



## Challenges in blast protection research

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### ARTICLE INFO

#### Article history:

Received 29 March 2018

Received in revised form

10 May 2018

Accepted 19 May 2018

Available online 21 May 2018

#### Keywords:

Explosive blast

Protection

Mitigation

### ABSTRACT

This paper presents a view of some of the challenges that are presented in investigating protection methodologies against explosive blast effects. In particular, the paper is concerned with experimental efforts that can aid in the understanding of complex blast effects in typical real world scenarios. Current progress in the implementation of blast mitigation methodologies in the landward defence environment is reviewed.

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## 1. Introduction

The use of explosives worldwide in terror campaigns has kindled international interest in blast research. The need to protect innocent civilians and peacekeepers from such acts requires in-depth knowledge of blast effects from explosives in complex scenarios, as well as ways to prevent or mitigate damage [1]. The CSIR in South Africa has been investigating this field, mainly in an empirical way, for some time and have obtained recognition for pioneering work performed on early MRAP concepts [2]. The blast research conducted by the CSIR is aimed at advising the SANDF on matters concerning explosive blast threats and aim to characterise the effects of such threats in surrogate conditions by whatever experimental means available. In the course of such investigations, it is attempted to assimilate the current state of the art knowledge in blast science and it has been realised that significant challenges still exist in this field.

In this paper, the various challenges identified will be highlighted and reviewed. These areas are by no means exhaustive and are limited to the expertise field of the CSIR. In terms of blast protection research, for instance, it is realised that by far the biggest challenges lie in the explosive device detection and neutralisation field, since in the case of an IED there is no better protection than to prevent the device from functioning. However, these aspects will not be addressed in this paper and it will be assumed that by blast

protection it is implied that an explosive blast wave is the ultimate threat.

Research into blast protection from explosive threats can essentially be divided into two domains. These are (a) understanding the propagation and loading from blast and shock waves through and in complex media and geometries, and (b) mitigation mechanisms to minimise the damage from the shock and blast loading [3]. Each of these domains is packed with multi-disciplinary study fields. In the former, chemistry, physics, mathematics, computational mechanics and fluid dynamics feature heavily, while in the latter material science, structural response, fracture mechanics, computational mechanics and human response is paramount.

It is therefore obvious that academic institutions will have an acute interest in blast protection research, since many aspects in these domains require basic research to enhance the fundamental knowledge to adequate levels, for use in technology solutions. However, the inherent complexity of real world events in these domains also requires a comprehensive research approach for implementation of solutions and therefore it has become the trend to have research collaboration across the spectrum of academic and industrial institutions [4].

## 2. Challenges

### 2.1. Modelling of complex blast scenarios

Great strides have been made with mathematical models and computational methodologies to simulate complex blast scenarios

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Peer review under responsibility of China Ordnance Society

### Abbreviations

CFD	Computational Fluid Dynamics
CSIR	Council for Scientific and Industrial Research
DBEL	Detonics Ballistics and Explosive Laboratory
IED	Improvised Explosive Device
HSV	High-Speed Video
kPa	kiloPascal
LS	Landwards Science
MRAP	Mine Resistant Armour Protected
SANDF	South African National Defence Force
VLIIP	Vertically Launched Impulse Plate

[5–7]. Most of the tools available rely on the solving of the Euler conservation equations for mass, momentum and energy and differ only in the description of the source terms, the boundary conditions and the numerical approach to the computation [6]. The efficient treatment of the blast propagation through 3-D numerical meshes and the use of new CFD techniques, as well as the availability of improved computer processing power, have allowed the investigation of complex interaction of blast and shock waves with material configurations and structures [8–10]. Further investigation of new computational techniques with artificial neural networks is also explored for blast effects prediction [11].

Some major challenges still exist in this field despite the increased sophistication of the computational tools. A particular requirement is the implementation of non-ideal energetic behaviour in the longer time frame that typically occurs with explosive mixtures used in IEDs. In these instances, a number of factors are important:

- accounting for the time-dependent energy release from the explosive source itself,
- accounting for the aerobic energetic behaviour of the gaseous explosive products,
- estimating energy release from the re-energizing of the explosive products when subjected to successive reflection waves in confined and semi-confined space.

The term afterburning is usually used to refer to the ability of the products of an explosive to continue to release energy when either mixing with the surrounding atmosphere or with an inherent delayed reaction over longer time span. The normal way of addressing the energy release in the computational tools, is to use an equation of state to determine the release parameters at a fixed position and time. Several modifications of this approach have been investigated [12–15]. A relatively successful approach is to use additional thermochemical codes to predict the additional chemical energy release potential from either the aerobic mixture of the explosive products, or the latent time-dependent energy release from the products itself. This energy release is then added to the computation with general thermodynamic rules.

