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Optical Characterisation of the Thermo-Chemical-Geometric State of High Explosive Fireballs

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14. ABSTRACT The overarching aim of this project was to develop advanced diagnostics to allow for quantification of the physical state of an explosive reball in the near-eld region. The original objectives for the project were: 1. The continued development of a dataset of spatial and temporal loading distributions arising from the detonation of near-eld free air charges for a range of explosive types. 2. Optical temperature measurement of the reball using a specially altered high-speed video (HSV) camera. 3. A high-speed, non-intrusive, spectroscopy-based optical measurement system for the gas species present in the reball. 4. 3D maps of the reball expansion for di erent explosive types and shapes using stereo Schlieren techniques. 5. Quantification of how the thermo-chemical state of the reball a ects the loading in the near-eld region.			
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Optical Characterisation of the Thermo-Chemical-Geometric State of High Explosive Fireballs

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Background

The global threat from terrorist attacks has increased markedly in recent years, with 2014 and 2015 seeing the highest number of fatalities since comprehensive records began at the start of the century (32,765 and 29,376 respectively). A sharp increase in the number and severity of attacks in OECD countries [1] has also been observed. The estimated annual global economic impact of terrorist attacks is around US\$100bn, of which 40-45% is attributed to attacks using explosives. The political and societal consequences of high profile bombings (such as 7/7, MetroJet 9268, Istanbul Airport, and Manchester Arena) are severe, if difficult to quantify. The challenge for blast protection engineers is to understand and control the risks associated with events such as these. This requires a firm understanding of the loads imparted to structures by explosions, but this is currently limited by a fundamental lack of understanding in two key areas:

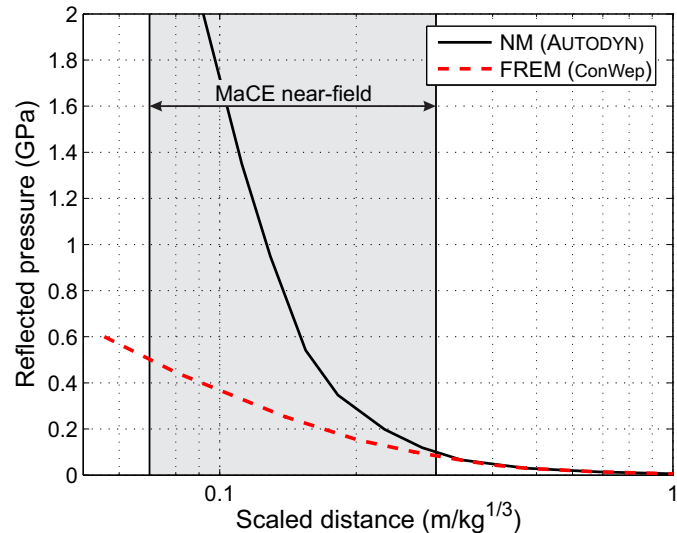


Figure 1: NM [2] and FREM [3] reflected pressure predictions illustrating the variation between methods

• Characterisation:

- What are the spatial and temporal distributions of pressures imposed on a target from a blast wave, especially very close to a detonation where physics-based numerical modelling (NM) [2] and semi-empirical fast-running engineering models (FREMs) [3] give widely different predictions? (Figure 1)

• Mechanisms:

- What is the thermo-chemical state of the detonation products in the very early post-detonation phase?
- Is there significant post-detonation energy release whilst the detonation product fireball is still expanding and driving the air shock?
- Can we quantify these effects and their consequences for loading?

In 2018 the UK Engineering and Physical Sciences Research Council (EPSRC) awarded a grant to the project team, allowing a focussed effort on the **Characterisation** of loading (*MaCE*). The two main strands of the *MaCE* project were to a) develop a higher resolution quantification of the output from explosives and b) to understand the post-detonation energy release rates through varying diagnostic techniques. The *AFOSR* project was designed to enhance the diagnostics deployed in the *MaCE* testing, thus leveraging support to provide additional non-invasive optical techniques for the second objective: **Mechanisms**.

It should be noted that the funding was cut short of the original goal, with only Increment 1 being claimed (due to UoS errors). The original workplan is shown in Table 1. The following sections describe the current status against the project deliverables for Year 1.

Accomplishments

Aims & objectives

The overarching aim of this project was to develop advanced diagnostics to allow for quantification of the physical state of an explosive fireball in the near-field region. The original objectives for the project were:

1. The continued development of a dataset of spatial and temporal loading distributions arising from the detonation of near-field free air charges for a range of explosive types.
2. Optical temperature measurement of the fireball using a specially filtered high-speed video (HSV) camera.
3. A high-speed, non-intrusive, spectroscopy-based optical measurement system for the gas species present in the fireball.
4. 3D maps of the fireball expansion for different explosive types and shapes using stereo Schlieren techniques.
5. Quantification of how the thermo-chemical state of the fireball affects the loading in the near-field region.

Table 1: Original Workplan

	Year 1						Year 2					
	2	4	6	8	10	12	2	4	6	8	10	12
WP1 Temperature sensing	Development		T1-5		T6-10		T11-30					
WP2 Spectroscopy development	Purc.		Low-speed dev.		T6-10		High-speed dev.		T11-30			
WP3 Integration with CoBL/MaCE							Rig modifications		T11-30			
WP4 Model development	Integration of testing with proposed 3 stage theory											

WP1 Develop and benchmark the high-speed temperature sensing system for the determination of the temperature evolution of the fireball. Initial testing conducted.

