



Conor James Nolan

Design of shaped charges

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Academic integrity declaration

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- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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Abstract

Designs of two shaped charges were analysed for performance characteristics and then most optimal design was analysed in 3D Lagrangian and Coupled Lagrangian-Eulerian Explicit solver. Key performance criteria were found and suggestions were made for future work.

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1 Introduction

The shaped charge is a staple in military anti-armour warhead technology due to its superior penetrative power. Due to the perpetual evolution of armour and fortification technology, it is essential that the mechanics of the shaped charge concept are well understood, such that modifications can be made to alter the performance characteristics as necessary. Computational modelling presents itself as a perfect medium for such investigations due to its low material cost, speed, safety, and ease of use, as well as the lack of a requirement for explosive licensing.

2 Literature Review

3 Design Concepts

3.1 Liner

As can be concluded from the Gurney equations, the ratio of explosive charge mass to metal mass has a significant influence on the velocity with which the metal will be projected, as such, the shaped charge simulated in this report was selected to be 2mm thick. Additional consideration was given to the liner tip shape, as letting the shockwave impart force normal to a surface would allow for greater momentum of the elements in the tip. As such, a flat tipped cone shape was selected for the liner, with a secondary curved tip selected as a compromise.

A Mie–Grüneisen EoS was selected for copper.

The material selected for the liner was copper, due to its enhance ductility, which would allow it to form a coherent jet. The properties and parameters [11,12] used in the later simulations are available in Tables 1 & 2.

Table 1: Mie–Grüneisen Parameters for Copper

Mie–Grüneisen EoS		
C^0 - Bulk speed of sound	s - Hugoniot slope	Γ_0 - Grüneisen's gamma
3933	1.5	1.99

Table 2: Johnson-Cook Plastic Deformation Parameters for Copper

JC Plastic						Rate dependent		Density / Kg ^m - ³
A / Pa	B / Pa	n	m	Melt / K	Transition / K	C	ε ₀	
900000000	2.92E+08	0.31	1.09	1356	293	0.025	1	8960

3.2 Case

Using Hirsch's assumption that most of the acceleration of the liner is due to HE near to the liner, efficiencies in space and mass can be made in the rear section of the charge without significantly affecting the overall performance of the charge. This has been reflected in the case design of this report's shaped charge via boat-tailing Fig.1.



Figure 1: Boat-tailing of casing

The case material was not heavily considered due to the focus on the mechanics of the jet in this report, so a typical steel formulation as been assumed with properties and parameters given in Tables 3 & 4 [11,13].

Table 3: Physical Properties for Steel

Shear Modulus / Pa	Poisson's Ratio	Density / kgm-3
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2.06E+11	0.29	7872
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Table 4: Johnson-Cook Plastic Deformation Parameters for Steel

JC Plastic						Rate dependent	
A / Pa	B / Pa	n	m	Melt / K	Transition / K	C	ϵ_0
3.5E+08	2.75E+08	0.36	1	1811	293	0.022	1

3.3 HE Fill

Many explosives are used in modern shaped charge applications, but this report decided upon HMX due to its identity as a high-performance military explosive with greater gas production and VoD than other typical explosives like RDX or TNT.

As previously mentioned, a JWL equation of state was selected for HMX due to its compatibility with Abaqus CAE's Explicit Solver. The corresponding properties and parameters are recorded in Table 5 [14].

Table 5: JWL parameters for HMX

JWL							
Detonation Velocity / ms^{-1}	A / Pa	B / Pa	ω	R1	R2	Energy density / Pa	Density / Kgm^{-3}
9110	7.78E+11	7.07E+09	0.3	4.2	1	5552618	1891

4 Results and Discussion

Abaqus CAE Explicit Solver was used to simulate 2D axisymmetric, 2D standard, 3D standard and 3D CEL models of shaped charges.

4.1 Lagrangian Analysis of 2D Design

4.1.1 Meshing

Preliminary attempts at running a 2D axisymmetric simulations revealed that matching the mesh density along interacting faces was vitally important for proper element interactions. Without this matching, elements would violently distort and often cause simulation crashes. An optimistic solution would be to mesh every part with the same fine mesh, however due to computational efficiency, a smarter strategy was deployed.

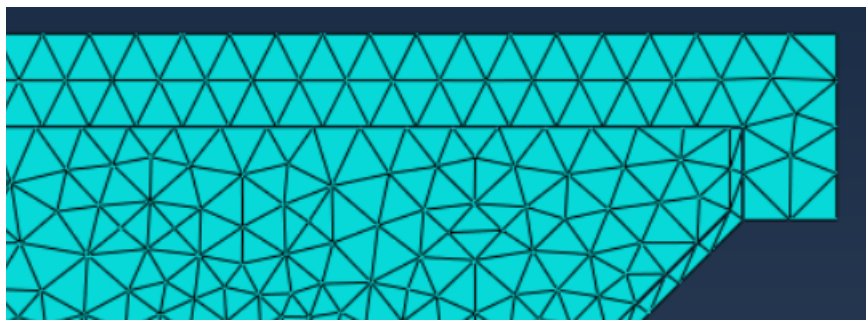


Figure 2: Casing to HE boundary mesh

The mesh density of the case was completely irrelevant for the investigation of the shaped charge jet so immediately a very coarse global mesh was applied. Matching this, interacting faces of the HE filling were made coarser Fig 2.

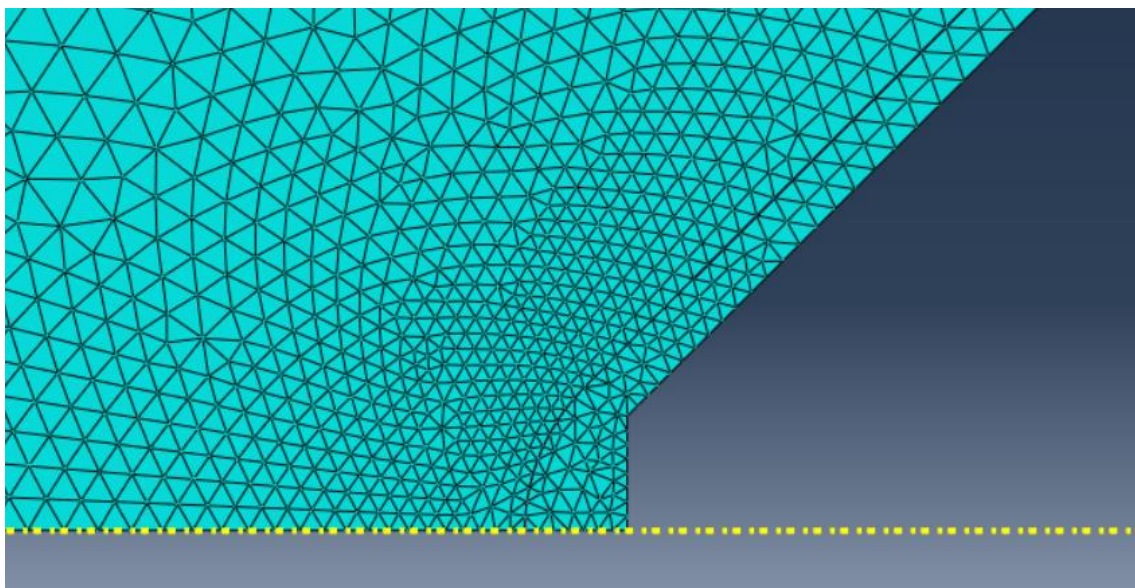


Figure 3: Liner to HE find boundary mesh

The liner itself was the subject of the investigation so a finer mesh was natural, however it is known that the tip of the liner contributes significantly more to the jet than the base, so a biased edge mesh was applied, with the finer bias being at the tip Fig 3. Corresponding interaction faces of the HE were then matched accordingly and finally the lip at the base of the liner was given a coarse mesh to match the case.

4.1.2 Simulation

Initially, 2D axisymmetric models with Lagrangian meshes were used to produce two designs where were to be compared, with the idea of saving the computational resources by not meshing 50% of a 2D model and instead having a boundary condition along the axis which prevents movement of the mesh across itself.

However, it was quickly discovered that with the axisymmetric model, mesh elements at regions of high pressure near the boundary condition were being pushed against it and distorted to an extreme degree, often moving through other mesh elements and in some cases causing simulation crashes Fig 4.



Figure 4: Distortion against the boundary condition

To prevent this, full 2D models were later verified with compromises to the mesh density and the resulting two designs were compared.

