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by Oliver Overton

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**An investigation into the effects of material
properties versus physical changes when modelling
shaped charges.**

by

Olly Overton

Project submitted as part of the requirements for the
award of BEng (Hons) OME

March 2024

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ABSTRACT

The calculations involved when modelling shaped charges in a hydrocode, implement many complex equations. The equation parameters include: shock interactions, particle interactions, fluid dynamics and temperature changes. The way these equations interact influence the output of a simulation. It is not common knowledge amongst the wider community, how these equations are affected by changing a singular variable, such as the poisson ratio of a shaped charge liner. A singular change to just one variable i.e. the poisson ratio of the liner, may subject a simulation to produce a different output. This output can be measured in many ways such as: the change in the velocity of the jet, the change in length of the jet, the change in breakup of the jet and the change in temperature of the jet. Each variable contributes a significance to the output. This significance will vary across the different variables.

This report will cover the most significant variables, and how they work holistically to alter the output of a simulation. The rationale is that tolerances when manufacturing shaped charges, and their impact on jet performance is not properly understood. The manufacture of shaped charges typically uses the highest quality copper available; this copper is oxygen free and low phosphorous. The grade of copper is usually either C101, C103 or C109 all of which are above 99% pure copper. However, there are still discrepancies across different batches and manufacturers.

This work will explore the effect those discrepancies play in changing the performance of a shaped charge by producing models with pre-defined parameters on certain variables. These parameters will simulate manufacturing tolerances, with the resulting data analysed to see if they play a significant part in the overall performance of a shaped charge. The effects of the tolerances could then be investigated by industry to assess if it is worth investing in making more accurate products.

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CHAPTER 1 – SETTING THE SCENE

1.1 INTRODUCTION

A shaped charge is a device whereby a liner, often made from a malleable material such as copper, is inverted when subject to elevated temperatures and extreme pressures. These extreme conditions are produced by an explosive event under confinement. This results in the liner being exposed to such a temperature that it becomes a plasma, a state whereby it does not obey the rules of the 3 known states: solid, liquid or a gas [1]. During this plasma state, the liner can elongate up to 3-5 times its original diameter. This elongation forms a long molten jet, which when explosively driven speeds in excess of 7kms^{-1} can be achieved. Thus, making it a perfect formula for enhanced penetration, especially on hardened targets such as tanks. This phenomenon is known as the Munroe effect, and is widely adopted by the majority of defence companies who produce shaped charge devices.

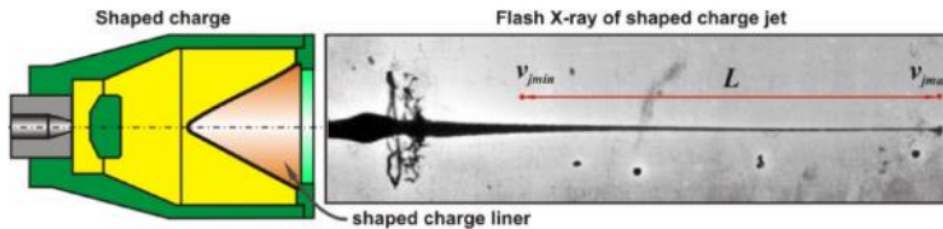


Figure 1 – Shaped charge jet forming from a conical liner [36].

It is important to highlight that a shaped charge is a device and not defined a weapon. Despite having the capability to be used as a weapon, like in a tandem warhead such as an RPG-7. A shaped charge can also be used as a render safe tool to disrupt Improvised Explosive Devices (IEDs). Furthermore, shaped charges can also be used in the mining industry to break apart rock formations to reach precious metal ores.

These shaped charge devices can be replicated in a virtual environment using a hydrocode. A hydrocode is a computer program that can be used to simulate numerically highly strain dynamic events, specifically those that include shocks [2]. Due to the explosive nature of a shaped charge, the malleable liner is exposed to a

shockwave, which is a propagating wave of air that travels faster than sound in the medium. Therefore, Hydrocodes such as ALE3D [3] are ideal for simulating this shockwave and the interaction it has between the many components within a shaped charge.

The modelling of shaped charges requires the yield stresses, fracture pressures and Poisson ratios of each material to be considered. All of which determine a material's malleability, plastic deformation and failure points. Within the software, there are equations that use these variables to undertake calculations within the defined mesh of the hydrocode. All these variables work holistically and contribute significantly to the end output of the simulation.

When delving into the many components that affect the performance of a shaped charge the components can be categorised as either, material properties or physical changes in the setup of the simulation. It is unknown which components carry the most significance in altering the end output of a simulation. Therefore, a study into the magnitude of each individual component is required to determine its importance in the model.

1.2 AIM

The aim of modelling these individual components is to produce a hierarchy of controls, that when other users attempt to model a shaped charge, they can refer to it to determine predicted outcomes. Currently, extensive research has been carried out for around 80 years in perfecting the shaped charge; however, this research has mainly had a focus on physical testing. It is only within the last 20 years that Hydrocodes have been simulating these devices in a virtual environment.

Therefore, there has been less focus on the modelling and replication of shaped charges in a virtual environment. Which is why this study will focus on the smaller variables such as: fracture pressures, yield stresses and Poisson ratios as they have been previously overlooked [4].

1.3 OBJECTIVES

The aim for this project is to explore the effects that altering material properties has on the jet formation of a shaped charge. In turn this will help inform the larger community when modelling experimental setups.

Objectives to achieve this include:

- Attempt to validate a shaped charge simulation from data collected on a trial involving a specific shaped charge device.
- Determine a list of major components that affect a shaped charge's performance.
- Alter these components within a pre-defined range, and record the output.
- Analyse the new velocities observed, once a component has been altered.
- Produce a Velocity Jet Mass (VJM) plot to further analyse the jet breakup of each simulation.

CHAPTER 2 - RESEARCH & REVIEW OF LITERATURE

2.1 INTRODUCTION

This chapter will look to present existing information on shaped charges and their lethality effects. The review of existing information will be separated into two major aspects, the first focussing on the trials and testing of shape charges the second delving in on how shaped charges are modelled. Both will cover the fundamental theories that underpin some of the variables within a shaped charge. These variables will be altered in the simulations, so it is important to understand how they interact in affecting the performance of a shaped charge.

2.2 PHYSICAL PARAMETERS

A particular parameter that should be of interest is the liner of a shaped charge and its role in affecting the jet formation. The conceptual mechanics on how a jet elongates was first explored by Birkhoff and others in 1948 [5], however this initial concept was expanded on by Pugh, Eichelberger and Rostocker [6]. The major change between the two opinions refers to the non-uniform collapse of the liner.

The line assigned 'A through Q' symbolises where the conical liner sits. The line V_d replicates the shockwave. When the shockwave propagates down the conical liner,

the velocity of collapse V_0 decreases from the apex to the base. This is caused by mass of the liner decreasing. When taking two points, P and P1 the shockwave takes an identical time for point P to reach J, as it does for P1 to reach the curve M. If the velocity of collapse were to be uniform then P1 would reach line N in the time taken for P to reach J. This causes a shaped charge jet to have varying velocity. The tip of the jet will always be faster than that of the rear slug; this is because there is simply more mass of the liner at the rear. This varied velocity theory was not touched on by the research from Birkhoff. Nowadays it is common knowledge amongst the wider user group that the tip has a higher velocity.

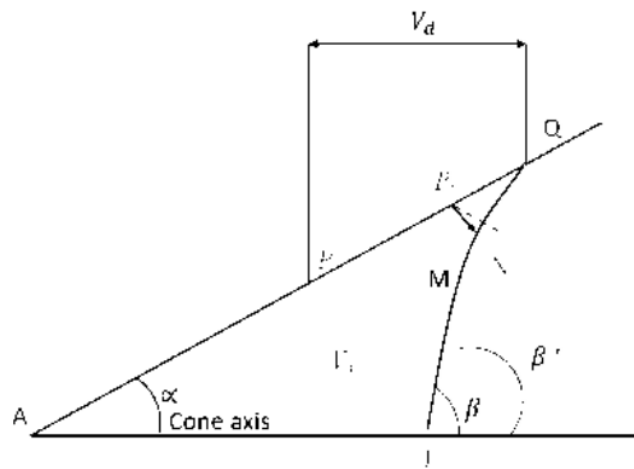


Figure 2. - The collapse of a shaped charge liner illustrated by Pugh [6].

A limitation to the work carried out by both Birkhoff and Pugh, is that their concepts suggest the collapse of the liner is repeatable. Meaning each firing will be identical. However, a shaped charge has varied results within a certain bandwidth. This bandwidth is caused by: manufacturing defects, inconsistent explosive reactions, temperature of the environment and how interactions influence one another. If 100 shaped charges from the same manufacturer, and same batch were fired, a range of outputs would be observed producing a bell curve of varied results. There are numerous factors contributing to this variance. The likelihood is that the variance is due to chance causes as opposed to assignable causes. One factor may not have

an influential effect on these varied results, whereas multiple factors combined may [7].

On the other hand, modelling 100-shaped charge firings would not provide a variance in any results observed. The simulation uses perfect materials with no defects. There are no environmental discrepancies within the simulation either. To make the simulations more realistic, the varied results from trials can be implemented. To successfully do this a range is assigned to each variable. The software will then select a value within the pre-defined range and take that value forward in any calculations. A limitation is that many simulations will be required in order to capture the full range of results. Further limitations include not being able to conduct a sensitivity study on each variable, due to the software choosing values at random.

Another parameter affecting the performance of a shaped charge is the shockwave, and its tendency to shear/deform materials. The fundamentals behind shockwaves and their utilisation in shaped charges has been extensively researched. The explosive material will exert a shockwave through a medium. When this shockwave passes through said medium, it exposes the medium to a harsh change in pressure. The pressure before and after the shockwave differ due to the Rankine Hugoniot conditions [8]. This overall change in pressure experienced by the medium has a tendency to push then pull said material. This is because the scaling is nonlinear. When the shockwave interacts on a shaped charge liner, the large magnitude of pressure exerted makes the liner behave like a plasma. This is due to the liner yield stress being overmatched [9]. A high Net Explosive Quantity (NEQ) and high brisance can vaporise the liner when the yield stress is significantly overmatched. The simulation uses the Bernoulli equation for the flow of the material and characterises the plasma as inviscid fluid [5].

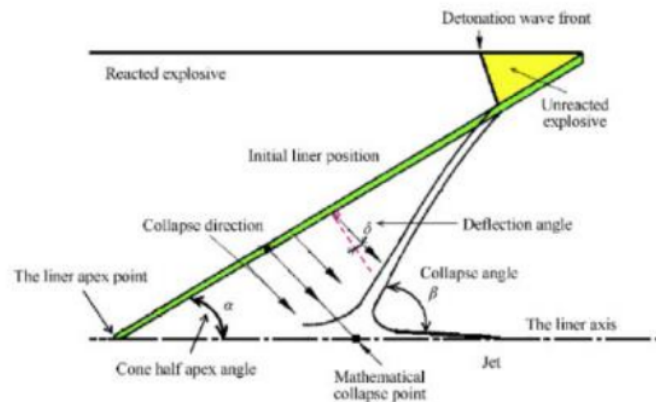


Figure 3 - The nonlinear collapse of a shaped charge liner [39].

It is also important to look at the geometry of all the components in a shaped charge. All shaped charges follow the concept of the Munroe effect; however their physical makeup will differentiate depending on their intended use [5]. Specific shaped charges can be altered to maximise penetration, whereas others can be altered to maximise reliability for use in harsh environments, such as in deserts or underwater. Figure 4 shows a Pluton device used underwater versus on land. The underwater design incorporates a funnel to direct the jet and prevent any losses momentum to the surrounding environment.



Figure 4 – Pluton shaped charge underwater versus land use [40].

World War 2 produced numerous iterations of shaped charges. This was due to the requirement of successfully penetrating thick armours such as steel and concrete bunkers [5] [10]. Within the mining industry, the blasting of rock using shaped charges is thoroughly researched [10] [11]. Mining shaped charges are much larger as they require penetrating a wider surface area. On the other hand, shaped charges used within the defence industry are smaller. This is because they require being more precise; this is to penetrate smaller specific targets/threats such as a

power source located within an IED. There will always be a variation in shaped charge sizes dependent on the intended target [5].

Despite differing applications, all shaped charges follow similar principles. In the diagram below the diameter of the liner is LD , the diameter of the charge is CD , and the warhead diameter is WD [5]. The head height is the distance between the apex of the liner and the point of detonation [5].

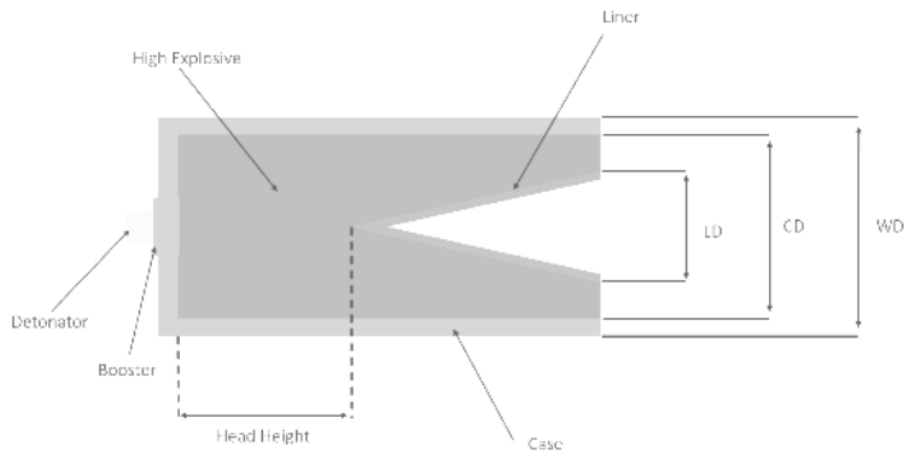


Figure 5 - A diagram of a shaped charge and its fundamental components [5].

The major output of a shaped charge is its penetration capability. This is heavily affected by the standoff. The standoff is the distance between the target and apex of the liner. The effect of standoff has been researched extensively [12] [13]. However, the following investigation is going to focus on the variables that affect the jet formation. Although the standoff will not be investigated in this study, an appropriate domain is required to visualise the full formation of the jet.

