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AN INVESTIGATION ON THE EFFECTS OF MULTI-LAYER CHARGE LINERS
ON EFP FORMATION AND PERFORMANCE

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Project submitted as part of the requirements for the award of BEng
(Hons) Ordnance, Munitions and Explosives (Test and Evaluation)

22nd of March 2024

Declaration of Originality

I, Samuel Martin Darcy-Page, declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

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Abstract

Directed Energy Warheads have been used extensively in conflicts around the world, in particular, Shaped Charges (SC) and Explosively Formed Projectiles (EFP). Shaped Charges have a complex formation mechanism that requires very high precision. In recent times, considerable research and modelling has been conducted on improving the performance of EFPs including adding multi-layered liners in the attempt to create tandem EFPs from the detonation of a single charge. This paper looks at the performance of dual layer liner EFP charges and the performance characteristics with different configurations of copper and aluminium liners. This paper has six different configurations. It was observed that for the configurations including aluminium liners, forming coherent EFPs was not possible as the projectiles consistently particulated during the formation process. Similarly, whilst tandem EFPs can be reliably formed from double copper liners, the flight characteristics were unstable leading to no appreciable increase in performance. The configurations with one copper and one aluminium layer equated to approximately 32% and 25% increases in depth of penetration of the target, whilst also observing a 13.5% and 30% decrease in Total Kinetic Energy upon impact. Additionally, a gold-coloured compound had formed on the target after back-spall. These findings led to the conclusion that it seems possible to increase EFP performance using multiple layered liners, but further work is required to understand the formation process and target interaction of the novel configurations.

Contents

Abstract.....	3
Acknowledgements.....	6
i. Figures.....	7
ii. Tables	8
iii. Abbreviations	8
1. Project Definition.....	9
1.1. Introduction.....	9
1.2. Scope	9
1.3. Aim	9
1.4. Objectives.....	9
2. Prior Research and Literature Review	9
2.1. The Munroe Effect	9
2.2. The Shaped Charge Phenomenon.....	10
2.3. The Mischay-Schardin Effect.....	10
2.4. The Explosively Formed Projectile Phenomenon.....	10
2.5. Current uses of Explosively Formed Projectiles	12
2.6. New Developments in EFP and Shaped Charge Technology	12
3. Methodology and Results	15
3.1. Introduction.....	15
3.2. Experimental Design	16
3.2.1. In-flight Stability	16
3.2.2. EFP Velocity	16
3.2.3. EFP Formation	17
3.3. Charge Design.....	18
3.3.1. Explosive	18
3.3.2. Liner Design	19
3.3.3. Case Design.....	19
3.3.4. Expected Target Penetration	20
3.4. Charge Inspection	20
3.5. Results.....	22
3.5.1. EFP Velocities	22
3.5.2. Kinetic Energy	23
3.5.3. Depth of Penetration	25
4. Discussion	26
4.1. EFP Formation	26
4.2. EFP Velocity	31

4.2.1. Single Liner EFPs.....	31
4.2.2. Double Lined EFPs with Similar Materials	33
4.2.3. Double Lined EFPs with Dissimilar Materials	34
4.3. Kinetic Energy	34
4.4. In-flight Stability	36
4.5. Crater Diameter and Target Damage.....	37
5. Conclusions	38
6. Reflection.....	39
7. Recommendations for Further Study	39
References.....	40
Bibliography	42
Appendix A.....	45

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i. Figures

Figure 1 - Shaped charge liner collapse [5]	10
Figure 2 - Numerical simulation of a forward fold EFP mechanism [7]	11
Figure 3 - Representation of a backward folding EFP [7]	11
Figure 4 - Dual liner shaped charge composition [8]	13
Figure 5 - Formation process from computer modelling of triple layer EFP [3].....	13
Figure 6 - X-ray images from testing conducted on dual lined EFP charges [9].....	14
Figure 7 - EFP formation from a dual liner shaped charge consisting of both a high explosive and low explosive.....	15
Figure 8 - Experimental set-up detailing charge stand position (centre), flash x-ray head position (Right) and x-ray cassette position (Left).....	16
Figure 9 - High-speed image showing fiducial marker (bottom right).....	17
Figure 10 - Assembled charge design	18
Figure 11 - Static x-ray of Serial 3 charges.....	21
Figure 12 - Graph of theoretical kinetic energy and depth of penetration for Scenarios 1 – 4	24
Figure 13 - Flash x-ray image of firing 18 216 μ s post-formation	29
Figure 14 - Snapshot of high-speed imagery to show aluminium flash upon impact from firing 8	29
Figure 15 - Snapshot of high-speed imagery from firing 3 showing flash from copper impact	29
Figure 16 - Snapshot of high-speed imagery from firing 18 to show flash upon leading projectile impact.....	29
Figure 17 - Snapshot of high-speed imagery for firing 21 showing the pyrophoric burn of aluminium following the leading EFP	31
Figure 18 - EFP formed from single aluminium liners.....	32
Figure 19 - EFP formed from single copper liners 355 μ s after trigger	32
Figure 20 - Flash x-ray image of dual lined aluminium EFPs after 143 μ s	33
Figure 21 – High-speed image showing the pyrophoric nature of aluminium liners	34
Figure 22 - Graph of theoretical maximum kinetic energy vs depth of penetration with trend	35
Figure 23 - Graph of theoretical maximum kinetic energy and depth of penetration including Serials 5 - 6 (red and blue respectively)	36
Figure 24 - Presence of gold coloured compound on rear of target plate.....	38
Figure 25 - Static X-ray for Scenario 1.....	45
Figure 26 - Static X-ray for Scenario 2.....	45
Figure 27 - Static X-ray for Scenario 3.....	46
Figure 28 - Static X-ray for Scenario 4.....	46
Figure 29 - Static X-ray for Scenario 5.....	47
Figure 30 - Static X-ray for Scenario 6.....	47

ii. Tables

Table 1- Explosive properties of high explosive 8701	18
Table 2 - Explosive properties of PE-4 [12]	18
Table 3 - Charge configuration	19
Table 4 - Density of mild steel, copper and aluminium	20
Table 5 - Theoretical maximum depth of penetration for copper and aluminium EFPs	20
Table 6 - Average EFP velocity (bold are theoretical)	22
Table 7 - Theoretical maximum kinetic energy	23
Table 8 - Depth of penetration	25
Table 9 - X-ray images for firings 6 – 8 143µs post-formation	26
Table 10 - X-ray images for firings 2 and 4 355µs post-formation	27
Table 11 - X-ray images for firings 9, 10 and 11 333 - 355µs post-formation	27
Table 12 - X-ray images for firings 13 - 16 143µs post-formation	28
Table 13 - X-ray for firings 18 - 20 216µs post-formation	30
Table 14 - X-ray images for firings 21 - 24 216µs post-formation	31
Table 15 - Crater diameter	37

iii. Abbreviations

CA – Cone Angle

CD – Charge Diameter

CSA – Cross-Sectional Area

EFP – Explosively Formed Projectile

HE 8701 – High Explosive 8701

HEAT – High Explosive Anti-Tank

KED – Kinetic Energy Density

kJ – kilojoules

L/D – Length to Diameter

PE-4 – Plastic Explosive 4

SC – Shaped Charge

1. Project Definition

1.1. Introduction

Throughout history, a keen focus has been placed on armour defeating mechanisms; emerging out of the development of armoured fighting vehicles in World War I [1]. Ever since then, much effort has been devoted to improving armour defeat munitions, the delivery systems, and the platforms on which they operate [2]. Armour has been developed extensively to resist armour defeat munitions with the introduction of oblique armour, explosively reactive armour, and disruptor bars. These methods were developed specifically for the defeat of anti-armour munitions such as Shaped Charge (SC), Explosively Formed Projectiles (EFP), High Explosive Anti-Tank rounds (HEAT) and later, Long Rod Penetrators (LRPs) [1]. In this project, the focus is on recent developments in EFP technology, specifically the use of a novel dual liner approach to EFP munitions [3].

1.2. Scope

The scope of this project is to assess the formation characteristics of an EFP charge when a novel dual liner approach is used. Performance is defined as a measure of the EFP velocity, formation characteristics such as Length to Diameter Ratio (L/D), depth of penetration and crater diameter.

1.3. Aim

The aim of this project was to investigate the relationship between:

- layering charge liners and the ability to form a coherent EFP; and
- having layered charge liners and the damage ability of the resulting EFP (penetration depth and crater size).

1.4. Objectives

To achieve these objectives, an experimental approach was adopted based on modelling previously conducted by other organisations which will be able to assess the EFP velocity, formation, impact penetration, crater diameter and in-flight stability. These are all important factors to consider when assessing EFP charge performance.

2. Prior Research and Literature Review

2.1. The Munroe Effect

The Munroe Effect is a well-documented and understood phenomenon that was first discovered by Charles E. Munroe in 1888 [4]. Munroe observed this effect when detonating blocks of explosives with the US Navy initials inscribed on the side in contact with the target plate [4]. The resulting effect was a reproduction of "U.S.N." on the steel target plate which he later investigated further, observing that the deeper the cavity within the explosive mass, the greater the penetrative ability of the charge [4].

The explanation was that the cavity within the explosive mass focussed the detonation products causing an area of higher pressure focussed on the target plate [4]. This led to a new area of development when it was discovered that the shockwaves within the explosive were of sufficient pressure to permanently deform a metal liner within the cavity [4]. This was one of the first developments in Shaped Charges (SC).

2.2. The Shaped Charge Phenomenon

When examining Shaped Charges, how the liner collapses must be considered. Upon single point detonation, a spherical detonation wave travels through the explosive until a planar wave meets the apex of a small angle metallic liner [5]. The high pressure at this detonation wave causes the apex of the cone to be forced ahead at high velocities creating the Shaped Charge jet, and the remaining liner material flows behind to create a low velocity slug [5]. Figure 1 is a graphical representation of this phenomenon.