4.1.3 Design A

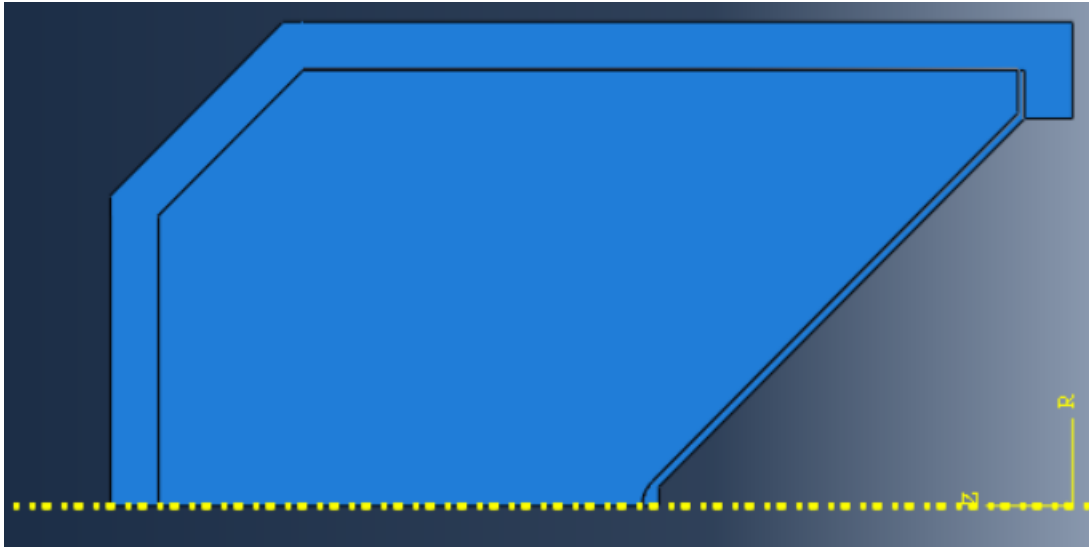


Figure 5: Design A full size

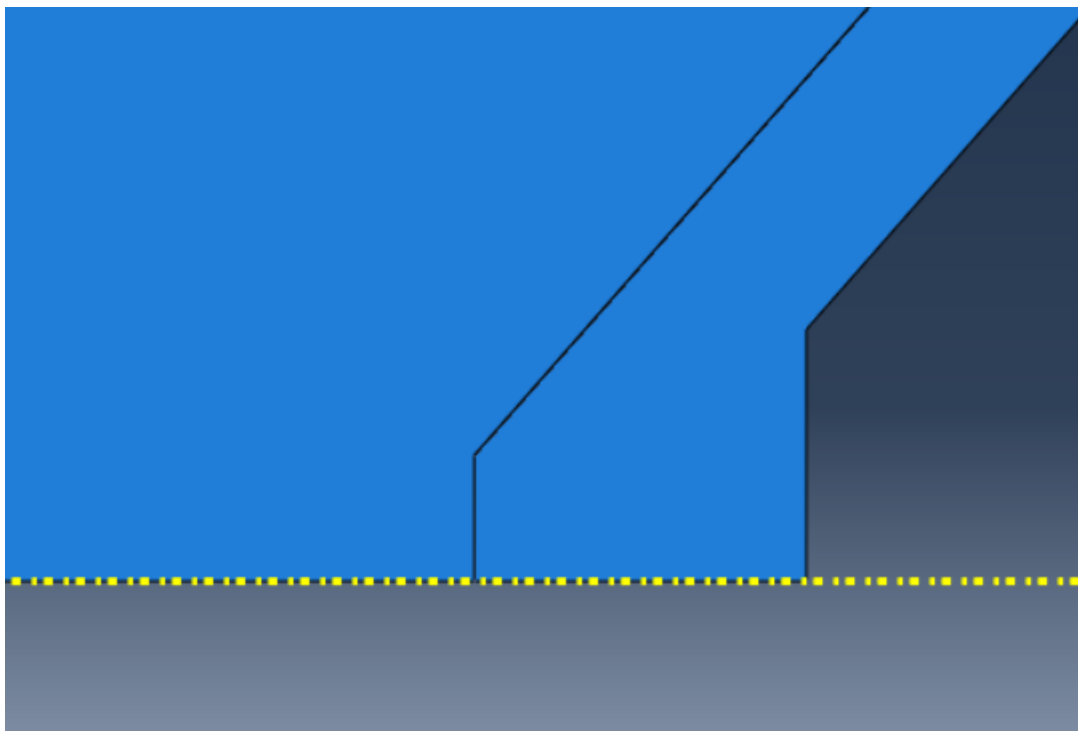


Figure 6: Design A tip close-up

The first design Fig 5 featured a flat edge on the internal tip of the liner Fig 6 with the intention of providing a surface normal to the pressure wave's direction of travel, such that the elements in the tip would be imparted a higher proportion of kinetic energy, as opposed to a curved or sharp tip, which would both allow the pressure wave to move past with greater ease, imparting less kinetic energy.

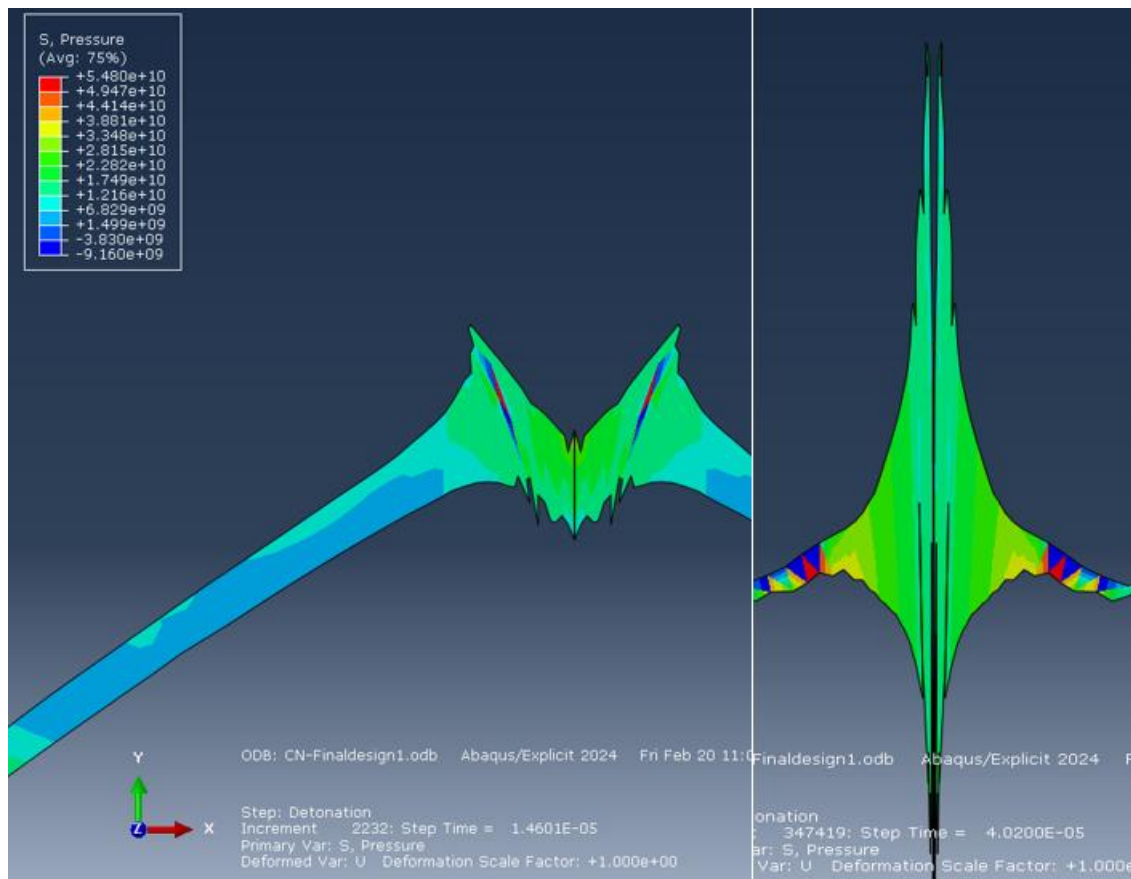


Figure 7: Design A splitting in tip

It was found however that this resulted in splitting of the liner down the middle Fig 8, likely because the elements central to the HE charge sheared through the elements of the liner due to concentration of force against a normal surface. A more curved surface would have allowed some of that force to be dispersed as a horizontal component.

