

University of Wales Trinity Saint David

Ordnance, Munitions and Explosives



Data Capture and Evaluation

ACDA6021

Laboratory Report – Identification of an OME item

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Abstract

An arena trial was conducted at Cranfield Ordnance Test and Evaluation Centre, where an unknown item was detonated. The aim of the test was to collect sufficient data on the blast, fragmentation and explosive residue to allow the identification of an unknown munition. To do this pressure gauges, strawboard and velocity foils, and attenuated total reflectance – Fourier transform infrared spectroscopy were utilised. During analysis of the data, limitations were noted, such as only one set of pressure gauges were used, as well as a low number of velocity foils. Despite the limited data, analysis of the collected fragmentation, pressure and explosive residue data was performed, enabling the identification of the item from a list of seven possible munitions. It was found the RGD-5 was a good match to the trial data throughout the analysis.

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1. Introduction

On the 15th of October 2024, an arena trial was set up at Cranfield Ordnance Test and Evaluation Centre (COTEC) to evaluate blast, fragmentation and explosive residue data from the detonation of an unknown munition. The aim of the test was to identify the item from a list of possible munitions using appropriate methods of data collection and analysis.

1.1. Blast Pressure

Pressure gauges use piezoelectric sensors which convert the force from the blast wave into a voltage signal. This can then be processed to produce a pressure-time history graph.

1.2. Fragmentation

Strawboard and velocity foils are a standard method of fragmentation analysis. Velocity foils consist sets of conductive strips, separated by a short distance, connected to a power supply and a data logger. When fragmentation pierces the sheets, it completes the circuit which generates a signal. The time at which this signal is generated is recorded, the distance from the charge is known, therefore the average velocity of the fragment over that distance can be calculated. [1]

1.3. Attenuated total reflectance – Fourier transform infrared spectroscopy (ATR-FTIR)

ATR-FTIR measures infrared absorption and emission spectra of materials by probing molecular vibrations of chemical bonds [2]. It is a quick process compared to other chemical analysis techniques, such as Gas Chromatography – Mass Spectroscopy. However, used alone, FTIR cannot identify an unknown compound as bonds between chemical groups can be similar. It is an indicative test, showing if bonds are present. [3]

2. Method

2.1. Arena set-up

The arena was set up as shown in Figure 1, with pressure gauges placed at 1.003m, 2.036m and 3.012m, each slightly offset from the gauge in front to reduce the possibility of shadows affecting the subsequent gauge. A ricochet trap was positioned behind the charge and a fragmentation pole immediately behind this, both placed to protect the gauges from fragmentation. Four strawboards, each with three velocity foils were placed in a hemisphere, averaging 1.566m from the charge position. The charge was placed at a height of 0.30m off the ground.

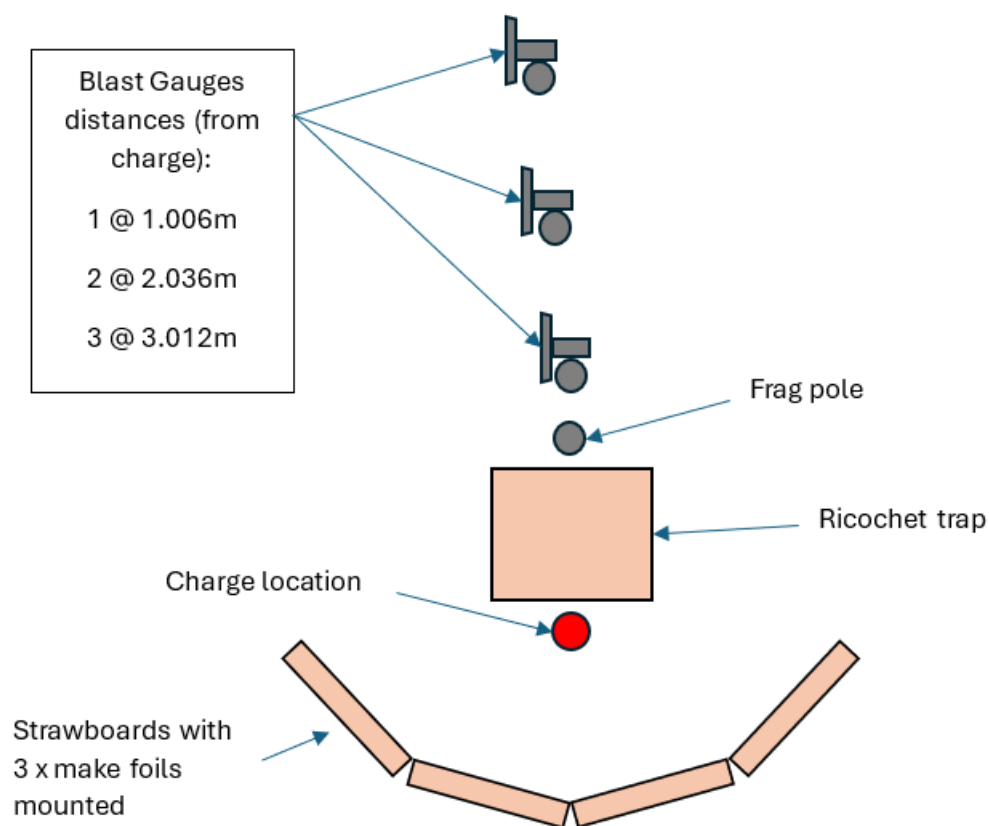


Figure 1 Test arena set-up (image provided by UWTSD staff)

2.2. Data collection

Data was collected using:

- Strawboards with velocity foils for fragmentation analysis.
- Pressure gauges for blast analysis.
- ATR-FTIR for chemical analysis of residues.