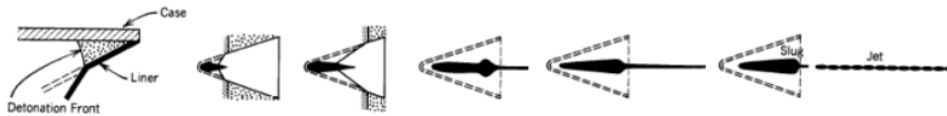


Figure 1 - Shaped charge liner collapse [5]

2.3. The Mises-Schardin Effect

The Mises-Schardin Effect is when a liner has a sufficiently wide angle, a jet is not formed, as seen in shaped charges. Instead, the liner inverts to form a single slug with near 100% mass conversion [2].

2.4. The Explosively Formed Projectile Phenomenon

An extension of the Shaped Charge phenomenon is the Explosively Formed Projectile (EFP) also known as a Self-Forging Fragment. EFP charges consist of a hemispherical dish of metal ahead of the explosive fill which collapses, as described previously - the Mises-Schardin effect - to form a high velocity slug of metal with a velocity in the region of 1500 - 3000 m/s [4]. Whilst easier to design and manufacture than shaped charges, the design, and therefore penetrative ability, is a function of many parameters. These parameters can range from physical properties of the explosive, liner and casing materials as well as liner geometries and contours [6]. The importance of these choices will affect the kinetic energy density (KED) of the projectile as these parameters will affect the velocity, mass and projectile cross-sectional area [2]. Kinetic energy density is one of the most important considerations with EFPs to ensure the target is overmatched causing failure [2].

EFPs can form under different processes depending on liner geometries. As an example, using a uniform thickness liner allows the EFP to 'backward fold' whereas a tapered liner will permit a 'forward fold' mechanism [6]. Figure 2 and Figure 3 show this comparison.

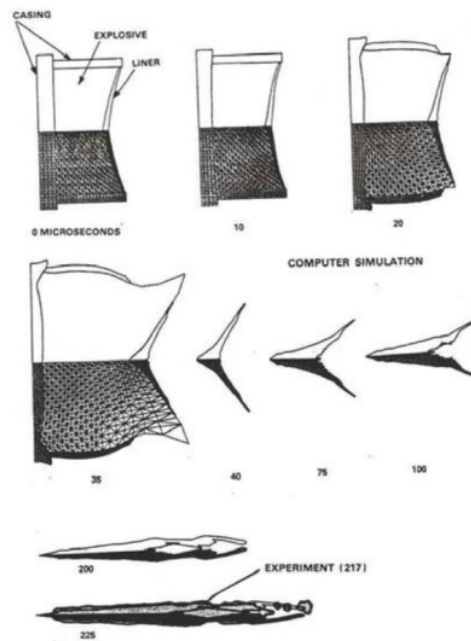


Figure 2 - Numerical simulation of a forward fold EFP mechanism [7]

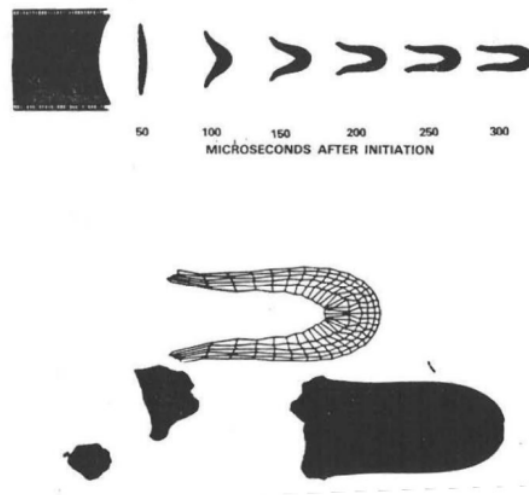


Figure 3 - Representation of a backward folding EFP [7]

Whilst EFPs are formed from a seemingly similar method to Shaped Charges, there are key differences in their formation and characteristics. EFPs are formed from a large angle liner, $>140^\circ$ at the apex, and form one coherent slug with little to no velocity gradient - unlike Shaped Charges which have a very large velocity gradient from jet tip to slug [4]. EFPs,

owing to their larger size, tend to produce large crater diameters in the target, and are effective over very large stand-off distances, up to 1000 Charge Diameters (CD) [4]. However, there is a limitation with the EFP phenomenon where short stand-off distances mean unpredictable penetration abilities. This is because the penetrator requires greater time, and therefore distance, to fully form [4]. It is also believed that within the initial 400 - 500 μ s of liner collapse, the liner experiences temperatures in the range of 1000K, strains up to 300% and strain rates in the region of $1 \times 10^5 \text{ s}^{-1}$ [5].

The EFP phenomenon has secondary effects on the target other than perforating armour. Common behind armour effects from EFP impact are: intense heat; blast overpressure; fragmentation of both the penetrator and armour target; and the spalling seen from the back of the target [5].

2.5. Current uses of Explosively Formed Projectiles

Due to the simple nature of their construction, EFPs have been used by terrorist organisations to attack armoured fighting vehicles. EFPs are an effective attack method against light armour such as the underside and the top of such vehicles. Due to this, they have been extensively used in mines such as the M70 Remote Anti-Armour Mine and the Yugoslav TMRP-6 anti-tank mine [1]. EFPs are also used in top-attack sub munitions, such as in the M898 Sense and Destroy Armour (SADRAM) projectile and widely in guided weapons [1]. Recently however, there has been an increased focus on improving the performance of EFP charges.

2.6. New Developments in EFP and Shaped Charge Technology

EFP developments have been focussed on improving the performance of EFPs and their ability to inflict effective damage to the target as defensive aids change. One such area of research is being able to form multiple EFPs from a single warhead improving the damage capability. There have been various methods proposed to enhance the EFP effect, such as using Micro-EFP warheads [5]. This method uses small diameter EFPs to produce multiple penetrators capable of overmatching the target and creating a devastating behind armour effect as explored in Section 2.2.

Recently, a dual liner approach to shaped charges has been adopted to include a reactive PTFE/Aluminium liner behind a conventional copper Shaped Charge liner [8]. The addition of a second liner to a Shaped Charge allows a charge of the same mass to have, not only the characteristics of a conventional copper shaped charge with the same penetration capability, but also to have a secondary chemical energy behind armour effect [8]. Figure 4 shows an example of this type of Shaped Charge.

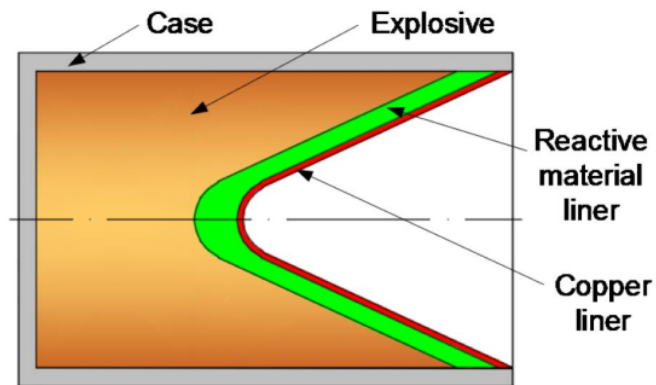


Figure 4 - Dual liner shaped charge composition [8]

Similar concepts have recently been applied to EFP research, where the assessment of double lined EFPs has been conducted. Recently, this has become an area of great focus due to the simple structure and energy utilisation of these designs and the potential for an enhanced damage capability on complex armour systems such as Explosively Reactive Armour [3]. The formation mechanisms of these charges have been modelled extensively and indicates that with the addition of multiple liners, multiple EFPs can be formed from a single detonation, as shown in Figure 5.

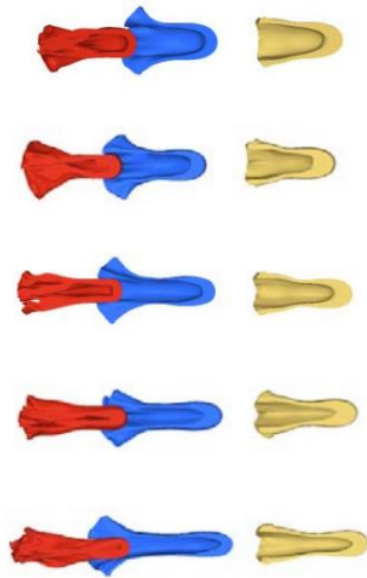


Figure 5 - Formation process from computer modelling of triple layer EFP [3]

A series of experiments have also been conducted to further confirm this concept. Figure 6 is an example where the formation of tandem EFPs from a dual lined EFP charge was investigated.

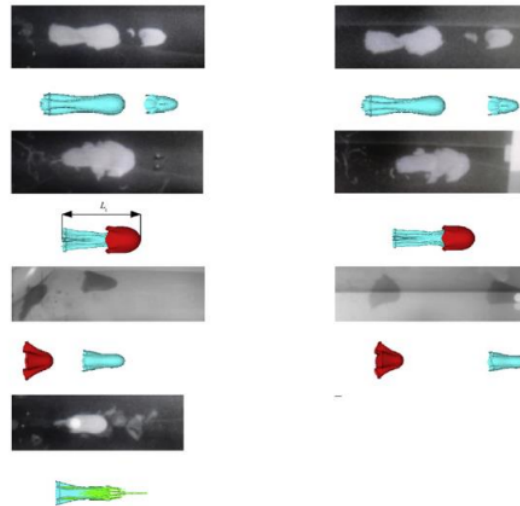


Figure 6 - X-ray images from testing conducted on dual lined EFP charges [9]

It was proposed that whilst this was able to produce tandem EFPs as shown in Figure 6, the formation mechanism was more complex than that of a conventional single lined EFP. The formation of tandem EFPs from dual liners can be split in to four distinct stages [9]:

1. Impact
2. Propulsion
3. Slide
4. Free flight [9]

During Stage 1, the rearward liners impact the forward liners creating a Kinetic Energy exchange between the two, resulting in one travelling faster axially ahead and one travelling slower behind [9]. This is due to the impact accelerating the forward liner, then allowing the rearward liner to catch up and impact again [9]. This 'impact – catch up – impact' stage is Stage 2. Stage 3 is where the liners separate, and can lead to the necking of projectiles as the leading EFP begins to pull the rearward EFP at a faster velocity and then both transition into a free flight stage [9].