There are other variables to consider when designing a shaped charge. These include technical variables such as the weight and dimensions; also non-technical factors such as the cost and availability of the materials. The intended use of the shaped charge influences its weight. Shaped charges can vary in size drastically depending on the target set. For example, a shaped charge such as Vulcan™ is filled with just 10g of Plastic Explosive (PE) to defeat small IEDs with little protection [14]. Whereas, Saab' SM-EOD 130 uses 2540g of PE to defeat buried Unexploded

Ordnance (UXO) [15]. Other considerations are the cost, materials, assembly/manufacturing, shipping and marketing. The common trend amongst the defence industry is to increase performance whilst saving money and materials.

Applying this to shaped charges, a way to reduce both weight and cost per individual unit is to exploit boat-tailing. This is where the charge is tapered so that sections of the explosive are removed, reducing the cost and weight [5]. The diagram below alters the design previously seen to incorporate boat-tailing. The effect boat-tailing has on the performance is minor. However, if implemented properly the boat-tail can act as a wave-guide producing a uniform shockwave on the liner. This results in an even collapse of the liner.

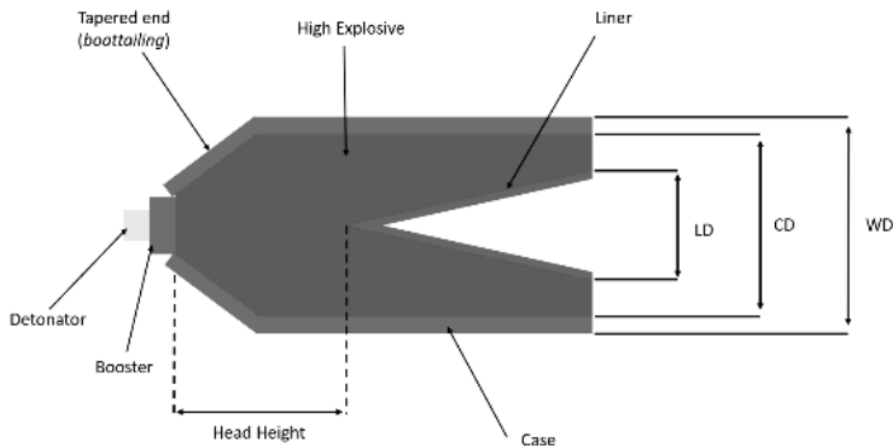


Figure 6 - A diagram of a shaped charge with a boat-tail rear [5].

Although there are numerous variables to increase the performance of a shaped charge, there is no set defined script to achieve this [5]. However, one example of increasing performance is to optimise penetration by altering the apex angle of the liner. This variable has been studied since World War 2 and continues to be a relevant topic in modern research, especially when analysed with different combinations of liner material and thicknesses [5] [16]. Studies have shown it is possible for the liners: thickness, angle and shape to have an effect on the jet formation and velocity. However, these variables do not have a defined construction nor relationship that can be applied to all shaped charges [12] [16]. Therefore, it is

important to take caution when trying to conclude that any one variable of the shape charge geometry is responsible for the change in performance. For example, a steel liner with a small cone angle, and a copper liner with a larger cone angle may produce unexpected results. Research would suggest the copper liner with the larger cone angle would observe a better jet formation, due to a more malleable material and steeper cone angle. However, this may not be the case and may impose a limitation when it comes to modelling a shaped charge. Because there are so many relationships between such a vast list of variables, the dataset in order to capture all the interactions would be unachievably large. In order to bound the study from becoming unachievable, only the most significant variables will be analysed.

To identify the most significant variables further literature will be researched. It will be important to distinguish work conducted between Explosively Formed Projectiles (EFPs) and shaped charges. Although similar, EFPs do not follow the Munroe effect, they follow the Misznay-Schardin effect. EFPs differ to shaped charges as they have a larger cone diameter with a much shallower angle. EFPs are used in situations that require a greater standoff, sometimes of which is 100 times their charge diameter. Therefore, although similar, research on EFPs will not provide any benefit in understanding the jet formation of a shaped charge.



Figure 7 - Hierarchy of physical variables that affect the jet formation of a shaped charge [31].

As previously mentioned, further research is required to find the most significant variables that affect jet formation. However, after multiple discussions amongst Subject Matter Experts (SMEs) those variables have been identified and listed in figure 7.

A description of each variable and how it affects jet formation:

Standoff – the standoff is the distance between the liner of the charge, and the intended target. A small standoff results in less penetration, this is because the jet needs time and space to elongate to its full length. On the other hand, a standoff too large causes the jet to break apart. This occurs because the mass separates out depending on its velocities. Heavier parts of the jet move more slowly and are typically located at the rear of the jet. The tip of the jet is the fastest, because it has the least material. If the jet does break-up, the penetration decreases.

Material of the liner – the choice of the liner material is vital to the performance of a shape charge. Malleable materials such as copper elongate better than those of non-malleable materials. Gold has been trialled and tested, however it is too expensive to manufacturer. The more malleable a material, the more the jet can elongate. This results in better penetration.

Type of explosive – explosives have varying VODs (velocities of detonation). A higher VOD results in a faster jet and better penetration. Another measurable of an explosive is its brisance. This is the shattering effect of the explosive. A high brisance will promote the liner to elongate, however if it is too high the pressures will overmatch the casing too early, resulting in a loss of pressure to invert the liner. A fine balance of pressure production is required to optimise performance.

Cone diameter – the cone diameter as illustrated in figure 5, is the overall diameter of the liner. The general rule of thumb, is that penetration of a shaped charge is 3-5 times its cone diameter [17].

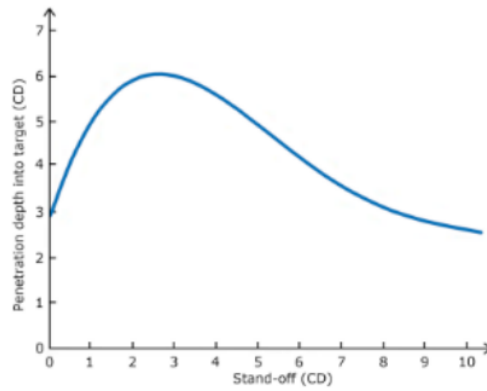


Figure 8 - A graph illustrating the relationship between penetration and standoff [4].

Angle of the apex of the cone – the apex of the cone is the sharpness of the angle that the liner folds. The apex of the liner heavily influences the liners relationship with the shockwave. An obtuse angle means the shockwave is exposed to a flatter liner, this means more surface area is exposed to the shockwave at the same time. Therefore, the liner is pushed away from the casing, rather than be inverted on itself. The liner will still invert, just not to the same elongation as that of an acute angle. An obtuse angle replicates that more of an EFP.

Amount of explosive – the net explosive quantity (NEQ), is the amount of explosive within the housing of the shaped charge. This housing is often made of steel, this allows immense pressures to build up inside, which results in the liner inverting on itself. However, in special operations shaped charges are made of plastics and even carbon fibre. The pressure still builds up enough to invert the liner successfully, however the casing then fragments into small pieces that look like cloth. This allows the special operations units to be discreet and quick, whilst leaving little to no evidence behind. This technique is also used in EOD tools such as disruptors [18]. As for the amount of explosive, it is a delicate balance between too much and too little. Too much explosive ruptures the casing before the liner starts to invert. On the other hand, too little explosive does not produce enough pressure to invert the liner.

Headspace – the headspace of a shaped charge is the distance between the apex of the liner and the initiation point of the explosive (often the booster). Similar to the NEQ, the headspace can be too long or too short. A long headspace means the shockwave loses its momentum resulting in less elongation of the liner. Whereas, a short headspace means the shockwave doesn't have a nice uniform front [5].

Some conclusions can be made from the above literature research. Firstly, it is near on impossible to determine the relationship between all the variables within a shaped charge. With each shaped charge being purpose built to fulfil a specific role/duty, it is not right to assume that the same rules apply to every one. They will all obey the fundamentals such as the Munroe effect; however, they will all achieve this differently. Secondly, not all shaped charges are designed for maximum penetration. Many are designed for EOD tools, in which you do not want maximum penetration. This is because the target will be completely destroyed and limit forensics on the IED parts recovered. Therefore, they will not have the optimised conditions seen in figure 7 to produce an elongated jet. Finally, there is such a variation in the manufacture of shaped charges, which may cause the jets elongation to vary despite the device being identical.

A limit to the current research conducted is that it does not focus on the modelling of shaped charges. To aid the structure of the simulations due to be ran in this investigation, a further literature review detailing the modelling of shaped charge devices is required.

2.3 MATERIAL PARAMETERS

When researching existing work on the modelling of shaped charges, it is worthy to know that it does not directly relate to the work conducted in this study. This is because the modelling of shaped charges carried out by others, is difficult to apply to work carried out by one's self. This is due to the nature of modelling and the numerous variables within it. This is because many different software's exist, all of which implement varying ways of carrying out the basics. The basics to modelling a shaped charge include: the mesh, the units, the material inputs, the strength model, equations of states and if it is Lagrangian or Eulerian. All of these basics help produce a model, but they do it in different ways. For example, a Lagrangian software follows all the particles and describes the variations around each particle along its trajectory [19], the mesh essentially moves with the particles. Whereas, an Eulerian software describes the particles and their interactions in a fixed area as a function of time [19]. The two software's would produce different results for identical simulations.

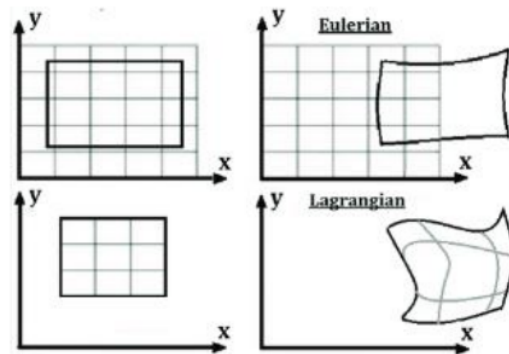


Figure 9 – A visual representation of Eulerian versus Lagrangian mesh [41].

Despite previously saying, modelling done by another user cannot be applied to the modelling in this study. The lessons learnt by other users can be exploited to prevent limitations being encountered. A recent report from February 2023 highlighted how a jet breaks up. It states the breakup time is calculated as soon as the original slug deforms into two new individual fragments. An assumption made is that each fragment has a constant velocity and that each fragment is axially aligned with the firing axis. Before the separation of the slug, each individual fragment is assumed to have the shape of a circular cylinder of known length and radius. A limitation to

this assumption is that fragments of a shaped charge jet actually look like an ellipsoid. However, it is difficult to determine the specific time point of when the ellipsoid forms. Figure 10 shows how the cylinders overlap as cylinders.

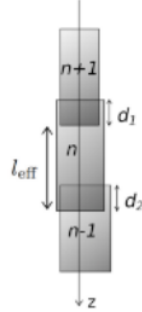


Figure 10 - The breakup time of fragment n is determined by considering the overlap, d_1 and d_2 , of its neighbouring fragments in the jet. The effective length, l_{eff} , is determined from the overlap of the fragment $n + 1$. In this case, the breakup time for fragment n is calculated as $t_{br} = \max ((d_1/(v_n - v_{n+1})), (d_2/v_{n-1} - v_n))$. [4]

The overlapping of the fragments occurs before the separation, the effective length of a fragment is only the non-overlapping length with the following fragment. Because of this, the radius of the fragment is assumed to scale with the effective length in such a way that conserves the volume of the fragment [4]. When it comes to analyse the simulations in this investigation, it will be crucial to use a VJM plot to compare the jet breakup of cumulative mass. Many experiments have been done where only the velocity has been analysed. This does not elude to the bigger picture of how the jet breaks up.

An important lesson when modelling shaped charges is to understand how the code uses material properties. A hydrocode will use fracture pressures, melting temperatures, poisson ratios, yield stresses and more to determine how the individual materials obey the laws of physics and chemistry. Different datasets can be used in certain software's. For example, some may use the SESAME Tabular format, and others may use the Mie–Grüneisen format [20] [21]. They differ in the way they represent a material using different equations of states.

A more extensive literature review has been conducted on material properties and their sensitivity to changes. This can be found in Appendix 1.

CHAPTER 3 – METHODOLOGY FOR THIS STUDY

3.1 PRODUCING A REPLICANT SHAPED CHARGE SIMULATION

First, to obtain any valid data from a shaped charge simulation, a validated simulation is required. To achieve this the simulation should try to replicate that of an existing off the shelf product. Therefore, conclusions from the simulation can be translated across to industry. The end goal being manufacturers gaining a better understanding in how their tolerances affect the jet formation and performance i.e. “If the manufacture were to produce a new batch of shaped charge ‘x’ with a new copper that is 2% more malleable, the resulting change in performance would be...” In order to set up a shaped charge simulation that replicates an existing product pre-existing trials data is required.

In October 2019, a trial took place firing a shaped charge at a 10cm x 10cm x 10cm aluminium block. Flash x-ray systems were used to capture still images of the jet mid-flight. The geometry and dimensions of the shaped charge are known, and images of the jet formation are available. This data can aid the set-up of an initial shaped charge simulation to replicate that device.

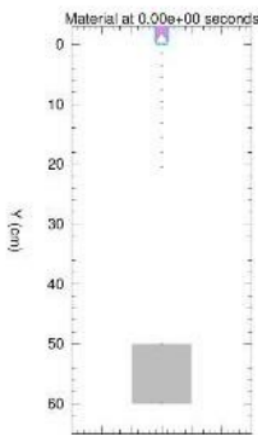


Figure 11 – Modelled shaped charge that replicates the device used in the October 2019 trial [34].

Figure 11 shows the replicated shaped charge in a simulation. The device will fire in the y-axis towards the aluminium block. The ten black dots between the shaped

charge and target are tracers. These are not physical material in the simulation. They are merely co-ordinates that record the velocity of material passing through them. Some of these tracers have been fixed, with others being fluid. The idea being that the jet tip captures fluid tracers, thus recording the highest velocity observed. Whereas, fixed tracers record the velocity of the rear of the jet which moves much more slowly than the tip.

