

SP 3000 word report

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Data Capture and Evaluation – A Critique of the Fragmentation Arena Trial

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Introduction

As part of the Ordnance, Munitions and Explosives (OME) degree apprenticeship, students were invited to Cranfield Ordnance Test and Evaluation Centre (COTEC) to get hands on, range experience at an explosively licenced facility. The day involved setting up a

fragmentation arena, with the appropriate instrumentation to capture a small detonative event. COTEC staff provided the munition that was detonated, and the necessary instrumentation for the day. Students attending the range day were deliberately not told the identity of the munition, and were instead given a list of 6 possible devices. The overall aim of the range day was to use suitable data capture methods to determine the identity of the munition that was detonated. Figure 1 below shows the finished fragmentation arena setup. The standard for producing fragmentation arenas comes from a document known as ITOP 4-2-813 [1], created by the United States Department of Defence (US DoD), and is titled 'Static testing of high explosive munitions for obtaining fragment spatial distribution'.



Figure 1 - Range Setup

Types of Data Capture Equipment Used

Pressure

For the pressure measurement, a data capture tool capable of measuring a high density of molecules resulting from a sudden, rapid release of energy – therefore, something such as high-speed imagery would not be appropriate. Instead, blast gauges were used. The pressure is the force per unit area, and there are different types of pressures that should be considered. Namely, these are:

- Absolute pressure – the pressure in reference to a vacuum
- Gauge / Over pressure – the pressure with reference to ambient (atmospheric) conditions
- Quasi-static pressure – were changes in the pressure that occur gradually are measured, after the system readjusts, typically taking a long amount of time [REF]

The type of event being measured in this experiment is often referred to as a dynamic event, and so will use a particular type of blast gauge.



Figure 2 - Blast Gauges

Blast gauges vary mainly in the type of sensor used to measure pressure waves. In this trial, an Integrated Electronics Piezoelectric (IEPE) sensor was used. As the name suggests, the electronics providing feedback to the data recorder are integrated within the sensor housing. The sensor contains a piezoelectric material that generates a voltage proportional to the force it experiences, such as a blast wave (higher pressure produces higher voltage). This material, often a crystal, is sandwiched between two non-conducting metal plates, with the piezoelectric crystal located at the diaphragm—the central point of the metal dish, shown in Figure 2.

As seen in Figure 1, the gauges are positioned so the detonation wave travels parallel to the diaphragm, causing depression rather than a head-on impact. To minimize turbulence, the three gauges were slightly offset rather than aligned in a straight line, ensuring that those further from the detonation point were unaffected by interactions with upstream gauges or stands.

Velocity

The measurement of the velocity requires a physical measure of the movement of the fragment. There are several different types of velocity measurement methods that can be used, for example heterodyne velocity (HetV) [2], ionisation probes [3], high speed imagery and the method used in this trial – velocity foils.

One of the most important considerations concerning velocity measurements is the scale of the item that you are trying to measure. For small scale measurements, the most appropriate method would be HetV, but for larger scale measurements velocity foils, or high speed imagery are often used. On this trial, a type of velocity foil, known as a make foil, was used, shown in figure 3 below.

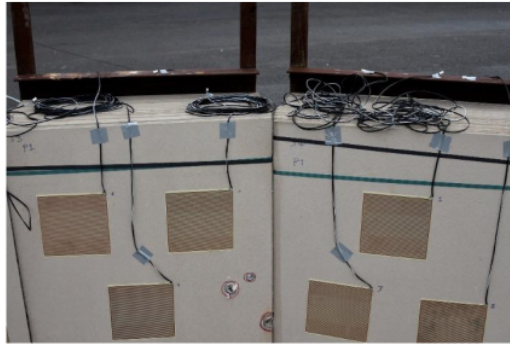


Figure 3 - Velocity Foils

A make foil relies upon the completion of an electrical circuit to provide the reading. The circuit is completed when a piece of fragment from the metal casing bridges the gap across the copper wires. This metal fragment completes the circuit, and will start the electrical signal going to the data control unit, which records the data.

Fragmentation

To capture the fragmentation, strawboard was used – which can be seen in figure 1. As the figure shows, there were four stands containing a stack of strawboard, as well as one on the ground, beneath where the munition was detonated. There was 80 sheets of strawboard in each stand, which was made of 4 packs of 20, shown in figure 4 below. The coverage for the arena was 113°. Strawboard has been used to capture fragments from detonative events for over 50 years and is used because of its historical significance. The idea behind using strawboard is that the density of the material is known, and the manufacturer produces them to a known standard. This means that data across all fragmentation trials can be used for comparative purposes. The size and spatial distribution of the fragmentation is not the only thing strawboard is used to record. Due to the known density, the depth of penetration is also an important consideration, as it allows researchers to calculate the velocity of the fragments. When considering the velocity of the fragment according to their penetration depth, it is critical to take into account the geometry and size of the fragments, as this will heavily influence the degree of penetration that is seen [4].