It has also been attempted to combine this concept with that of introducing a charge that consists not only a High Explosive but also a Low Explosive component. When modelled, this leads to high L/D ratio projectiles as shown in Figure 7.

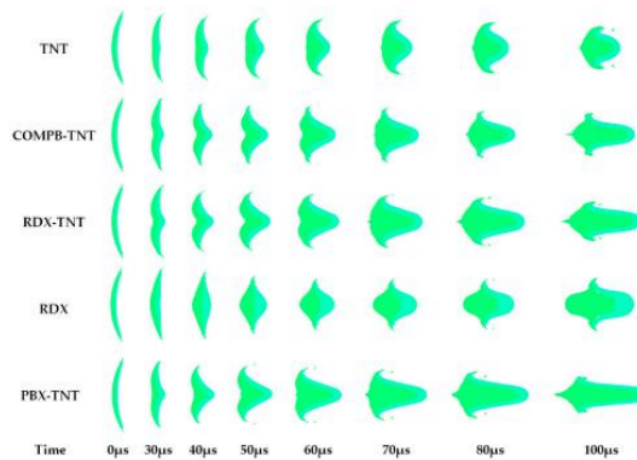


Figure 7 - EFP formation from a dual liner shaped charge consisting of both a high explosive and low explosive

3. Methodology and Results

3.1. Introduction

An experimental method was developed and employed for this investigation following on from modelling conducted in previous work [9]. For this project, to assess the performance of an EFP, it was determined that the important factors were:

- penetration depth;
- diameter of the damage inflicted by the EFP impact;
- damage volume defined as the overall volume of the deformed impact point;
- in flight stability;
- velocities of the EFP or, EFPs in the cases where there were multiple liners: and
- overall shape and orientation of the EFPs.

Distances in the case of directed energy charges, such as EFPs, is commonly represented as CD. The experimental research was conducted over 50 CD from the apex of the EFP liner to the impact face of the target plate. When developing the Textron Hornet¹, the performance criteria stated:

'EFPs should operate successfully between 50 – 100 CD' [10]

This was further defined as:

'The warhead must be able to penetrate the target between 50 and 100 CD' [11]

As this is a performance requirement set out for the design of an EFP munition, 50CD was chosen as the stand-off for this research. Further, due to the requirement to look at velocity, formation and in-flight stability, a limitation was put on the charge to target distance to ensure that there was sufficient distance to position all instrumentation appropriately.

¹ The Textron Hornet is an American wide area anti-tank mine

The instrumentation and the data they were used to capture are detailed below.

- Phantom TMX 6410 High Speed Digital Video Camera – to capture EFP velocities, Flight Stability and target interaction.
- Scandiflash 150kV Flash X-ray systems with L3 Harris X-ray Heads – to capture EFP characteristics and orientation.
- Leica RTC360 LiDAR Scanner to analyse the target damage.

Figure 8 shows the experimental set up.



Figure 8 - Experimental set-up detailing charge stand position (centre), flash x-ray head position (Right) and x-ray cassette position (Left)

3.2. Experimental Design

3.2.1. In-flight Stability

For this project, in-flight stability, and in-flight linearity (whether the multiple EFPs were following the same flight path) was vitally important. This was assessed through the capture of flash x-ray images of the projectile within 350mm of the initial flight. Flash x-ray requires precise timings to ensure the capture of the projectile, therefore, a High-Speed camera was also employed to assess both the in-flight characteristics and inform these timings.

3.2.2. EFP Velocity

EFP velocities were captured using a high-speed camera with a fiducial marker placed within the image as shown in Figure 9.

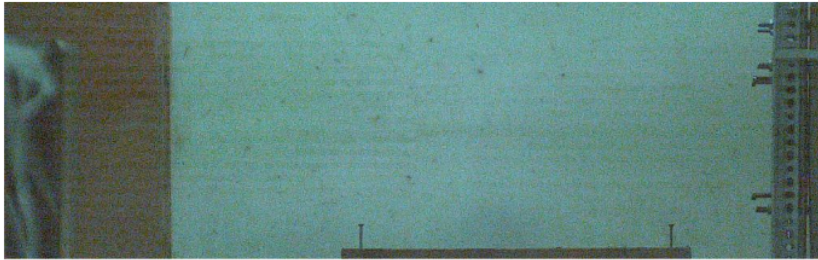


Figure 9 - High-speed image showing fiducial marker (bottom right)

This known distance allowed the image to be calibrated to provide an accurate velocity. The High-Speed Camera was positioned orthogonal and 15 metres from the shot line to reduce the chance of parallax errors being introduced in the velocity measurements.

3.2.3.EFP Formation

EFP formation was assessed using the flash x-ray images and the high-speed footage where appropriate. The High-Speed footage was used as a comparative measure to confirm that the EFPs were able to fully form before the flash x-ray capture. It also ensured that there is no change to the form of the fragment before target impact.

3.3. Charge Design

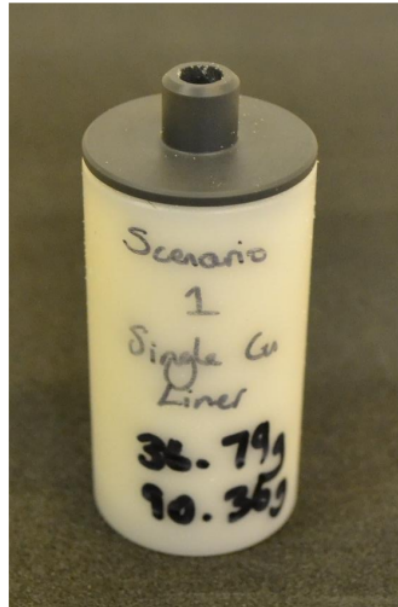


Figure 10 - Assembled charge design

3.3.1. Explosive

Previous research into this area commonly used High Explosive 8701 (HE 8701) which is a press cast explosive with the parameters shown in Table 1 [9].

Material	ρ (g·cm ⁻³)	D (m·s ⁻¹)
8701 explosive	1.69	8425

Table 1- Explosive properties of high explosive 8701

Due to limitations on the provision of press casting at the trials site, it was decided to replace HE 8701 with a plastic explosive. The explosive could then be hand pressed into the charge casing, replacing the press cast explosive fill mentioned above. Plastic Explosive 4 (PE-4) was chosen for its similar properties, such as density and detonation velocity. The properties of PE-4 are shown in Table 2. In both Table 1 and Table 2, 'D' represents the detonation velocity of the explosive.

Material	Density ρ (kg/m ³)	D (m/s)
PE-4	1.666	7500

Table 2 - Explosive properties of PE-4 [12]

After all charges were complete, a comparison between expected density and actual density was drawn and an average density of 1.300 kg/m³ was achieved.

3.3.2.Liner Design

As mentioned previously, EFPs are reliably formed from large cone angle (CA) liners, which is the main distinction between EFPs and Shaped Charges. A CA of 140° has been comprehensively proven to reliably produce an aerodynamically stable EFP [4]. This was the liner geometry adopted for Scenarios 1 - 6 detailed in Table 3.

Serials	Scenario No.	Number of Liners	Liner Material 1	Liner Material 2	Liner 1 Thickness (mm)	Liner 2 Thickness (mm)
1 to 4	1	1	Copper	-	2	-
5 to 8	2	1	Aluminium	-	2	-
9 to 12	3	2	Copper	Copper	1	1
13 to 16	4	2	Aluminium	Aluminium	1	1
17 to 20	5	2	Copper	Aluminium	1	1
21 to 24	6	2	Aluminium	Copper	1	1

Table 3 - Charge configuration

3.3.3.Case Design

As shown in Figure 10, a light plastic case design was chosen due to the vulnerable nature of the instrumentation and the likelihood of fragmentation being projected from a heavy cased charge. Also, this case design works to ensure that the static x-ray images are of sufficient strength to show any density gradients in the explosive. This is due to the plastic casing being of lower density, thereby, ensuring a lower x-ray attenuation. A head height of between 0.75 and 1 CD is optimal [13]. Due to the nature of the explosive fill likely introducing irregular density, a greater head height² was used to ensure a planar detonation wave reached the apex of the liner. The use of a lower density casing will affect the EFP formation. However, studies into the effect of confinement on EFP formation have shown that the increase in velocity is of low consequence as is the overall formation of the EFP [13].

² Head height is defined as the distance from initiation at the top of charge to liner apex

3.3.4. Expected Target Penetration

Equation 1 shows how the target penetration was predicted prior to the experimental work.

$$P = l \sqrt{\frac{\rho_p}{\rho_t}}$$

Equation 1 - Depth of penetration from an EFP in the hydrodynamic region [2]

Where:

P = Depth of Penetration (m)

L = Length of Penetrator (m)

ρ_p = Density of Penetrator (kg/m³)

ρ_t = Density of Target (kg/m³)

Densities of mild steel, copper and aluminium are shown in Table 4.

Material	Density, ρ (kg/m ³)
Mild Steel	7800 [14]
Copper	8940 [15]
Aluminium	2710 [16]

Table 4 - Density of mild steel, copper and aluminium

Using the values from Table 4 and Equation 1, theoretical depth of penetration was calculated and are shown in Table 5 for single liner configurations³. These theoretical depths were calculated to allow a target of sufficient thickness to be selected to ensure actual depth of penetration could be determined.