Figure 2 shows the arena set-up:



Figure 2 Arena set-up

3. Results and Analysis

It is possible to discount several munitions by logic alone from the list, without needing data to prove the point. The Mk.83 and 155mm would have caused significant damage to the arena at the recorded distances. Whilst there were some fragmentation hits to the equipment, it was minimal. As can be seen in Figure 3, the damage is not significant enough to have been caused by these munitions. Nonetheless, they will remain as options throughout this analysis; to prove they are not the suspect munition.



Figure 3 Fragmentation damaged pole

3.1. Pressure Data

Using data processing software D-plot, a 9-point moving average was used to smooth the pressure data collected in the trial. This method averages the chosen number of points, then moves to the next data point and repeats the process. A lower number will capture brief fluctuations, while a higher number provides a smoother curve but flattens peaks.

The peak incident overpressure at each distance is identified and presented in Figure 4. Gauge one shows a late time peak – the cause of which is unclear. It could indicate the gauge was struck by fragmentation and is ringing, or it could be a reflected pressure or Mach stem effects. This is interesting as it is not clear from the trial information if this test is an air or surface burst. The difference being whether or not the blast wave interacts with the ground before impacting a structure. If it does, a Mach stem is formed, and this is an air burst [4]. Mach stem formation could affect the blast pressure and may vastly increase values [5].

COTEC Munition Trial (25/10/2024)

