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Experimental and numerical studies of confined blast from detonation of plasticised high explosives in reactive and non-reactive atmospheres

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Abstract

We present the results of a small-scale experimental study of the temporal development of pressure following the detonation of 10-50 gram plastic explosive charges in a 275 litre sealed chamber. RDX- and PETN-based charges are used, and the tests are conducted in atmospheres of air, nitrogen and argon. The pressure-time data for repeat tests of the same explosive/atmosphere combination exhibit striking consistency, even over timescales encompassing many passes of the confined shock waves along the chamber. This suggests that both the quantity and rate of release of both the detonation energy and the energy of combustion of the partially oxidised detonation products are highly consistent and throws an interesting light on the issue of what consistency we should expect to observe in blast trials. Comparison of the pressure traces in air and non-reactive atmospheres gives strong evidence of the duration quantitative consequence of the combustion phase (commonly known as "afterburn"). This is supported by data from a purpose-built high bandwidth infra-red thermometer, which appears to be identifying the flame temperature of the afterburn reactions. Finally, the experiments are modelled using the APOLLO code, with results showing excellent correlation with the experimental data.

Introduction

Small scale experimental blast testing is frequently conducted to enable better understanding of fundamental mechanisms of high explosive detonation and the subsequent development of blast waves in the surrounding environment. The benefits of small-scale testing include the ability to accurately control many of the variables as well as relatively low cost and lower demands on infrastructure. Increasingly the findings from such small-scale testing are used to interrogate and validate numerical modelling approaches.

However uncertainty persists in the consistency and repeatability that should be expected the results from such tests. At the extreme variations in results from nominally identical tests of up to +/-50% average have been reported in free-field explosions [1]. This uncertainty has spurred a detailed experimental investigation at University of Sheffield, concentrating initially on plasticised variants so-called “ideal” explosives (defined here as an explosive in which the reaction zone on detonation is of negligible physical length). This has found a very high level of consistency in the reflected blast parameters at scaled distances above ~3m/kg$^{1/3}$ [2]. At closer scaled distances, naturally forming structures in the fireball do appear to cause significant variations in the spatial distribution of blast

wave parameters, although the total loaded integrated spatially and temporally appears highly consistent [3].

This latter finding appears to be particularly significant. It implies that even where there is genuine local variability global energy release from the explosive is highly consistent. This is perhaps to be expected for explosives prepared on the careful quality assurance procedures. It suggests the high variability reported by some studies may actually reflect poorly controlled experimental procedures. It is clearly matter of some importance to establish the correct position here. If the reality is that well controlled experimental detonations produce very consistent results this allows us to have more confidence in variations of outputs seen when inputs are changed.

Relatively little experimental evidence has been published on the repeatability of pressure parameters in confined explosions. Studies that have been published generally suggest good repeatability e.g. [4,5]. In this light a study has been conducted at the University of Sheffield on the pressures generated in confined explosions plasticized ideal explosives referred to above. More extensive details of this study presented in [6].

Test methodology

All tests were conducted purpose built 275 litre sealed steel chamber. The chamber is cylindrical in shape, 1 metre long by 592mm diameter with a 10mm wall, capped by 30mm thick end plates (Fig 1). Spherical charges of high explosive were suspended on a lightweight glass fibre mesh and detonated using Davey NonEl non-electrical detonators. Charges were in the range 10-50g, and comprised PE4 and PE10 plastic explosives. These are respectively,86-87% RDX and PETN, combined with a long-chain hydrocarbon mineral oil binder/plasticiser. Since the heat of combustion per unit mass of the mineral oil is around seven times that of the primary explosives, it was anticipated secondary combustion of this fuel (so-called, “afterburn”) would add greatly to the total energy release, and therefore temperature and pressure in the chamber. Consequently, the mass/volume ratio of the charges and chamber were chosen to ensure the presence of sufficient atmospheric oxygen to allow complete oxidation. To further study the afterburn process, the chamber could be purged of oxygen and filled with nitrogen or argon.