Copper Liner	21mm
Aluminium Liner	12mm

Table 5 - Theoretical maximum depth of penetration for copper and aluminium EFPs

3.4. Charge Inspection

Due to the hand pressed plastic explosive used, it was important to assess the uniformity of the charges and explosive fill. This was important to ensure that the shockwave travelling through the explosive was as uniform as possible and not influenced by density changes before reaching the liner. This also ensured that the formation of the EFP was as consistent as could be across all firings, and any variation in the formation was due to the EFP liner configurations.

To assess density, static x-rays were taken using the Scandiflash x-ray system. An example of the static x-rays is shown below in Figure 11. Appendix A provides the static x-ray images for all six scenarios.

³ Projectile length is defined as 0.7 CD (21mm)

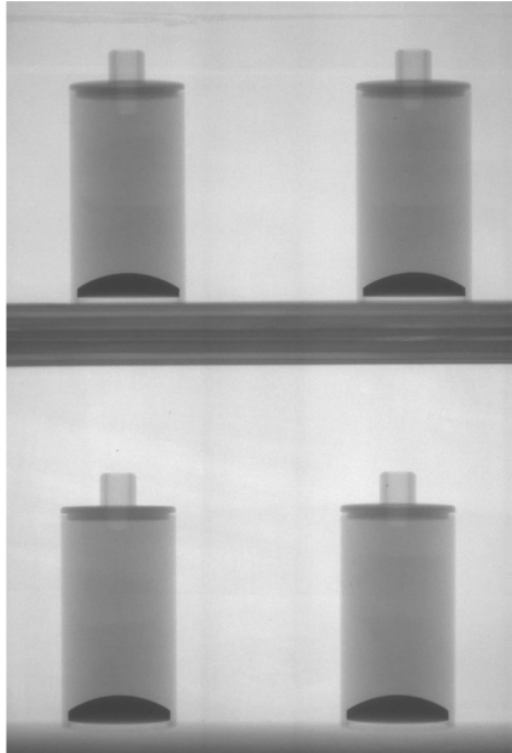


Figure 11 - Static x-ray of Serial 3 charges

3.5. Results

3.5.1. EFP Velocities

Firing Number	Scenario	Average EFP Velocity 1 (m/s)	Average EFP Velocity 2 (m/s)
1	1	1108.477	-
2	1	1148.433	-
3	1	1114.020	-
4	1	1121.470	-
5	2	2884.077	-
6	2	2858.120	-
7	2	2810.800	-
8	2	2786.817	-
9	3	1141.227	1069.013
10	3	1248.000	1123.750
11	3	1185.800	1066.503
12	3	1163.787	1071.903
13	4	2797.000	2286.510
14	4	2765.363	2329.349
15	4	2770.020	2310.929
16	4	2920.257	2411.516
17	5	1821.680	1645.920
18	5	1790.343	1607.177
19	5	1810.980	1625.677
20	5	1845.430	1577.333
21	6	1687.537	1578.741
22	6	1669.137	1506.915
23	6	1790.127	1617.267
24	6	1709.537	1546.963

Table 6 - Average EFP velocity (bold are theoretical)

3.5.2. Kinetic Energy

Firing No	Kinetic Energy of 1st Impact (J)	Kinetic Energy of 2nd Impact (J)	Total Kinetic Energy (kJ)
1	8508.89	-	8.509
2	9133.37	-	9.133
3	8594.21	-	8.594
4	8709.54	-	8.710
5	16854.15	-	16.854
6	16552.13	-	16.552
7	16008.58	-	16.009
8	15736.56	-	15.737
9	4509.56	3956.91	8.466
10	5392.86	4372.49	9.765
11	4868.70	3938.35	8.807
12	4689.61	3978.33	8.668
13	7925.89	5296.75	13.223
14	7747.60	5497.08	13.245
15	7773.72	5410.49	13.184
16	8639.83	5891.74	14.532
17	11490.37	2744.61	14.235
18	11098.45	2616.92	13.715
19	11355.78	2677.51	14.033
20	11791.93	2520.63	14.313
21	2885.16	8630.02	11.515
22	2822.58	7862.62	10.685
23	3246.61	9056.35	12.303
24	2960.87	8286.09	11.247

Table 7 - Theoretical maximum kinetic energy

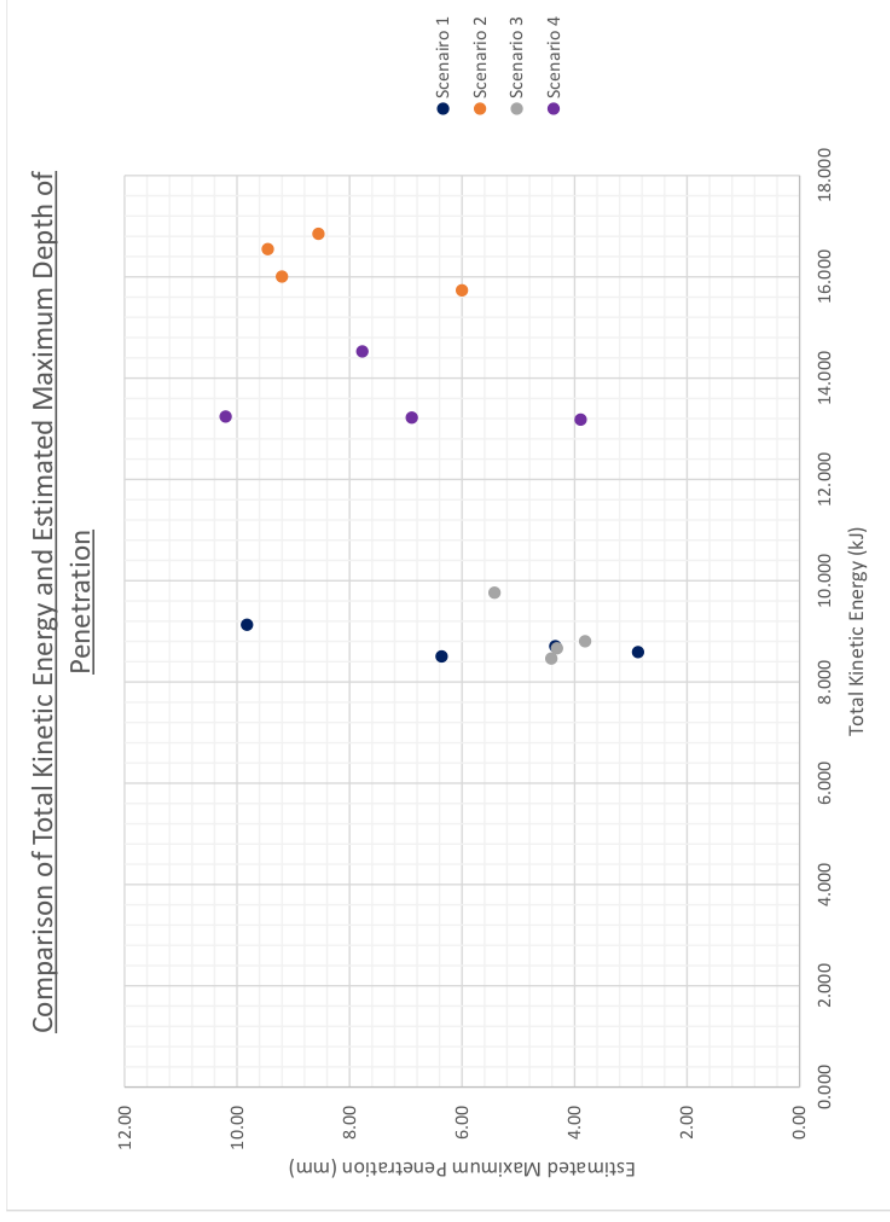


Figure 12 - Graph of theoretical kinetic energy and depth of penetration for Scenarios 1 – 4

3.5.3. Depth of Penetration

Firing Number	Depth of first impact (mm)	Depth of second impact (mm)	Cumulative Depth (mm)
1	3.27	3.09	6.36
2	9.82	N/A	9.82
3	2.87	N/A	2.87
4	4.34	N/A	4.34
5	8.55	N/A	8.55
6	4.21	5.24	9.45
7	7.38	1.82	9.20
8	6	N/A	6.00
9	2.58	1.83	4.41
10	2.67	2.75	5.42
11	3.81	N/A	3.81
12	2.76	1.55	4.31
13	3.18	3.71	6.89
14	6.76	3.44	10.20
15	3.89	N/A	3.89
16	7.77	N/A	7.77
17	8.07	3.59	11.66
18	4.86	1.1	5.96
19	8.21	5.32	13.53
20	8.03	3.35	11.38
21	10.98	N/A	10.98
22	7.7	3.11	10.81
23	9.48	N/A	9.48
24	12.99	N/A	12.99

Table 8 - Depth of penetration

4. Discussion

4.1. EFP Formation

One measure of EFP formation is the Length to Diameter ratio (L/D). Commonly, conventional EFPs have a L/D of 3 [2]. A L/D assessment was performed on the fully formed EFPs seen from Scenarios 1 – 6 and the copper EFP's from Scenario 1 had an average L/D of 2.27. However, this is based off a small data set so further firings would be required to improve the accuracy of this measurement. From Scenario 2, the EFP was the leading fragment, and the average L/D was 3.95. However, as can be seen from Table 9, the EFPs formed from the single aluminium liners, whilst producing long thin projectiles, struggled to reliably form coherent EFPs.