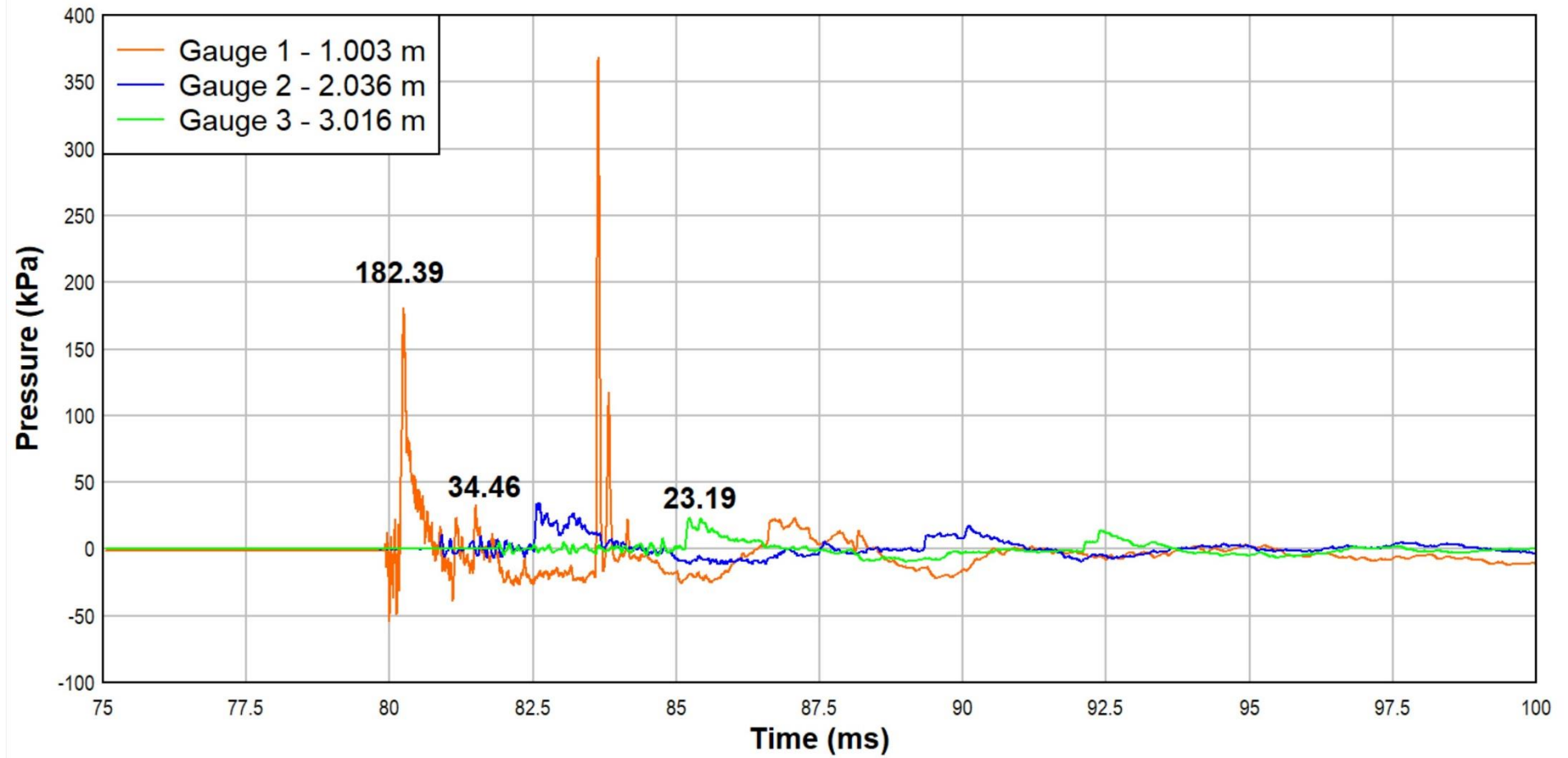


Figure 4 Incident overpressure data

Due to lack of clarity on the type of burst, pressures at each distance for both surface and air burst were considered. Equivalent bare charge masses for each munition were calculated using Equation 1.

$$W_b = 1.19 \times \left(\frac{1 + M_r \times (1 - M_c)}{1 + M_r} \right) \times c$$

Equation 1 Equivalent Bare Charge Mass [6]

Table 1 Equation 1 key

Where:	
W _b =	Equivalent bare charge mass (kg)
M _r =	Case to charge ratio
M _c =	1 where M _r > 1 or = m/c where M _r < 1
c =	Mass of charge (kg)
m =	Mass of case (kg)

To then determine the overpressure for each munition, Kingery-Bulmash calculations were performed using an Excel tool provided by Mr Gareth Collett [7]. The overpressure trial value was compared with that of the munitions on the list, producing a percentage comparison for both air and surface bursts. These two values for each munition were then averaged and this value used to rank the munitions, with a visual indication of good to poor match using a RAG system. This ranking system is used through the analysis. The data is shown in **Error! Reference source not found.** with additional information in Appendix 1.

Table 2 Air burst pressure data and calculated average percentage of the trial value

Munition	Air burst average percentage of trial value (%)	Surface burst average percentage of trial value (%)	Average of surface and air percentages (%)	Percentage difference from trial data (%)	Ranking
M-67 grenade	98.68	138.17	118.43	18.43	1
RGD-5 grenade	61.86	85.23	73.55	26.45	2
Pipe bomb	108.58	152.51	130.54	30.54	3
RPG PG-7VL	186.19	265.62	225.91	125.91	4
81mm mortar	211.57	302.73	257.15	157.15	5
155 mm	229.92	329.57	279.74	179.74	6
Mk 83	12490.72	15180.22	13835.47	13735.47	7

Based on the above results, the M-67, RGD-5 grenade and the pipe bomb all appear to be a reasonable match to the trial data at this stage. The results support the earlier assumption that the 155mm and Mk.83 can be discounted. These ranked sixth and seventh respectively. The fragment velocity for the Mk 83 is considerably faster than any fragmentation collected in the trial. It is unlikely that the 155mm is a match given a difference of 179.74% to the trial data.

3.2. Fragmentation Analysis

Fragmentation velocity was captured using velocity foils and data plotted in the graph shown in Figure 5. Tabulated data is shown in Appendix 2. A line of best fit, excluding outliers shown in grey, was plotted to examine fragment slow-down. The line shows a slight increase in velocity, suggesting an increase in velocity at the further distances. Obviously, this is not possible and highlights a limitation with the data provided and the best fit line cannot be relied upon.

The noted outliers appear to be considerably slower than the majority of fragments therefore were not included in further analysis. It is possible these slower fragments had ricocheted, losing energy before impacting the foils. They should not be used to calculate an accurate average velocity in this instance.