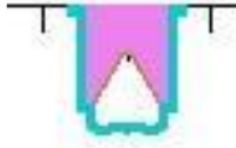


Figure 12 - An enlarged section of Figure 11 [34].

Figure 12 illustrates an enlarged image of the shaped charge from figure 11. The blue/teal material is the casing, the brown/orange material is the liner, and the pink material is the explosive.

In order to produce this set-up, many draft simulations were completed. This involved learning how to implement a 'user defined shaped (UDS)' to produce the correct dimensions for the charge. A UDS is a series of co-ordinates, where the software then draws a line between them; similar to that of children's dot to dot books. Because this simulation is 2D, it had to replicate a cut through image of the 3D real device. Therefore, the UDS had to be scaled to use the correct amount of explosive. This was calculated using a simple technique of drawing the device on graph paper, and working out the area within the UDS. As a result, this meant the geometry of the model replicated that of the real life device. However, the performance of the modelled charge still needed validating.

3.2 VALIDATING A SIMULATED DEVICE

The validation of a simulated device can be done in a variety of ways. One method is to compare the images of the simulated device against images captured on trial. A second method is to analyse the data from both in the form of a VJM plot. This latter method is heavily dependent on the type of data recorded on the trial.

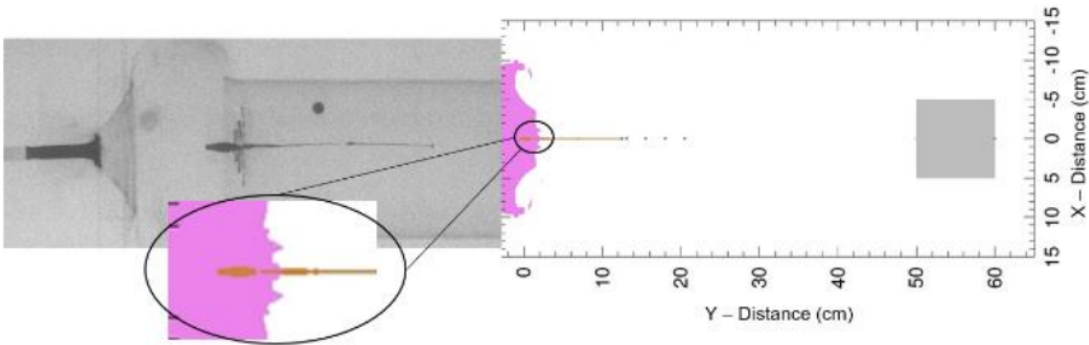


Figure 13 - Modelled shaped charge Vs flash x-ray still. [32]

Figure 13 shows the modelled device from figures 11 and 12 (right hand side) and a flash x-ray still image from the October trial (left hand side). A flash x-ray image is produced using a backscatter plate and x-ray generator. Although the quality of the flash x-ray image may seem poor, it reveals more than what a high-speed camera would achieve. A high-speed camera would not see the early stages of the jet forming, due to the intense light and gas produced from the explosive reaction.

Using method 1, the two images can be analysed. To do this, the exact same timeframe across the two images is required. The flash x-ray system was initiated once the jet had passed through two light gates. These light gates were setup with a known distance and incorporated a timer between when the jet hit the first and second light gate. This allows for the velocity of the jet to be calculated. To obtain the same time stamp from our simulation, the time step needed to be refined. The time step affects the frequency that calculations take place in the simulation. The simulation uses this time step to produce an image, so it is important the time step is refined to produce an image that mimics the time of the flash x-ray. Looking at the image in figure 13, a few conclusions can be observed.

The first conclusion is that the device tested on the trial in figure 13 suffers from co-axial drift. Co-axial drift is the shift of fragments produced by a shaped charge away from the normal. This normal being the intended firing axis. This occurs when the liner does not collapse uniformly; resulting in the fragments having a varied velocity. This is caused by the shockwave not propagating perfectly as a planar wave front

[22]. This is the consequence of minor defects in the explosive called voids. A void is a very small hole in which air or a contaminant has been trapped in the explosive during manufacturing. This most commonly occurs in the filling process of a shaped charge. Technology is improving to fill the charges using a technique called Resonant Acoustic Mixing (RAM). These voids make the shockwave front slightly bent from the normal. In an ideal world, the shockwave would reach the liner at the same time as one continuous planar detonation front. Because the voids bend the shockwave, the liner then collapses wherever the shockwave first strikes. This causes tumbling of fragments which can be observed in the trials data from figure 13.

The simulated device does not suffer from co-axial drift. This is because the model does not incorporate voids or crystals within the explosive. Instead, the explosive behaves as a uniform planar detonation front, which strikes all parts of the liner simultaneously. Thus resulting in a uniform collapse of the liner, which resultantly produces a jet that is perfectly straight in the y-axis.

A second conclusion can be made between the flash x-ray and simulated image. The simulation does not include the rings around the rear of the jet. This is because a discard function was implemented into the simulation. The discard function eliminates material when it drops below a user-defined density. Both the liner and explosive were discarded when their density became so minute to the point it was no longer affecting the jet formation. Less calculations are required once this material has been discarded, resulting in faster simulation run times.

3.3 COMPARING SIMULATED VS TRIALED DATA USING VJM PLOTS

Validating the simulation from initial observations is it not a reliable way to state any conclusions with much certainty. Data analysis is the more reliable approach. A technique used in the work carried out by Pelfalt [4] analyses the material spread within the jet. This technique involves producing a VJM plot. The plot produces a graph of the cumulative mass against velocity. There are different ways to produce a VJM. However, it is not stated in Pelfalt' work which method is best. Pelfalt

assumes the individual fragments are cylinders like that observed in figure 10, whereas trials data suggest they actually take the shape of an ellipsoid.

To produce a VJM for the device used on trial seen in figure 13, a second flash x-ray still of the jet formation at a later timeframe is required. This second image will provide data to calculate the fragment's velocity by working out the difference in their y co-ordinates. Sadly, the data captured on the trial in 2019 did not include a second x-ray still. Therefore, the simulation cannot be validated using data analysis. This means relying on just initial observations of the images. A method that does not provide much certainty. As the simulated device cannot be validated, it may need to be replaced with a new simulation. Despite the lack of x-ray stills for the device seen in figure 13, a second trial testing a new shaped charge did provide sufficient x-ray stills. This means VJMs can be produced to test if the method works at validating a simulation. Resulting in potential future work to carry out the validation of the attempted simulation in figure 13; if further data was ever sourced/recovered from the October trial.

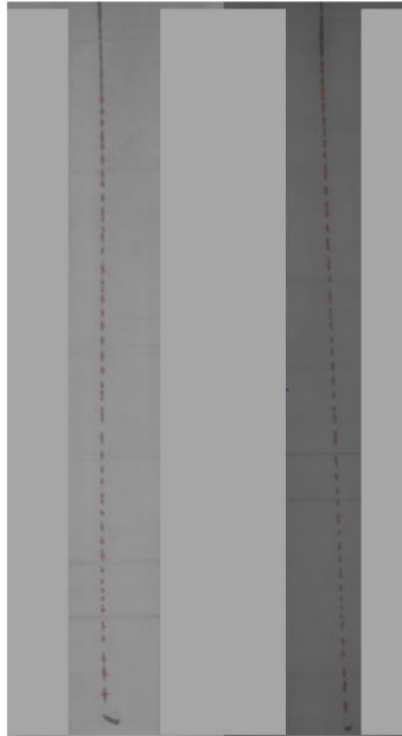


Figure 14 - Two flash x-ray stills of a new device, at different time stamps. [32]
The fragments are much clearer in figure 14 than of those in figure 13, this is because the x-rays were taken later; meaning the jet has more time to

elongate/separate. A calibration is required before undergoing any calculations. Figure 14 has been cropped for classification. However, a known distance will be used for this calibration. The full calculation process for the VJM can be found in Annex 2. It was previously mentioned that the fragments can be assumed as either cylinders or ellipsoids. The actual mass of the liner from the device used in figure 14 weighs 75.95g.

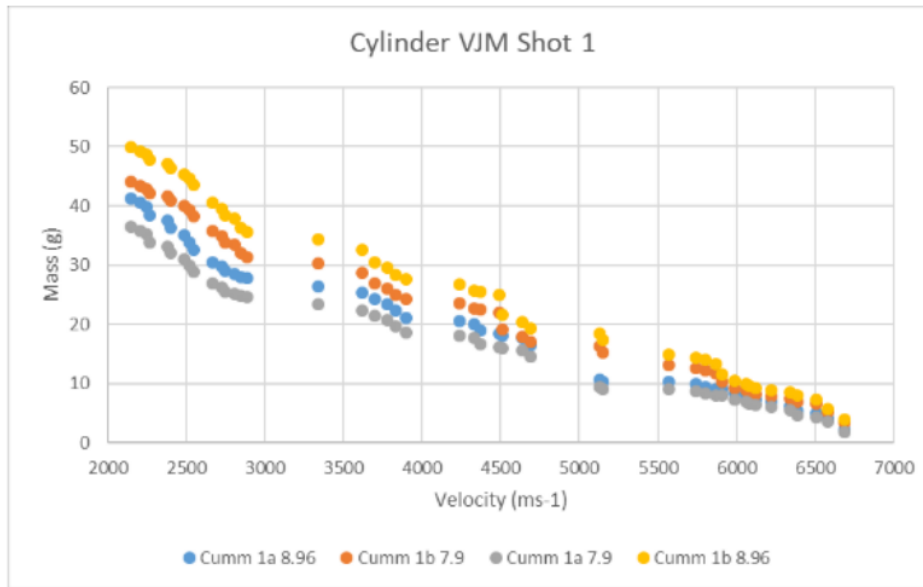


Figure 15 - VJM plot of the device in Figure 10, assuming the fragments as cylinders.

Figure 15 shows the cumulative mass of the liner to range from 36g to 49g. This range in mass is a result of the different densities of copper. Different densities of copper were used in the calculations because the density of copper in plasma state is unknown. The two values replicate the density of copper at room temperature (8.96g/cm^3) and at melting (7.9g/cm^3).

The calculations in figure 15 do not match the 75.95g total mass of the liner. This is expected because not all of the liner mass will form into separate fragments. The calculations only take into consideration the separated fragments. Yet there is still liner material located in the rear slug. This rear slug is not included in the calculations as it differs in shape i.e. it is not an ellipsoid or cylinder. An approximated mass of 10g for the rear slug material was calculated in paint.net. Overall, this means the VJM method assuming the fragments as cylinders provides inaccurate data to

validate a model. The justification for this being 16.95g of liner mass is unaccounted for, which is 22.32% of the original liner mass.

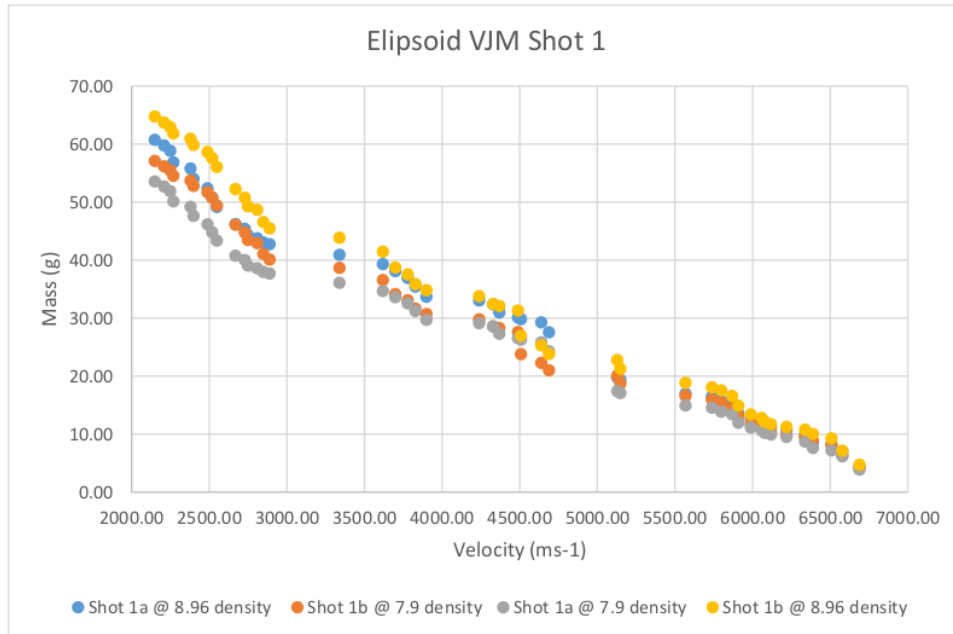


Figure 16 - VJM plot of the device in figure 10 using the ellipsoid assumption.

When comparing figure 16 to figure 15 the highest total mass calculated is now 65g as opposed to the 49g seen previously. This is a value closer to that of the measured liner mass of 75.85g. When adding the calculated 10g mass of the rear slug, the calculations near perfectly match the measured 75.95g liner mass. Therefore, using the ellipsoid assumption could provide a reliable method of validating a shaped charge model.

Due to lack of trials data, a VJM cannot be produced for the device found in figure 13. Meaning the replicated device in the simulation would not be validated. Without this validated simulation, it could be argued that any changes in the velocity and jet formation of the simulated device, would not be witnessed if the same changes were made to a real device. To overcome this, a standardised shaped charge script needs to be produced. This new script will not attempt to recreate an off the shelf product, but instead replicate the fundamental processes within a shaped charge. Once the script is setup and functional, any change in the output will be due to a parameter modification.

3.4 CREATING A NEW SIMULATION

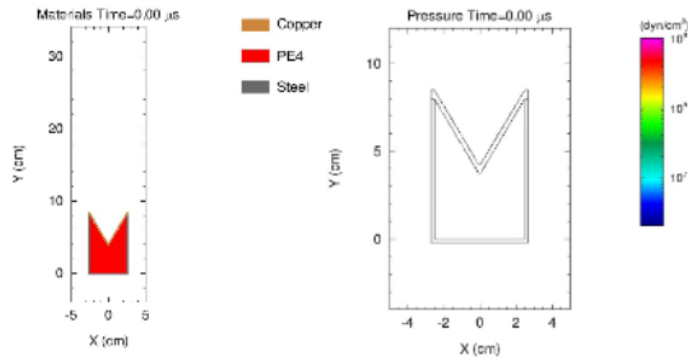


Figure 17 - Simplified shaped charge simulation, material vs pressure [35].

