07/2007

Co-examiner: ________________________________
# Appendix B

## B1 – RHS Calculations

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Figure B.6
Appendix C

C1 – Static Analysis

Figure C1.1
Figure C1.2

\[ \Sigma M_j = 0 \]
\[ -921.1 \times F_{x2} + 6975 \times 1.144 = 0 \]
\[ F_{x2} = \frac{6975 \times 1.144}{921.1} \approx 867.9 \text{ N} \]

\[ \Sigma F_j \uparrow = 6975 + F_{y1} + F_{y2} \]
\[ F_{y2} = \frac{6975}{867.9} \approx 8.091 \text{ N} \]
Figure C1.3

\[ EM_1 = 0 \]
\[ M = 8.0 \times 6.0 \times 0.75 \]
\[ = 480 \text{ Nm} \]

\[ \Sigma F_y = 0 \]
\[ F_y = 6975 \text{ N} \]

\[ \Sigma F_x = 0 \]
\[ F_x = F_{ax} - 3165 \text{ N} \]

\[ EM_2 = 0 \]
\[ = M - 3165 \times 3.2 \]
\[ = 8161.6 \text{ N} \]
Figure C1.4
Figure C1.4

Area of Horsing Removed
= \pi r_i^2
= \pi \times (3.56)^2
= 123.68 \text{ mm}^2

Force on Horsing
\vec{F} = P \vec{A}
= 110 \times 12.68
= 1393.8 \text{ N}

\begin{align*}
\sum F_y &= 0 \\
F_y &= \sum F_y = 0 \quad \Rightarrow F_y = -222.95 \text{ N}
\end{align*}

\begin{align*}
\sum F_x &= 0 \\
F_x &= \sum F_x = 1393.8 - F_{x1} - F_{x2} - F_{x3} - F_{x4} - F_{x5}
\end{align*}

Assume \( F_{x1} = F_{x2} = F_{x3} = F_{x4} = F_{x5} \)

\begin{align*}
\sum F_x &= 1393.8 - F_{x1} = 0 \\
F_{x1} &= 1393.8 \text{ N}
\end{align*}

\begin{align*}
\sum F_x &= F_{x2} + F_{x3} + F_{x4} = F_{x5} = 1393.8 \text{ N}
\end{align*}
C2 – Finite Element Analysis

Figure C2.1

Figure C2.2
Figure C2.5

Figure C2.6
Figure C2.7

Figure C2.8
Figure C2.9

Figure C2.10
Figure C2.23

Figure C2.24
Figure C2.25

Figure C2.26
Figure C2.29

Figure C2.30
Figure C2.33

Figure C2.34
Figure C2.35

Figure C2.36
Figure C2.37

Figure C2.38
Figure C2.41

Figure C2.42
Figure C2.45

Figure C2.46
Figure C2.51
Appendix D

D1 – ThunderBolt Test Frame Drawings

Figure D1.1

Figure D1.2
Figure D1.11

Figure D1.12
Figure D1.19

![Figure D1.19](image)

Figure D1.20

![Figure D1.20](image)
Figure D1.27
D2 – Drop Weight Test Frame Drawings

Figure D2.1

Figure D2.2
Figure D2.3

Figure D2.4
Figure D2.7

Figure D2.8
Figure D2.9

Figure D2.10
Figure D2.11

Figure D2.12
Figure D2.13

Figure D2.14
Figure D2.17

Figure D2.18
function drop_test1_graphing
clc;
clear;
load 'drop1.txt'
sensor1 = drop1(:,1);
%sensor2 = drop1(:,2);
%sensor3 = drop1(:,3);
%sensor4 = drop1(:,4);
%sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor1, 'b', time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13000/3500 18000/3500]);
ylim([0 0.85]);
hold
% EOF

function drop_test1_closeup1
clc;
clear;
load 'drop1.txt'
sensor1 = drop1(:,1);
sensor2 = drop1(:,2);
sensor3 = drop1(:,3);
sensor4 = drop1(:,4);
sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor1, 'b', time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13440/3500 13550/3500]);
ylim([0 0.9]);
hold
% EOF

function drop_test1_closeup2
clc;
clear;
load 'drop1.txt'
sensor1 = drop1(:,1);
sensor2 = drop1(:,2);
sensor3 = drop1(:,3);
sensor4 = drop1(:,4);
sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor1, 'b', time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([17450/3500 17550/3500]);
ylim([0 0.9]);
hold
% EOF