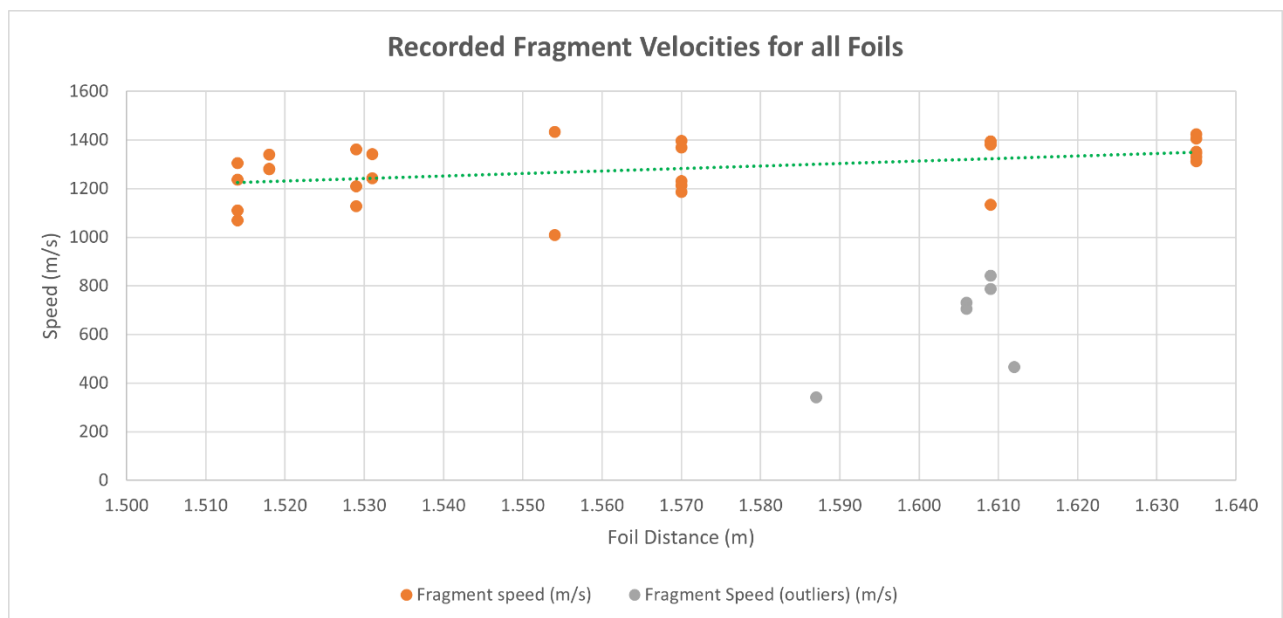


Figure 5 Recorded velocities of all fragmentation which struck the velocity foils - outliers separated

A comparison was made between the fragment velocities obtained from the trial at 1.566m (average distance of all foils) and the fragment velocity which would be achieved by each of the potential munitions at the same distance (where drag coefficient data was provided). This was done by using the fragment slow down equation shown in Equation 2.

An average velocity and foil distance for the trial data was calculated, excluding outliers.

Average velocity - 1279.194m/s^{-1}

Average distance of foils – 1.566m

$$V_s = V_d \times \exp\left(\frac{-C_d \times \rho_a \times A \times S}{2 \times m}\right)$$

Equation 2 Fragment Slow-Down [8]

Table 3 Equation 2 key

Where:	
V _s =	Initial velocity (m/s)
V _d =	Velocity at distance (m/s)
C _d =	Drag coefficient
ρ _a =	Air density (kg/m ³)
A =	Fragment cross-sectional area (m ²)
S =	Distance (m)
m =	Fragment mass (kg)

Table 4 Fragment velocity for possible munitions at 1.566m

Average trial fragment velocity at 1.556 m - 1279.194 ms ⁻¹		
Munition	Fragment Velocity at 1.556 m (ms ⁻¹)	Ranking
RGD-5 grenade (0.46g)	1404	1
RGD-5 grenade (0.12g)	1028.7	1
81 mm mortar	1668	2
Pipe bomb	1871	3

In the case of the 81mm mortar and pipe bomb, weight and mass data were used from the recovered fragmentation as this was not provided. The M-67 grenade, Mk.83 and the 81mm mortar were discounted immediately due to having fragment velocities significantly faster than the data recorded in the trial, at further distance. It is clear from Table 4 the only good match here is the RGD-5 grenade.

3.3. ATR-FTIR Data

Fragmentation retrieved from the test was soaked in acetone and isopropyl alcohol to recover any explosive residues. These were analysed using ATR-FTIR spectroscopy. Analysis with isopropyl alcohol did not provide useful results. The result from the acetone analysis is shown in Figure 6.

Fourier Transform Infra-Red (FTIR) Results

PerkinElmer Spectrum IR 10.7.2

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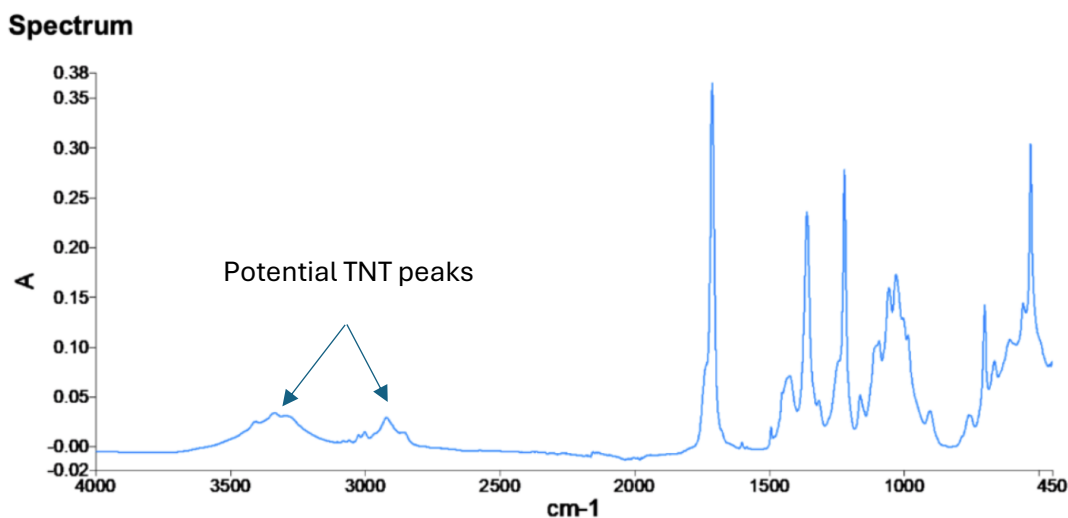


Figure 6 ATR-FTIR Spectrum from explosive residue soaked in acetone

Analysis of FTIR spectra is by identifying functional groups which may indicate the presence of a particular explosive [9]. Spectra are compared to a library allowing comparison to known bonds and compounds [10]. Without access to a library, conclusions were drawn based on the presence or absence of bonds.