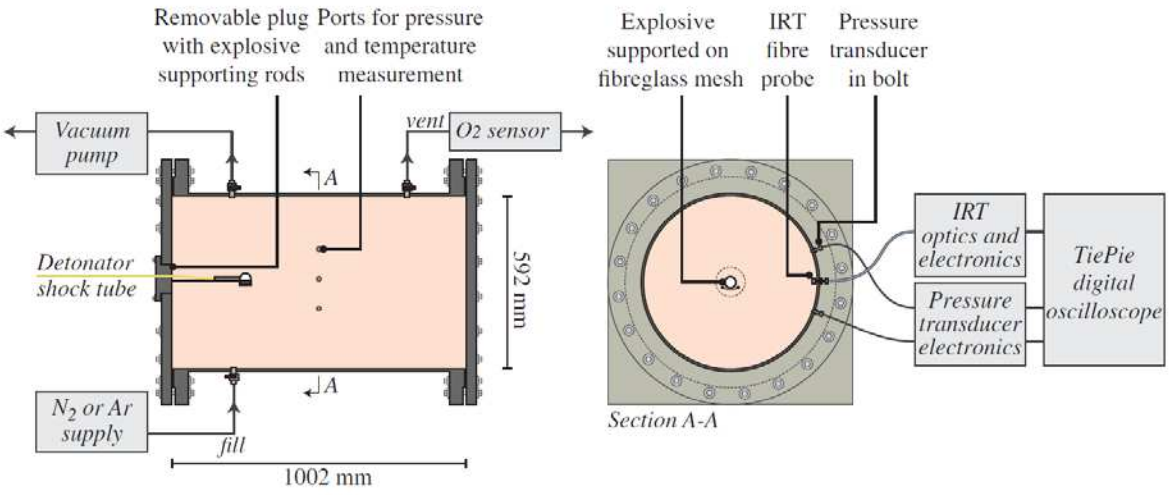

FIGURE 1. Schematic of confining chamber

Pressures were recorded using commercially available Kyowa HKM375 piezoresistive gauges. To protect the gauges from the possibility of damage from impact of fragments of detonator casing, the gauges were mounted in a simple isolating chamber detailed in Fig 2. This had the effect of attenuating the first shock wave to arrive at the gauge, but thereafter there was little difference between the readings taken from a gauge in the isolating mounting, and one mounted adjacent flush with the inside face of the chamber wall (Fig 3).