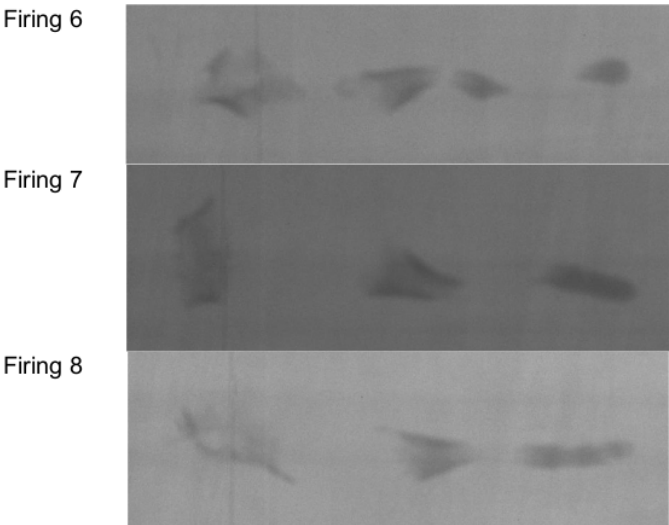
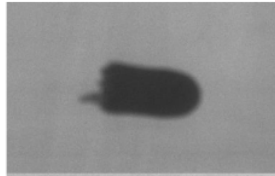


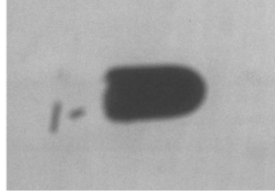
Table 9 - X-ray images for firings 6 – 8 143µs post-formation

While the L/D of the copper liners was less than the expected ratio of three, the shape of the resulting fragment was consistent with that of an EFP formed by a backward fold mechanism shown in Figure 3 [7]. It can also be seen in Table 10 that the EFPs have started to form fins which aid the in-flight stability of the projectiles [13].

Firing 2

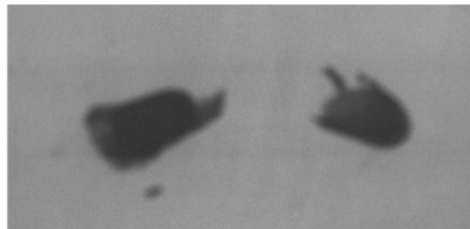


Firing 4

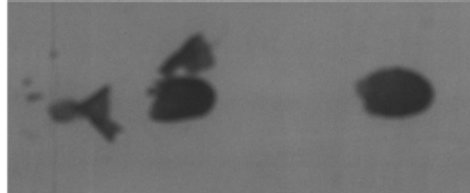
Table 10 - X-ray images for firings 2 and 4 355 μ s post-formation

A comparison of the double copper liner EFPs (Table 11) shows that this configuration reliably forms two separate projectiles with, the leading EFPs having an average L/D of 1.65 and the following EFPs have an average L/D of 1.99. As discussed in Section 2.6, the formation of these tandem EFPs can be separated into four stages: the impact; propulsion; slide; and free-flight stages [9]. The impact stage will largely affect these L/D ratios, accelerating the leading EFP ahead of the detonation products [9]. Table 11 also presents an instability in the copper EFPs from the double liner configuration. This is discussed in Section 4.4.

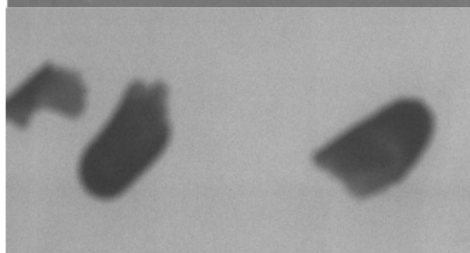
Firing 9



Firing 11



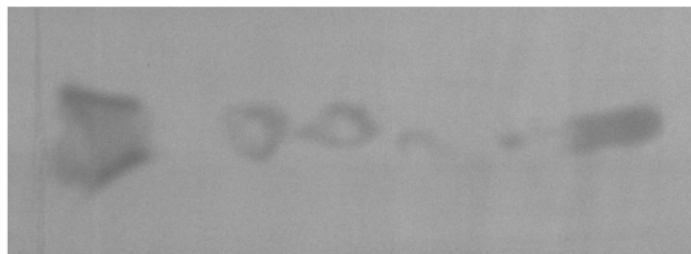
Firing 12

Table 11 - X-ray images for firings 9, 10 and 11 333 - 355 μ s post-formation

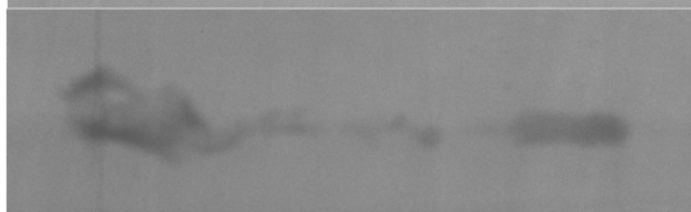
In contrast, double aluminium liners were unable to reliably form coherent tandem EFPs. This is to be expected, as the single aluminium EFP liners consistently particulated. There is evidence of a thin projectile formed from Scenario 4 firings with an average L/D ratio of 2.67.

Table 12 also shows that this projectile is followed by apparent rings of aluminium suggesting that the projectile is either a small section from the centre of the overall liner or, due to the velocity difference, the projectile from the inner liner being forced through the outer liner.

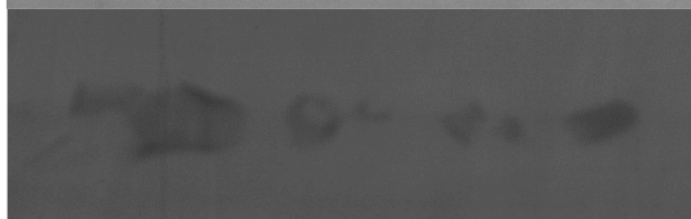
Firing 13



Firing 14



Firing 15



Firing 16

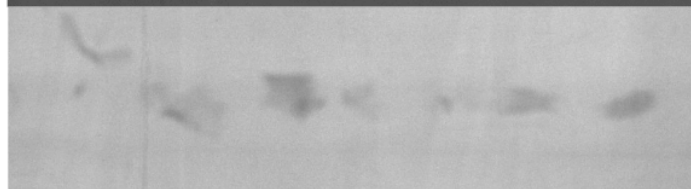


Table 12 - X-ray images for firings 13 - 16 143µs post-formation

Scenario 5 consistently produced coherent tandem EFPs, most commonly with the leading EFP being aluminium of a low L/D ratio with a larger copper projectile following, at a distance much greater than that seen from previous scenarios. This is likely because of the aluminium being of much lower density than the copper. Therefore, in the impact stage where the copper, deforms first, it will impart more momentum to the lighter aluminium liner producing a higher velocity projectile. However, it can also be seen from Figure 13 that, on Firing 18, the copper EFP looks to be forced through the aluminium liner. This is likely due to a change in the slide phase of the formation where it is believed that the two slugs slide apart in the final stages [9]. This results in a copper EFP coated in aluminium as confirmed by the high-speed imagery as a bright flash is observed on impact consistent with the aluminium EFPs. This is shown in Figure 14, Figure 15 and Figure 16.

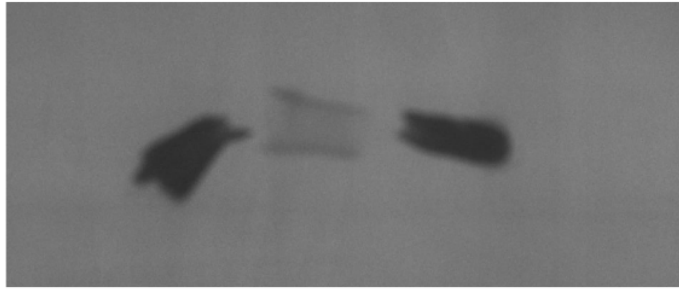


Figure 13 - Flash x-ray image of firing 18 216µs post-formation



Figure 14 - Snapshot of high-speed imagery to show aluminium flash upon impact from firing 8



Figure 15 - Snapshot of high-speed imagery from firing 3 showing flash from copper impact

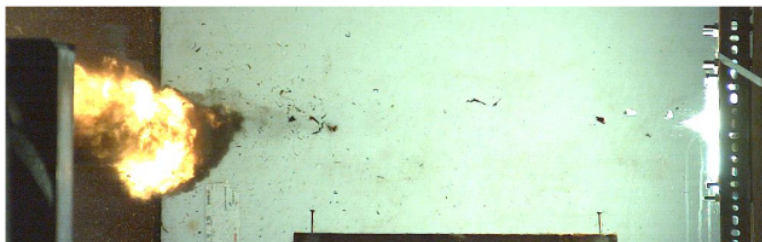
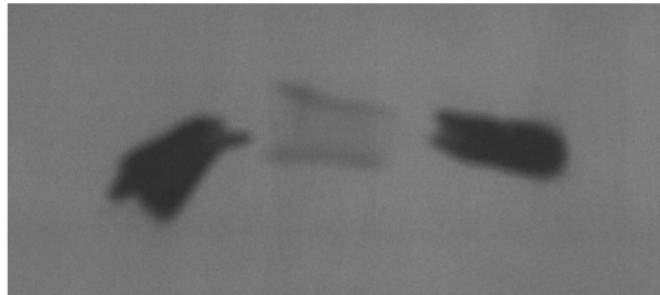


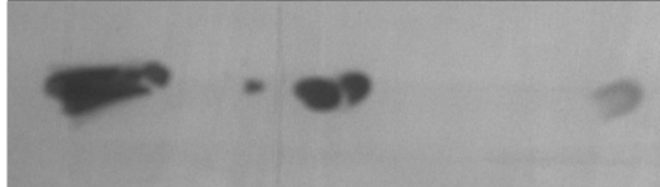
Figure 16 - Snapshot of high-speed imagery from firing 18 to show flash upon leading projectile impact

Table 13 shows the EFP formations for Scenario 5.