WP2 Develop and benchmark the gas sensing spectroscopy system for the determination of the chemical states of the fireball.

WP3 Identify the thermo-chemical gradients present in the fireball, especially in the near-field, in combination with load measurements and 3D Schlieren techniques.

WP4 Perform a multi-variate cross-correlation on the measured thermo-chemical state versus loading generated, to develop a mechanistic model.

WP1 Temperature sensing

The aim of WP1 was to develop a sensor (based on a Photron SA-Z) to allow high-speed temperature measurements to be made using standard HSV camera. This was required the development of data processing algorithms to turn the camera output into inferred temperature.

The SA-Z, was calibrated in May 2021 using a blackbody furnace at two operating temperatures of 1382°C and 1478°C. The calibration is heavily dependent on the exact settings for the camera being maintained. In this case the following parameters were used:

- Distance from end of lens to target: 5.25 m
- Filter: Zomei 850 nm screw in filter
- Lens: Tamron 70-200 mm macro lens @200mm, with aperture set to f/22
- Exposure time: 0.16 μ s
- Shading correction applied before measurement

In general, this arrangement should be able to measure the temperature as long as the fireball is quite opaque. If the fireball is not opaque then it is harder to quantify the temperature with certainty. The work done at the

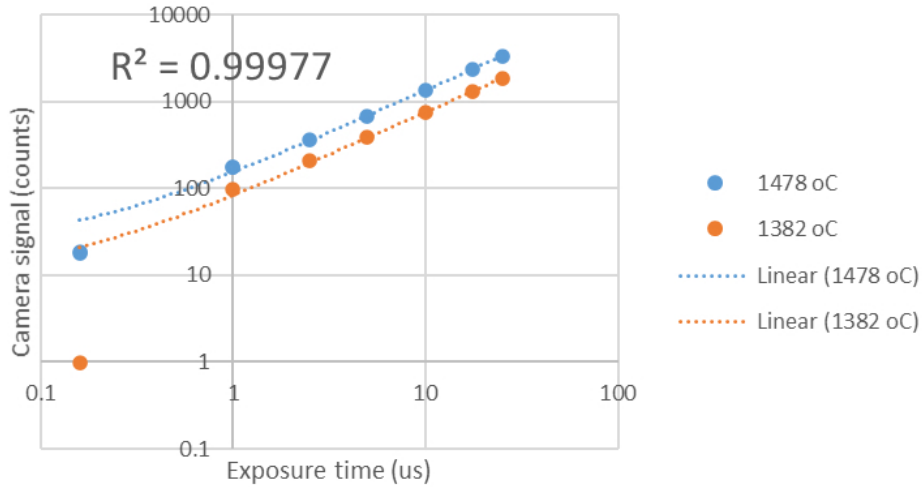


Figure 2: Relationship between raw camera signal and exposure time

moment is limited by the range of lenses we have available for the Photron. A lens with a larger aperture and a 950nm band pass filter would theoretically be able to look at the water vapour which should be the most opaque object in the scene. This would however require additional calibration. Please note that the camera can only give accurate temperatures using exactly the same parameters as given above.

One of the difficulties in using the near-IR response of the SA-Z is that the lens / filter combo lets little light through when calibrating against the blackbody even at its maximum temperature (1478 °C), while using the exposure time of 0.16 μs. This can be seen in Figure 2 that the signal should be linearly proportional to the exposure time but at 0.16 μs the signal is low. A linear extrapolation of the signal was forecast down to 0.16 μs using the data with longer exposure times and calibration coefficients were calculated to allow the greyscale images to be transformed into thermal images.

$$T = \frac{c_2}{A \ln\left(\frac{C}{S} + 1\right)} - \frac{B}{A} \quad (1)$$

The calibration coefficients for the Sakuma-Hattori [4] equation are (using 0.16μs exposure time):

$$A = 7.99e-7$$

$$B = 6.22e-5$$

$$C = 2.46e7$$

Use this to convert the camera signal S into temperature T .

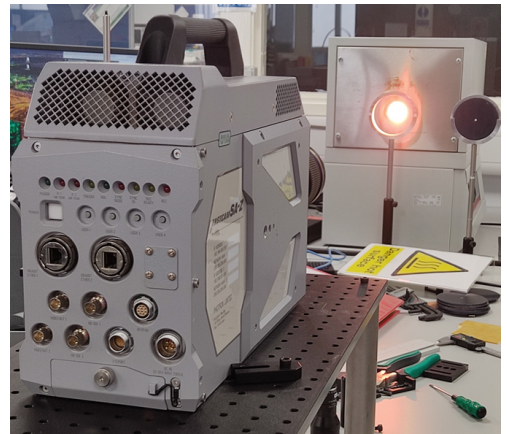
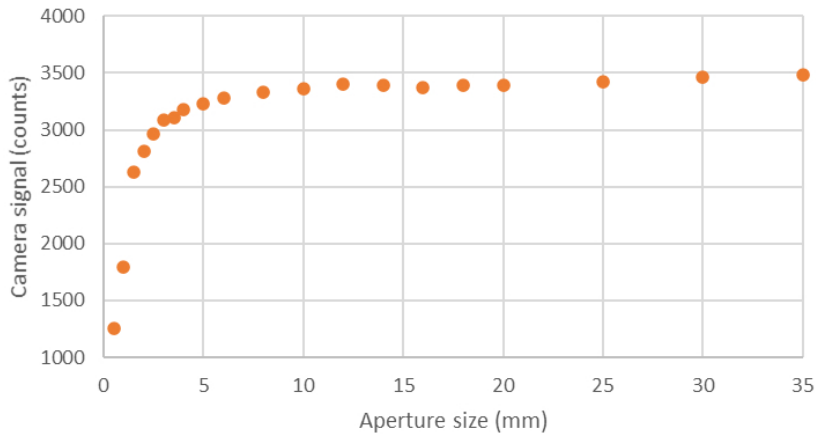