Figure 4 - Packs of Strawboard

FTIR

IR spectroscopy identifies chemical structures and functional groups by analyzing molecular vibrations caused by IR energy absorption. Techniques include KBr disks and attenuated total reflectance (ATR), the method used in this experiment. In ATR, IR light reflects at the crystal-sample interface before reaching a receiver to generate a spectrum, which plots wavenumbers (4000 cm^{-1} to 500 cm^{-1} for mid-IR) on the X-axis and % transmittance or absorbance on the Y-axis. Spectra are traditionally shown in transmittance.

Chemical bonds vibrate in six modes (stretching and bending), but only IR-active modes—those causing a dipole moment change—appear in spectra. For example, N_2 and O_2 are not IR-active, and symmetric stretches are IR-inactive. Mid-IR spectra focus on stretching and bending vibrations.

Other Important Considerations

Whilst the data capture methods that were used in this trial have been covered, there are another key factors that make the data capture process possible. These will be briefly covered in this next section

One example would be the triggering system used. The electric methods discussed above, namely the velocity foils and blast gauges require a signal to start gathering the data – they cannot just be left to record the entire time, or the data files that would be produced after would be too large, and impossible to manipulate. To get around this, a time zero (T_0) event is needed that lets the capture systems know when to start recording. For the blast gauges a common technique is to start from the firing pulse from high voltage detonators. In this trial, an auto-trigger of 30 mV (equating to approximately 3kPA) was set. Meaning that when the gauge sees this voltage, the data capture begins. A 10% (40 ms) pre-trigger and 40% (360 ms) post-trigger were also used. A pre-trigger ensures that data is not missed from the start of the event, and a post-trigger cuts off the recording, helping to reduce the overall file size. For the velocity measurement, a breakwire was attached to the casing of the munition. As the detonation occurs, the breakwire is broken, which starts the data capture process. Ethernet cables ran from the pressure gauges and velocity foils to a logic analyser. This is what captured the data, so that it could be exported and analysed.

Another important consideration is the method of measuring the distances that gauges are set at. As the blast wave is travelling at extremely high speed, small discrepancies in the stated distance, and the actual distance, can lead to significant errors in the results. For this trial, a laser measurement was used for precise distances. However, as the point being measured to was a human holding a marker, there could be errors introduced. For example, the marker could not be perfectly in line with the gauge, or it could have been held at angle, reducing the accuracy of the measurement.

Strengths and Weaknesses

Pressure

Proper sensor mounting is critical for accurate pressure measurements. The sensor must be rigidly mounted so only the diaphragm moves in response to the pressure wave, not the frame. Additionally, using a sensor made of a different material than the stand reduces noise (or "ringing") by altering vibration transmission. When effectively set up, these gauges provide a highly sensitive method for measuring blasts, with the gauge quality adjustable to suit trial requirements.

However, blast gauges have limitations. Debris striking the sensor can cause anomalous spikes in the data, as seen in this trial, potentially masking accurate pressure readings. Furthermore, meteorological conditions significantly influence blast wave propagation. Hieu found that blast overpressure increases with higher humidity and wind speeds [5]. Smog or pollutants can cause temperature inversions, where a warm air layer traps cooler air below, disrupting atmospheric conditions and affecting wave propagation.

Velocity

One of the main advantages of using make-foils to measure the velocity of the fragments is that they are relatively cheap to use. As the intention is that they get destroyed, or damaged by the fragments during the detonation, they must be cheap to procure, as if they were expensive to use each time, it would not be practical. Another advantage is that they are very easy to setup, which although may sound trivial, is an extremely valuable asset when trying to setup a complex trial.

One of the main disadvantages of using velocity foils for fragment velocity measurements is that sometimes it can be difficult to determine if the fragment from the case is causing the time measurement. If there is any debris lying around, that is capable of making the circuit on the copper foil, then there is a chance that it can give a reading. If this occurs, results that are not from the fragmentation of the device could be included in the real data. In the data from the trial that was performed, there are some initial strike triggers that were up to 3 ms later than the average strike time. It is not clear where these fragments have come from, as they are often look very similar to the fragments that would be expected from the casing. The position of the velocity foils can also be a disadvantage. In an ideal world, they would be large enough to cover the entirety of the capture medium placed behind. There were 30 strike triggers during the trial that was conducted, and a total of 138 fragments collected. This only equates to 22% of the total fragments being used in the velocity measurements, which is relatively low. If the fragments were larger, or if there were less of them, then it is possible that there would not be sufficient data to get an accurate representation of the fragment velocity.