Firing 18



Firing 19



Firing 20

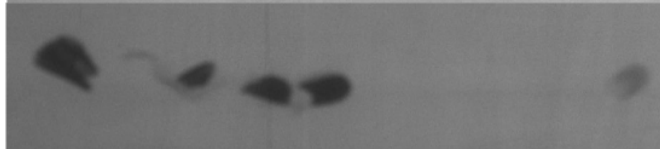
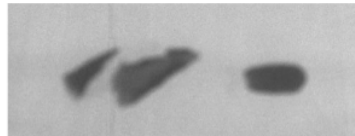


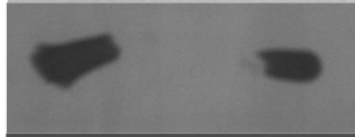
Table 13 - X-ray for firings 18 - 20 216 μ s post-formation

Scenario 6 consistently produced tandem projectiles. However, the following fragment was not representative of an aerodynamically stable EFP. Table 14 presents the formations of these fragments but it is also worth noting the densities of the projectiles as there is no obvious presence of the aluminium liners.

Firing 21



Firing 22



Firing 23



Firing 24



Table 14 - X-ray images for firings 21 - 24 216 μ s post-formation

The leading EFP has an average L/D of approximately 2. However, due to the irregular geometries of the following fragment, it is not appropriate to conduct a L/D analysis. When considering the aluminium liner, it is believed that the aluminium has been encased during the slide phase in the following projectile. This is further bolstered by the high-speed imagery showing the 'tail' of burning aluminium following the leading fragment and masking the following fragment, as shown in Figure 17.

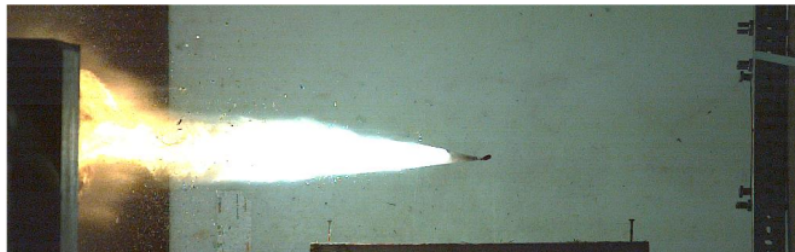


Figure 17 - Snapshot of high-speed imagery for firing 21 showing the pyrophoric burn of aluminium following the leading EFP

4.2. EFP Velocity

4.2.1. Single Liner EFPs

From Table 6, it can be seen that the velocity of single liner copper is significantly lower than that of the single liner aluminium charges; with the average velocity of all Scenario 1 firings being approximately 1,712 m/s slower than that of Scenario 2. This is likely due to the difference in liner densities between aluminium and copper. The lower the density of the liner

material, the faster the EFP will travel [17]. Assuming 100% mass conversion, the EFP mass for the aluminium projectile will be 4.05g compared to 13.85 for the copper slug.

For all 24 firings, the net explosive content was kept constant, with a total variation of 7%. This will ensure that the energy released from the detonation remains consistent irrespective of the liner material. Due to the lower density of aluminium, less energy is likely to be consumed in the deformation of the liner allowing more energy to be converted to kinetic energy of the projectile [18]. As mentioned in Section 2.4, this is vital in achieving a high KED.

However, it can be seen from Figure 18, that the aluminium liners frequently particulate under the high pressure and strain rates of the detonation event. Therefore, 100% mass conversion is unlikely resulting in a lighter projectile impacting the plate.

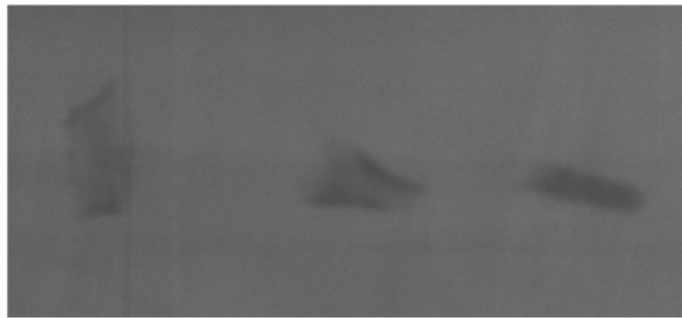


Figure 18 - EFP formed from single aluminium liners

This phenomenon was not observed from the single copper liners, as a coherent EFP was consistently formed as shown in Figure 19.

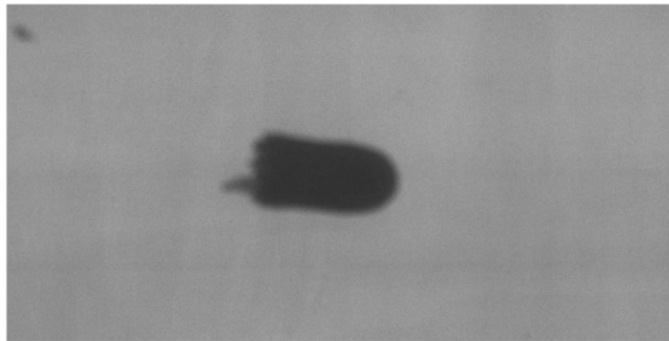


Figure 19 - EFP formed from single copper liners 355 μ s after trigger

As well as the aluminium projectiles being of a lower fragment mass, there is also a potential for an enhanced blast effect being produced on the boundary of the explosive and the liner material as aluminium powders have been added to explosive compositions for this effect [19]. Whilst the aluminium is not in powder form, the intense heat of detonation is likely to

cause the degradation of the outer layer of the liner creating an enhanced blast effect potentially driving the EFP to higher velocities [19].

4.2.2. Double Lined EFPs with Similar Materials

When comparing the velocity of the conventional copper EFP and the leading copper EFP from Scenario 3 in Table 6, there is a velocity increase of approximately 60 m/s over the conventional EFP. This is likely due to the impact of the inner liner on the outer causing a transfer of momentum allowing a velocity gradient to be established [9]. This is further confirmed from analysis of the velocity of the following EFP, where there was an average velocity decrease of approximately 40 m/s when compared to the conventional EFP. This is consistent with the expectation that the inner liner will be deformed by the detonation wave before the outer liner, causing an impact and reducing the overall energy transferred to the inner liner [9]. Due to the transfer of energy, the energy to convert to translation of the EFP will be lower, resulting in a lower fragment velocity. When an average of the leading and following EFPs is taken, however, the resulting velocity is approximately 10 m/s faster than that of the conventional EFP. This is consistent with the theory of repeated impacts within the formation stage of the EFPs.

When comparing the conventional aluminium EFP and the double aluminium liners (Figure 20), tandem EFPs were not reliably formed. Therefore, for a velocity comparison, the leading fragment was considered as the forward-most fragment and the following fragment was considered as the next largest projectile. From Table 6, the average leading fragment velocity was approximately 20 m/s slower than the single liner EFP from Scenario 2. This increases to approximately 500 m/s when considering the following fragment. This is likely to result from the formation process of the EFP causing particulation and therefore, not focussing the energy from detonation on deforming the liner. Instead it was 'torn' apart.

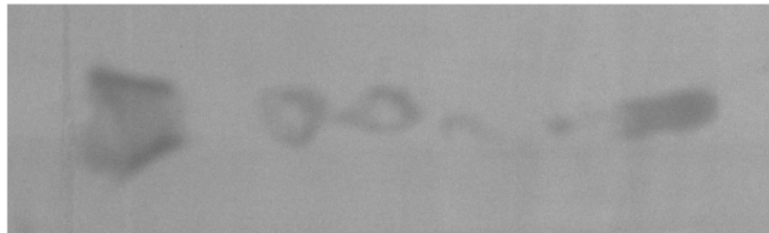


Figure 20 - Flash x-ray image of dual lined aluminium EFPs after 143µs

Another limitation is the pyrophoric nature of aluminium under very high temperatures [20]. This presents a problem when attempting to calculate a velocity using high speed imagery as the burning aluminium masks the following projectiles - as seen in Figure 21.

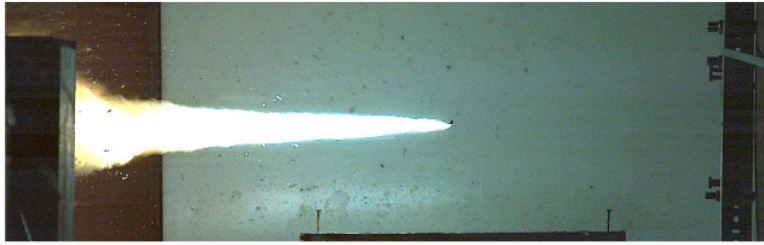


Figure 21 – High-speed image showing the pyrophoric nature of aluminium liners

To calculate the velocities of any following fragments that have been masked to the high-speed camera, a back calculation approach was implemented. A verification check was then performed to compare this back calculation method and the direct measurement using known velocities. This returned an error value between 0.5 and 2.7%. Velocities determined via this method are highlighted in bold in Table 6. Whilst this is a source of error, with such a low percentage error, the errors are negligible and of little consequence to further calculations. As a result, this method was deemed sufficient.

4.2.3. Double Lined EFPs with Dissimilar Materials

When considering Scenario 5 and 6, configuration shown in Table 3, it was important to consider the liner material in contact with the explosive, as the previous scenarios have presented very different velocities depending on the liner material. As it was unclear if this is due to an effect enhancement or just the mechanical properties of the material, the comparisons were conducted between the liner material in contact with the explosive.

It was decided that a comparison should be drawn between the conventional copper EFP and Scenario 5. As can be seen from the EFP velocities in Table 6, the addition of an aluminium liner ahead of the copper liner, led to approximately a 700 m/s increase in leading fragment velocity. Similarly, when compared to the double copper liner, the leading fragment velocity increased by approximately 630 m/s. When comparing the following fragment velocities to the single and double copper liners, a velocity increase of approximately 490 m/s and 530 m/s respectively was observed. The overall liner thickness remains constant at 2mm, however, as 50% of the liner was replaced with a lower density, and therefore, with less massive material, the pressure wave from the detonation was able to deform and drive the EFPs faster. However, the aluminium EFP is travelling slower than those in Scenarios 2 and 4. This was likely due to the copper being deformed first and requiring more energy to complete this deformation.