Figure 3: Relationship between camera signal and target object size (in this case the aperture of the blackbody furnace opening)

Figure 3 shows the size-of-source effect using the camera/lens. When looking at very small targets (in this case looking at the furnace through a small metal aperture) the camera signal drops off rapidly. Typically, we would use 95% of the plateau signal value to choose the minimum object size. Hence, the smallest feature which can be accurately measured is ≈ 4.5 mm.

Using Equation 1, the raw pixel value (from a .tiff image) can be converted from the greyscale value to an inferred temperature.

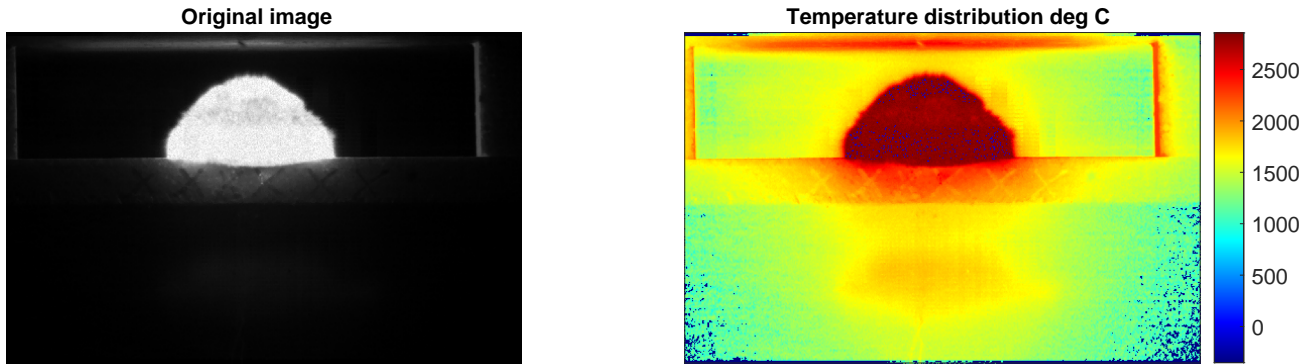


Figure 4: Inferred temperature from a cylindrical charge, 100k fps, 1st frame after detonation, resolution 640×280 px

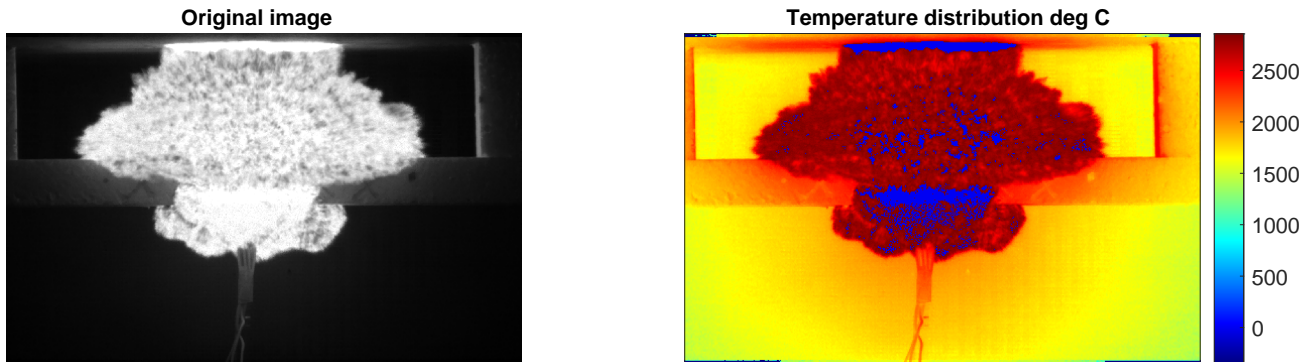


Figure 5: Inferred temperature from a cylindrical charge, 100k fps, 2nd frame after detonation, resolution 640×280 px

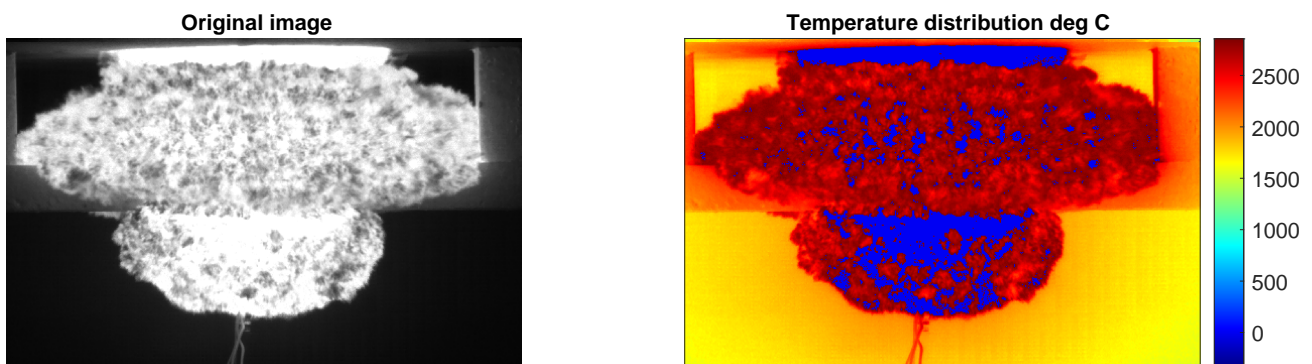


Figure 6: Inferred temperature from a cylindrical charge, 100k fps, 3rd frame after detonation, resolution 640×280 px