Due to the amount of acetone present, it was difficult to positively identify anything in the fingerprint region. This is likely due to the low concentration of detonation residue on the fragments, while acetone is present in much greater quantities.

The explosives in the suspect munitions are TNT, Comp B (RDX/TNT mixture) and HMX. Of these, TNT contains a nitroaromatic ring consisting of a benzene ring with three nitro groups, the remaining compounds are nitramines, with no benzene ring [11].

The only useful peaks on the trace are consequently the ones between approximately 2900-3400 cm⁻¹, indicated on Figure 6. The aromatic C-H stretch found in TNT can give peaks from 3150-3050cm⁻¹ [12]. Nitramines have no aromatic ring therefore do not show the same peaks in this region. A comparison of a TNT spectrum is shown in Figure 7 and a direct comparison of RDX and TNT in Figure 8. A similar peak is seen on both the RDX and TNT trace, however there are distinct differences on the spectra between 500-1750cm⁻¹ and TNT shows two peaks rather than one between 2900-3400cm⁻¹

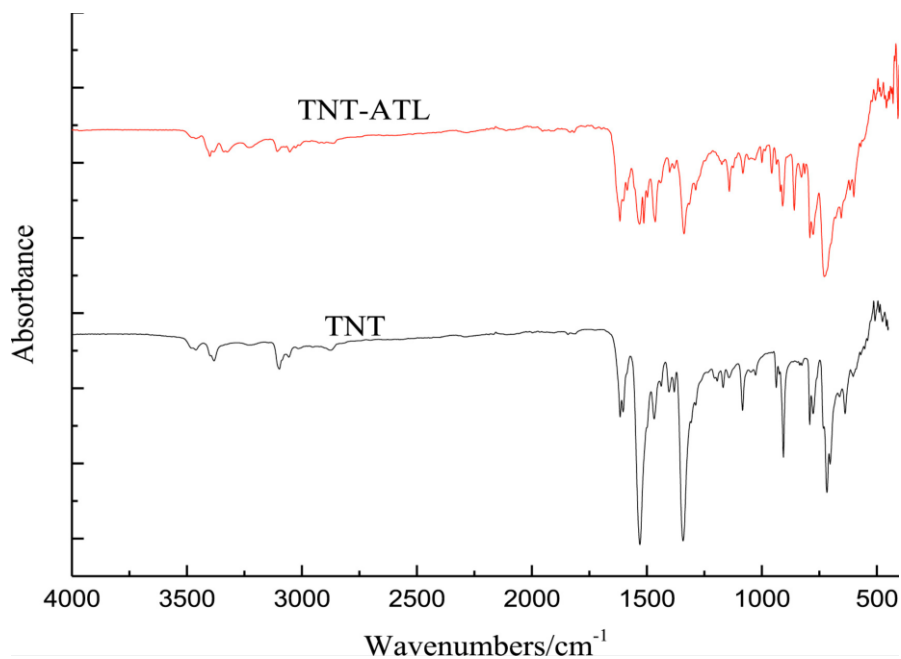


Figure 7 FTIR spectrum for TNT [13]