At the DBEL facility of the CSIR a semi-confined chamber is used to study the detonation of explosive charges in partially confined conditions [16]. The evolution of the explosive product boundary (fireball) after the detonation of 0.5 kg cylindrical composition B charge was observed together with simultaneous pressure measurements at the chamber walls [17]. In Fig. 1 below a collage of high-speed video footage is shown with images depicted 3 ms apart starting at 1 ms after the detonation of the charge. The charge was suspended from a cradle centrally in the chamber and was detonated in the downward direction.

It can be observed that the detonation products remain confined to the centre of the chamber (apart from the jet in the downward direction) and exhibits renewed energetic behaviour after each re-compression cycle of the reflected blast wave from the chamber walls.

In Fig. 2 the pressure measurements in the same chamber from a 2 kg total mass HMX based charge and a 2 kg RDX based charge containing aluminium powder, is shown. The measurements were taken at the same position in the chamber wall approximately 2 m away from the detonation of the charge.

The pressure recordings in Fig. 2 shows the effect of enhanced reaction of the product cloud containing aluminium at longer times when the reflection waves pass through the cloud, but also show activity for the HMX products at similar times. This enhanced activity is a combination of the aerobic reactions, the secondary expansion after the rarefaction waves collapse the centre of the fireball and recompression of the products by the reflected pressure waves from the wall of the chamber.

It is obvious that there is a need to be able to model the contributions from reflected waves re-energizing the products of detonations in the longer time frame. In the light of detonations in complex environments where it is required to estimate the yield of the threat, there can be a substantial difference compared to the free field case.

### 2.2. Effect of charge geometry and detonation direction at short standoff

Many IED instances concern explosive charges in very close proximity to the target and small-scale blast tests are mostly performed at close standoff distances. The anomalies of blast characteristics as a function of geometry at short standoff have been addressed in earlier studies [18–20]. Significant differences in the blast yield are found for cylindrical charges compared to spherical charges, at even quite large scaled distances [21]. This has important implications in protection research where it is a normal occurrence to expect non-spherical charges as the threat and shorter application standoff distances. Another significant issue that needs to be addressed is the dynamic loading from larger charges due to such circumstances.

In Fig. 3 below the pressure distribution in the product cloud of a cylindrical 0.5 kg composition B charge of  $L/D = 1$  is shown at  $116 \mu\text{s}$  after initiation, as predicted by the LS-Dyna hydrocode. The charge symmetry axis is on the centreline and it was initiated in the centre on the left face.

The peak pressure at this time in the frontal direction of the expansion is about twice that of the lateral and rear expansion envelopes and about 3–5 times that of the bridge waves. The loading from such a charge will be strongly dependent of the orientation of target with respect to the charge at this time.

Furthermore, whereas the product cloud velocity in the case of a spherical charge rapidly decreases with distance and typical blast arrival times from scale tables can be obtained at scaled distances of approximately  $Z = 1 \text{ m/kg}^{1/3}$ , the product propagation velocity in the forward direction for cylindrical charges remain higher for much larger scaled distances. This has implications for the dynamic loading in this particular direction. In Fig. 4, a collage of high-speed photographs ( $10 \mu\text{s}$  intervals) is shown for a 1 kg cylindrical composition B charge with the field of view over the forward direction. At early times, the actual detonation product boundary is obscured by the ionisation light around the charge but from approximately  $40 \mu\text{s}$ , the progression of the frontal boundary of the products can be obtained. The velocity of this boundary was measured from recordings of tests with 0.5 kg, 1 kg and 4 kg composition B charges and is shown in Fig. 5. Predictions from the