Figures 4-6 show the early time behaviour of a 20 g PE10 cylindrical charge (12 mm high, diameter 38 mm) supported by a foam beam and being detonated by a non-el detonator from the base. The current calibration is capable of reading temperatures up to 2850°C , and pixels which are maxed out are presented as blue in the right hand sub-figures. Theoretically the calibration can be extended to read temperatures above 2850°C , requiring a higher temperature blackbody source and a neutral density filter. As the time of writing this has not been conducted. Also the minimum temperature which can be 'seen' by the camera is $>1000^{\circ}$ which is why the surrounding are once not zero jumps in temperature.

One of the advantages of using a standard non-IR camera is the increased frame rate which can be brought to bare on the problem. In the case of the Photron SA-Z-2100K, this is a maximum windowed frame rate of 2.1M fps at a resolution of 128×8 pixels.

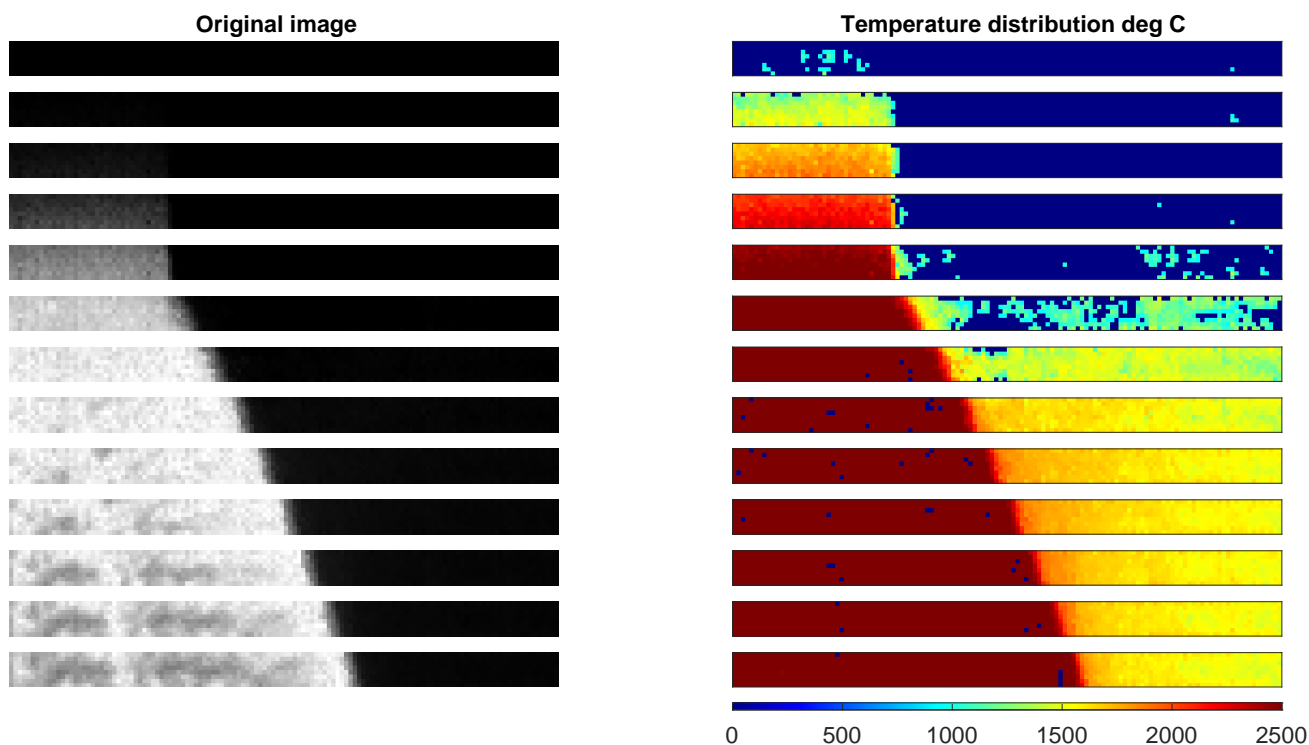


Figure 7: Inferred temperature from a cylindrical charge, 2.1 Mfps, resolution 128×8 px

WP2 Spectroscopy development

To allow the tracking of the pre- and post-detonation gasses we plan to identify the gas species present in commonly used explosives to ensure that the emissivity of gasses fall within the spectral response of the MWIR cameras to be used (e.g. NO₂ pre-reaction in TNT detonations). The original plan was to purchase a low-resolution but high-speed MWIR video camera on the grant to allow the development of the sensing techniques. We were fortunate to be awarded the strategic equipment grant which allowed us to purchase a high-speed high resolution MWIR camera.

The initial calibration of this is yet to take place due to issues with finding acceptable filters for use with the Telops camera. Sadly, the camera came limited to sensing 150°C which means in its default state there is little we can use if for without further development which was planned for Year 2 of the project. We are currently leveraging the results from another project to help in the prediction of the gasses present in the fireball through a series of quasi-static pressure tests, looking at the development of both temperature and pressure with time after a HE explosion.