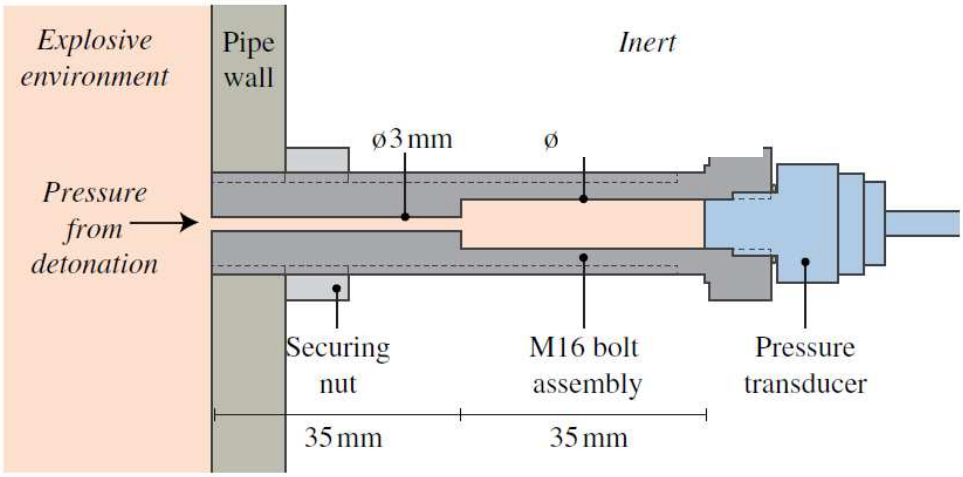

FIGURE 2. Schematic of pressure sensor mounting

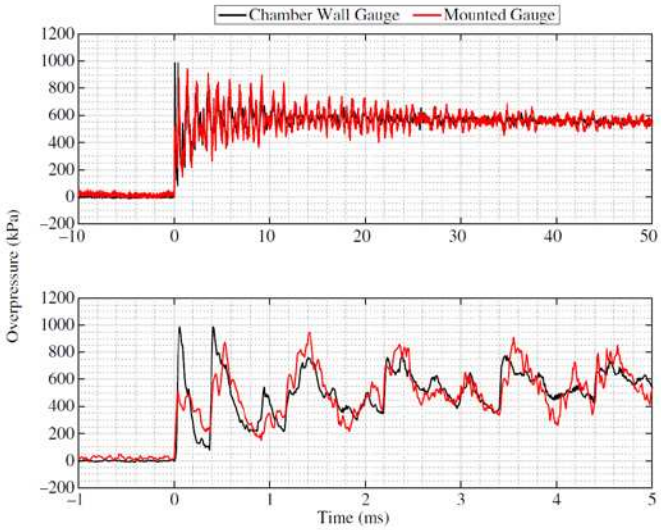

FIGURE 3. Comparison of results with pressure sensor fitted in mounting and flush with chamber wall.

Additionally, direct measurements of the temperature inside the chamber were made using a purpose-built high temperature, high bandwidth infra-red thermometer (IRT). Full details of the experimental methodology are presented in [6] with the design of the IRT is described in [7].

Experimental results and discussion

An extensive test programme was conducted, with detailed presentation in [6]. Here, we will concentrate on the repeatability of the results and what that means for our ability to understand mechanisms.

Fig 5 shows the pressure vs time relations from 5 nominally identical tests with 50g PE4 charges. The upper graph shows the long-term trend, while the lower graph shows the early stages to highlight the initial shocks propagating around the chamber. In both cases, the raw data is shown with grey-black lines, while the pink lines are time-dependent smoothed average (TDSA) traces to emphasise the

long term trend, known as quasi-static pressure (QSP). The test-to-test consistency is remarkable, with variations in the QSP of the order of 1%, and even the timings and magnitudes of the first 10+ early time shocks being highly consistent. We consider this to be of high importance in the debate on the consistency and predictability of blast loading from detonations. Note that, although the chamber was fully sealed, the QSP magnitude reduces over a timescale of 10s ms. This is believed to be due to the exchange of thermal energy between the hot gas and the chamber walls. Attempts are ongoing to better understand this effect.