Fragmentation

The only real pro of using strawboard is that because it has been used historically in many different trials, data comparisons are possible. Otherwise, it is an outdated methodology that should be replaced with a more modern and reliable solution. For collecting the size and spatial distribution of the fragments it is not necessarily a bad option, but any further analysis for fragment velocity can be unreliable.

One example of why strawboard is a poor material to calculate the velocity of the fragments is because the density of the material can change, depending on the weather conditions. If the air is humid, or there is rain, the water will be absorbed into the strawboard which will change its density. This increase in the density will make the fragments have less penetration, and therefore underestimate the fragment velocity. There are also issues when it comes to collection the overall number of fragments. Figure 1 shows that there are gaps between the adjacent panels when they are placed on the supporting stand. It is possible that fragments hit these edges, penetrate through and exit the strawboard, therefore not being captured. In an ideal world, the capture medium would be one continuous face, to mitigate against this issue. One final disadvantage of using strawboard is the amount of time the analysis takes, post-trial. Frag picking from strawboard is a laborious, and time intensive task making it susceptible to human error during the counting.

FTIR

FTIR plays a significant role in analysing energetic materials. Explosives are typically organic molecules, which makes them IR active. Furthermore, in most cases, energetic molecules will contain a nitrogen atom. This often leads to a characteristic peak in the FTIR spectrum, especially when it is directly bonded to a hydrogen (an N-H bond). Traditional benchtop FTIR systems require a stable and well-maintained laboratory environment for reliable sampling, advancements in technology have led to the development of portable, ruggedized instruments [6]. These devices can be quickly deployed to evaluate samples directly at incident scenes with high accuracy. A key application of FTIR is the analysis of post-blast residues [7]. This application highlights that even small sample quantities are sufficient to produce a meaningful spectrum, as peak intensity does not depend on the sample size, as long as it is pure. Although FTIR is not suitable for trace-level detection, it excels at identifying macroscopic residues, making it a valuable tool for the analysis of energetic materials.

A potential issue with using FTIR however, is that you are limited by the library software that you use to analyse the samples. If the library you are using does not have the explosive, then you cannot get the analytical % match, meaning that you cannot identify what material is present. This could be an issue where you have a mix of explosives (e.g. in Comp B), where one explosive is present in the library, but the other is not.

Alternative Methodologies

Pressure

For a basic trial, like the one carried out, the pressure is an appropriate measurement technique. An improvement that could have been made, would be to include more gauges at different positions (e.g. two more staggered 3 stacks of the gauges, forming a triangle around the munition, but not obstructing the strawboard). This would improve the reliability of the data. Another, but more novel technique could be to use high speed Schlieren imagery. This is an optical method that visualises the changes in air density caused by blast waves. The intensity and displacement of the waves can be analysed to estimate the blast overpressure [8]. Combining this technique, with the data gained from the pressure gauges will provide a more accurate picture of the blast overpressure, as the results can be compared. Schlieren imagery is a very expensive technique however, so would only be employed for high importance trials (e.g. relating to components of the deterrent).

Velocity

High speed video is another technique that could be used to calculate the fragment velocity. An issue with using high speed video however, is that you need an accurate distance scale behind the flying fragments, so you can see how long the fragment takes to travel a certain distance, giving the velocity. However, there is a significant issue with this type of measurement as unless the fragment is flying perfectly parallel to the measurement board behind, the distance that it is travelling will actually be larger than the video shows, negatively impacting the velocity calculated.

FTIR

While FTIR is an appropriate technique for analysing energetics, there are other techniques that can be coupled with it, to provide a more accurate analysis. An example of this could be high performance liquid chromatography (HPLC), which is a much more sensitive technique.

With HPLC, trace amount of the explosive may be used, to get an extremely reliable result [9]. There are also other techniques that could be used alongside FTIR, such as mass spectrometry. In general, the more analytical techniques you can use on a sample, the more trust you can have in the result. For example, if FTIR, HPLC and mass spectrometry all came back confirming the presence of TNT, you can be confident in the result.