The simulation in figure 17 has been simplified when comparing it to that in figure 11. The reason for this is to reduce computational strain and run time. But to also create a simulation that follows the fundamentals of a generic shaped charge. Existing research depicts the generic shaped charge to look like that of figure 5, which was inspiration when constructing the simulation in figure 17. The aluminium block has also been removed because any change in penetration cannot be validated against trials data.

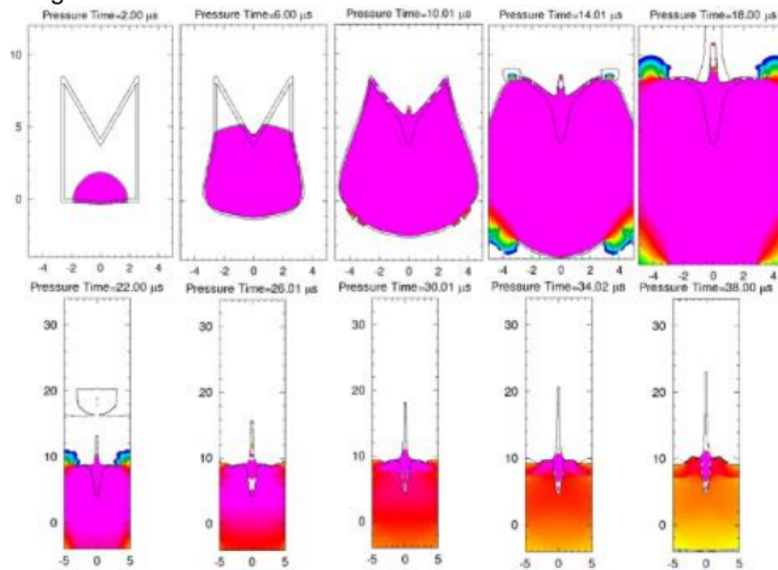


Figure 18 - Propagation of the liner collapsing uniformly [35].

CHAPTER 4 DATA COLLECTION AND RESULTS

The first modifications to the simulation involve the fracture pressures of the liner. The fracture pressure is the point at which a materials structure deforms under pressure. The fracture pressure is a significant material property. Previous research would suggest the higher the fracture pressure, the less ductile the liner would be due to holding its rigidity better at higher pressures. This would result in reduced elongation.

	A	B	C
1	Run No.	Pfrac1	Pfrac3
2	1	-1.50E+10	-3.03E+12
3	2	-1.53E+10	-3.03E+12
4	3	-1.56E+10	-3.03E+12
5	4	-1.59E+10	-3.03E+12
6	5	-1.47E+10	-3.03E+12
7	6	-1.44E+10	-3.03E+12
8	7	-1.41E+10	-3.03E+12
9	8	-1.50E+10	-3.09E+12
10	9	-1.50E+10	-3.15E+12
11	10	-1.50E+10	-3.21E+12
12	11	-1.50E+10	-2.97E+12
13	12	-1.50E+10	-2.91E+12
14	13	-1.50E+10	-2.85E+12

Figure 19 - Matrix of scheduled simulations to be run when altering fracture pressures [23].

Figure 19 highlights the simulations ran to test the affect that altering the fracture pressure (Pfrac) has on the jet formation. Initially a $\pm 2\%$ increment was used to see the affect it has on the velocity of the jet. Both the Pfrac of the liner (Pfrac 1) and casing (Pfrac 2) was altered. The explosive does not have a Pfrac to vary. Observing solely the output images from the simulation will not provide reliable conclusions. To reduce computational strain the resolution of the output images was not refined to capture such small changes. To analyse any changes across the simulations, the highest velocity observed was recorded. It was predicted the jet will have a higher velocity with an increased Pfrac. The rationale being that more pressure can build

up before both the liner and casing suffer from any deformation, resulting in more pushing force.

	A	B	C	D	E
1	Run No.	Pfrac1	Pfrac3	Highest Velocity Recorded (ms-1)	Notes
2	1	-1.50E+10	-3.03E+12	6170.513	Control run - no alterations.
3	2	-1.53E+10	-3.03E+12	6171.046	
4	3	-1.56E+10	-3.03E+12	6172.922	
5	4	-1.59E+10	-3.03E+12	6171.119	
6	5	-1.47E+10	-3.03E+12	6170.319	
7	6	-1.44E+10	-3.03E+12	6161.569	Calculation terminated due to tbad exceeded. Upping tbad as a result (doubling it). Still failed after doubling tbad. Run again with another doubled tbad . Possible
8	7	-1.41E+10	-3.03E+12	6168.987	refelction of pressure at that certain value.
9	8	-1.50E+10	-3.09E+12	6170.513	Interestingly worked, whereas Run 6 did not
10	9	-1.50E+10	-3.15E+12	6170.513	
11	10	-1.50E+10	-3.21E+12	6170.513	
12	11	-1.50E+10	-2.97E+12	6170.513	
13	12	-1.50E+10	-2.91E+12	6170.513	
14	13	-1.50E+10	-2.85E+12	6170.513	

Figure 20 - Results from altering the Pfrac of both the liner and casing [23].

Figure 20 shows the highest velocity observed from the simulations ran. The first conclusion is that there is negligible difference in the highest velocity observed when altering the liners Pfrac. The second conclusion is that altering the Pfrac of the casing has no effect on the highest velocity observed. This second conclusion is expected because the liner is deforming before the casing. The pressure build up within the device ruptures the liner before the casing, this is expected as the casing has a Pfrac 2 magnitudes of order greater than the liner.

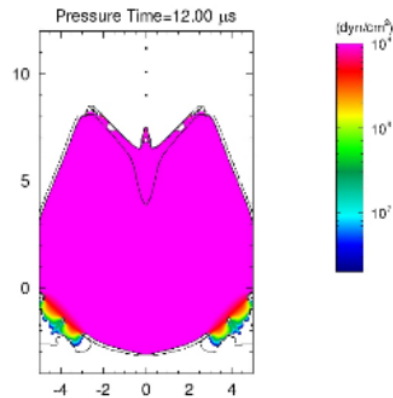


Figure 21 - Still image at 12 microseconds showing the liner deforming before the casing [35].

In Figure 21, it can be observed that the liner has already started its process of inverting. Whereas, the sidewalls of the casing have not deformed but merely pushed outwards.

There is only a 0.0098% increase in velocity between runs 1 and 4. However, there might be a significant change in the jet formation. Plotting a VJM will show the cumulative mass and its velocity, which represents the spread of material through the jet.

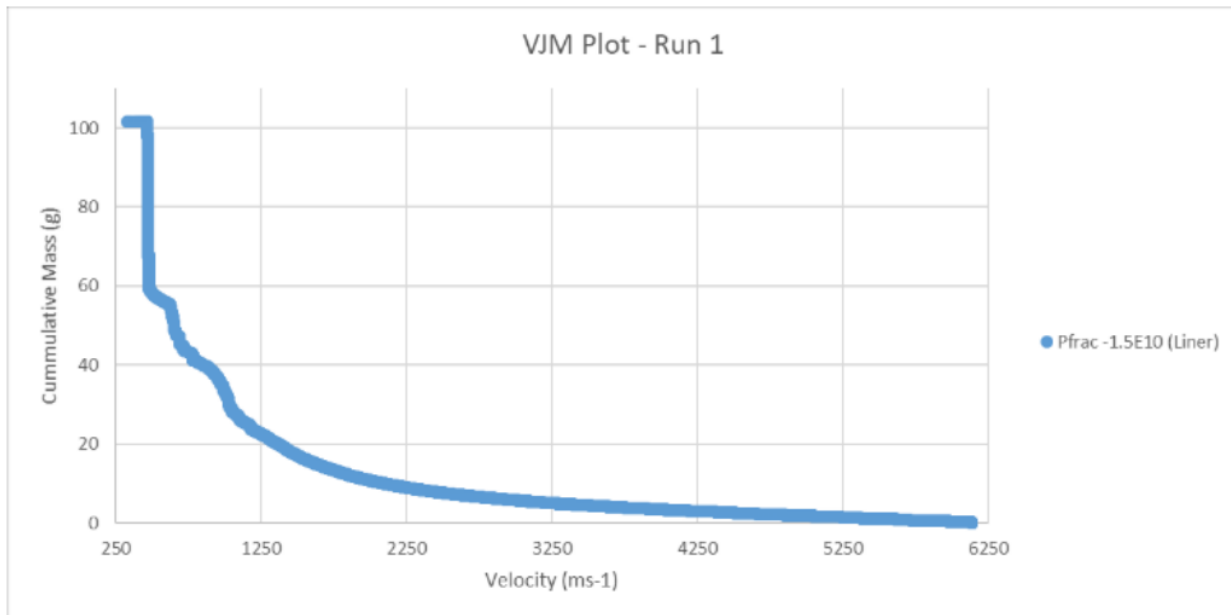


Figure 22 - VJM Plot of Run 1 [25].

Figure 22 contains 4750 data points. These data points correspond to the recording rate of the simulation i.e. how many calculations are taken throughout the 100 micro second simulation. It can be seen the smaller fragments within the jet travel the fastest, whereas the larger fragments travel more slowly. When comparing Figure 22 to Figure 23 the total cumulative mass should be identical. This is because the liner dimensions are not changing; therefore, no mass is taken away nor added. Furthermore, there is now no discard function so all material is accounted for. Figure 20 eluded to negligible change in the highest velocity recorded. Therefore, the two VJM plots should have similar velocities across the x-axis.

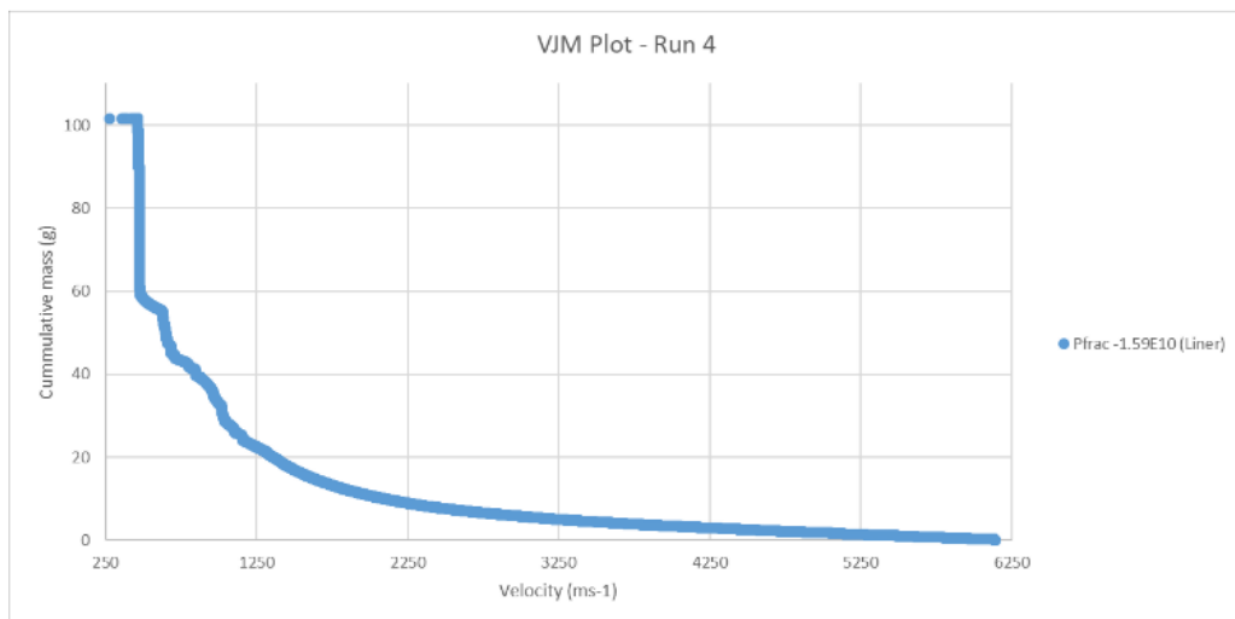


Figure 23 - VJM Plot of Run 4 [25].

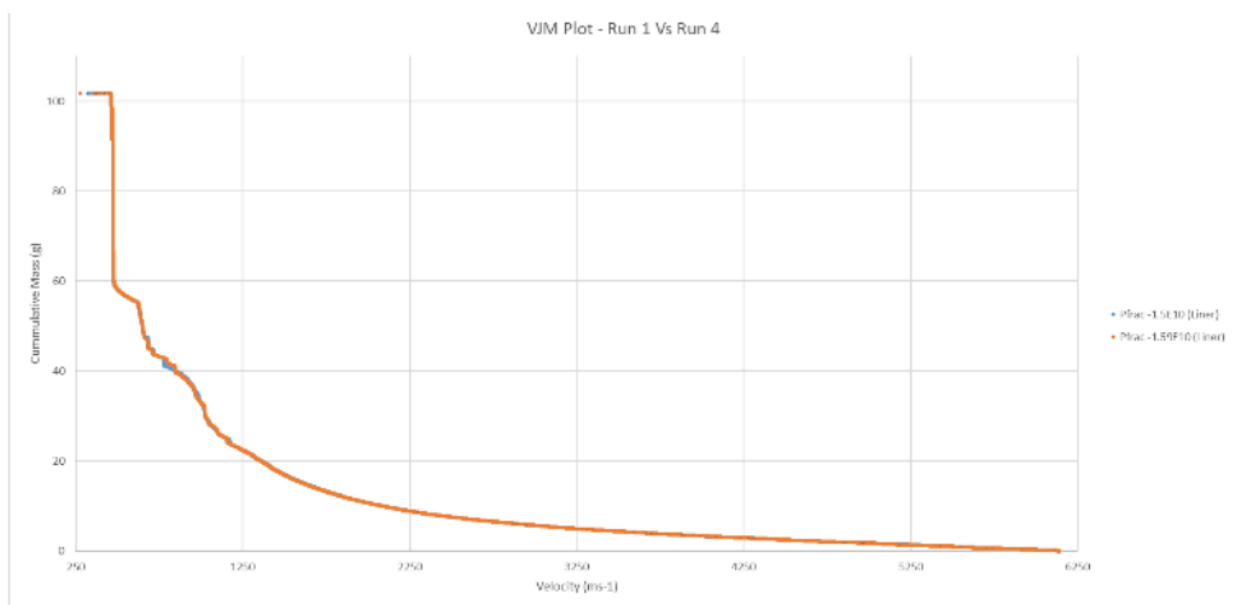


Figure 24 - VJM Plot of Run 1 Vs Run 4 [25].