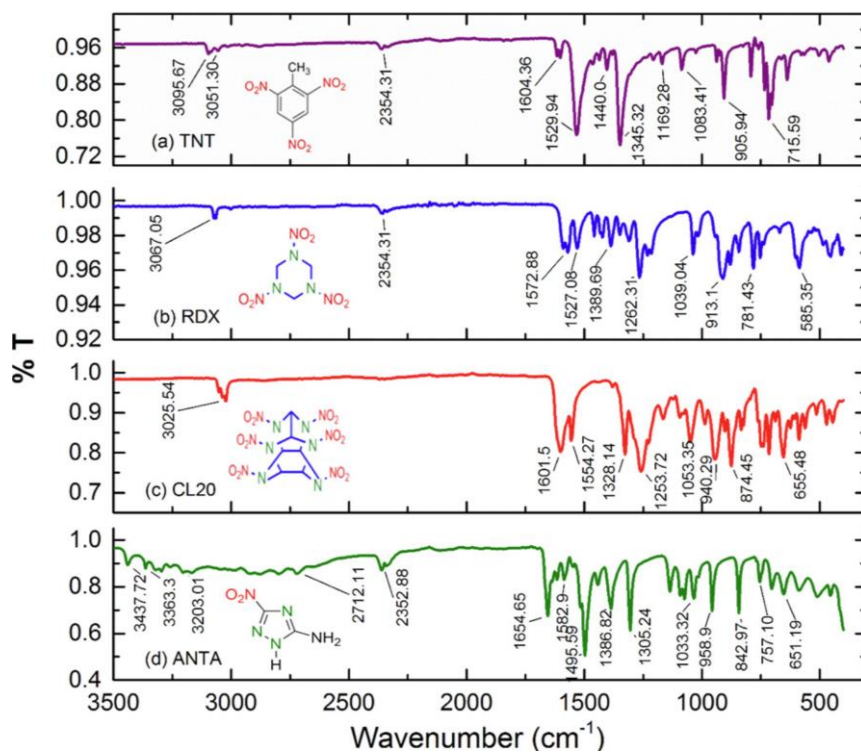


Figure 8 FTIR spectra comparison for several explosives [14]

There are several peaks around the 3050-3100 cm^{-1} region on the spectrum from the trial in Figure 6, indicative of an aromatic C-H stretch [12]. Figure 9 shows acetone gives a return around 3000 cm^{-1} therefore one must be careful to avoid confusion with the TNT peak.

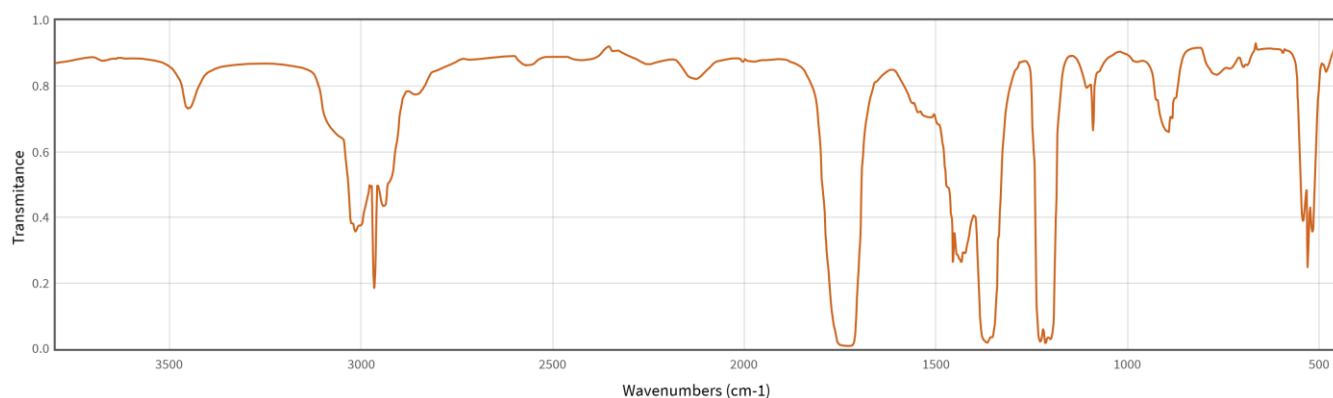


Figure 9 FTIR Spectrum for acetone [15]

Any munition not containing TNT can be discounted (RPG). Comp B being a mixture containing TNT and RDX, shows peaks for TNT. The key here is to identify the presence of peaks indicating RDX is also present. These would be around 1550cm^{-1} and 1350cm^{-1} region. There is nothing in the 1550cm^{-1} on the spectrum provided and it is unclear with the limited resources available what is indicated by the peak in the region of 1350cm^{-1} .

4. Discussion

The data provided for this trial was limited making it challenging to reach a firm conclusion. Several items were easy to discount immediately given the obvious impact had they detonated in the arena.

The lack of distinction between air and surface burst is unhelpful. With Mach stem formation, the pressure can increase vastly at the point the incident and reflected pressures combine [5]. This could result in higher pressures being recorded with no indication if they are the incident wave or from a Mach stem.

Fragment mass distribution analysis of each munition, using Mott's equation, may have been possible and a comparison of these to the trial distribution could then have been made, had this data been collected on the day [16]. This would have been time consuming, but useful, especially given there was only one munition to fire.

Despite the limitations and inconsistent data for the suggested munitions it was possible to critically analyse the results. Best practice trial set up and data collection techniques would have beneficial, providing a greater degree of confidence in the results.

Additional analysis, such as comparing the time of arrival between gauges, or the average mass of fragmentation could be beneficial if there was more confidence in the quality of the data. For example, no trigger time was provided but comparing between gauge 1 to 2, and 2 to 3 is possible, however the results will be limited.

Table 5 shows a direct comparison of all munitions across each analysis. All but one performed badly in one or more tests, with a clear “winning” munition – the RGD-5 grenade.

Table 5 Combined results - ranking removed for clarity

Munition	Pressure	Fragment	FTIR
RGD-5 grenade			
M-67 grenade			
155 mm			
81mm mortar			
RPG PG-7VL			
Pipe bomb			
Mk 83			

5. Conclusion

The only munition to provide a consistent good match throughout the analysis is the RGD-5 grenade. Based on the evidence presented, the RGD-5 is identified as the suspect munition.