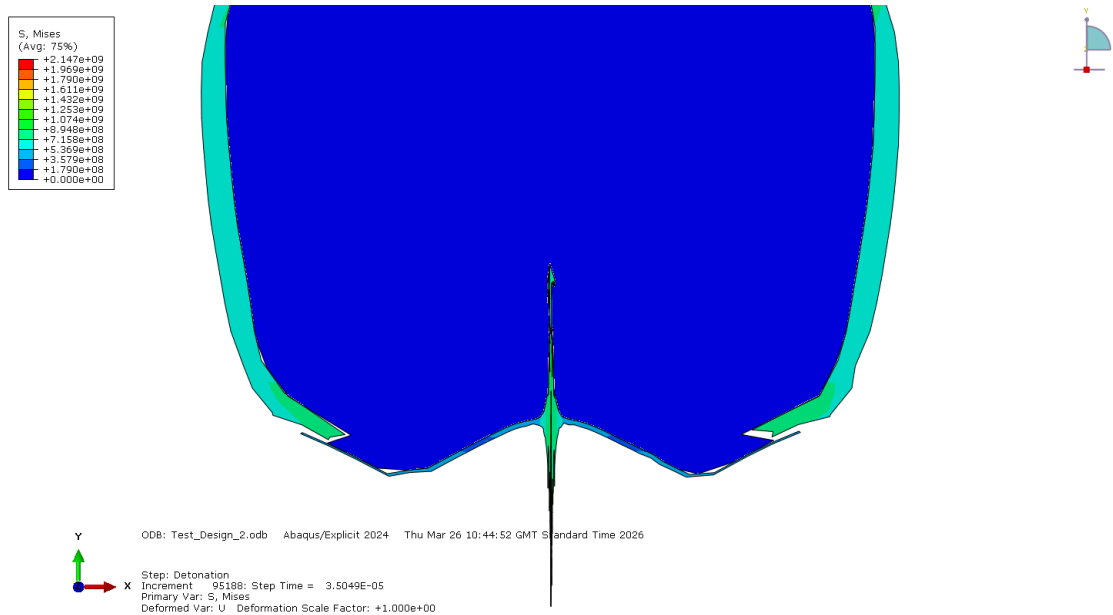


Figure 8: Design A gas leakage through lip

An additional design feature that was noticed due to this simulation was the position of the base of the liner. In design A it sits below the lip of the casing, and it was noticed that gas is allowed to escape during later stages of the detonation. This implies that some of the pressure that could have been driving the liner to form a jet was lost. This lead to the conception of Design B.

4.1.4 Design B

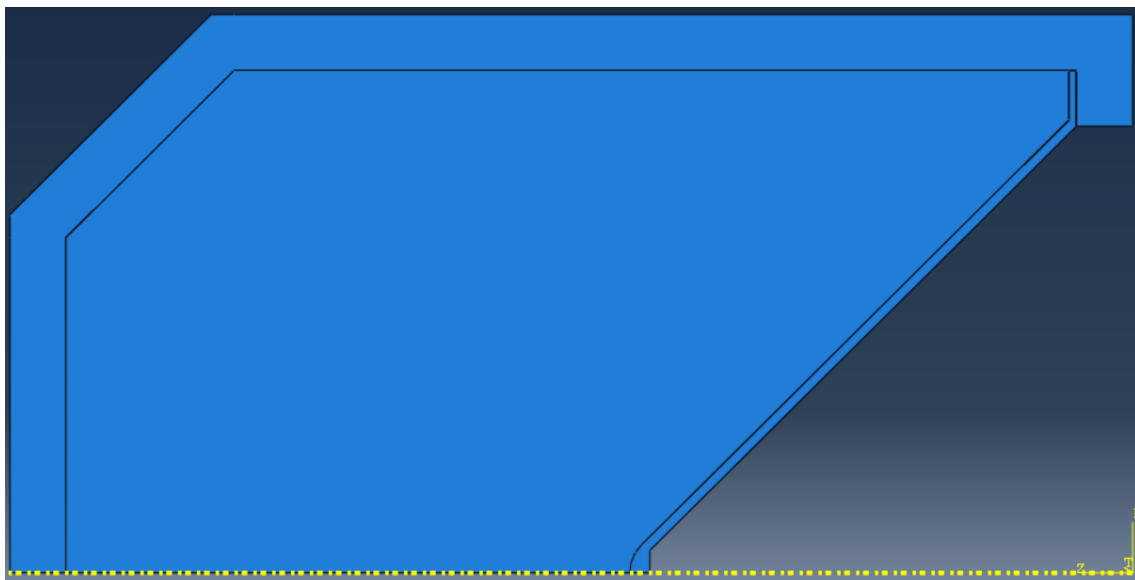


Figure 9: Design B full size

Due to the findings of Design A Fig 9, a curved tip was introduced, and the base of the liner was recessed inside the casing. This reduced the volume of HE slightly.

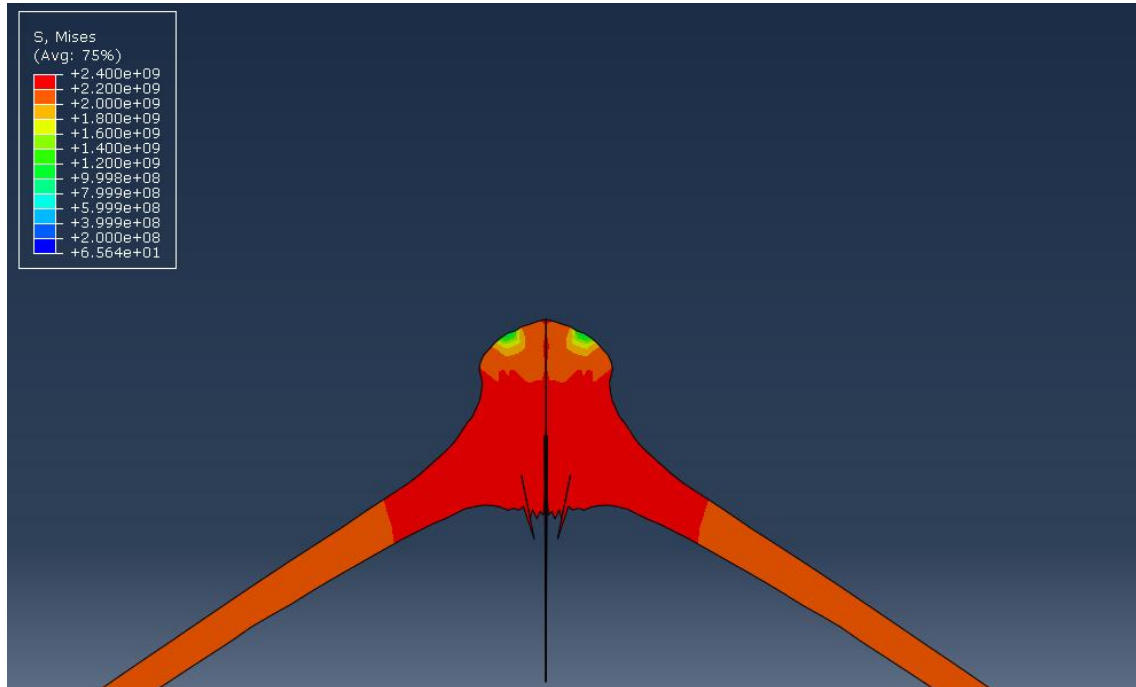


Figure 10: Design B tip forming

The splitting of the liner tip was no longer present, and a more cohesive jet was produced as a result Fig 10.

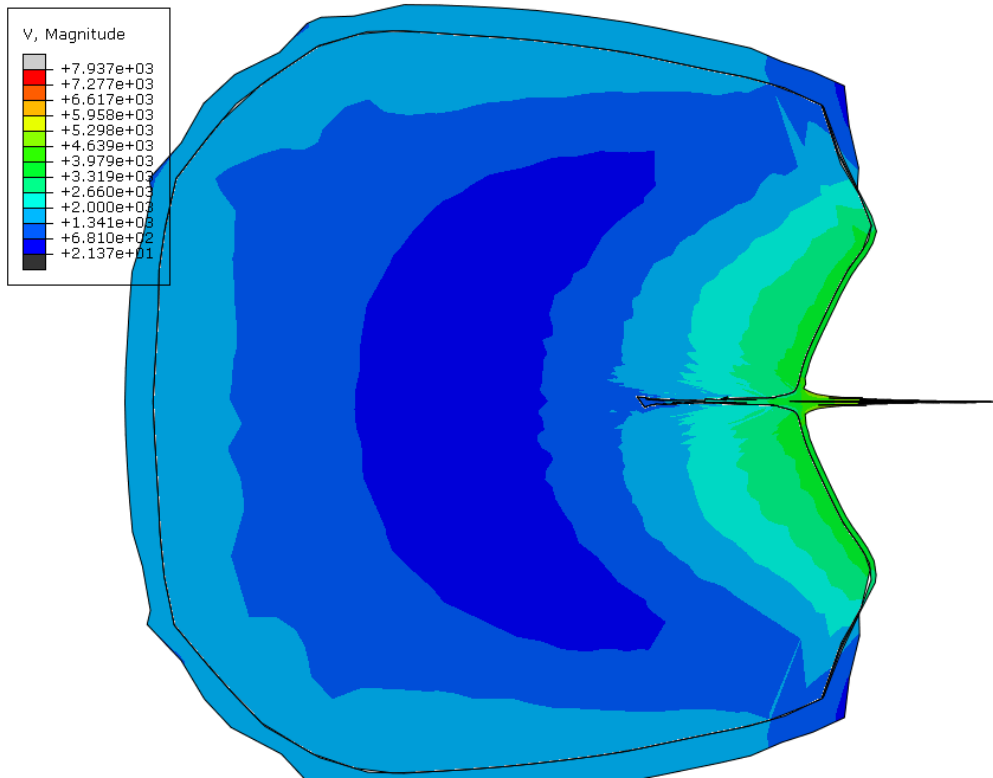


Figure 11: Design B pressure sealing

Furthermore, a better pressure seal was created by recessing the lip of the liner, as observed by the bulging effect in Fig 11.