Had Year 2 of the project been funded we would have expected to spend a considerable amount of time working with the camera to ensure that the best possible diagnostics are made before trialling both the spectroscopy and temperature sensors.

WP3 Integration with CoBL/MaCE apparatus

The original intention of this work package was to heavily leverage the EPSRC funding for the MaCE grant to provide benefit to the *Fireball Quantification* project. The existing CoBL facility used 10 mm diameter EN24T steel HPBs, arrayed across the target to provide a spatial map of the loading. This gave an upper limit of ~4–500 MPa to the pressure which could be recorded. Furthermore, the relatively large bars, whilst necessary to pick up strikes from discrete gravel particles in buried explosion tests, led to significant dispersive effects on

the measured signals which limits the effective bandwidth of the transducers. This is of great importance since FE modelling work suggests that there are important transients in the pressure-time histories which cannot be recorded with the existing bars [2]. Consequently, a full re-design of the instrumentation will be conducted as part of the MaCE project. This design has taken place but at the time of writing the newly gauged bars have still not been returned to us from Micron (US).

One of the key elements of the MaCE experimental apparatus has been the reduction in the size of the Hopkinson pressure bars (HPBs) we deploy in our measurement arrays to increase both the spatial and temporal resolution of the loading captured. A numerical simulation of the impact of the change from 10 mm to 4 mm HPBs is shown below in Figure 8. It is worth noting how well the 4 mm bars can capture the true signal (shown in black).

At the time of writing the HPBs themselves have been manufactured from maraging steel (allowing much higher pressures to be measured >1GPa) To enable the measurement of higher pressures (>1 GPa) associated with extreme NF environments, a new set of 3–4 mm diameter tungsten HPBs will be commissioned. The high strength and stiffness of these bars will facilitate measurement of pressures up to 1 GPa before the yield strength of the bars or the limit of the strain gauges is exceeded. FE modelling results

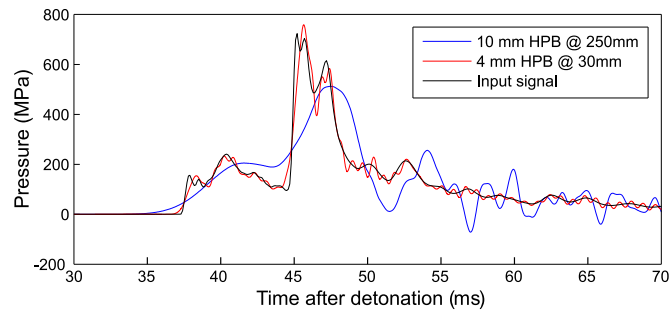


Figure 8: Minimisation of dispersion in HPBs

indicate that the smaller diameter/high-bandwidth bars can resolve the key transient pressure features. This will produce load maps of unprecedented accuracy and detail, allowing us to investigate loading at distances <1/2 a charge radius from the surface of an explosive ($Z < 0.07 \text{ m/kg}^{1/3}$) where there is currently an absence of experimental data, and where the uncertainty is the greatest (see Figure 1). It is envisaged that a total of up to 40 measurement locations will be used, to give detailed spatial maps of the loading.

WP4 Model development

The project team have conducted applied experimental research studies over the past 5 years aimed at capturing pressure loads on targets very close to a detonation. This work was aimed at providing guidance to practitioners on the validity of existing predictive models and resulted in the development of two key hypotheses which challenge the current standard model of blast wave generation from a high explosive detonation:

- There is significant energy release in the early post-detonation stage, possibly due to ongoing reactions between partially oxidised chemical species in the fireball and oxygen in the shocked air displaced by the fireball expansion.
- In late-stages of fireball expansion, Rayleigh-Taylor (R-T) instabilities at the interface between the fireball and the surrounding shocked air produce chaotic variations in the loading imparted to a target.

This leads us to propose a three-stage model of the generation of blast loading. This is described below for the detonation of a spherical charge and shown schematically in Figure 9.

Stage One: Immediately Post-Detonation (Extreme NF)

After detonation the fireball products expand violently. Initially, it is postulated that there is insufficient time for R-T instabilities to form in the fireball. Hence, loading on a target in this region should be essentially deterministic.

Proving this requires the new MaCE apparatus to be commissioned to allow charges to be placed closer to the target plate.

Stage Two: Rapid Afterburn (Intermediate NF)

Over time (10s–100s of microseconds after detonation), the surface of the fireball is seen to be irregular, with turbulent plumes emerging. These result in large variations in the pressure loads imparted to a target

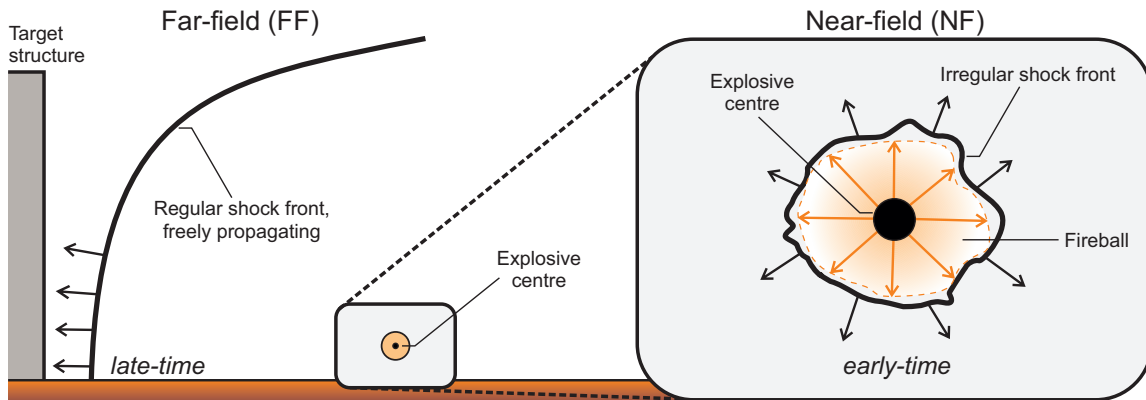


Figure 9: Far-field and near-field regimes of explosive loading

and the loading is essentially chaotic. It is thought that these turbulent plumes enhance mixing with the surrounding atmosphere, facilitating reactions between atmospheric oxygen and partially-oxidised detonation products, resulting in substantial further energy release.