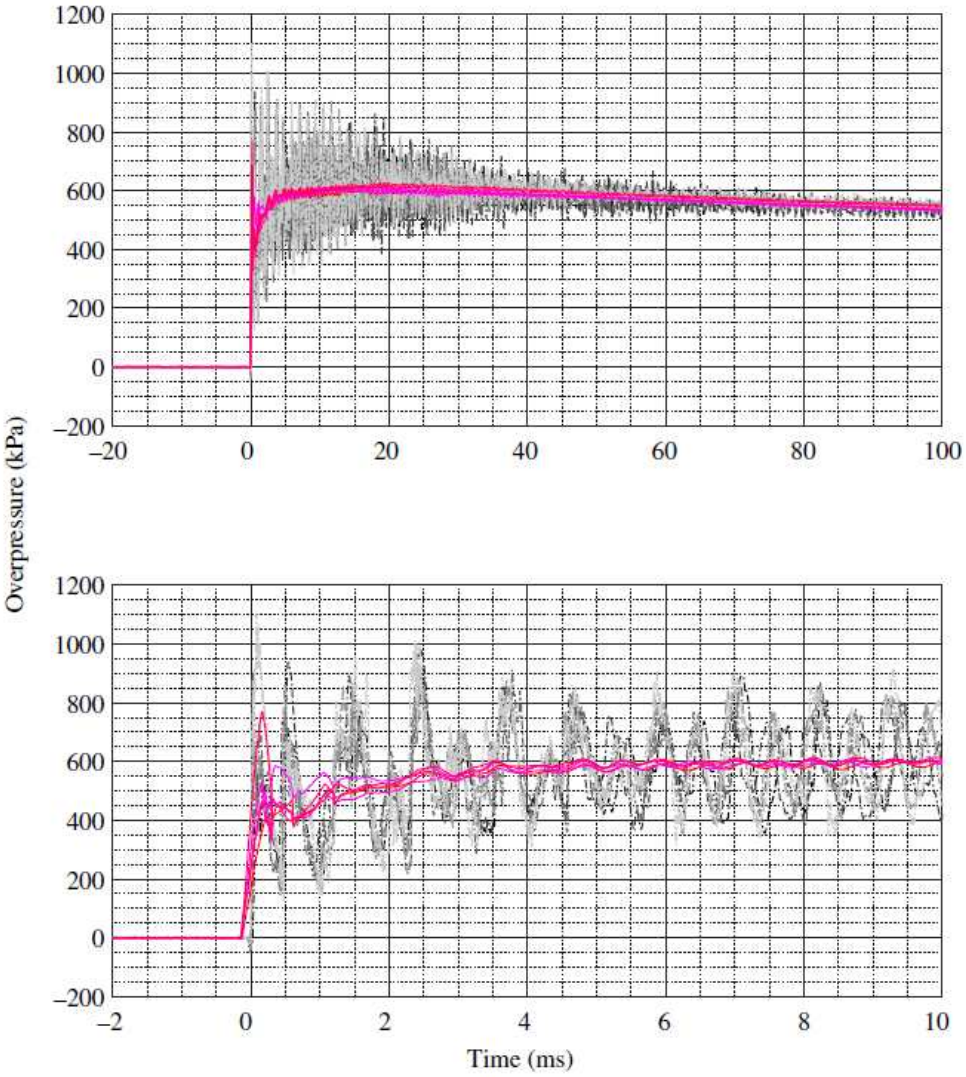

FIGURE 4. Pressure records from 5 nominally identical tests (50g PE4 charge). Black lines are data as recorded, pink lines are centred running averages to suppress the peaks and troughs and highlight the trend.

With this degree of expected repeatability, we are better able to draw firm conclusions on the effect of changing test variables. Fig 5 shows the pressure vs time from three tests with 30g PE10 charges, in air, nitrogen and argon atmospheres. As expected, the suppression of afterburn results in a significant reduction of QSP magnitude, with the argon atmosphere resulting in a higher magnitude than that from the nitrogen atmosphere due to differences in the specifical heat capacities of the two gases. A closer inspection of the TDSA traces in the upper graph in Fig 5 reveals that in inert atmospheres, there is a rapid rise to peak QSP magnitude, whilst in the air atmosphere this initial rise is followed by a secondary increase over a timescale of 5-10ms. The lower graph shows that the deviation between the results in reactive and inert atmospheres begins from the arrival of the 2nd or 3rd shocks at the pressure sensor. These are shocks reflected from chamber walls, and as discussed in [6], must have passed through the detonation products cloud. It seems therefore that the effect of afterburn becomes

highly significant as soon as the interface between the detonation products and the oxygen-containing atmosphere is disturbed.