6. References

- [1] Z. Yu and D. Shi, "Study on Fragment Velocity Measurement Technology of Prefabricated Fragment Warhead," in *3rd International Conference on Materials Science, Machinery and Energy Engineering*, Shijiazhuang, 2018.
- [2] C. Berthomieu and R. Hienerwadel, "Fourier Transform Infrared (FTIR) Spectroscopy," *Photosynthesis Research*, vol. 101, pp. 157-170, 2009.
- [3] N. Abidi, *Introduction to FTIR Microspectroscopy*, Springer, 2022.
- [4] V. Karlos and G. Solomos, "Calculation of Blast Loads for Application to Structural Components," Joint Research Centre, 2013.
- [5] I. Sochet, "Effects of Height of Burst (HOB)," in *Blast Effects Physical Properties of Shock Waves*, Springer, 2018, pp. 10-11.
- [6] E. M. Fisher, "The Effect of the Steel Case on the Air Blast from High Explosives," Armed Services Technical Information Agency, Maryland, 1953.
- [7] C. N. Kingery and G. Bulmash, "Air blast parameters from TNT spherical air burst and hemispherical surface burst," Ballistic Research Laboratories, Aberdeen Proving Ground, 1984.
- [8] W. F. Braun, A. C. Charters and R. N. Thomas, "Retardation of Fragments," Ballistic research Laboratory, 1943.
- [9] C. Berthomieu and R. Hienerwadel, "Fourier transform infrared (FTIR) spectroscopy," *Photosynthesis Research*, vol. 101, p. 157-170, 2009.
- [10] R. Sharma and S. Kumar, "Rapid Prediction of ANFO Based Explosives through ATR-FTIR Analysis – Use of ATR-FTIR in Explosives," *Brazilian Journal of Analytical Chemistry*, vol. 11, no. 43, pp. 92-100, 2024.
- [11] J. Akhavan, *The Chemistry of Explosives*, Cambridge: The Royal Society of Chemistry, 2004.
- [12] *FTIR Spectroscopy Reference Guide*, Agilent Technologies.
- [13] N. Sen, "Characterization and properties of a new energetic co-crystal composed of trinitrotoluene and 2,6-diaminotoluene," *Journal of Molecular Structure*, vol. 1179, pp. 453-461, 2019.
- [14] K. S. Rao, D. Ganesh, F. Yahya and A. K. Chaudhary, "A comparative study of thermal stability of TNT, RDX, CL20 and ANTA explosives using UV 266nm-time resolved photoacoustic pyrolysis technique," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 211, pp. 212-220, 2019.

- [15] "Acetone," National Institute of Standards and Technology US Department for Commerce, 2025. [Online]. Available: <https://webbook.nist.gov/cgi/cbook.cgi?ID=C67641&Type=IR-SPEC&Index=2>. [Accessed 03 09 2025].
- [16] N. F. Mott, "A Theory of the Fragmentation of Shells and Bombs," in *Fragmentation of Rings and Shells. Shock Wave and High Pressure Phenomena*, Springer, 2006, pp. 243-294.

7. Appendix 1 - Blast

Air and surface burst pressure data for the suspect munitions with a percentage comparison to the values obtained in the trial.

Table 6 Air burst pressure data

	Air Burst						
Stand off (m)	1.003	2.036	3.016	1.003	2.036	3.016	Average
Munition	Pressure (kPa)			Percentage of trial value			
Mk 83	15604.844	5764.905	2826.198	8555.756	16729.265	12187.141	12490.721
M-67 grenade	166.400	39.807	20.706	91.233	115.515	89.287	98.678
RGD-5 grenade	94.110	25.313	14.038	51.598	73.455	60.534	61.863
81mm mortar	400.314	84.312	39.550	219.483	244.667	170.549	211.566
RPG PG-7VL	347.206	74.268	35.408	190.365	215.520	152.689	186.191
155 mm	438.743	91.594	42.529	240.552	265.799	183.395	229.915
Pipe bomb	186.447	43.697	22.424	102.225	126.804	96.698	108.575

Table 7 Surface burst pressure data

	Surface Burst						
Stand off (m)	1.003	2.036	3.016	1.003	2.036	3.016	Average
Munition	Pressure (kPa)			Percentage of trial value			
Mk 83	17678.855	6849.562	3703.660	9692.886	19876.848	15970.938	15180.224
M-67 grenade	241.421	55.279	28.230	132.365	160.415	121.736	138.172
RGD-5 grenade	134.031	34.723	18.886	73.486	100.763	81.439	85.229
81mm mortar	591.244	119.653	54.914	324.165	347.223	236.799	302.729
RPG PG-7VL	512.241	104.979	49.020	280.849	304.641	211.382	265.624
155 mm	648.128	130.335	59.164	355.353	378.220	255.127	329.567
Pipe bomb	271.433	60.832	30.650	148.820	176.528	132.170	152.506

Table 8 Averages of air and surface burst pressure data

Munition	Air burst average percentage	Surface burst average percentage	Average of surface and air percentage
Mk 83	12490.72081	15180.22374	13835.47227
M-67 grenade	98.67831725	138.1718197	118.4250685
RGD-5 grenade	61.86251051	85.22948975	73.54600013
81mm mortar	211.5661195	302.7288129	257.1474662
RPG PG-7VL	186.1910017	265.6240262	225.9075139
155 mm	229.9154582	329.566641	279.7410496
Pipe bomb	108.5754223	152.5061825	130.5408024

8. Appendix 2 - Fragmentation

Fragmentation data showing the impacts at each distance, the time taken to impact the foil and the calculated velocities. The data greyed out shows the outliers.