Fragmentation

There have been studies looking at replacing strawboard with medium density fibreboard (MDF) [4] [10]. It has been found to be a readily available, and more importantly, cheap alternative to strawboard. It does however, encounter similar issues to strawboard, where the environmental conditions can influence the density of the material, and therefore the penetration of the fragments, and it also does not form a continuous surface. An interesting idea would be to use a wall of gelatine of known density. This would allow users to easily visualise the penetration depth of the fragments, and has the benefit of being a homogenous layer, with no air gaps – as is between the strawboard / MDF packs. This solution would likely be considerably more expensive than the two board option, and so would not be commercially viable.

Recommendations For Future Data Capture Events

There are a number of improvements that could have been made to this range setup, to make the data more accurate, without having to use expensive highly sophisticated data capture techniques. For example, sweeping the arena clear of debris from existing trials. Fragments from other another device / devices was found within the strawboard, meaning that the detonation wave must have blown them off the ground, and into the strawboard. Another improvement that could have been made would be to add ground ricochet traps, to catch the fragments as they bounce off the ground. This could help prevent the anomalous data seen in the blast pressure data, prevent any fragments from penetrating the strawboard after bouncing off the ground, and also help mitigate against the delayed impacts on the velocity foils.

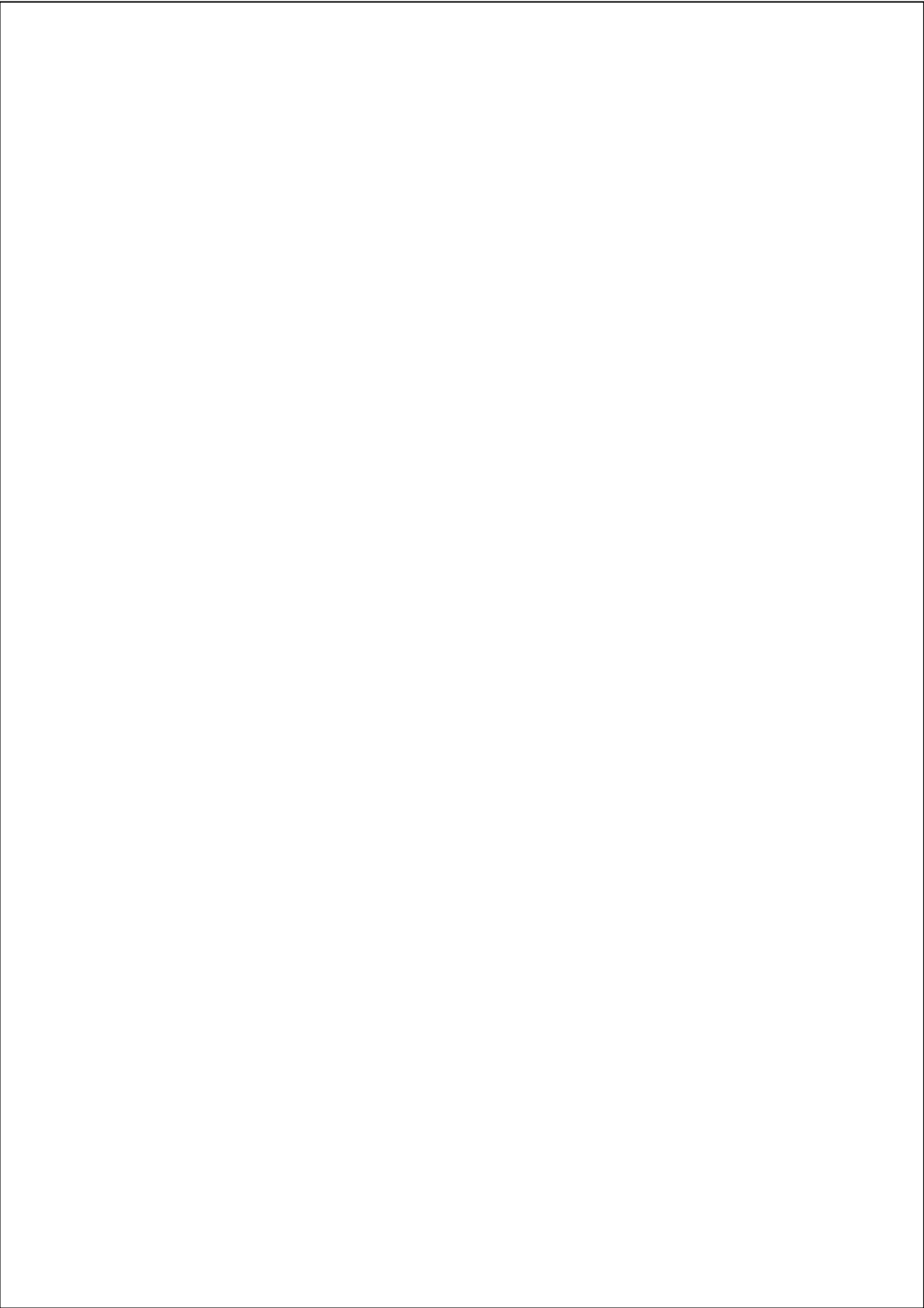
Further improvements could be to use more blast gauges, and velocity foils for more representative data, without significantly increasing the cost of the trial. If the munition was of high importance, and more accurate data was required, additional techniques such as high speed Schlieren imagery could be used for more accurate overpressure values. Also, if the munition was suspected have been used in an incident (e.g. terrorism) then the additional chemical identification techniques could be used. Finally, the McMahon equations for fragment penetration could also be used, and rearranged to give the velocity. As we had this data available to us from the straw board capture, it could also be used to validate the velocity measurements.