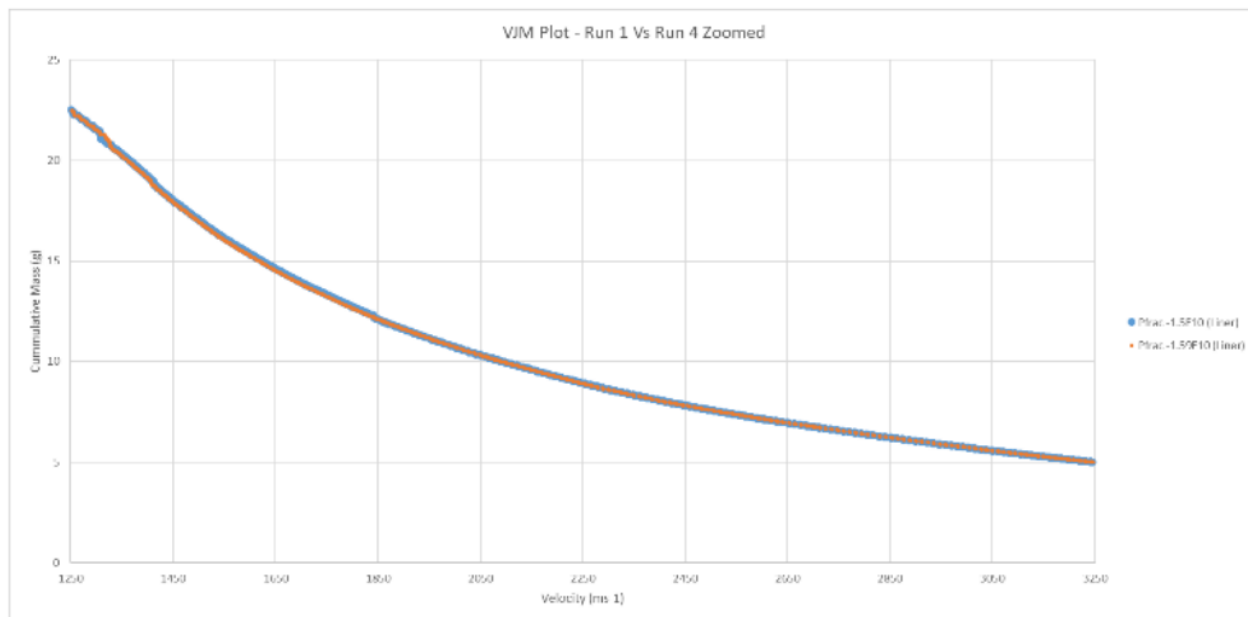


Figure 25 - VJM Plot of Run 1 Vs Run 4 Zoomed [25].

Figure 24 shows overlaying plots of the two runs, this allows for an easier comparison. It was expected there would be a change in the spread of material i.e. the two lines in figure 24 would be different. However, the figures show negligible difference. There is a small difference at approximately $750\text{ms}^{-1}/40\text{g}$, this can be seen in figure 24. However, any differences in this region would not be significant in real life. This is because the rear of the jet does not contribute to the initial penetration. Figure 25 shows a zoomed in section from figure 24. This zoomed in section identifies the section of the jet that contributes to the penetration. For example, 90% of penetration is covered with the first 30% of the jets mass [22]. This section therefore represents the region in which most change in performance would occur. Because figure 25 shows little to no change across the two runs, it can be concluded that increasing the Pfrac by up to 6% from its original value does not affect the performance of a simulated shaped charge. Thus meaning manufacturing tolerances with a +6% altered fracture pressure on the liner would not affect performance. However, the lower bound alteration to the fracture pressure may affect performance because the liner will deform earlier at lower pressure levels.

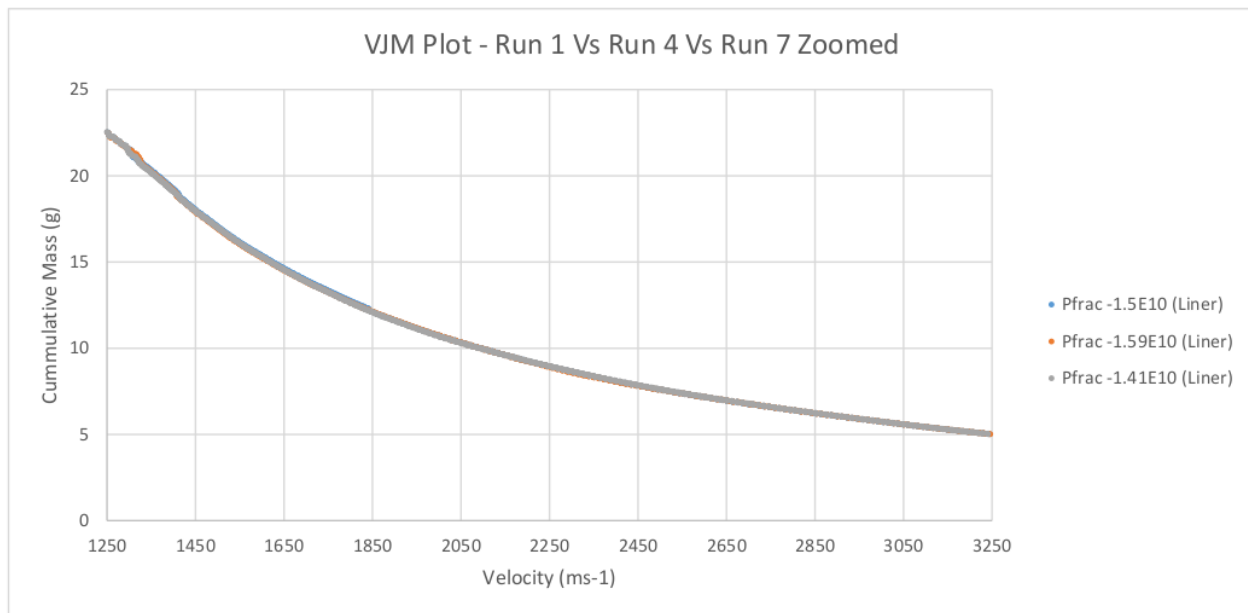


Figure 26 - VJM Plot of Run 1 Vs 4 Vs 7 [25].

Figure 26 shows there is still no difference in performance even with lower fracture pressures. However, if manufacturing tolerances were greater than $\pm 6\%$ would there then be a significant difference? To test this the intervals will be increased from 2% to 10%.

	A	B	C	D	E
1	Run No.	Pfrac1	Pfrac2	Highest Velocity Recorded (ms 1)	Notes
2	1	-1.50E+10	-3.03E+12	6170.513	Control run - no alterations.
3	26	-1.65E+10	-3.03E+12	6171.021	
4	27	-1.80E+10	-3.03E+12	6172.92	
5	28	-1.35E+10	-3.03E+12	6170.932	
6	29	-1.70E+10	-3.03E+12	6170.767	
7	30	-1.50E+10	-3.33E+12	6170.513	
8	31	-1.50E+10	-3.64E+12	6170.513	
9	32	-1.50E+10	-2.72E+12	6170.513	
10	33	-1.50E+10	-2.42E+12	6170.513	

Figure 27 - Simulations with 10% intervals in Pfrac differences [23].

From figure 27, the highest velocity recorded still remains negligible, however the VJMs may elude to a difference in the material spread.

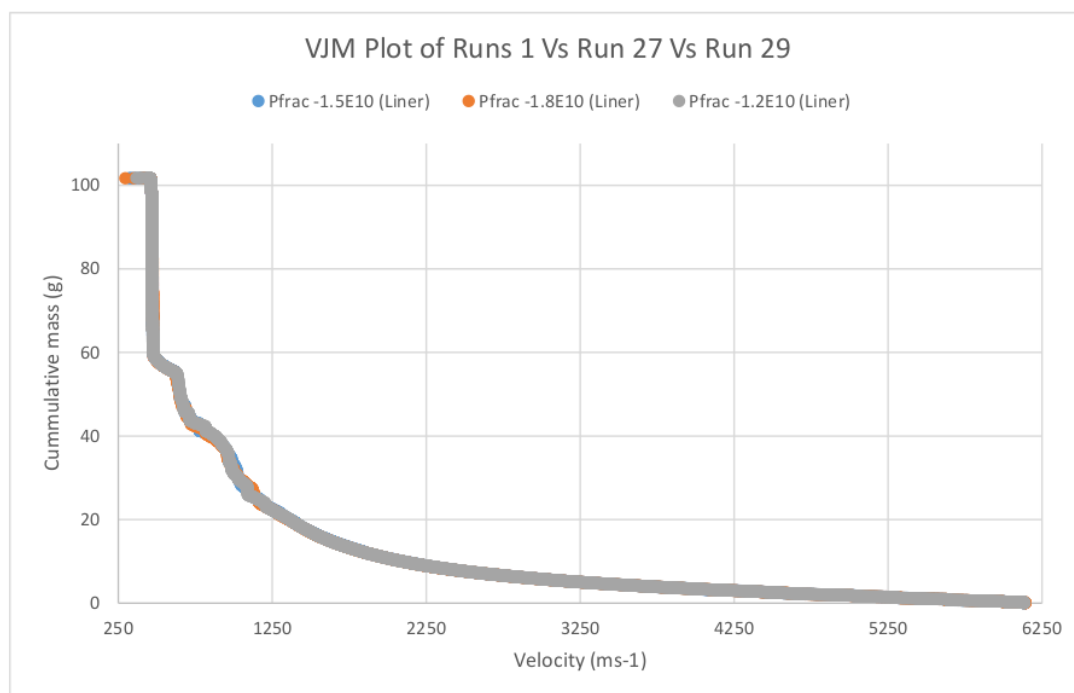


Figure 28 - VJM Plot of Runs 1 Vs 27 Vs 29 [25].

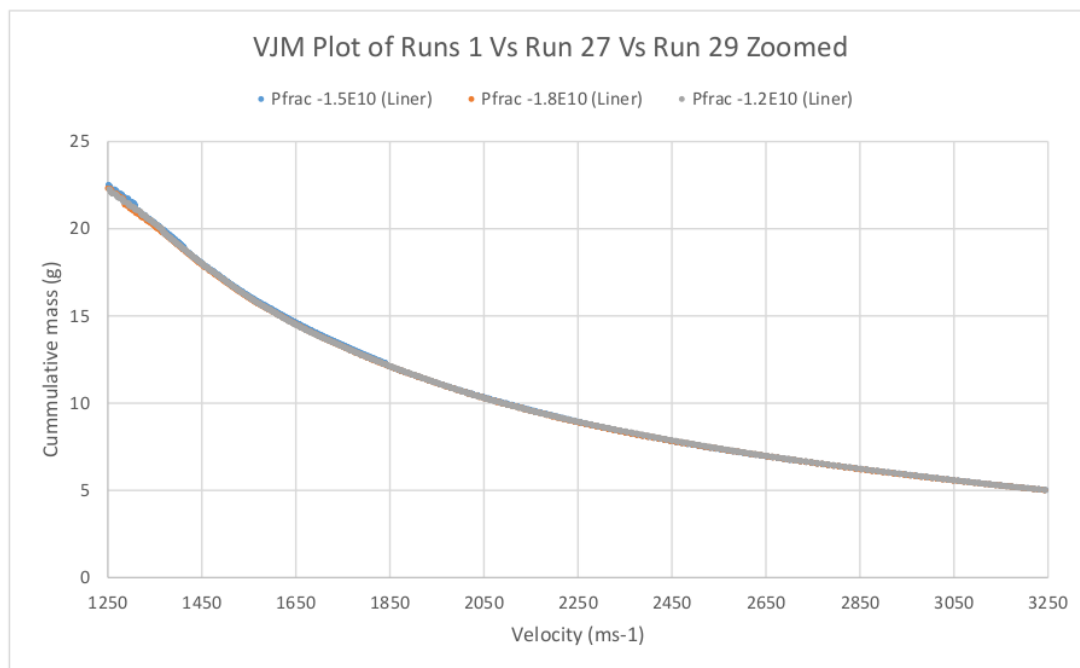


Figure 29 - VJM Plots of Runs 1 Vs 27 Vs 29 Zoomed [25].

Despite upping the intervals from 2% to 10%, there is still no negligible difference. Figure 29 shows the VJM plot for a $\pm 20\%$ increase/decrease, where there is still no observed difference. However, there is a small separation of mass at 1250ms^{-1} across the 3 runs. When adding error bars to the data, this separation of mass is deemed not to be a significant difference.