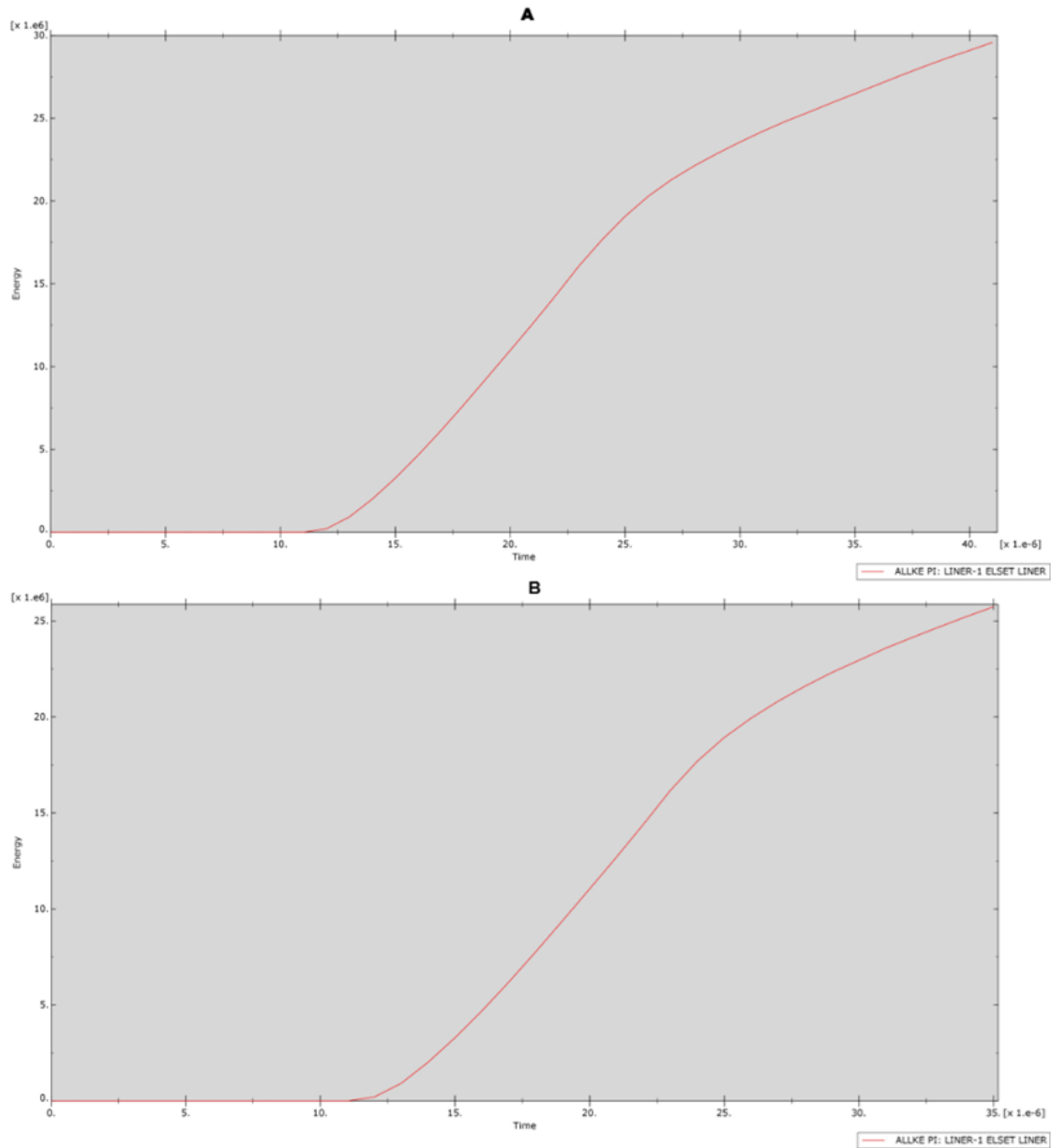


Figure 12: Kinetic Energy comparison between Design A and B

The loss in HE volume does not seem to have significantly affected the performance of the shaped charge as the velocity for elements in the jet do not change meaningfully, possibly due to the greater retention of pressure Fig 12. However, the efficacy of this change is questionable, as the base regions of the liner do not seem to meaningfully contribute to the jet in this simulation.

4.2 Lagrangian Analysis in 3D

With Design B being chosen as the preferred design, a 3D model was produced and simulated.

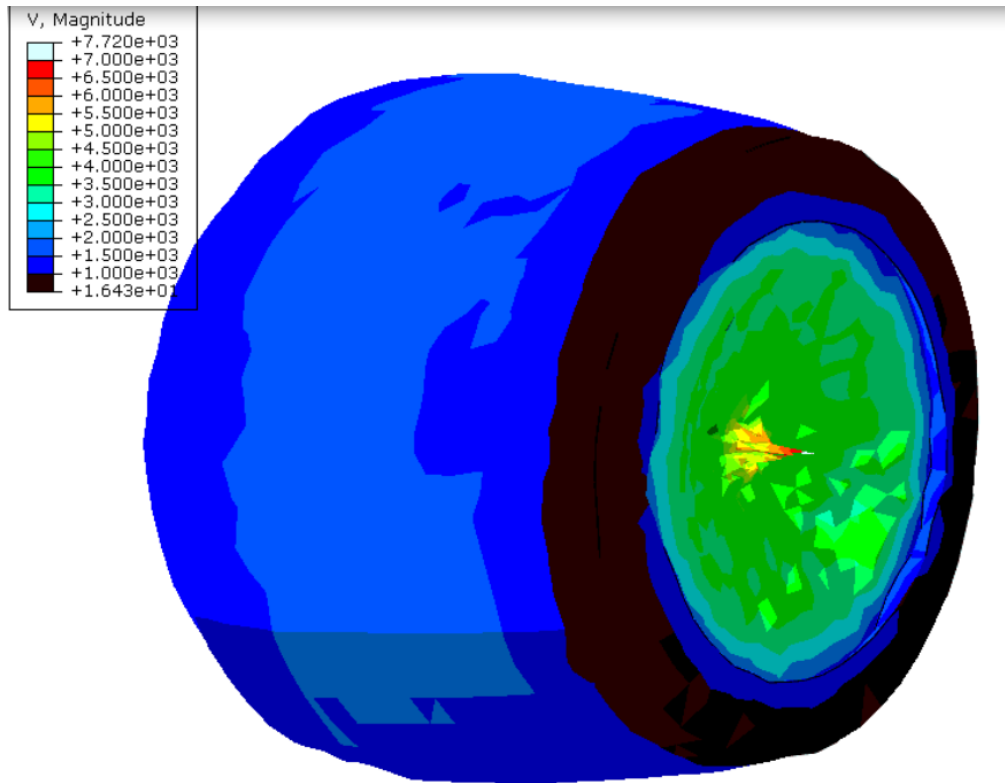


Figure 13: Full 3D design with jet tip forming

Initial frames of the 3D simulation Fig 13 show immediate formation of a pointed jet forming in the centre of the liner, with the parts reaching a velocity of 7200 ms^{-1} , still less than the detonation velocity of HMX, 9110 ms^{-1} .