It was also decided that a comparison should be drawn between the conventional aluminium EFP and Scenario 6. In this case, the velocity of the leading fragment decreased by approximately 1120 m/s and the following fragment similarly decreased by approximately 1270 m/s. As Table 14 shows, the leading EFP is copper. Therefore, more energy was required to deform the copper ahead of the less dense aluminium. This results in a perceived decrease in velocity; however notably, this represents an actual increase of approximately 590 m/s over a conventional copper EFP.

4.3. Kinetic Energy

Using the velocities from Table 6, and a theoretical projectile mass, assuming 100% conversion during liner collapse, a theoretical Kinetic Energy upon impact was calculated. These are shown in Table 7. A graph of Theoretical Maximum Kinetic Energy was plotted for

Scenarios 1 - 4 (Figure 22) and an R^2 analysis was completed. An R^2 analysis is a statistical measure of the proportion of the variance that can be explained by the independent variable [21].

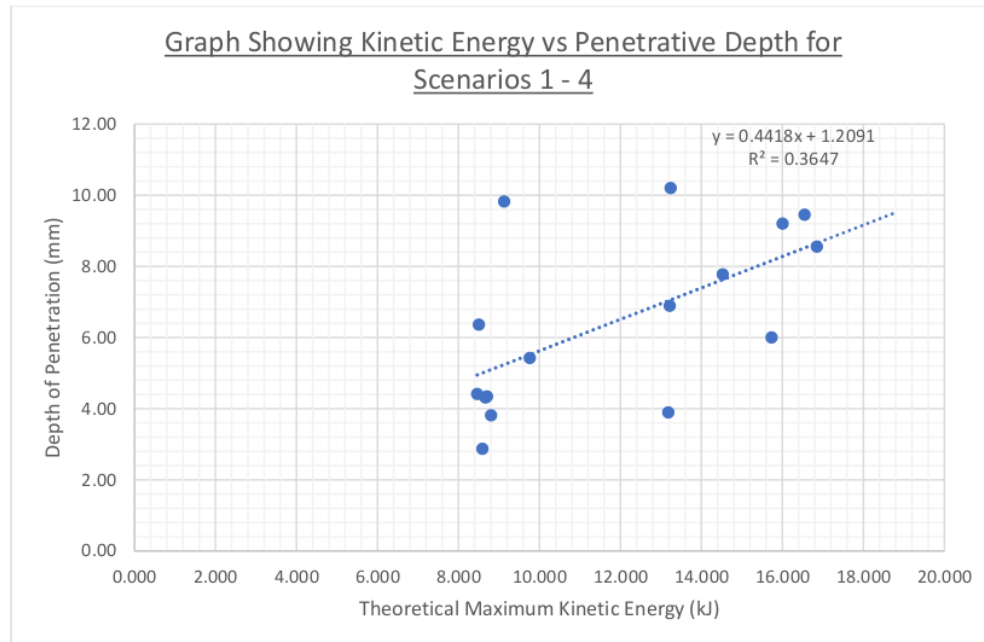


Figure 22 - Graph of theoretical maximum kinetic energy vs depth of penetration with trend

As can be seen from the graph, when a linear trend is applied, the R^2 value is 0.3647. This indicates that whilst the correlation is low, there is a moderate relationship to the proposed model. Therefore, it is reasonable to assume that there was a degree of linearity in the relationship, meaning that the higher the kinetic energy, the greater the depth of penetration for Scenarios 1 - 4. Despite this, the R^2 analysis did not provide information on the degree of causation between the two variables. To therefore, confirm this relationship, more firings should be conducted [21]. Figure 12 shows this relationship with the Scenarios 1 - 4 identified.

The results from Scenarios 5 and 6 were then plotted on the same graph, as shown in Figure 23. It can be seen from this graph that Scenario 5 yields, on average, a 32% increase in depth of penetration when compared to a conventional aluminium EFP, whilst producing a 13.5% decrease in theoretical maximum kinetic energy. This effect is further shown by Scenario 6, where an increase of 25% in depth of penetration and a decrease of 30% was observed in kinetic energy.

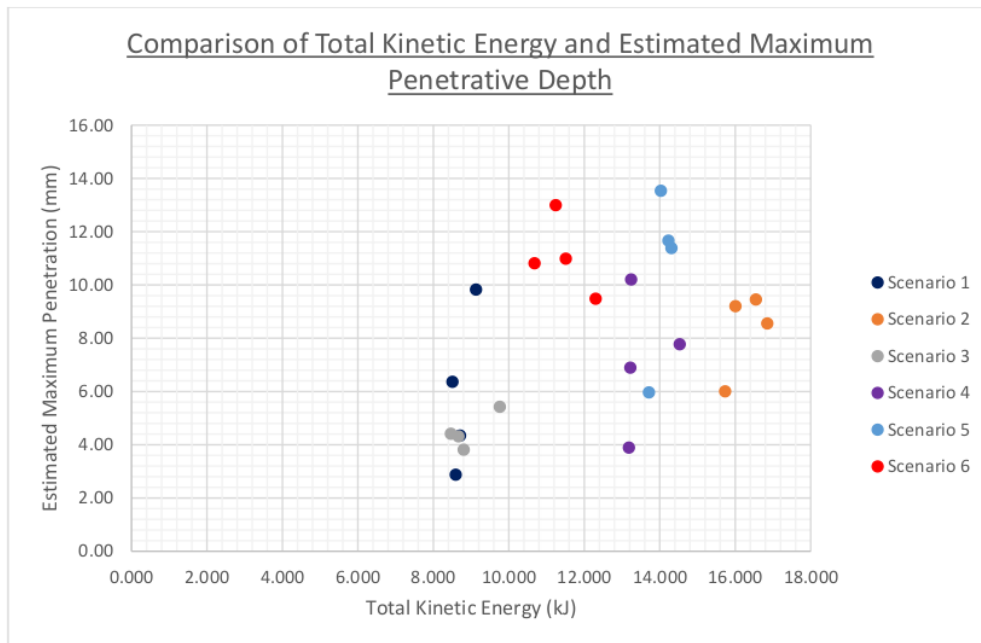


Figure 23 - Graph of theoretical maximum kinetic energy and depth of penetration including Serials 5 - 6 (red and blue respectively)

This anomaly could be due to many different effects such as changes to the properties of the target surface as the burning temperature of aluminium oxide is between 2000 - 2100K [22]. When compared to the melting point of steel (between 900 – 1000K) it is likely, despite the transient nature of the heat flux, that the material properties of the target will be altered [23]. Also, as seen from Table 14, the projectiles are travelling in closer proximity. Therefore, the impacts are more likely to cause damage as the target material may not have sufficient time between subsequent impacts to return to its original state. However, more firings are needed to fully explore and understand this theory.

4.4. In-flight Stability

The conventional copper EFPs consistently had excellent in-flight stability as proved in Table 10. This is likely due to the well understood EFP characteristics of this type of EFP charge and the aerodynamic shape of the projectiles formed via a backward fold mechanism [24].

In contrast to this, from Table 11, despite consistent formation, the double copper EFPs were consistently unstable in flight, resulting in tumbling projectiles that were unable to aerodynamically stabilise. This reduced the penetrative ability of the EFPs, due to penetration of the target leading to erosion of the projectile, so upon a side impact from a tumbling projectile, the L/D ratio is no longer the main feature affecting penetration [17].

This could be due to many features such as uneven density within the explosive filling leading to uneven detonation. However, the uniformity of the explosive density was confirmed prior to trial commencement. Therefore, it is more likely to have resulted from the formation process of the tandem EFPs during the impact and slide phases but this formation process is not yet fully understood, and would need further investigation.

Scenarios 5 and 6 consistently formed stable EFPs, despite the following fragments having an irregular formation. The in-flight stability was good, and upon target inspection resulted in a single impact point, whereas Scenarios 3 and 4 had multiple impact points. The flight stability of Scenarios 5 and 6 can be explained by the increase in velocity as the stability of an EFP is improved by increasing the velocity [2].

4.5. Crater Diameter and Target Damage

Firing Number	Diameter of first impact (mm)	Diameter of second impact (mm)
1	16.97	18.1
2	19.94	N/A
3	17.82	N/A
4	19.33	N/A
5	16.28	N/A
6	14.06	19.02
7	20.03	19.23
8	15.02	N/A
9	13.95	12.42
10	15.33	15.65
11	15.23	N/A
12	14.04	9.46
13	13.77	19.45
14	13.74	9.61
15	15.46	N/A
16	15.52	N/A
17	16.17	12.78
18	14.7	9
19	18.4	12.42
20	16.24	13.57
21	17.45	N/A
22	18.66	22.07
23	21.84	N/A
24	16.4	N/A

Table 15 - Crater diameter

Table 15 shows that the crater diameters for double copper and aluminium lined charges were significantly smaller than those of any other charge configuration. This is likely due to the instability in the projectiles as well as the poor in-flight stability, leading to a poor transfer of energy to the target.

However, Scenario 6 consistently presented larger crater diameters than any previous firing. Also observed, was a large amount of back-spall which is consistent with a high energy impact causing tensile waves generated in the metal to coalesce creating a fracture plane [5].

Interestingly, a gold-coloured metallic compound was also observed (See Figure 24) not present in the liners. This indicates the presence of an alloy of copper and aluminium, either formed during formation or, upon impact under the high strain rates, pressures, and

temperatures. Further study and analysis using a Scanning Electron Microscope is recommended to confirm this anomaly.



Figure 24 - Presence of gold coloured compound on rear of target plate

5. Conclusions

While the findings of this project for improving EFP performance through using a dual liner configuration are encouraging, it is also evident that further study is required to fully understand the mechanism by which tandem EFPs are formed.