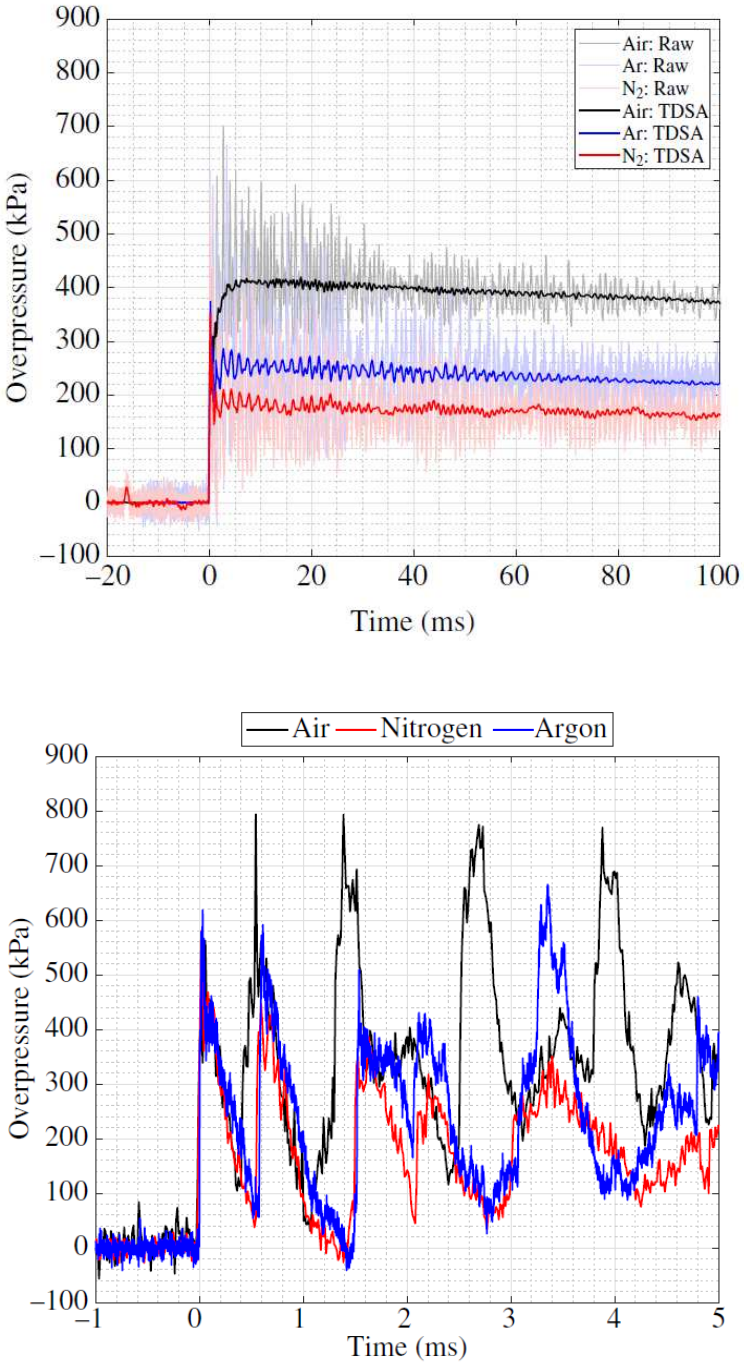

FIGURE 5. Pressure records from 30g PE10 firings in Air, Argon and Nitrogen atmospheres (upper 0-100ms highlighting trend, lower 0-5ms highlighting initial shock reflections)

Direct temperature measurements were taken using the IRT in the three tests shown in Fig 5. Using ideal gas theory and simple assumptions about the chemical reactions occurring in detonation and afterburn to estimate the final moles of gas in the chamber, the temperature records were converted to inferred pressure and compared to the directly recorded pressures (Fig 6). There is excellent correlation between the inferred pressure and the TDSA trend of the directly measured pressure in theine air atmospheres from a very early time. In the air atmosphere, the correlation is excellent after

about 5ms, but the magnitude of pressure inferred from the temperature measurement is significantly higher than the directly measured pressure. Notably, this difference ends around the time that the secondary rise on the directly measured pressure reaches a maximum. We conclude from this that the discrepancy is driven by afterburn and suggest that the IRT is actually recording temperatures enhanced by the afterburn reactions during this time.