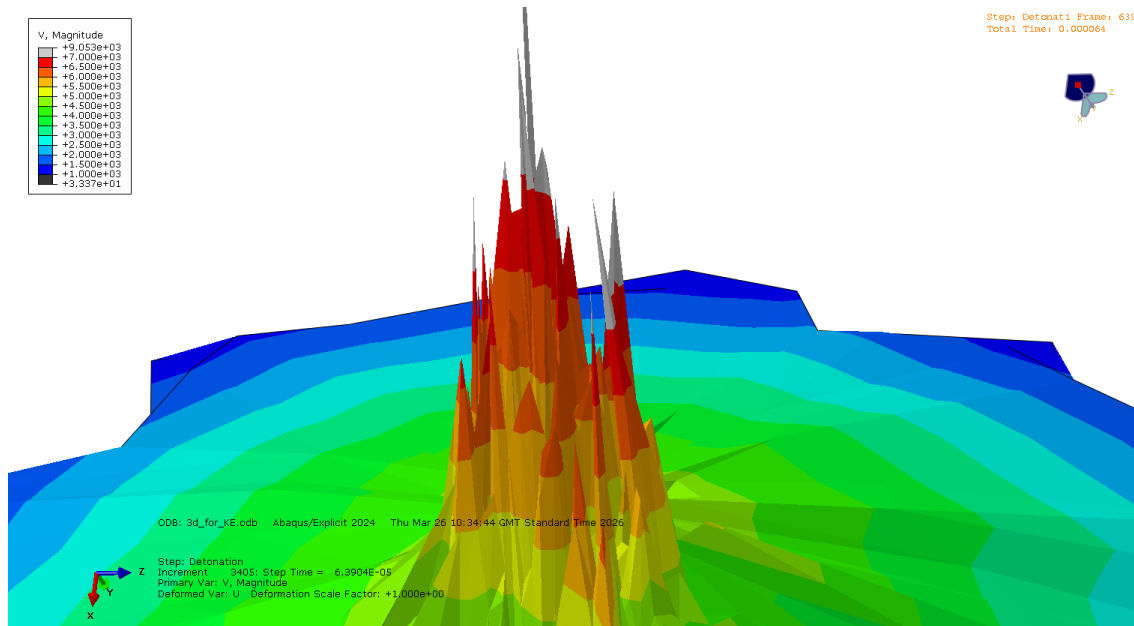


Figure 14: Spiked tip of 3D jet

As the simulation progresses Fig 14, it is increasingly clear that the jet consists of a series of spike-like vertices. This is a natural consequence and limitation of simulation software: elements are programmed as polygons, in this case tetrahedrons, and so with enough resolution, any jet no matter the mesh density would appear as a collection of spikes. Increasing mesh density would make the jet appear smoother, but it would still by its nature be geometrically similar upon sufficient magnification.

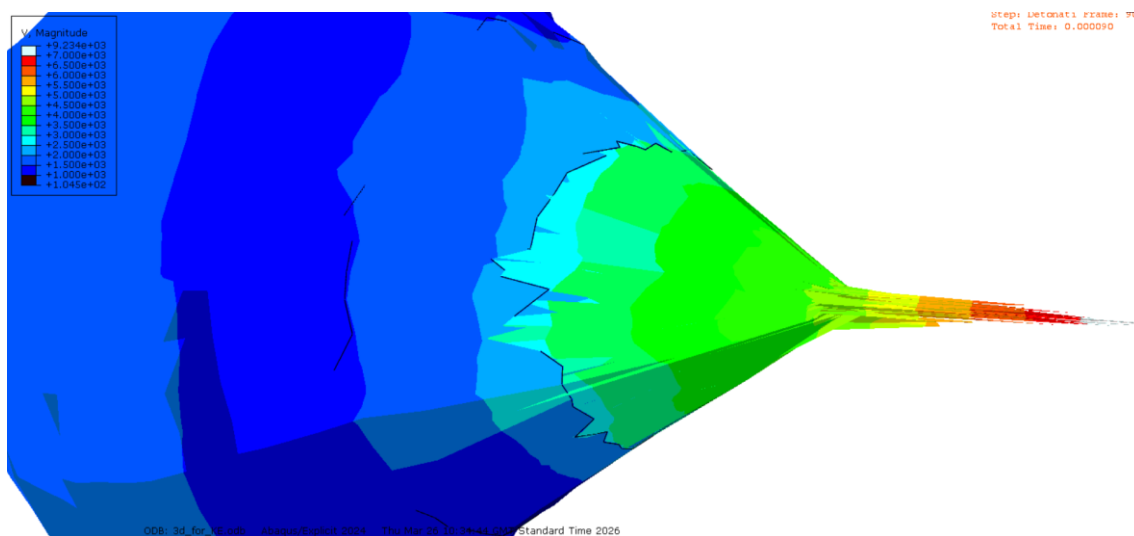


Figure 15: Jet formation beginning to pick up speed

At the latest stages of the simulation Fig 15, the jet tip can be seen to be reaching a velocity exceeding the VoD of HMX, at 9234 ms^{-1} . An expected behaviour for a shaped charge.

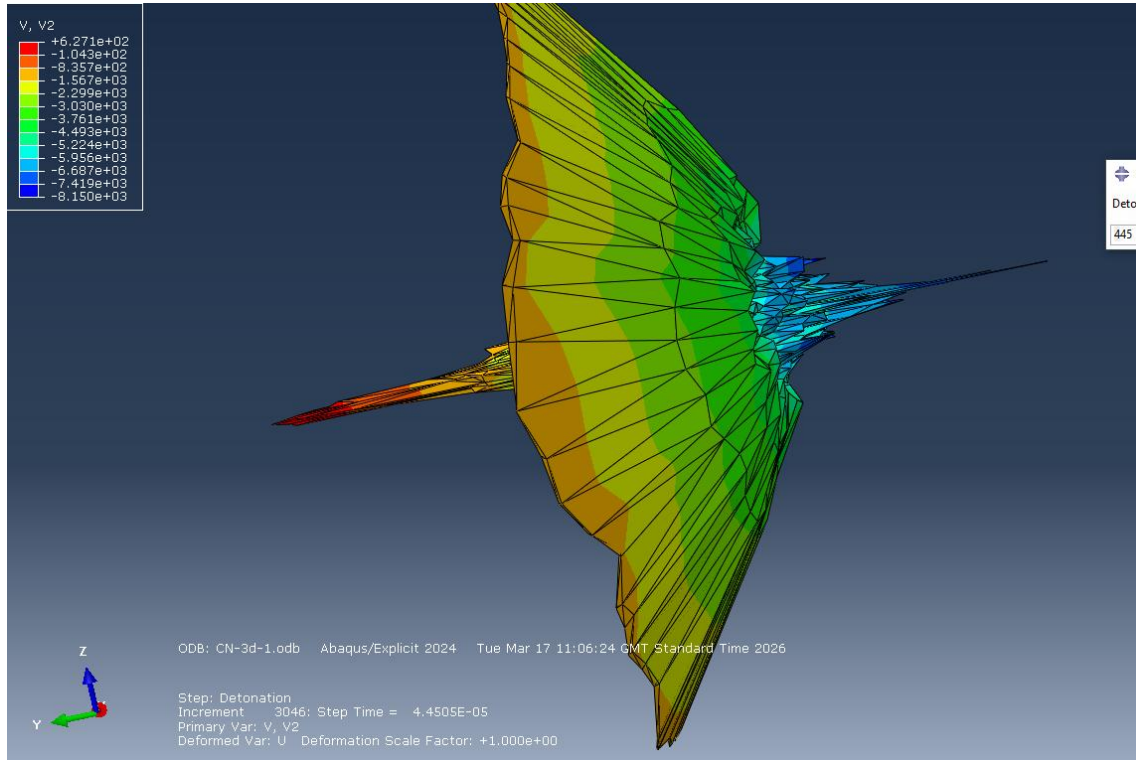


Figure 16: Umbrella-like shape showing jet elongation in both directions

Another expected behaviour is displayed when the case and fill are hidden: stretching of the jet and slug in opposite directions Fig 16. As can be seen by the colour differential scale, the red slug is moving aft at 627 ms^{-1} , while the jet tip is moving forward at over 6000 ms^{-1} . This screenshot also highlights a limitation of the choices made during this simulation. The exclusion of a damage model for the liner results in an umbrella-like effect on the outer edges of what was once the base of the liner. This likely does not comport with reality.