Table 9 Fragmentation velocity data

Distance from charge to foil (m)	Strike time from trigger (ms)	Fragment speed (m/s)
1.635	1.14818	1423.992754
1.635	1.16342	1405.33943
1.635	1.20954	1351.753559
1.635	1.21438	1346.366047
1.635	1.22976	1329.527713
1.635	1.24564	1312.578273
1.609	1.15358	1394.788398
1.609	1.16518	1380.902521
1.609	1.41908	1133.833188
1.609	1.91314	841.0257482
1.609	2.04420	787.1049799
1.570	1.12476	1395.853338
1.570	1.14754	1368.14403
1.570	1.27588	1230.523247
1.570	1.29344	1213.817417
1.570	1.32382	1185.961838
1.531	1.14036	1342.55849
1.531	1.23266	1242.029432
1.606	2.19952	730.1593075
1.606	2.27682	705.3697701
1.554	1.08476	1432.574947
1.554	1.54112	1008.357558
1.518	1.13296	1339.853128
1.518	1.18522	1280.774877
1.518	1.18648	1279.414739
1.514	1.15976	1305.442505
1.514	1.22370	1237.231348
1.514	1.36470	1109.401334
1.514	1.41664	1068.726
1.529	1.12384	1360.513952
1.529	1.26486	1208.829436
1.529	1.35510	1128.330013
1.612	3.46030	465.8555617
1.587	4.64982	341.3035343
Average distance from charge to foils - 1.566 m (excluding outliers)		
Average velocity of fragments at foils - 1279.194 m/s (excluding outliers)		

9. Appendix 3 – Suspect munition data

Mk 83 air dropped munition

- Charge mass – 225 kg
- Mass of case – 229 kg
- AUW – 454 kg
- Explosive – Comp B
- Average fragment area - 0.48 cm^2
- Average fragment mass – 0.115 kg
- Frag drag coefficient – 0.82
- Density of air 1.23 kg m^{-3}
- Frag $V_i = 1950 \text{ ms}^{-1}$
- Frag $V_f = 1911 \text{ ms}^{-1}$ at 92 m

M-67 grenade

- Charge mass – 185 g
- Mass of case – 213 g
- AUW – 398 g
- Explosive – Comp B
- Average frag area – 1.0 cm^2
- Average frag mass – 2 g
- Frag drag coefficient – 0.5
- Density of air – 1.29 kg m^{-3}
- Frag V @ 5m - 1674 ms^{-1}
- Frag V @ 15m – 1424 ms^{-1}
- Frag V @ 230 m – 44 ms^{-1}

RGD-5 grenade

- Charge mass – 110 g
- Mass of case – 200 g
- AUW – 310 g
- Explosive – TNT
- Average frag area – 1.0 cm^2
- Average frag mass – 0.12 - 0.46g
- Frag drag coefficient – 0.5
- Density of air – 1.29 kg m^{-3}
- Frag $V_i = 1567 \text{ ms}^{-1}$
- Number of fragments 350

81 mm Mortar AR-M81

- Charge mass – 0.76 kg
- Mass of case – 1.334 kg
- AUW – 4.15 kg
- Explosive – TNT
- Frag drag coefficient – 1.6
- Density of air 1.23 kg m^{-3}
- Frag $V_i = 1734 \text{ ms}^{-1}$
- Frag V @ 1m – 1700 ms^{-1}

- Frag V @ 4m – 1600 ms^{-1}
- Frag V @ 20m – 1150 ms^{-1}
- Frag V @ 32m – 900 ms^{-1}
- Frag V @ 77m – 357 ms^{-1}

RPG PG-7VL

- Charge mass – 730 g
- Mass of case – 1600 g (including rocket motor)
- AUW – 1975 g
- Explosive – 95% HMX 5% wax
- Average frag mass – 0.1 g
- Density of air – 1.29 kg m^{-3}
- Frag Vi - 1831.5 ms^{-1}

155 mm

- Charge mass – 1150 g
- Mass of case – 3105 g
- AUW – 4255 g
- Explosive – Comp B
- Average frag mass – 2.1g
- Density of air – 1.29 kg m^{-3}
- Frag Vi - 1551 ms^{-1}

Pipe Bomb

- Charge mass – 200 g
- Mass of case – 200 g
- AUW – 400 g
- Explosive – TNT
- Average frag mass – 0.23 g
- Frag drag coefficient – 0.5
- Density of air – 1.29 kg m^{-3}
- Frag Vi - 1990 ms^{-1}