$$V_s = \frac{KP}{M^{\frac{1}{3}}\rho^{\frac{2}{3}}} + V_L$$

Equation 1 - McMahon Equation [10]

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SP 3000 word report

GRADEMARK REPORT

FINAL GRADE

65 / 100

GENERAL COMMENTS

Hi Sam,

This was a good submission, scoring in the mid 2:1 range with 65%. You included a lot of good detail but your structure could have been improved to get your message across more coherently. My sense is that you could have clarified some points you raised better, and with some further degree of evidence. One could argue that, for cost reasons, the setup originally established with an increased number of firings and better evaluation techniques could have sufficed. There was only limited explanation on additional evaluation techniques that focuses mainly on FTIR.

In detail:

1. I think you missed a word(s) out in the first sentence under the sub-heading Pressure. Should the sentence end in 'is required' before the hyphen?
2. I note you did not enter the reference beside your description of quasi-static pressure.
3. Good use of diagrams and figures throughout. Correctly captioned and cross-referenced to the text. However, I note that your contents page does not have a List of Figures or List of Equations.
4. You have used some detailed reference points throughout the submission in areas where explanation may be required.

5. For your section on velocity, I think you are saying that the HetV would have been more appropriate than the velocity foil for the size of the device?

6. For fragmentation into strawboard, should we have been less hasty and measured depth of penetration before removal of the fragmentation itself. Based on depth and mass, this would provide an indication of more accurate velocities. There is also the consideration of the heat of explosion, which can impact on the readings of velocity foils via ionisation. We should, perhaps, have covered them with paper?

7. What about a partial penetration through a velocity foil? Will this negate the ability for the foil to detect further perforations?

8. Should Other Important Considerations be a major heading? I think so. It is not in your TOC.

9. Agreed, the human error associated with the laser pointer was quite significant. I reckon about ± 5 cm, thereby over or under-playing velocity measurements dependent upon the velocity foil number and position. Same argument for pressure gauges since blast overpressure diminishes by $1/r^3$ in the near field.

10. Agree all your comments on velocity and fragmentation. Posts did move, not ideal, there was no ricochet trap. Do you think that 22% of frag collection is a low figure based on your knowledge of the munition and the arena arc of 113 degrees? I think it was higher than should be anticipated suggesting there was ricochet capture and previous detritus present. Also, there were a number of fine penetrations into the strawboard which were not collected, thereby altering the average fragment size/mass significantly. Perhaps explains some of the errors in the trial results.

11. Having read to page 7 at this stage of comment, I believe you would have been better splitting the sub-sections for pressure, velocity and fragmentation into strengths/weaknesses. Indeed, also include FTIR.

12. Agreed FTIR was limited in its application. However, the result from fragmentation steeped in acetone solvent wasn't bad at all and showed very few impurities in the trace. And yes, you are limited to what is in the library relating to explosive compositions and solvents. Raman may have been better.

13. For alternative methodologies, you could have used smaller pressure gauges closer in and considered raising the munition higher above the ground - and not used the strawboard beneath it - another attenuating surface may have been better to reduce the noise caused by reflected overpressure on gauge 1. Nothing wrong with your triangular approach though.

14. Yes, high speed video but what about other methodologies such as flash x-ray, doppler.

15. HPLC would be more sensitive than FTIR. Also mass spectrometry.

16. I liked your view on a wall of gelatine - quite novel. Were you able to find a reference to demonstrate efficacy? MDF calibration could replace strawboards but in this instance, and with several firings, would strawboard and the current pressure/velocity fit array have sufficed? High speed Schlieren yes, but as you say for more expensive items. And the use of the McMahon equation would allow V_s to be calculated. But, what are the other variables and how would this apply to the RGD-5. Explain.

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