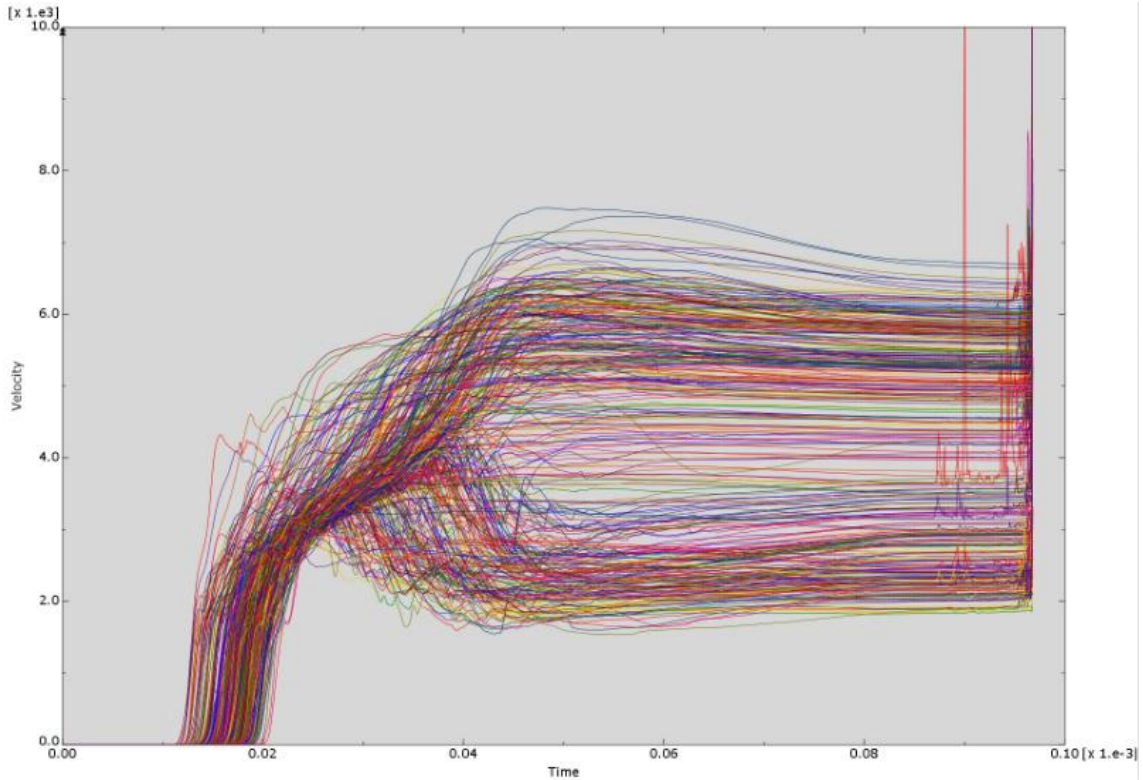


Figure 17: Velocity graph for many nodes in jet

In Fig 17 nodes from parts of the line that became the jet were measured for velocity. Reflective of the PER hydrodynamic theory, a velocity gradient is present along the jet, with some parts continuing to accelerate while others decelerate. Some nodes near the tip of the jet accelerate to almost 8000 ms^{-1} , while others are closer to 2000 ms^{-1} near the rear of the jet. It can also be observed that near the end of the capture period, several nodes spike in velocity somewhat chaotically. This is due to excessive mesh distortion still present in the Lagrangian mesh. Preliminary 3D and 2D runs were all plagued with excessive mesh distortion, and as such significant linear smoothing had to be applied, which may have compromised the integrity of the metrics derived from the simulations.

4.3 Combined Eulerian-Lagrangian Analysis in 3D

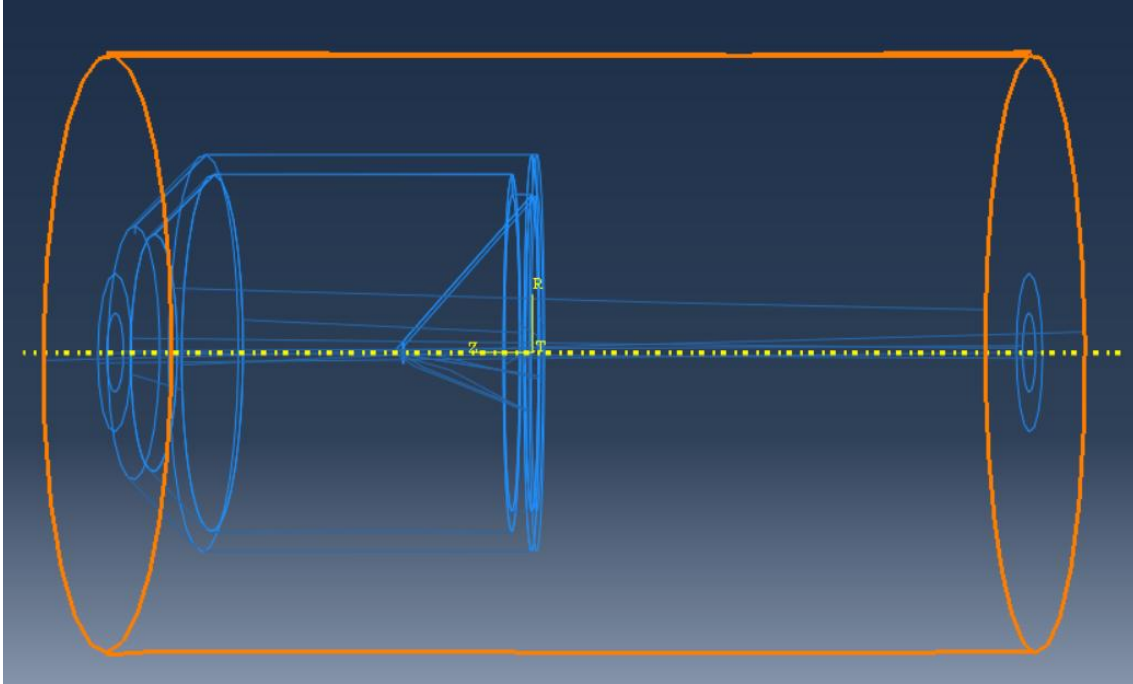


Figure 18: Eulerian Volume Fraction wire view

To overcome some of the limitations of pure Lagrangian analysis, CEL was implemented. A EVF of roughly double the length of the full shaped charge assembly was used Fig 18.



Figure 19: Mesh density along cylinder height

To save on computational resources a very coarse global mesh was applied to the applied to the EVF, followed by a single edge fine mesh along the entire height of the cylinder Fig 19.

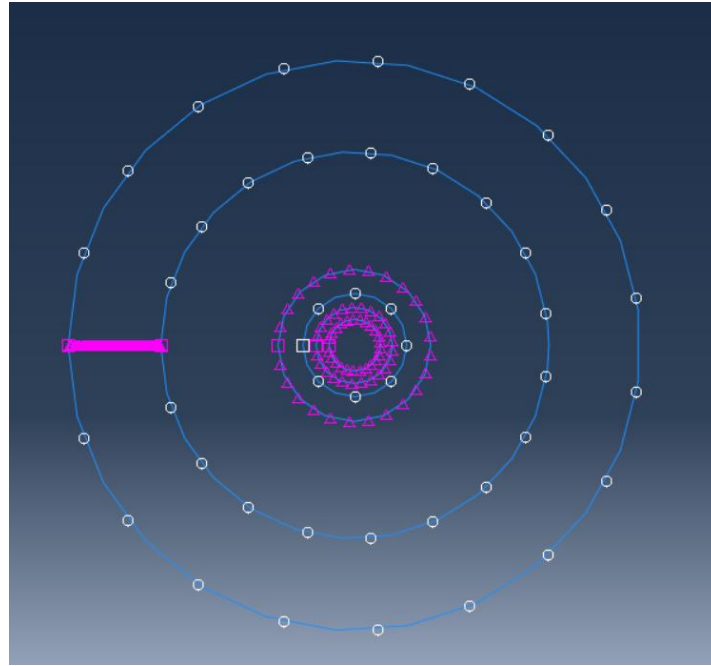


Figure 20: Mesh density of centre partition

Then concentric circular partitions were created with an increasingly fine mesh towards the centre of the liner in Fig 20.