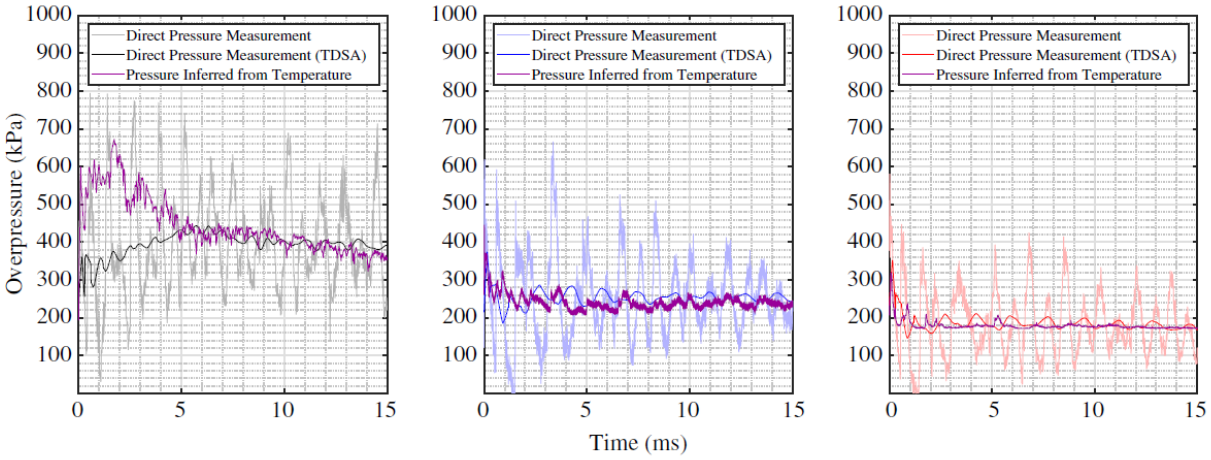

FIGURE 6. Pressure records from 30g PE10 firings in Air (left), Argon (centre) and Nitrogen (right) atmospheres – comparison of directly measured overpressure and overpressure inferred from temperature measurements.