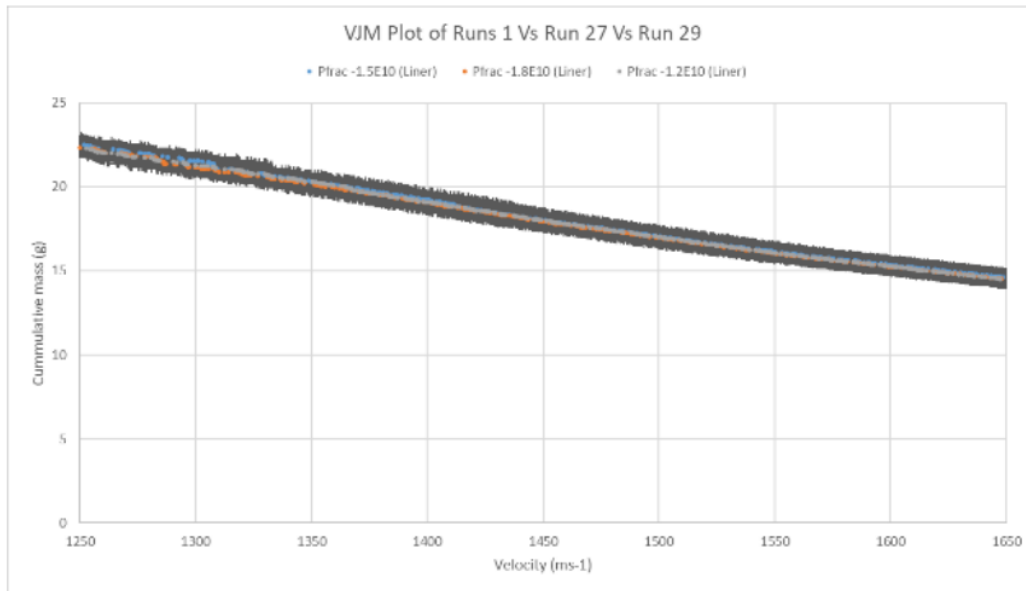


Figure 30 - VJM Plot of Runs 1 Vs 27 Vs 29 with error bars [25].

This negligible change would suggest that the fracture pressure of the liner is not significant when producing shaped charge devices with tolerances of up to $\pm 20\%$. To conclude, changing the fracture pressure of a copper liner by up to $\pm 20\%$ from its original value does not significantly affect the performance of a simulated shaped charge. This conclusion is somewhat surprising. To understand why this negligible change occurs, the way the hydrocode uses the fracture pressure needs to be studied. However, the hydrocode manufacture does not show how the fracture pressures are used and in what equations. However, using existing equations, the fracture pressure is not squared and plays a small role on small objects. Because the liner is so small (millimetres thick) the cross sectional area is insignificant when it comes to the force per unit area. Thus meaning the fracture pressure of the liner will not contribute much output.

Other material properties that may change the way a jet forms include the yield stress and Poisson ratio.

	A	B	C	D	E
1	Run No.	yield	poisson	Highest Velocity (ms ⁻¹)	Notes
2	18	3.50E+09	3.63E-01	6171.85	3.5e9 is normal for yield and poisson is 0.33
3	19	3.50E+09	3.96E-01	6170.62	
4	20	3.50E+09	2.97E-01	6165.88	
5	21	3.50E+09	2.61E-01	6170.07	
6	22	3.85E+09	3.30E-01	6172.20	
7	23	4.20E+09	3.30E-01	6164.56	
8	24	3.15E+09	3.30E-01	6178.41	
9	25	2.80E+09	3.30E-01	6188.95	

Figure 31 - Simulations altering the yield stress and Poisson ratio [23].

Figure 31 shows the highest velocity recorded is fluctuating more than when the fracture pressure was altered. However, it is only a 0.07% decrease in velocity when increasing the yield stress by +20%. A difference that is not significant. The VJM plot may expose a change in the spread of mass though.

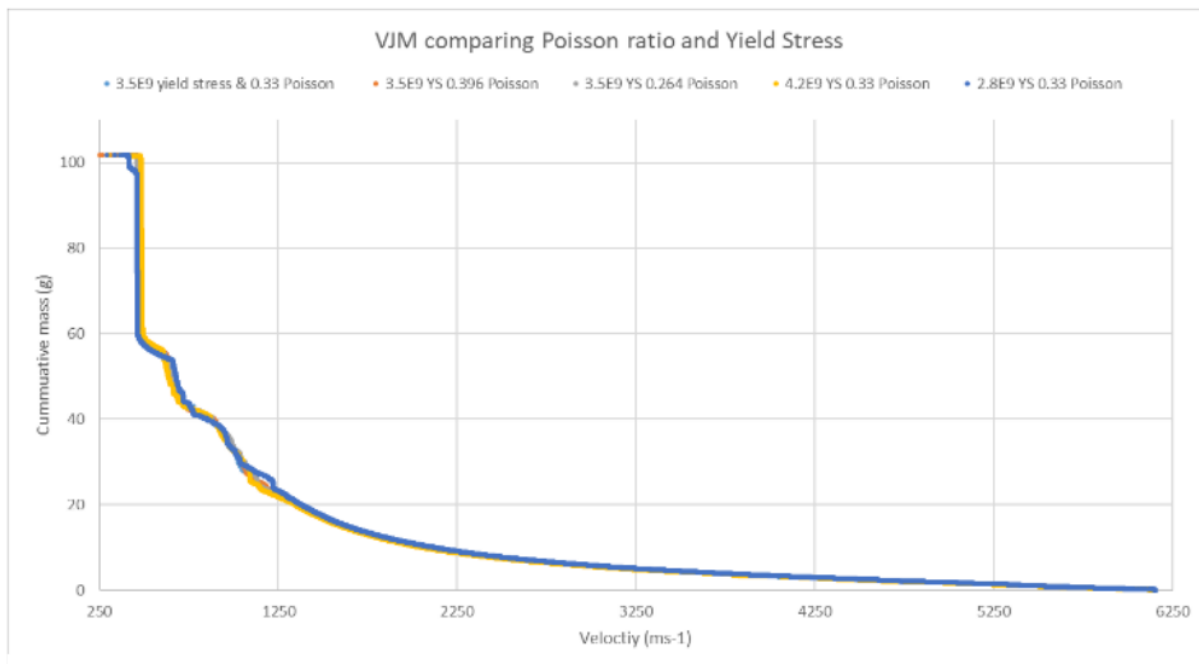


Figure 32 - VJM Plot of altering Poisson ratio and yield stress [25].

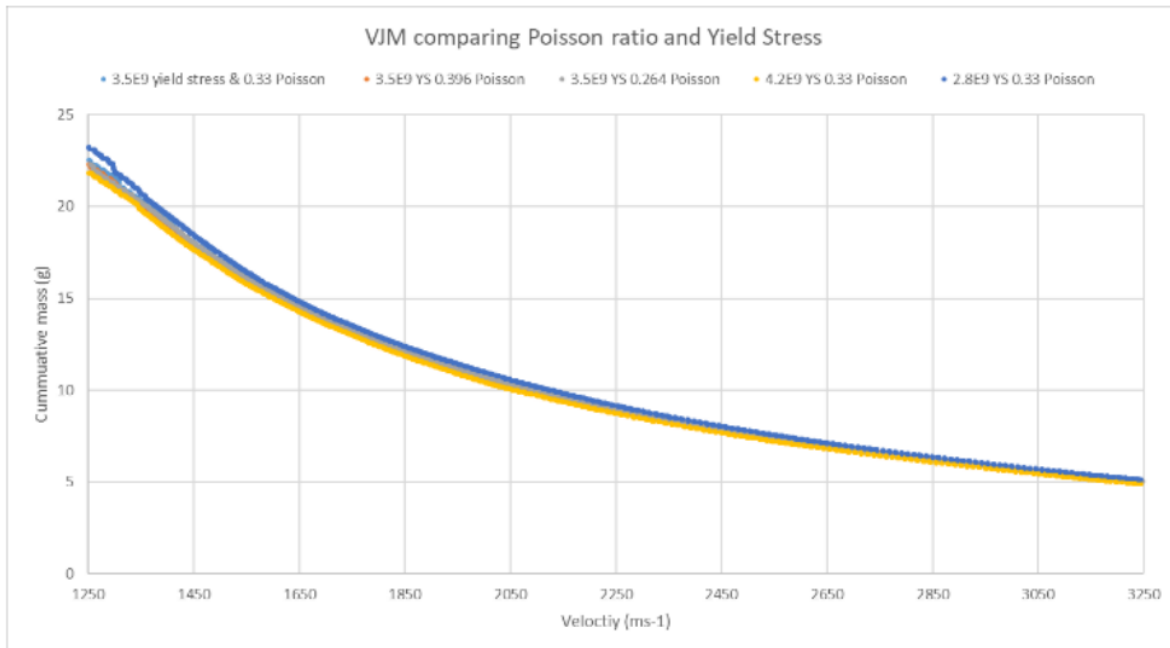


Figure 33 - VJM Plot of altering Poisson ratio and yield stress zoomed [25].

Figure 33 illustrates the change in mass when altering the Poisson ratio and yield stress. From this graph multiple conclusions can be made. Firstly, altering the yield stress of the liner has a greater effect on the material spread than altering the Poisson ratio. The yellow and dark blue lines show the largest drift from the control run coloured light blue. These two runs represent a $\pm 20\%$ change away from the normal yield stress. An increased yield stress reduces the spread of mass, whereas a decreased yield stress promotes further elongation of mass. The yield stress determines the point at which a material transitions from elastic to plastic behaviour. Therefore, the lower the yield stress the earlier the liner stretches and deforms. This results in the liner with a lower yield stress elongating more than a liner with a higher yield stress in the same amount of time. Relating this to real world performance is difficult because not all shaped charge devices are designed for maximum penetration. Therefore, it cannot be said altering the yield stress by 'x' improves performance. However, it can be concluded that decreasing the yield stress by up to 20% promotes more of the material usually found in the rear of the jet to be spread

towards the tip; resulting in more mass travelling faster meaning improved penetration.

The second conclusion is that the yield stress has a greater effect on the spread of mass than the fracture pressure. This is expected because the yield stress influences how much a material stretches, whereas a fracture pressure looks at the point at which it fails. The jet produced from the liner collapsing is extremely hot, meaning the ions are loosely spread apart, which in turn reduces the brittleness of the material. These loosely spread ions promote the elongation of a material and allow it to bend/stretch more easily. Within the simulation the software uses the yield stress to determine at which point the jet separates into different fragments. This is also dependent on the velocity; essentially the material is constantly outrunning itself. This is most commonly occurs at the jet tip where the material is less dense than the rear slug. Figure 33 illustrates an average 2.1g of extra mass present in the jet from the 1250ms^{-1} to 3250ms^{-1} . The simulation is not creating mass, this is shown by all the simulations starting at 102g. This gain in mass come from the rear slug. This is because the lower yield stress allows more mass from the rear slug to elongate off that large slug into new separate fragments.

CHAPTER 5 RESULTING DISCUSSION

5.1 CONCLUSION

Numerous studies have been conducted on the physical setup of shaped charges to analyse what physical factors affect their performance. The way in which the liner elongates affects the performance of a shaped charge. The jet is the end payload/delivery system of a shaped charge device, and is responsible for penetration. The hierarchy previously seen in figure 7 summarised some physical factors that affect the jet formation of a shaped charge, and thus its performance.

This study focussed on analysing the material factors that may affect shaped charge performance. This is because there are not as many studies deciphering what material factors affect the jet formation/performance of a shaped charge. To analyse the effect that altering material properties has on shaped charge performance; modelling is the more feasible option. Analysing material properties by conducting

real firings would require numerous control variables, all of which would be difficult to keep constant. Modelling these material properties takes less time and is less likely to be affected by environmental factors such as: humidity, temperature and ambient pressure. Three material properties were analysed in this study with the number of variables limited by the software's lack of customisation for pre-coded data.

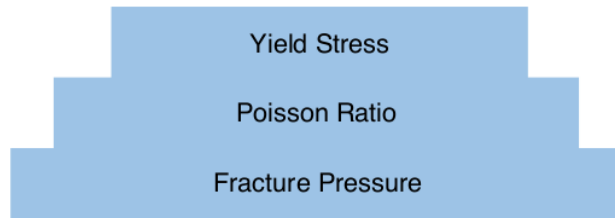


Figure 34 - Hierarchy of material factors affecting shaped charge jet formation [36].

Figure 34 illustrates the material properties that affect jet formation the most. It cannot be said without the use of trials data, if they increase or decrease the performance of a shaped charge. The data obtained from the VJM plots only depicts the change in velocity and mass from the standard non-edited simulation. It is known that the spread of mass and velocity of a jet directly affects penetrative performance. Therefore, it can be stated that yield stress affects the performance more than the poisson ratio and fracture pressure. This study benefits the wider community (specifically industry) because it highlights the material properties that should have tighter tolerances. The defence industry is constantly trying to reduce its costs. This study may help manufactures reduce costs; by making them aware of the negligible affect a variance in fracture pressure has on the performance of a shaped charge.

This study has successfully informed the wider community which material properties have a greater significance in affecting the jet formation and performance of a shaped charge. However, it is not possible to say to what extent these material properties affect the jet formation and performance of a shaped charge. Other simulations will differentiate from the one used in this study because the following will not be the same:

Dimensions – the liner, casing and explosive will vary across the wider community.
NEQ – the amount of explosive used in the simulation will also vary.

Mesh – the mesh will have a significant affect in any results as it refines calculations. Different software's have different mesh sizes.

Software – different software's use different standard material properties.

Therefore, a conclusion along the lines of 'altering material property 'x' by $\pm x\%$ will have 'x' effect on the performance of your shaped charge' cannot be stated. Nevertheless, it can be said that for the wider community the yield stress holds the most significance followed by the Poisson ratio and fracture pressure in affecting the shaped charge jet and resulting performance. Industry can implement this information by deciding to invest more or less money on manufacturing techniques to either relax/strengthen measures affecting tolerances.

A final conclusion is that the simulations capture a fine resolution of the particle interactions. The software implements the materials to be perfect i.e. there are no voids in the crystalline structures. Real devices will contain voids in the explosive when analysed on the microscopic level. This is not captured in the simulated device. Similarly, the simulation will not capture defects in the coppers surface. If a real copper liner were examined using synchrotron x-ray fluorescence microscopy, it would reveal the topography of the surface [26]. Specifically it would show how the liner is not perfectly flat and contains air gaps. A hydrocode will not simulate these imperfections. Therefore, further work to implement these imperfections into a simulation will provide data truer to real life firings.