It was observed that both single and double copper lined EFP charges reliably formed coherent projectiles. When the flight characteristics were considered, double lined copper charges were consistently unstable in contrast to the single lined charges. This resulted in a 22% decrease in depth of penetration (when considered as a cumulative function), despite an increase of 60 m/s in the leading projectile velocity. This arose from the reduction of L/D ratios in both projectiles from the double copper liners from 2.27 for the single lined copper projectile to 1.66 and 1.99 for the leading and following double EFPs respectively. It was therefore concluded that the layering of copper liners didn't yield any significant improvement in performance, but further study would be recommended to improve the flight stability of double copper EFPs.

In contrast, single and double aluminium liners were unable to reliably form coherent projectiles with them frequently particulating upon deformation. Despite the stable flight characteristics, there was an observed reduction in depth of penetration of 13% likely from the reduced L/D ratio of the EFPs from the double lined charges. It was also observed that there was a reduction in crater diameter from the double lined EFPs along with an average reduction in EFP velocity of 20 m/s and 500 m/s in the leading and following projectiles respectively. Further study would be recommended to form coherent aluminium EFPs

allowing a more comprehensive assessment of the performance as there was no significant improvement of EFP performance from this project.

When considering Scenarios 5 and 6, it appears that the penetrative ability is greatly increased with reliable plate perforation and desirable in-flight stability of tandem EFPs, despite lower velocities and Kinetic Energy upon impact. Also observed was significant back spall of the target plates, not seen on any other configurations, along with the presence of a gold-coloured compound. Whilst it is likely that this is a copper/aluminium alloy, more work is required to confirm this. Further firings would also be required to determine if this was being formed upon detonation or upon target impact. It is estimated that Scenarios 5 and 6 led to an increase in depth of penetration of up to 25% despite seeing up to a 30% decrease in estimated Kinetic Energy. This is likely due to an increase in KED or further secondary interactions between the EFPs and the target. Again, it is recommended that further study is conducted into this area.

6. Reflection

A double x-ray head system in future firings would be beneficial to reliably obtain velocity information for the double aluminium liners. This will eliminate the issue of masking the projectiles due to the pyrophoric nature of these liners. A further limitation to this project was the energetics used as the main explosive charge. In any future study, alternatives to the plastic explosive used here should be explored.

I learnt throughout this project that despite designing a trial to focus on the desired effect (EFP velocity and target effects) secondary effects can hinder the data capture. This leads to informed decisions on trial to ensure the maximum value can be drawn from trials work.

Upon reflection, I learnt the importance of comprehensive trial notes and photographs as these aid with further analysis. Should this project be carried out again, it would be necessary to record the liner mass. This ensures that any calculations on kinetic energy and kinetic energy density are accurate and not just an estimation. However, to truly understand these parameters, I would ideally conduct trials specifically tailored to capture this information.

Should the high-speed and x-ray imagery be required, it can be supplied separately upon request.

7. Recommendations for Further Study

1. Investigate metallurgy of EFPs formed from Copper/Aluminium dual liners.
2. Investigate target effects upon impact from these projectiles.
3. Further firings are conducted to obtain velocity information for aluminium liners.
4. Investigate liner interface and its effects.
5. Introduce different liner materials and investigate potential polymer liner configurations.
6. Investigate improving liner in-flight stability.
7. Investigate improving linearity of tandem EFP flight.

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Appendix A

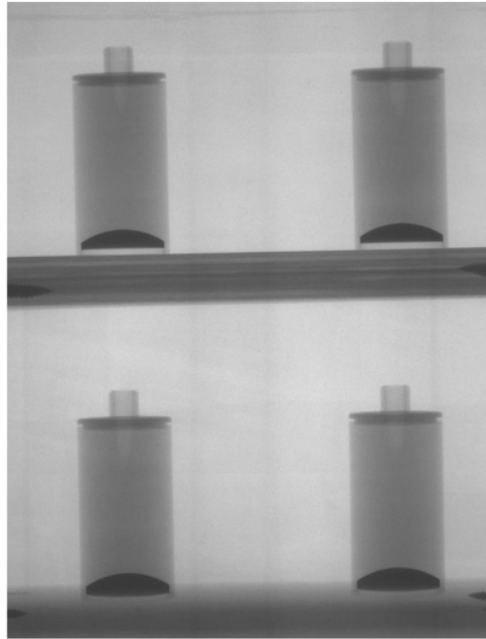


Figure 25 - Static X-ray for Scenario 1

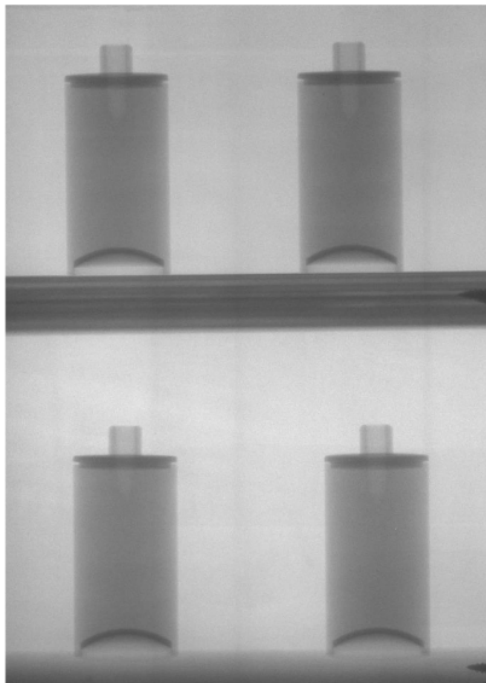


Figure 26 - Static X-ray for Scenario 2

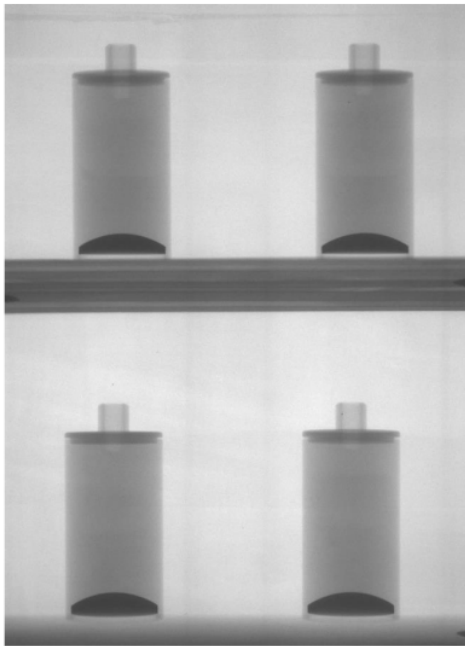


Figure 27 - Static X-ray for Scenario 3

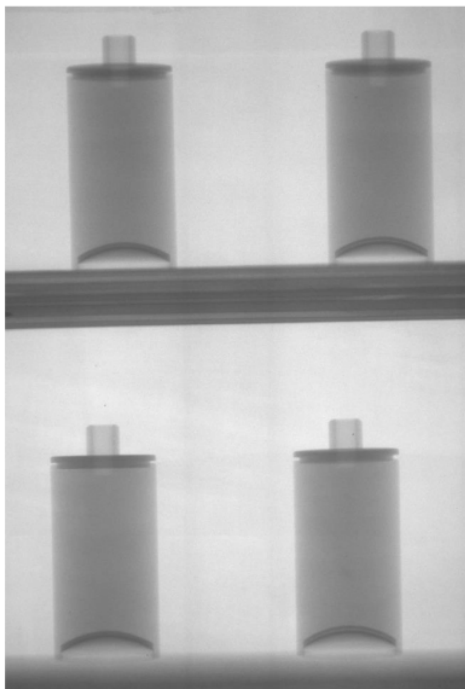


Figure 28 - Static X-ray for Scenario 4

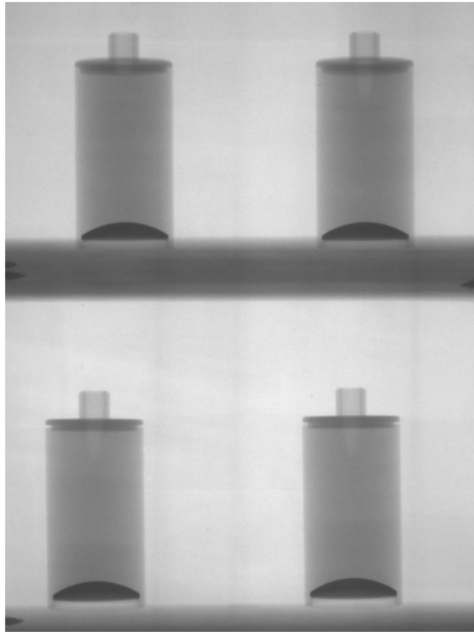


Figure 29 - Static X-ray for Scenario 5

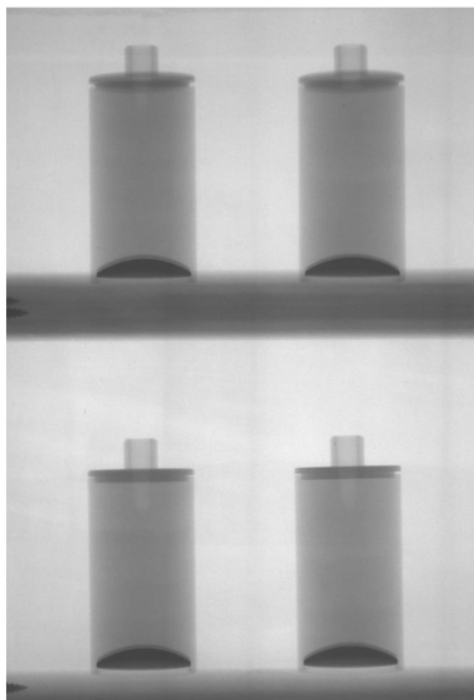


Figure 30 - Static X-ray for Scenario 6

Major Project Report - Samuel Darcy-Page (1910580)

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FINAL GRADE

GENERAL COMMENTS

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83/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15

PAGE 16

PAGE 17