We have now conducted quasi-static pressure (QSP) tests to show that the pressure in a confined system is indeed dependent on ongoing reactions in the fireball which can be 'switched off' if the detonation occurs in an inert atmosphere. Testing was conducted in a large steel pipe, 1 m in length with a diameter of 0.6 m. This pipe was fitted with a flange on either end so that two end plates could be fitted with rubber seals, creating a sealed chamber.

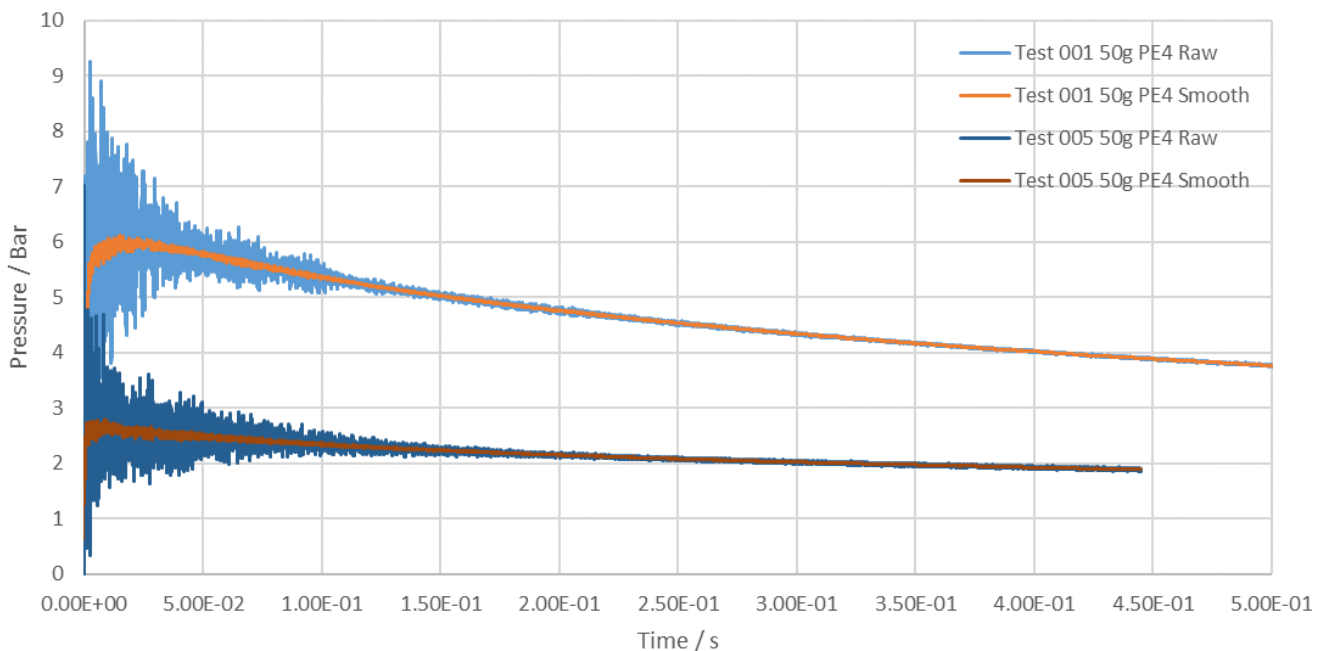


Figure 10: QSP generated from 50 g PE4 detonating in air vs nitrogen [5]

Figure 10 shows that an inert nitrogen atmosphere reduces the smoothed max QSP from 6 bar down to 2.6 bar, a 57% reduction. Nitrogen has a very similar density as atmospheric air, ruling out the effect of air density on the results. The drop in QSP shows that the afterburn in the explosion has a large effect on the development of QSP. This trend was repeated over multiple tests, always reducing the pressure by the same amount.

During the early-time post detonation, it is assumed that afterburn does not influence initial pressures. This is due to the idea that the remaining products in the detonation product cloud will react with the air too slowly. This is a sensible observation in the far-field research as the shock wave will always be in front of the detonation products until it hits a surface sometime after detaching from the product cloud, and then it must