5.2 RECOMMENDATIONS

There are many limitations to this study. Especially when trying to draw conclusions from the simulated results and applying them to real life firings. This is because modelling in general has many limitations. To touch on some of the major limitations;

1) Firing a shaped charge device in real life will not produce the same results each time. Even if the devices are from the same manufacture and batch, it will not produce the same result if fired numerous times. This is because the breakdown of the explosive is somewhat random. Yes, the results will follow a trend to that of a

bell curve, but the results will vary from the normal. Meaning a varied dataset. Whereas, a simulated device will produce the same result over numerous repeats. This is because simulations do not contain variations, voids or discrepancies in any materials. Therefore, like for like, the model will never perfectly replicate the device. It is possible to integrate probabilistic modelling; however, you then have to repeat your simulations. It would take many simulations to show the extent that probabilistic modelling plays on the results. These simulations are already a computational strain, repeating them would require a lot of free space on a drive. Another question is how you source the ranges to implement on the parameter changes. This would come from existing trialled results meaning is there a need to then produce the models?

2) A simulated shaped charge will have perfect asymmetric conditions. This results in a perfectly directional charge, where all the material is in one narrow plain. Furthermore, this also means all the momentum is directed perfectly into that same plain. A real life firing has a spread of mass. The below shows how the material spread of a jet penetrating a target looks from a directional point of view. The left target shows how a real life firing does not direct all its mass in one direction, there is a spread around the central penetration. The right target shows the modelled material spread with no material being lost outside the firing axis.

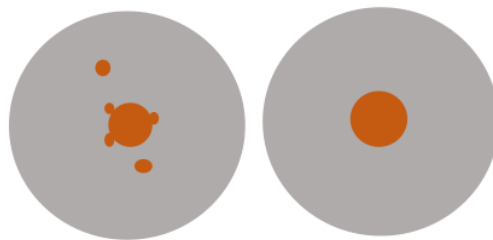


Figure 36 - An example of the potential liner spread of a real device Vs simulated device [37].

With these two limitations, it is recommended that any conclusions made from this study are not applied to that of real devices.

5.3 FURTHER RESEARCH

It has been said the conclusions should not be applied to real life devices. However, could the conclusions apply to other simulated devices? To assess this, it is important to acknowledge other software's used within the wider community. These different software's use different inputs for their material properties. For example, software's typically use one of two equations of state. These are SESAME and Mie–Grüneisen. The Mie–Grüneisen relates the volume and pressure of a solid at a given temperature, and is most commonly used to calculate the pressure in a shock induced solid [20]. Software's use the Mie–Grüneisen model to calculate the volume of the crystal lattice and how its vibrational properties differ when exposed to shock. The Mie–Grüneisen model can be expressed as:

$$\Gamma = V \left(\frac{dp}{de} \right)_v$$

Where V is the volume, p is the pressure, e is the internal energy, and Γ is the Grüneisen parameter that represents the thermal pressure from a set of vibrating atoms. When comparing this SESAME's equation of state, it can be observed that they use three different equations to express the materials temperature, pressure and energy.

$$E = F + TS = F - T \left(\frac{\partial F}{\partial T} \right)_v \leftarrow \text{Internal energy}$$

$$S = - \left(\frac{\partial F}{\partial T} \right)_v \leftarrow \text{Entropy}$$

$$P = \rho^2 \left(\frac{\partial F}{\partial \rho} \right)_T \leftarrow \text{Pressure}$$

Figure 36 - SESAME's 3 equations that contribute to their EOS [20].

To understand how these equations differentiate from one another, they need to be added into the software. This would involve re-writing the scripts and coding them to use different datasets. The hydrocode in which this study was performed in

automatically discards data that it does not 'agree' with. Therefore, further changes deep into the software would have to be re-written. These changes were successfully implemented and the following results were observed when altering the equations of state.

	A	B	C	D	E	F
1	Run No.	mgrun case	SESAME case	mgrun liner	SESAME liner	Highest Velocity Recorded (ms-1)
2	50					6170.513
3	51					6006.564
4	52					6177.915
5	53					6008.634

Figure 37 - Highest velocity recorded when changing out the EOS [23].

From figure 37, it can be seen that altering the Equations of State (EOS) has had the most significant change to the highest velocity observed. Further research in assessing the VJM plots these four runs would produce could elude to a significant spread in mass. Depending on what EOS is used, the jet formation of the shaped charge could significantly change. If implementing an element of penetration within the simulation, these EOS could play a significant role in affecting penetration. Therefore, the wider community would benefit from knowing which EOS replicates trial results better.

5.4 REFLECTION

Throughout my journey on this project, I was faced with many unpredicted limitations. Which at times made me feel as though nothing went to plan. I expected a couple of unpredicted setbacks; which is why when starting this study I conducted a thorough literature review. The aim of this being to make scientific assumptions, which in turn would help me direct the study to obtain relevant results. I originally expected the fracture pressures, Poisson ratios and yield stresses to play a significant part in altering the jet velocity. When I ran the Python scripts to obtain the highest velocity in each simulation, I was let down by the lack of change observed. I actually went back and altered the simulation by adjusting my tracers to ensure they were recording the velocity of the jet and not the shock front produced by the explosive detonating. I confirmed the tracers were working as planned by changing the liner material to a plastic. This directly affected the velocity and proved the tracers were working as expected.

After observing little to no change in the highest velocity, I sought guidance from SME's. They suggested the idea of running a VJM plot to see if the mass at independent velocities was changing. After running these for my multiple runs, I was starting to worry that this study would provide little benefit to the wider community. However, I was assured the data was still useful within the organisation because it did show that we do not need to be so stringent with our material parameters; and should instead focus on the mesh and physical setup of a simulated device when trying to replicate a real life product.

When trying to validate a model against an actual product as seen in figure 13, I was bound by the lack of trials data. I was on this trial back in 2019 of which the x-ray still came from. On this trial, I learnt many fundamental safety processes. However, I was in the early stages of my career and was not thinking about the data being captured. If I could go back in time, I would request further instrumentation. I could then have captured x-ray stills at later timestamps showing when the jet begins to separate. This would mean I could produce a VJM from the simulated device and product it was based on. Thus meaning the model could be validated and proven representative. This in turn would mean any conclusions could be transferred from the virtual environment into real world scenarios.

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1) Sensitivity literature review

1) Sensitivity literature review

$$\sigma = (A + B\epsilon^n) \left(1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) (1 - T_H^m)$$

Parameter	CE-CO ₂	Starch	Zirconium
Exposure of Sinter	0.97	0.97	0.97
Reference density (g/cm ³)	3.93	3.874	3.895
Reference density (g/cm ³)	1.002	0.0	0.0
Parameter C1 (m ² /s)	5.94E-10	4.60E-09	3.75E-10
Parameter S1	1.489	1.437	1.038
Relative volume, V _{rel} /V ₀	0.0	0.0	0.0
Relative volume, V _{rel} /V ₀	0.0	0.0	0.0
Relative volume, V _{rel} /V ₀	0.0	0.0	0.0
Parameter C2 (m ² /s)	0.0	0.0	0.0
Relative volume, V _{rel} /V ₀	0.0	0.0	0.0
Relative volume, V _{rel} /V ₀	3.0E-03	2.0E-03	0.0
Specific Heat (J/gK)	3.0E+03	4.8E+02	0.0
Thermal Conductivity (J/mK)	0.0	None	None
Thermal Conductivity (J/mK)	0.0	None	None
Thermal Conductivity (J/mK)	0.0	None	None
Material Color	-	-	-
Maximum Expansion	1.0E-01	1.0E-01	1.0E-01
Maximum Expansion	1.0E-01	1.0E-01	1.0E-01
Minimum Density Factor (SPR)	1.0E-01	2.0E-03	2.0E-03
Minimum Density Factor (SPR)	1.0E-01	2.0E-03	2.0E-03
Minimum Shrinkage (SPR)	1.0E-01	1.0E-01	1.0E-01
Minimum Shrinkage (SPR)	1.0E-01	1.0E-01	1.0E-01
Maximum Shrinkage (SPR)	1.0E-01	1.0E-01	1.0E-01
Maximum Shrinkage (SPR)	1.0E-01	1.0E-01	1.0E-01

Table 13: Layer Materials in AUTODYN

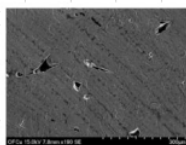


Fig. 3 SEM observation of the laser sintered liner microstructure revealing scan tracks and irregularly shaped pores before deformation

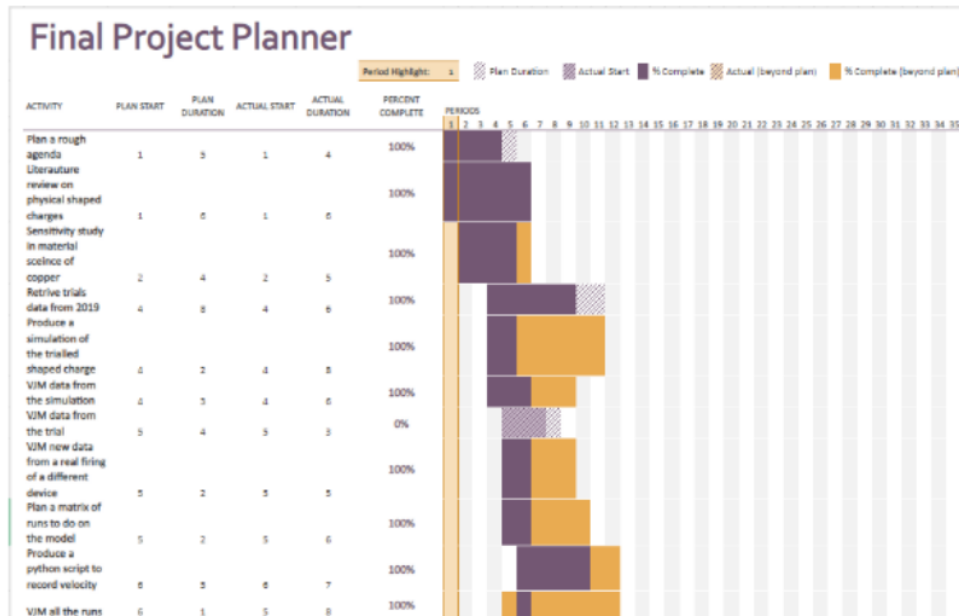
2) Excel data for VJM plotting the left image in figure 14

particle number	Extreme edge location (pixel)				Extreme edge location (mm)				Differences		volume (mm ³)	mass (g) rho=8.96	mass (g) rho=7.9	Cylinder Volume (mm ³)	Cyl Mass (g) rho=8.96	Cyl Mass (g) rho=7.9	Counting from the bottom up			
	y1	y2	x1 (pixel)	x2	y1 (mm)	y2	x1	x2	delta-y (mm)	delta-x (mm)							x	y	y2-y1	pixels
49	7560	7697	2046	2076																
48	7349	7488	2037	2065																
47	7205	7319	2034	2063																
46	7028	7105	2027	2048																
45	6896	6969	2029	2046																
44	6731	6805	2020	2037																
43	6632	6668	2012	2031																
42	6511	6505	2017	2036																
41	6457	6511	2010	2033																
40	6342	6391	2006	2030																
39	6162	6270	1996	2021																
38	6032	6101	1995	2020																
37	5885	5967	1992	2029																
36	5790	5815	1988	2011																
35	5577	5695	1980	2004																
34	5429	5468	1978	1997																
33	5304	5374	1974	1992																
32	5152	5237	1965	1995																
31	4973	5068	1962	1985																
30	4700	4846	1952	1981																
29	4505	4621	1950	1971																
28	4527	4775	1946	1974																
27	4441	4507	1942	1965																
26	4380	4361	1940	1964																
25	4124	4228	1937	1958																
24	3973	4076	1927	1954																
23	3821	3910	1925	1945																
22	3695	3762	1918	1943																
21	3745	3630	1918	1942																
20	3592	3528	1913	1941																
19	3228	3349	1904	1926																
18	3055	3122	1899	1924																
17	2907	3007	1895	1914																
16	2849	2901	1892	1915																
15	2850	2768	1888	1910																
14	2511	2605	1879	1907																
13	2362	2441	1874	1903																
12	2215	2354	1870	1901																
11	2094	2203	1866	1891																
10	1973	2050	1864	1889																
9	1889	1973	1863	1886																
8	1786	1817	1858	1884																
7	1609	1699	1855	1878																
6	1462	1581	1855	1877																
5	1358	1463	1849	1870																
4	1235	1318	1844	1867																
3	1061	1196	1840	1861																
2	944	1052	1833	1865																
1	760	929	1827	1859																