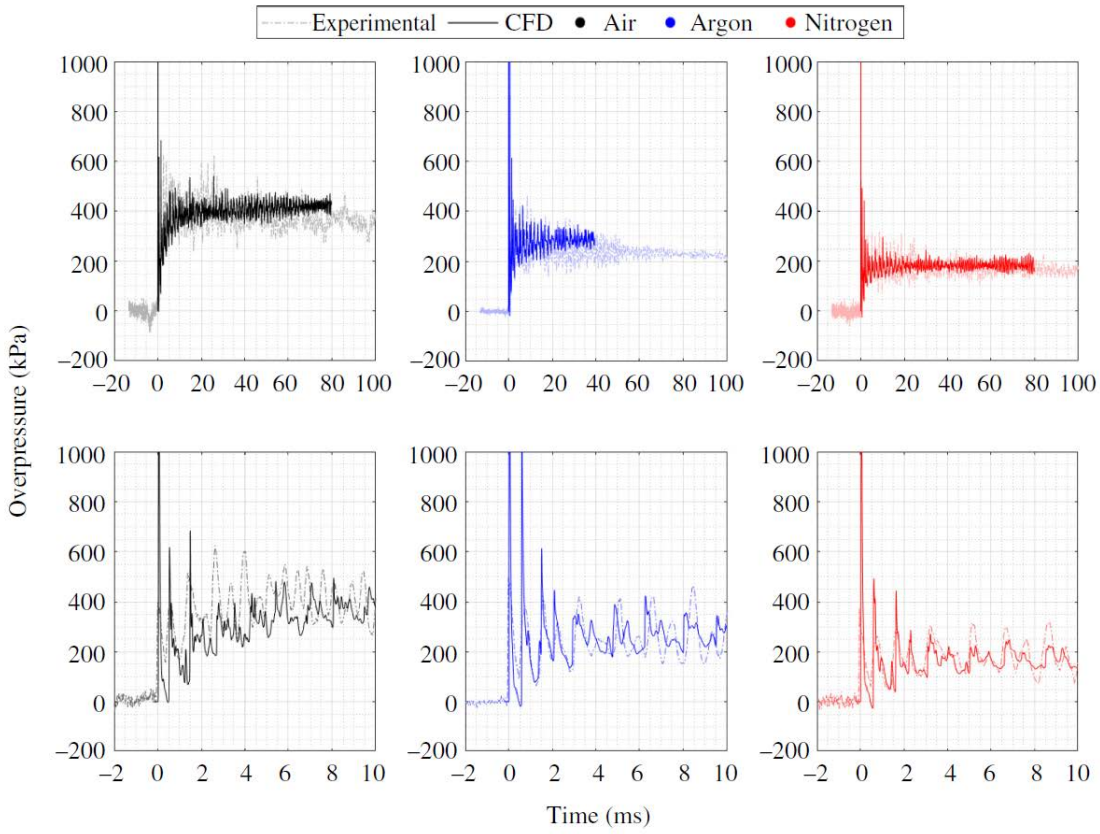

FIGURE 7. Pressure records from 30g PE10 firings in Air, Argon and Nitrogen atmospheres – comparison of experimental and numerical model results (upper 0-100ms highlighting trend, lower 0-10ms highlighting initial shock reflections)

Numerical modelling

The tests described above were modelled using the APOLLO Blastsimulator code [8] which includes the explicit secondary reaction of un- or partially oxidised detonation products with atmospheric oxygen. Full details of the modelling strategy and results are presented in [6]. Here we simply note that, allowing for the fact that the modelling does not incorporate the thermal energy loss described above, the correlation between the model and experimental result is generally excellent, although the model possibly slightly underpredicts the intensity of the early stage afterburn reactions in air.

Figure 8 shows how the amount of detonation product remaining in the model increases with time as they are converted to fully oxidised compounds. This broadly matches the duration of afterburn discussed in the previous section.

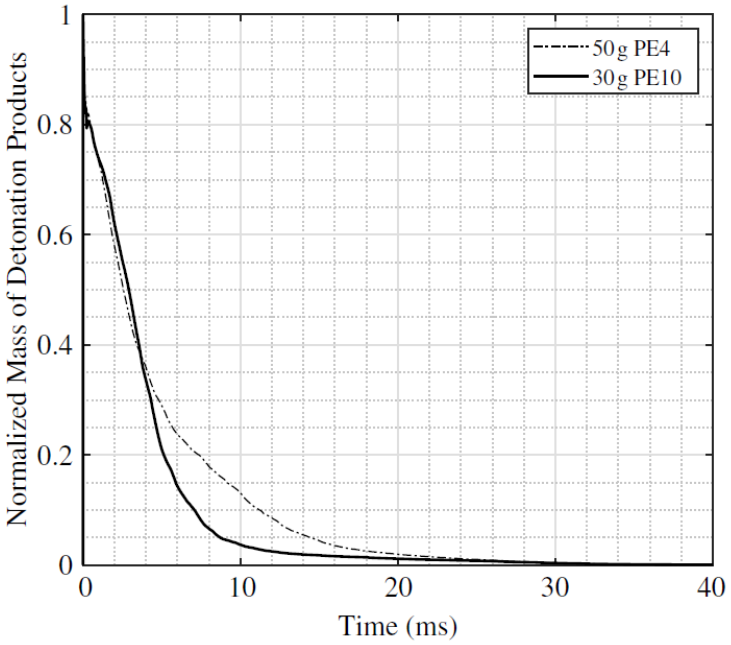

FIGURE 8. Rate of consumption of detonation products in APOLLO model.

Conclusion / Summary / Recommendations

We have presented results from an experimental investigation in the mechanisms of reactions and magnitudes of pressure generated when plasticised RDX and PETN high explosives are detonated in a sealed chamber. Perhaps the most important general finding is the remarkable degree of consistency in the results. We believe this to be highly important in the debate over the degree of repeatability we should expect in experimental blast trials. We have presented strong evidence that the afterburn process is stimulated by the forced mixing of the detonation products cloud and the atmospheric oxygen by the passing of shocks reflected from the chamber walls. The results also allow us to estimate the contribution to the internal pressure of the detonation and afterburn processes. Finally, we have shown that these results can be predicted with high accuracy by a suitable numerical modelling approach. A second paper by the authors at this conference will describe how these results have been used to validate a simple thermochemical model previously proposed to predict peak QSP magnitudes and subsequent publications will present follow-up work on the effect of mitigants on QSP.

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