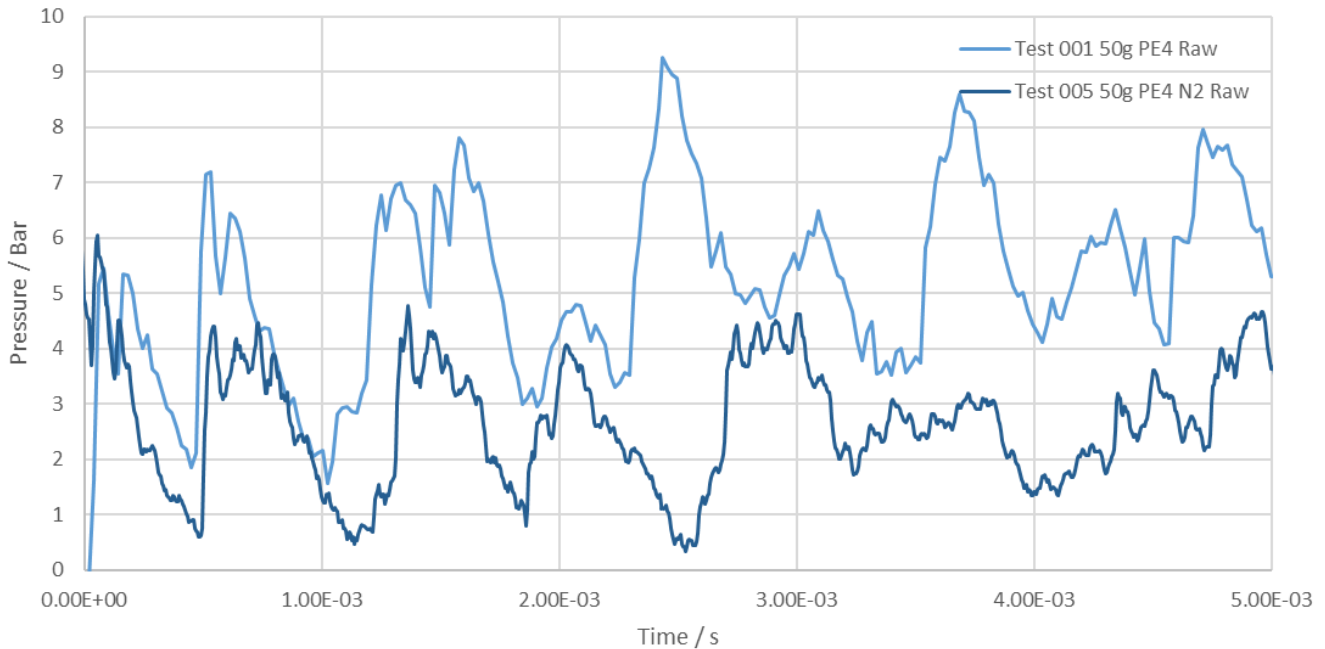


Figure 11: Early-time pressure comparison of 50 g PE4 in nitrogen vs air [5]

travel back to the products before mixing. However, by looking at the early time pressures in Figure 11, we can see that after the initial peak, there is an immediate change in the pressure in nitrogen compared to air, demonstrating the presence of rapid-afterburn with the atmospheric air.

The results from this stage have been written up for publication in the 19th International Symposium on Interaction of the Effects of Munitions with Structures (Sept 2022) and an early draft of the conference paper is attached in the appendix.

Stage Three: Shock Detachment (FF)

It is hypothesised that as the fireball stops expanding and driving the air shock, heterogeneities in the detached blast wave will begin to equalise. At sufficient distance, the blast wave should become smooth and loading should be essentially deterministic and determinable.

Testing has been undertaken to be able to look at the repeatability of blast wave parameters in the far-field. This has been written up into a separate paper which has been published in the International Journal of Protective Structures [6]. A copy is contained at the end of this report.

Impacts

There are a number of impacts which have the ability to enhance the diagnostics available in the blast field.

1. The use of traditional HSV cameras for the measurement of temperature (inferred). This allows, with suitable calibrations the fireball temperature to be recorded at higher frame rates than currently possible with MWIR cameras alone.
2. Development of optical tracking techniques for far-field shock waves looking at the statistical repeatability of HE detonations. This work has shown that the far-field blast loading is entirely repeatable and predictable.
3. The development of a thermo-chemical model for the pressure development in quasi-static pressure testing. This model demonstrates that there is a finite time over which the energy from a HE explosive is released. The fact that this pressure can then be reduced with the use of inert atmospheres is a strong indicator for us to develop mitigants to reduce the loading from HE blasts.
4. Associated development of a new internal blast facility at The University of Sheffield. The AFOSR funding supported the application for a Strategic Equipment Grant from the UK Engineering and Physical Sciences Research Council, which when completed will deliver some of the objectives currently not met. Please see the Changes section below for a commentary on the capabilities of the new facility.

Changes

The project team have conducted experimental testing over the past 2 years aimed at optically characterising the output of bare HE charges and for internal blasts where the development of quasi-static pressure as part of the MaCE project. This has served as a method for identifying the rate to energy deposition from an explosive into atmosphere.

Expenditure impacts

Sadly, funding was cut short of the original goal, with only Increment 1 being claimed (due to UoS errors). This, combined with project initial delays due to Covid-19 have had a massive impact on our ability to successfully deliver all the objectives. To date we have been only received the 1st year of funding and the project extension was not granted (due to UoS errors).

Covid-19 effects

The original grant was awarded in Mar-2020, days into the Covid-19 pandemic and the ensuing lockdowns in the UK. Whilst the procurement for the strategic equipment grant was able to go ahead (with it being largely paper based), physical testing at the Buxton blast and impact laboratory was put on hold until Sept 2020, albeit at a reduced capacity until 2021. This has meant that to date progress has been hampered.

Covid-19 has also had an effect on staffing with the named PDRA Tom Rockett being offered a position elsewhere. He has never been replaced on the project due to wider recruitment delays and staff competencies.