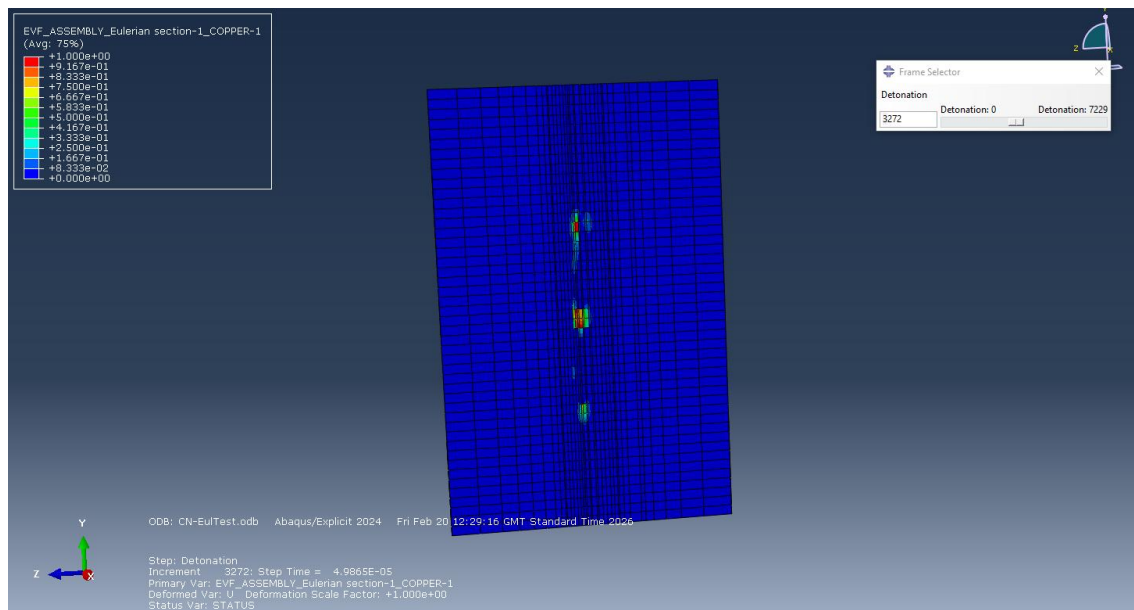


Figure 21: Failed simulation due to lacking field assignment

After each modification of the mesh, the discrete fields which defined the Lagrangian sections within the EVF had to be reassigned, as not doing so would result in a nonsensical simulation result Fig 21.

Additional trouble stemmed from the combination of the extremely rapid evolution of an explosive system and the highly resource intensive requirements of a CEL simulation. This culminated in >8 hr simulation run times, with stalling typically occurring at frame 27, Fig 22.

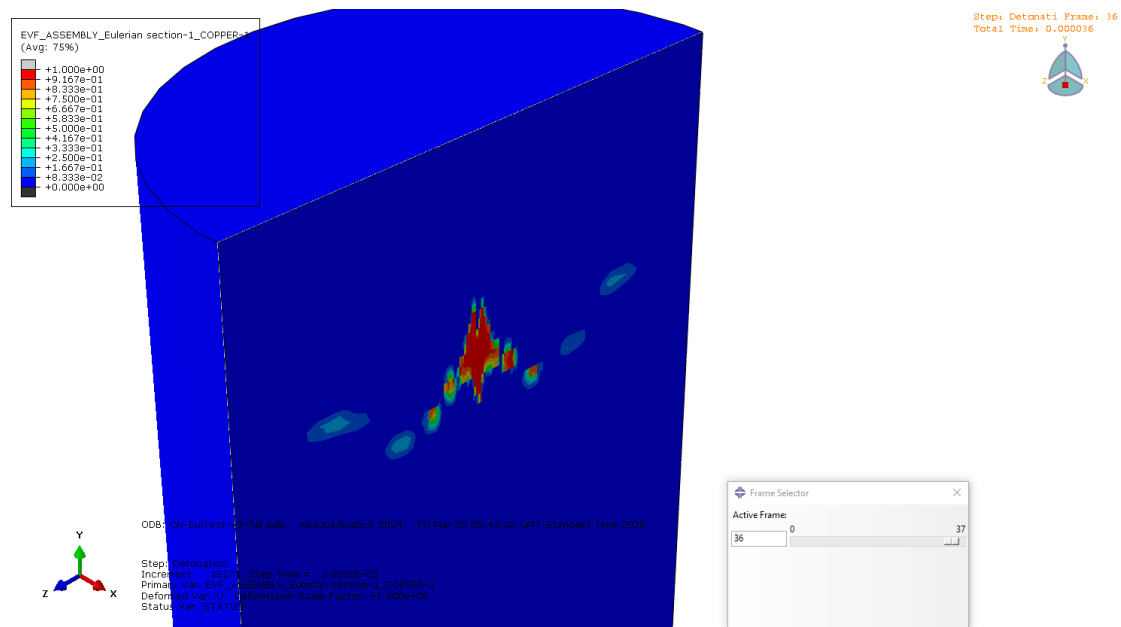


Figure 22: Stalled frame generation

It was eventually surmised that this was actually caused by the frame generation configuration rather, as frames were set to generate per time step, and with each calculation being performed in the order of 10^{-9} s with a time step of 10^{-7} s, this caused significant time delays in the render process. Solving this was simple, instead of producing a frame per time step, it was changed to produce a frame per 100 increments (i.e. calculations). This dramatically shortened the render times to <1 hr.

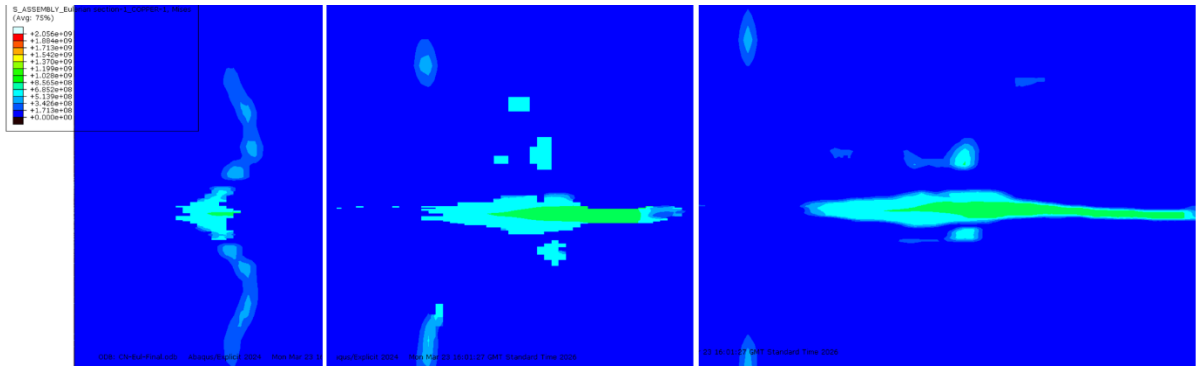


Figure 23: Step by step jet formation in CEL max principle

The advantage of CEL became clear once a simulation was rendered. Fig 23 shows the max principle stress experienced by elements containing 0.0001% copper by volume, clearly displaying step by step, the collapse of the liner followed by hydrodynamic jet formation.

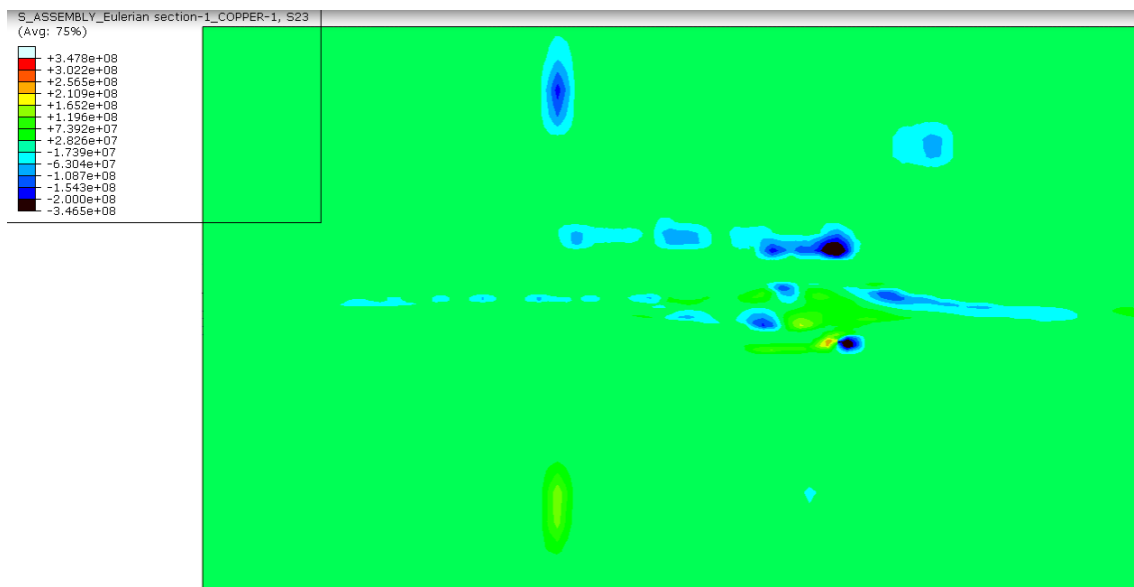


Figure 24: Faint shear stress in CEL

While not exceedingly clear, Fig 24 demonstrates the large shear forces present in the jet as it stretches and elongates, which will eventually cause fragmentation of the jet.