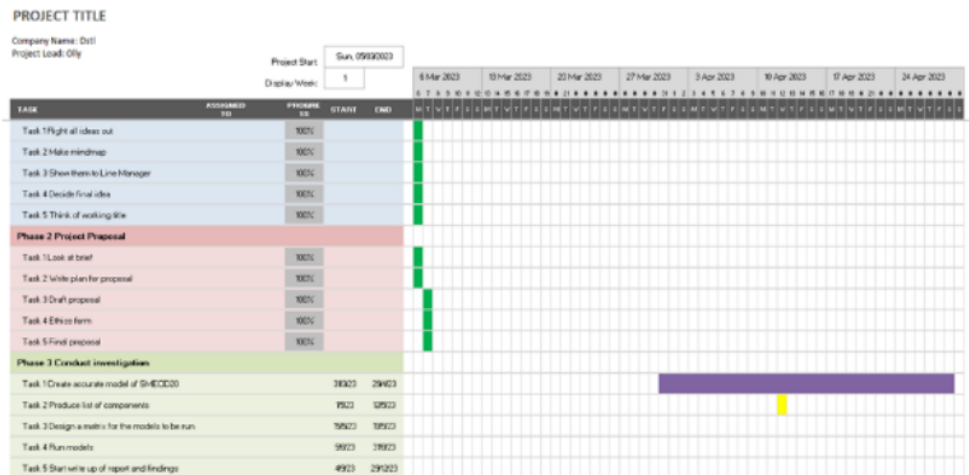
3) Excel data for VJM Plotting the right image in figure 14

particle number	Extreme edge location (pixel)				Extreme edge location (mm)				Differences		volume (mm ³)	mass (g) rho=8.96	mass (g) rho=7.9	Cylinder Volume (mm ³)	Cylinder Mass (g) rho=8.96	Cylinder Mass (g) rho=7.9	Counting from the bottom up			
	y1	y2	x1	x2	y1 (mm)	y2	x1	x2	delta-y (mm)	delta-x (mm)							x	y	y2-y1	pixels
45	6222	6361	3531	3600																
44	6036	6166	3524	3603																
43	5907	6018	3524	3605																
42	5755	5828	3524	3600																
41	5634	5726	3521	3605																
40	5494	5567	3515	3608																
39	5414	5464	3518	3608																
38	5240	5368	3520	3607																
37	5255	5310	3514	3604																
36	5154	5209	3516	3606																
35	4992	5166	3516	3611																
34	4888	4969	3512	3619																
33	4751	4839	3512	3611																
32	4648	4706	3514	3612																
31	4557	4603	3515	3614																
30	4488	4560	3512	3613																
29	4367	3443	3510	3618																
28	4250	4322	3513	3611																
27	4121	4208	3511	3619																
26	3960	4078	3510	3611																
25	3727	3876	3512	3612																
24	3642	3678	3510	3619																
23	3579	3614	3510	3615																
22	3508	3568	3513	3613																
21	3363	3445	3510	3610																
20	3215	3313	3510	3614																
19	3094	3196	3511	3618																
18	2967	3061	3513	3616																
17	2852	2944	3513	3611																
16	2734	2820	3513	3611																
15	2619	2715	3518	3613																
14	2590	2660	3516	3611																
13	2456	2575	3519	3617																
12	2305	2373	3516	3614																
11	2125	2282	3519	3614																
10	1990	2094	3517	3610																
9	1833	1911	3515	3616																
8	1715	1783	3516	3617																
7	1608	1710	3511	3617																
6	1494	1572	3513	3612																
5	1388	1463	3510	3616																
4	1278	1380	3510	3616																
3	1159	1248	3507	3616																
2	1056	1149	3504	3614																
1	950	1045	3508	3610																

4) Gantt chart changed to allow tracking of project progress



5) Original Gantt chart



ETHICS FORM

SECTION A: About You (Principal Researcher)

1	Full Name:	Oliver (Olly) Overton
2	Student Number:	1910610
3	Email address:	1910610@student.uwtsd.ac.uk
4	Programme of Study:	OME Apprenticeship Degree
5	Director of Studies/Supervisor:	Kapilan

SECTION B: Internal and External Ethical Guidance Materials

	Please list the core ethical guidance documents that have been referred to during the completion of this form (including any discipline-specific codes of research ethics, location-specific codes of research ethics, and also any specific ethical guidance relating to the proposed methodology). Please tick to confirm that your research proposal adheres to these codes and guidelines. You may add rows to this table if needed.	
1	UWTSD Research Ethics & Integrity Code of Practice	☒
2	UWTSD Research Data Management Policy	☒
3	<i>Dstl Permission To Publish</i>	☒

SECTION C: Details of Research Activity

1	Indicative title:	An investigation into the effects of material properties Vs physical changes when modelling shaped charges		
2	Proposed start date:	31/03/2023	Proposed end date:	22/03/2024
	Introduction to the Research (maximum 300 words in each section) Ensure that you write for a <u>Non-Specialist Audience</u> when outlining your response to the three points below: • <i>Purpose of Research Activity</i> • <i>Proposed Research Question</i> • <i>Aims of Research Activity</i> • <i>Objectives of Research Activity</i>			

	Demonstrate, briefly, how Existing Research has informed the proposed activity and explain - What the research activity will add to the body of knowledge - How it addresses an area of importance.
3	Purpose of Research Activity To find what components in a simulation contribute the greatest significance to the end result, when modelling a shaped charge.
4	Research Question What components affect the penetration of a shaped charge the most?
5	Aims of Research Activity The aim of this work is to validate a model from previous data, then run a series of models from a matrix that will be pre-defined by myself.
6	Objectives of Research Activity - Produce an accurate simulation of the SMEOD20 charge. - Produce a list of all components affecting penetration of a charge. - Run simulations and capture the velocity, jet break-up, penetration - Produce an end report with supporting hierarchy.
	Proposed data collection methods (maximum 600 words)
7	Using hydrocode software and tracers in the models. Using trials data from previous trials I have partook in.

SECTION D: Scope of Research Activity

	Will the research activity include:	YES	NO
1	Use of a questionnaire or similar research instrument?	☐	☒
2	Use of interviews?	☐	☒
3	Use of focus groups?	☐	☒
4	Use of participant diaries?	☐	☒
5	Use of video or audio recording?	☐	☒
6	Use of computer-generated log files?	☒	☐
7	Participant observation with their knowledge?	☐	☒
8	Participant observation without their knowledge?	☐	☒

9	Access to personal or confidential information without the participants' specific consent?	☐	☒
10	Administration of any questions, test stimuli, presentation that may be experienced as physically, mentally or emotionally harmful / offensive?	☐	☒
11	Performance of any acts which may cause embarrassment or affect self-esteem?	☐	☒
12	Investigation of participants involved in illegal activities?	☐	☒
13	Use of procedures that involve deception?	☐	☒
14	Administration of any substance, agent or placebo?	☐	☒
15	Working with live vertebrate animals?	☐	☒
16	Procedures that may have a negative impact on the environment?	☐	☒
17	Other primary data collection methods. Please indicate the type of data collection method(s) below.	☒	☐
	Flash x-ray images of shaped charges.		

If you have ticked NO to every question then the research activity is (ethically) low risk and you may skip section E and continue to section F.

If YES to any question, then no research activity should be undertaken until full ethical approval has been obtained.

SECTION E: Intended Participants

	Who are the intended participants:	YES	NO
1	Students or staff at the University?	☐	☒
2	Adults (over the age of 18 and competent to give consent)?	☐	☒
3	Vulnerable adults?	☐	☒
4	Children and Young People under the age of 18? (Consent from Parent, Carer or Guardian will be required)	☐	☒
5	Prisoners?	☐	☒
6	Young offenders?	☐	☒

7	Those who could be considered to have a particularly dependent relationship with the investigator or a gatekeeper?	☐	☒
8	People engaged in illegal activities?	☐	☒
9	Others. Please indicate the participants below, and specifically any group who may be unable to give consent.		
	Details of any other participant groups: (this box should expand as you type)	☐	☒

Participant numbers and source Provide an estimate of the expected number of participants. How will you identify participants and how will they be recruited?		
10	How many participants are expected?	N/A
11	Who will the participants be?	N/A
12	How will you identify the participants?	N/A

	Information for participants:	YES	NO	N/A
13	Will you describe the main research procedures to participants in advance, so that they are informed about what to expect?	☐	☐	☒
14	Will you tell participants that their participation is voluntary?	☐	☐	☒
15	Will you obtain written consent for participation?	☐	☐	☒
16	Will you explain to participants that refusal to participate in the research will not affect their treatment or education (if relevant)?	☐	☐	☒
17	If the research is observational, will you ask participants for their consent to being observed?	☐	☐	☒

18	Will you tell participants that they may withdraw from the research at any time and for any reason?	☐	☐	☒
19	With questionnaires, will you give participants the option of omitting questions they do not want to answer?	☐	☐	☒
20	Will you tell participants that their data will be treated with full confidentiality and that, if published, it will not be identifiable as theirs?	☐	☐	☒
21	Will you debrief participants at the end of their participation, in a way appropriate to the type of research undertaken?	☐	☐	☒
22	If NO to any of above questions, please give an explanation			
	<i>(this box should expand as you type)</i>			

	Information for participants:	YES	NO	N/A
24	Will participants be paid?	☐	☐	☒
25	Is specialist electrical or other equipment to be used with participants?	☐	☐	☒
26	Are there any financial or other interests to the investigator or University arising from this study?	☐	☐	☒
27	Will the research activity involve deliberately misleading participants in any way, or the partial or full concealment of the specific study aims?	☐	☐	☒
28	If YES to any question, please provide full details			
	<i>(this box should expand as you type)</i>			

SECTION F: Anticipated Risks

Outline any anticipated risks that may adversely affect any of the participants, the researchers and/or the University, and the steps that will be taken to address them.	
Risks to participants	
1	For example: sector-specific health & safety, emotional distress, financial disclosure, physical harm, transfer of personal data, sensitive organisational information. If you have identified in section D that there are no participants then enter N/A and go skip to question 3.
Risk to participants: N/A	N/A
2	If research activity may include sensitive, embarrassing or upsetting topics (e.g. sexual activity, drug use) or issues likely to disclose information requiring further action (e.g. criminal activity), give details of the procedures to deal with these issues, including any support/advice (e.g. helpline numbers) to be offered to participants. Note that where applicable, consent procedures should make it clear that if something potentially or actually illegal is discovered in the course of a project, it may need to be disclosed to the proper authorities
N/A	
Risks to the investigator	
3	For example: personal health & safety, physical harm, emotional distress, risk of accusation of harm/impropriety, conflict of interest
Risk to the investigator: Risk of physical harm from electronics, energetic materials, slips, trips, manual handling and adverse weather conditions.	<i>How you will mitigate the risk to the investigator:</i> Risk assessments will be undertaken prior to any work. Only trained personnel, as defined by ESA NOS, will be allowed to handle energetic materials. I am competently signed off for the ESA/NOS process.
University/institutional risks	
4	For example: adverse publicity, financial loss, data protection

	Risk to the University:	<i>How you will mitigate the risk to the University:</i>
5	Environmental risks For example: accidental spillage of pollutants, damage to local ecosystems	
		<i>How you will mitigate the risk to environment</i>

SECTION G: Feedback, Consent and Confidentiality

If you have identified in section D that there are no participants then enter skip this section and continue to section H.

1	Feedback What de-briefing and feedback will be provided to participants, how will this be done and when?
	N/A
2	Informed consent Describe the arrangements to inform potential participants, before providing consent, of what is involved in participating. Describe the arrangements for participants to provide full consent before data collection begins. If gaining consent in this way is inappropriate, explain how consent will be obtained and recorded in accordance with prevailing data protection legislation.
	N/A

3	Confidentiality / Anonymity Set out how anonymity of participants and confidentiality will be ensured in any outputs. If anonymity is not being offered, explain why this is the case.
	N/A

SECTION H: Data Protection and Storage

	Does the research activity involve personal data (as defined by the General Data Protection Regulation 2016 "GDPR" and the Data Protection Act 2018 "DPA")?	YES	NO
1	"Personal data" means any information relating to an identified or identifiable natural person ('data subject'). An identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person. Any video or audio recordings of participants is considered to be personal data.	☐	☒
	If YES, provide a description of the data and explain why this data needs to be collected:		
2	(this box should expand as you type)		
	Does it involve special category data (as defined by the GDPR)?	YES	NO
3	"Special category data" means sensitive personal data consisting of information as to the data subjects' – (a) racial or ethnic origin, (b) political opinions, (c) religious beliefs or other beliefs of a similar nature, (d) membership of a trade union (within the meaning of the Trade Union and Labour Relations (Consolidation) Act 1992), (e) physical or mental health or condition, (f) sexual life, (g) genetics, (h) biometric data (as used for ID purposes),	☐	☒
	If YES, provide a description of the special category data and explain why this data needs to be collected:		
4	(this box should expand as you type)		

	Will data from the research activity (collected data, drafts of the thesis, or materials for publication) be stored in any of the following ways?	YES	NO
5	Manual files (i.e. in paper form)?	☒	☐
6	University computers?	☐	☒
7	Private company computers?	☒	☐
8	Home or other personal computers?	☐	☒
9	Laptop computers/ CDs/ Portable disk-drives/ memory sticks?	☒	☐
10	"Cloud" storage or websites?	☒	☐
11	Other – specify:	☐	☒
12	For all stored data, explain the measures in place to ensure the security of the data collected, data confidentiality, including details of backup procedures, password protection, encryption, anonymisation and pseudonymisation:		
	All data will be captured using encrypted "standalone machines" on a closed network.		
	<i>(this box should expand as you type)</i>		

Data Protection			
	Will the research activity involve any of the following activities:	YES	NO
13	Electronic transfer of data in any form?	☒	☐
14	Sharing of data with others at the University outside of the immediate research team?	☐	☒
15	Sharing of data with other organisations?	☐	☒
16	Export of data outside the UK or importing of data from outside the UK?	☐	☒
17	Use of personal addresses, postcodes, faxes, emails or telephone numbers?	☐	☒
18	Publication of data that might allow identification of individuals?	☐	☒

19	If YES to any question, please provide full details, explaining how this will be conducted in accordance with the GDPR and Data Protection Act (2018) (and/or any international equivalent):	
	All data will be captured using encrypted "standalone machines" on a closed network. <i>(this box should expand as you type)</i>	
20	List all who will have access to the data generated by the research activity:	
	Principal researcher: Oliver Overton Lead Technical Reviewer University Supervisor	
21	List who will have control of, and act as custodian(s) for, data generated by the research activity:	
	Principal researcher	
22	Give details of data storage arrangements, including security measures in place to protect the data, where data will be stored, how long for, and in what form.	
	All data will be captured using encrypted "standalone machines" on a closed network. <i>(this box should expand as you type)</i>	
22	Confirm that you have read the UWTSD guidance on data management (see https://www.uwtsd.ac.uk/library/research-data-management/)	☒
23	Confirm that you are aware that you need to keep all data until after your research has completed or the end of your funding	☒

SECTION I: Declaration

The information which I have provided is correct and complete to the best of my knowledge. I have attempted to identify any risks and issues related to the research activity and acknowledge my obligations and the rights of the participants. In submitting this application I hereby confirm that I undertake to ensure that the above named research activity will meet the University's Research Ethics and Integrity Code of Practice which is published on the website: https://www.uwtsd.ac.uk/research/research-ethics/			
1	Signature of applicant:	x	Date: 05/03/2023
2	Director of Studies/Supervisor:		Date:

3	Signature:		
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FOR INTERNAL USE ONLY:

	Ethical approval given		
1	Signature of assessor:		Date:
2	Name:		
3	Role:		

Major Project Report Final

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Please ask Jenni Steen for your marking sheet for feedback.

55 / 100

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