Additional supporting funding

Prof. Clarke was awarded additional supporting funding in a strategic equipment grant from EPSRC in Oct 2020 to develop an experimental facility to address two key challenges in blast protection engineering. Firstly, synthesising understanding of the loading and the structural/material response when a high explosive detonation occurs very close to a target. This has implications for the protection of critical infrastructure against focussed small explosive threats. Secondly, mapping blast loading in complex environments such as dense urban cityscapes, where the shielding and channelling of the shock waves will lead to complex loading and damage patterns. This has key implications for urban planning, protection and risk management/insurance issues. In both these areas, experimental research has not kept pace with the development of powerful but often unvalidated computational modelling tools. The new blast chamber will help resolve this issue through a state of the art high-speed imaging diagnostic capability, bringing "white room" diagnostics into the investigation of high explosive blast and ballistic events. **This will enable us to better understand both the mechanisms of blast-loading, and structural response, allowing us to direct the effort to mitigate the damage done by explosions.** A table of the equipment purchased through the grant is contained below:

2 x Ultra-high speed video cameras – Shimadzu - HPV-X2	£362,522
High speed MWIR camera – Telops FAST M1k	£181,663
Flash x-ray equipment – Scandiflash 4-channel 150kV	£303,163
Beam splitter for co-optically located cameras and general laboratory setup	£54,715
Specialist low flicker lighting – Luminys LabLight	£37,458
Computing & data acquisition	£19,489
Infrastructure total cost £416,916: 50% requested from EPSRC	£208,098
Supporting staff time (academic, technical & administrative)	£215,873
University costs (Indirect, estates & infrastructure technicians)	£31,757
<hr/>	
Total cost to EPSRC (minus UoS contribution)	£1,414,738

Description of the equipment

The core equipment to be included in the laboratory are two ultra-high speed video (UHSV) cameras (Shimadzu HPV-X2) in a stereo arrangement, combined with a high speed medium wavelength infrared (MWIR) camera (Telops) on the same optical axis as one of the UHSV cameras via a beam splitter. The crucial new capability

is that the dual UHSV cameras allow digital image correlation (DIC) at up to 10 Mfps enabling imaging of early time behaviour in explosive events. In the procurement process we trialled the class leading Specialised Imaging Kirana 7M as it has a higher resolution (924×768 px). The Kirana while detailed had a major issue with ghosting when imaging explosive events meaning that it was not fit for our current purposes. The Telops is able to provide additional diagnostic information through direct temperature measurement or indirectly through gas spectroscopy (in the MWIR range), to enable tracking of the reaction front in explosive events. The Telops has one of the highest framing rates of any MWIR camera (up to 30 kfps windowed) facilitating the capture of several frames in the expansion of an explosive fireball. The key capability of the camera is the integration time (analogous to shutter speed) which is as low as 270 ns. This will allow us to capture very high quality thermal maps of the evolving fireball. When coaxially mounted this allows the temperature field (or reactive front) to be imaged at a point of interest in the test. Repeat testing can then be used to plot this evolution in time. To complement the camera system a data acquisition system and specialist low-flicker lighting (Luminys LabLight), that supports the ultra-high frame rates, are required. The Luminys Lablight is capable of flicker free illumination guaranteed to 1 Mfps, with an output of 100,000 lux at 3 metres. The final element in the laboratory is the ability to image internal interactions with a flash x-ray in the form of a Scandiflash 4-channel 150 kV system capable of 4 pulses allowing internal processes to be imaged at 4 discrete points in time. To facilitate the use of the equipment in a controlled environment the grant includes the cost of the creation of a dedicated blast chamber (Fig 12), which will allow for internal detonations of up to 1 kg of high explosive while protecting the equipment from the effects of the blast.

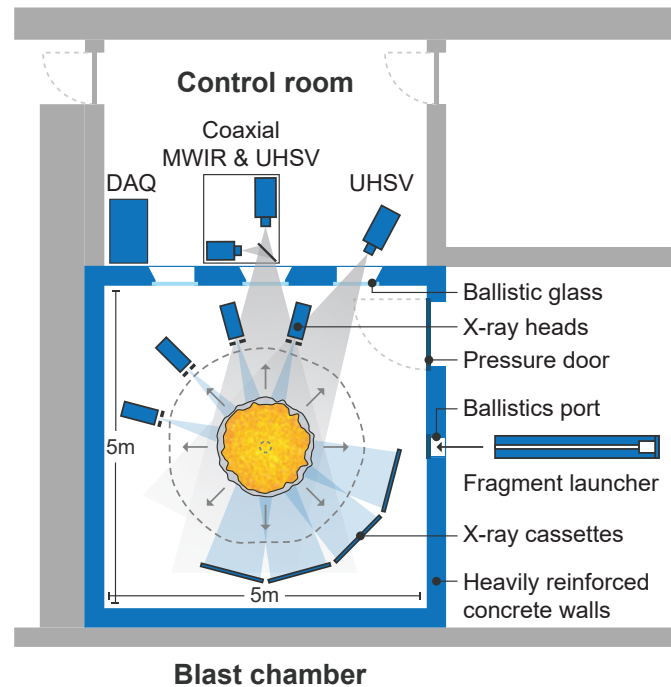


Figure 12: Proposed diagnostics lab

As of May 2022 the equipment has been purchased (the purchase of the MWIR camera has saved \$19,125 of equipment costs from Increment 1). The funding for the blast chamber has attracted further investment internally from the University which has led to an whole site refurbishment for the Blast and Impact group. However this has led to delays in the construction of the blast chamber, which is still at the detailed design (pre-tender) stage.

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