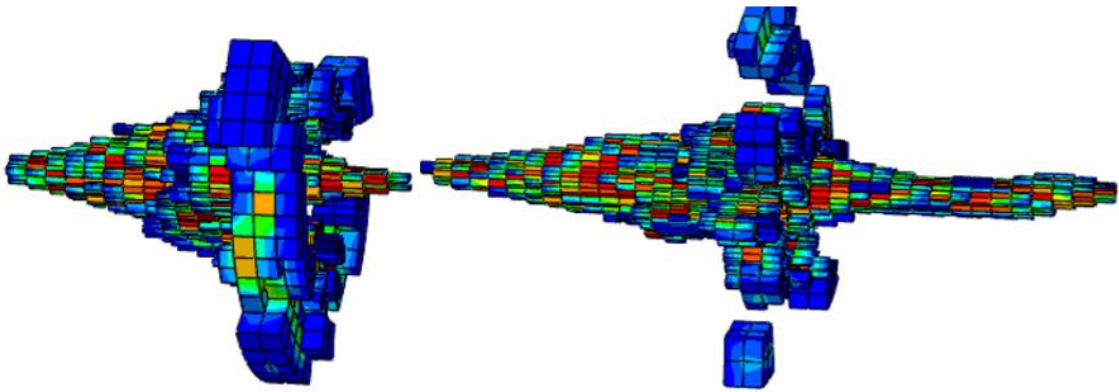


Figure 25: Start of CEL with >25% copper volume

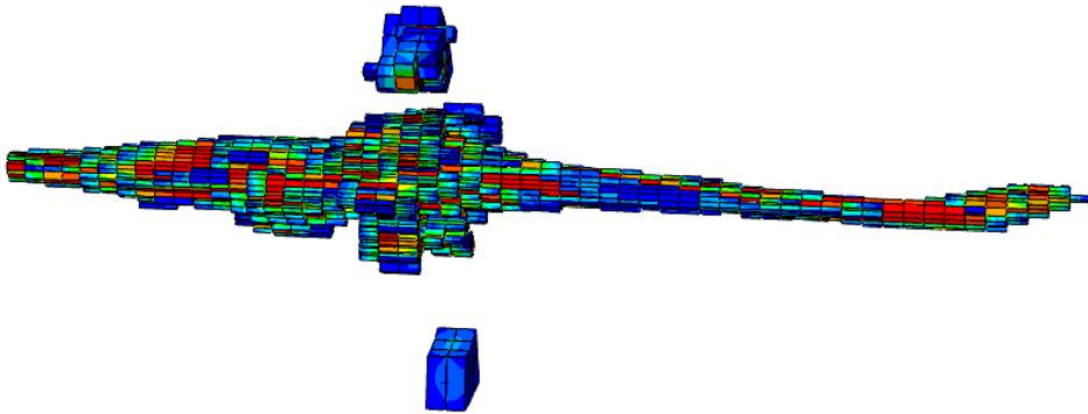


Figure 26: End of CEL with >25% copper volume

Selection of elements only containing >25% copper by volume gives a clearer 3D picture of the jet geometry, the cone collapse and subsequent jet formation can be observed in Fig 25, with significant elongation noticeable by Fig 26. It can also be observed that the outer liner which was once the base is slowly becoming lower in copper volume, indicating it is slowly combining with the slug/jet, or stretching extremely thin.

Fig 26 also identifies a couple of limitations that came with the decisions made in producing this CEL simulation. Firstly, the mesh density is still rather coarse and as such obscures much of the fine detail of surface geometry that could be present. Secondly the tip of the jet is cut off in the very next frame, indicating that the EVF was not long enough to capture full jet behaviour, meaning fragmentation of the jet is not captured, nor is an upper bound on stand-off distance discernible.

4.4 Future Design Considerations

There are several design features which should be considered for future shaped charge simulation and modelling.

Naturally, changing the HE filling would bring about different jet velocities, but consideration should perhaps be paid to alternative configurations of fillings outside of HE. Wave shapers have seen success in producing alternate performance characteristics by way of inserting a non-HE insert within the HE filling which affects the progression of the detonation wave which operates in similar ways to the presence of a cavity in the original hollow charge design.

Variations in liner material also come to mind, as viable shaped charges can be made with most metals and even glass. Perhaps an exploration into more economically viable materials such as steel could yield positive results. Further to this, liner thickness was not explored in this report and it is undoubted that there exists an optimal balance between a liner thick enough to maintain a jet, and thin enough to maintain optimal velocity.

Case material and thickness was largely ignored in this report to focus on the behaviour of the jet, but since the jet relies upon pressure to be driven into collapse, it should be considered that a weak case, or even a lack of confinement, would result in significant pressure losses that would undoubtedly affect the performance characteristics of a potential shaped charge.

Liner cone angle was also not varied in this report. It is already known that cone angle affects the viability of a jet, with large angle or dome shaped liners producing Explosively Formed Projectile (EFP) slugs rather than jets. Changing the angle of the liner along the edge has also been known to offer different effects [15] and a full spectrum of tests could be conducted to determine optimal angle configurations for different purposes.

5 Conclusion

Computational FEA methods were used to generate accurate simulations of a typical shaped charge, with differences being identified between different designs in 2D simulations and field data capture being used to quantify performance metrics in 3D simulations. Future work could involve investigating a greater range of features for performance characteristics, and the use of more advanced computational techniques such as adaptive meshing to provide a more accurate picture.

References

- [1] W. P. Walters, "THE SHAPED CHARGE CONCEPT N PART II. THE HISTORY OF SHAPED CHARGES," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, Sep. 1990. Accessed: May 15, 2026. [Online]. Available: <https://apps.dtic.mil/sti/tr/pdf/ADA226772.pdf>
- [2] F. von Baader, "Versuch einer Theorie der Sprengarbeit," *Bergmannisches Journal*, von Kohler and Hoffmen, Mar. 1792.
- [3] M. von Foerster, *Versuche mit Komprimierter Schiessbaumwolle*. Berlin, Germany: Mittler and Son, 1883.
- [4] C. E. Munroe, "On certain phenomena produced by the detonation of gun cotton," *Proceedings of the Newport Natural History Society*, Report no. 6, pp. 113–119, 1888.
- [5] M. Neumann, "Einiges über Brisanz-Sprengstoffe," *Zeitschrift für Angewandte Chemie*, vol. 24, pp. 2233–2240, Nov. 1911.
- [6] F. R. Thomanek, "The Development of the Lined Hollow Charge," Feltman Research Laboratories, Picatinny Arsenal, Dover, NJ, USA, Tech. Note FRL-TN-27, Mar. 1961. (Trans. from *Explosivstoffe*, vol. 8, no. 8, Aug. 1960.
- [7] W. P. Walters and J. A. Zukas, *Fundamentals of Shaped Charges*. Wiley-Interscience, 1989.
- [8] J. E. Kennedy, "Gurney energy of explosives: estimation of the velocity and impulse imparted to driven metal," Dec. 1970, doi: <https://doi.org/10.2172/4441869>.
- [9] J. F. Molinari, "Finite element simulation of shaped charges," *Finite Elements in Analysis and Design*, vol. 38, no. 10, pp. 921–936, Aug. 2002, doi: [https://doi.org/10.1016/s0168-874x\(02\)00085-9](https://doi.org/10.1016/s0168-874x(02)00085-9).

- [10] H. Johansson and J. Ollar, "POLYMER FLOW IN PACKAGE SEALING PROCESS -A Coupled Eulerian-Lagrangian Numerical Approach," May 2021. Available:
<https://www.byggmek.lth.se/fileadmin/byggnadsmekanik/publications/tvsm5000/web5175.pdf>
- [11] G. R. Johnson and W. H. Cook, "A Constitutive Model And Data For Metals : Gordon R. Johnson, William H. Cook : Free Download, Borrow, and Streaming : Internet Archive," *Internet Archive*, 1983. <https://archive.org/details/AConstitutiveModelAndDataForMetals/page/n3/model/2up> (accessed Mar. 17, 2026).
- [12] A. C. Mitchell and W. J. Nellis, "Shock compression of aluminum, copper, and tantalum," *Journal of Applied Physics*, vol. 52, no. 5, pp. 3363–3374, May 1981, doi: <https://doi.org/10.1063/1.329160>.
- [13] MatWeb, "Advanced Materials Search by Property, Composition, or Text," *Matweb.com*, 2021. <https://www.matweb.com>
- [14] B. M. Dobratz and L. Livermore, *LLNL explosives handbook : properties of chemical explosives and explosive simulants*. Livermore, Calif.: Lawrence Livermore National Laboratory, University Of California ; Springfield, Va, 1985.
- [15] X. Cheng, G. Huang, C. Liu, and S. Feng, "Design of a Novel Linear Shaped Charge and Factors Influencing its Penetration Performance," *Applied Sciences*, vol. 8, no. 10, p. 1863, Oct. 2018, doi: <https://doi.org/10.3390/app8101863>.

Appendices