function drop_test1_sensor1_graphing
clc;
clear;
load 'drop1.txt'
sensor1 = drop1(:,1);
%sensor2 = drop1(:,2);
%sensor3 = drop1(:,3);
%sensor4 = drop1(:,4);
%sensor5 = drop1(:,5);
time = [0:32990];
plot(time, sensor1, 'b');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([0 32990]);
ylim([0 1]);
hold
% EOF

function drop_test1_sensor2_graphing
clc;
clear;
load 'drop1.txt'
%sensor1 = drop1(:,1);
sensor2 = drop1(:,2);
%sensor3 = drop1(:,3);
%sensor4 = drop1(:,4);
%sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor2, 'm');
plot(time, sensor1, 'b');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13000/3500 18000/3500]);
ylim([0 0.85]);
hold
% EOF
function drop_test1_sensor3_graphing
clc;
clear;
load 'drop1.txt'
%sensor1 = drop1(:,1);
%sensor2 = drop1(:,2);
sensor3 = drop1(:,3);
%sensor4 = drop1(:,4);
%sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor3, 'r')
 ,time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13000/3500 18000/3500]);
ylim([0 0.85]);
hold
% EOF

function drop_test1_sensor4_graphing
clc;
clear;
load 'drop1.txt'
%sensor1 = drop1(:,1);
%sensor2 = drop1(:,2);
%sensor3 = drop1(:,3);
sensor4 = drop1(:,4);
%sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor4, 'y')
 ,time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13000/3500 18000/3500]);
ylim([0 0.85]);
hold
% EOF

function drop_test1_sensor5_graphing
clc;
clear;
load 'drop1.txt'
%sensor1 = drop1(:,1);
%sensor2 = drop1(:,2);
%sensor3 = drop1(:,3);
%sensor4 = drop1(:,4);
sensor5 = drop1(:,5);
time_interval = 1/3500;
finish_time = 32990/3500;
time = [0:time_interval:finish_time];
plot(time, sensor5, 'g', time, sensor2, 'm', time, sensor3, 'r', time, sensor4, 'y', time, sensor5, 'g');
title('Voltage vs Time');
xlabel('Time (seconds)');
ylabel('Voltage (volts)');
xlim([13000/3500 18000/3500]);
ylim([0 0.85]);
hold

% EOF
Appendix F

F1 – Drop Test Results

The size of the voltage is again very high. Higher voltage values were achieved than previous tests. This is likely to be a result of removing the air from above the water level in the pressure tube.
Figure F1.3

Figure F1.4
The above plot shows the data loggers had barely begun recording when the energy was transferred through the water column. Drop Test #10 was unsuccessful as the weight fell before it had even reached halfway up the 6.5m tube.
The entire data plot of Drop Test #11 show two interesting events taking place prior to the fall of the drop weight onto the water column. Both voltage spikes suggest the system could have been physically unstable during the test. The first spike occurs at approximately 24 seconds into the recording. This fall of voltage suggests the pressure tube underwent a fall in pressure, thus moving the crystal in the sensor toward the inside of the tube. The second spike suggests the opposite eventuated. It is possible the system was knocked twice, or moved and then adjusted back to the original state by the operator.
A close up of the voltage results in the timeframe before and after the falling of the drop weight is shown in Figure 11.33. The two spikes that occur in succession prior to the experiment would suggest the pressure tube was displaced twice while the weight was lifted to maximum height of the drop tube. Another theory would suggest a single knock to the tube at some stage prior to the drop and this impact may have taken some time to settle, thus giving a secondary spike.

![Figure F1.9](image)

The weight in this test again dropped before it was intended. This data plot shows the data recording was only just initiated before the weight impacted on the water column. The results of Drop Test #12 was therefore deemed to be unacceptable for analysis as the kinetic energy produced would not equal the expected 1250J for the strike. This also explains the low voltages produced by the pressure transducer in comparison to the results experienced from the full drops.
Drop Test #13 was another test where the drop weight quick-release device tripped before the weight had progressed to the pinnacle of the calibration tube. Similarly to the previous test, the results of this particular experiment cannot be considered in the analysis of a 1250J impact load.
It is obvious there are two distinct changes in the data as a result from the impact load on the water column. This will be shown in detail in Figure 14.43 with the irrelevant data removed from the plot. A spike is also visible at the beginning of the record. This high reading cannot be explained and will be disregarded from the analysis.
A closer investigation of the physical data clearly displays the variation in voltage from the initial strike and rebound on the water column. Although the voltage value from the initial strike is lower than many of the previous tests, this experiment has produced the clearest rebound spike from all the tests conducted. A rebound value of approximately 0.6Volts is comparatively greater than the secondary values seen of other experiments. Two further spikes are also visible in the data of the simplified plot.