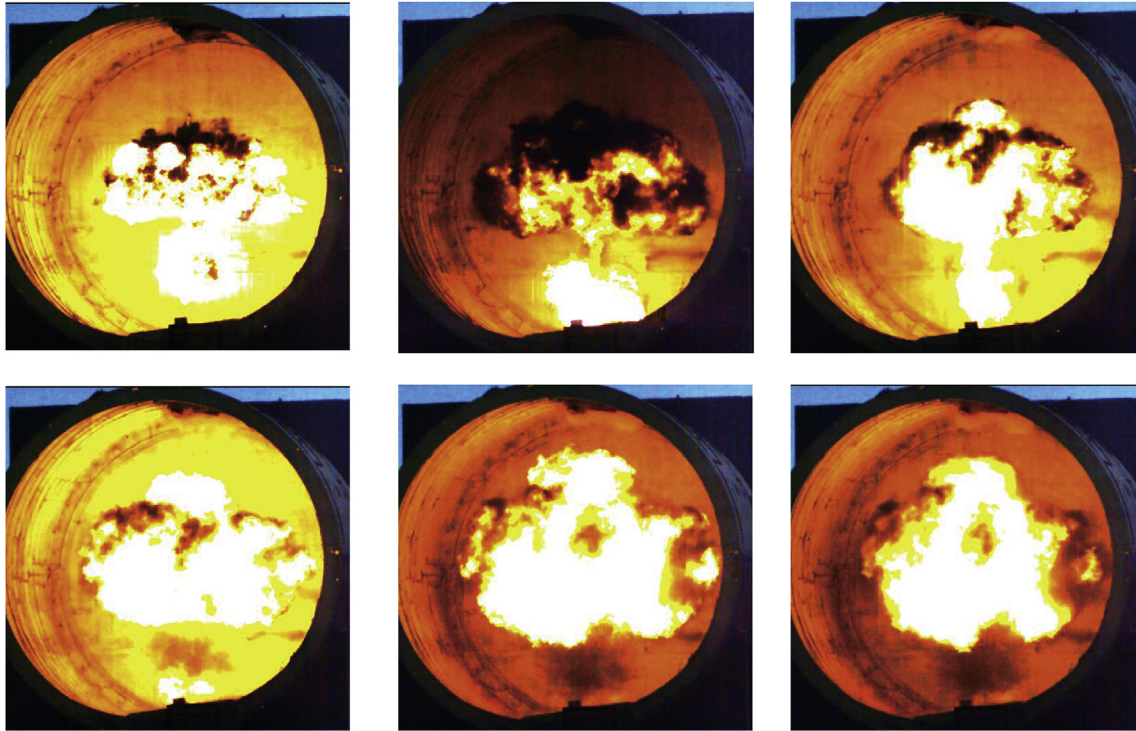


Fig. 1. HSV footage of the pulsations of 0.5 kg composition B fireball at 3 ms intervals in a semi-confined chamber.

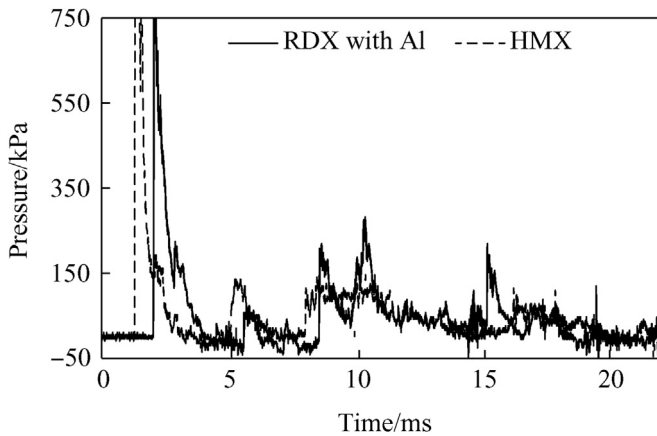


Fig. 2. Pressure recordings of 2 kg HMX based and RDX with aluminium explosive charges.

LS-Dyna hydrocode are also shown in Fig. 5.

Although the predicted velocity of the product cloud in the forward direction at a scaled distances are slightly higher than the measured velocities, it can be noted that the velocity at a scaled distance of  $Z = 1$ , is above 3 km/s. This is approximately 1.5 times the expansion velocity that is expected from spherical charges at this scaled distance.

The implications from these results are that the charge geometry and initiation position on the charge will affect the loading signature from typical explosive charges in close proximity and it needs to be taken in account in methodologies used in blast protection research.

### 2.3. Blast loading in semi-contained environments

One of the most challenging areas in blast protection research is

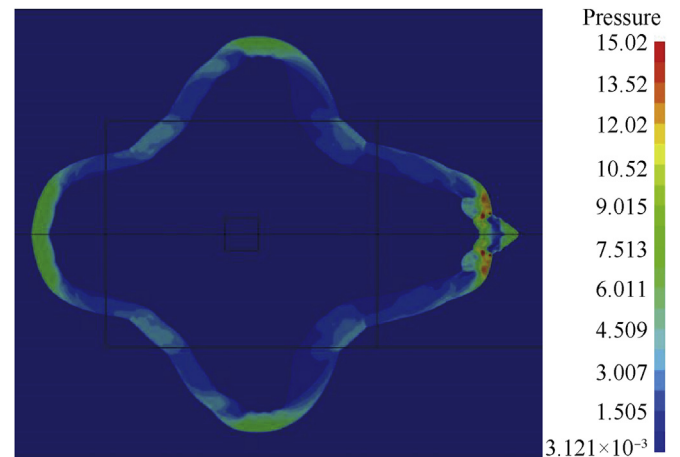


Fig. 3. LS-Dyna prediction of the evolution of the pressure distribution around a cylindrical 0.5 kg composition B charge at 116  $\mu$ s after initiation.

the estimation of the load on a particular structure due to the blast wave. Real world instances of blast loading happen in non-ideal environments where fracture, multiple reflections from asymmetric confinement and progressive venting occur. It is also in this field of study that misconceptions of blast wave interaction with structures often occur [22]. In free field environments with non-deforming structures, relatively simplified estimations of the loading can be made with analytical approaches [23–25]. In environments that are more complex, sophisticated tools are investigated [5,26].

At the CSIR, the availability of the DBEL testing capability allows the experimental investigation of blast loading from explosive charges up to 50 kg without casings and 20 kg with casings included. Due to the proliferation of IED incidents in urban environments, a particular interest is the loading of structures in semi-

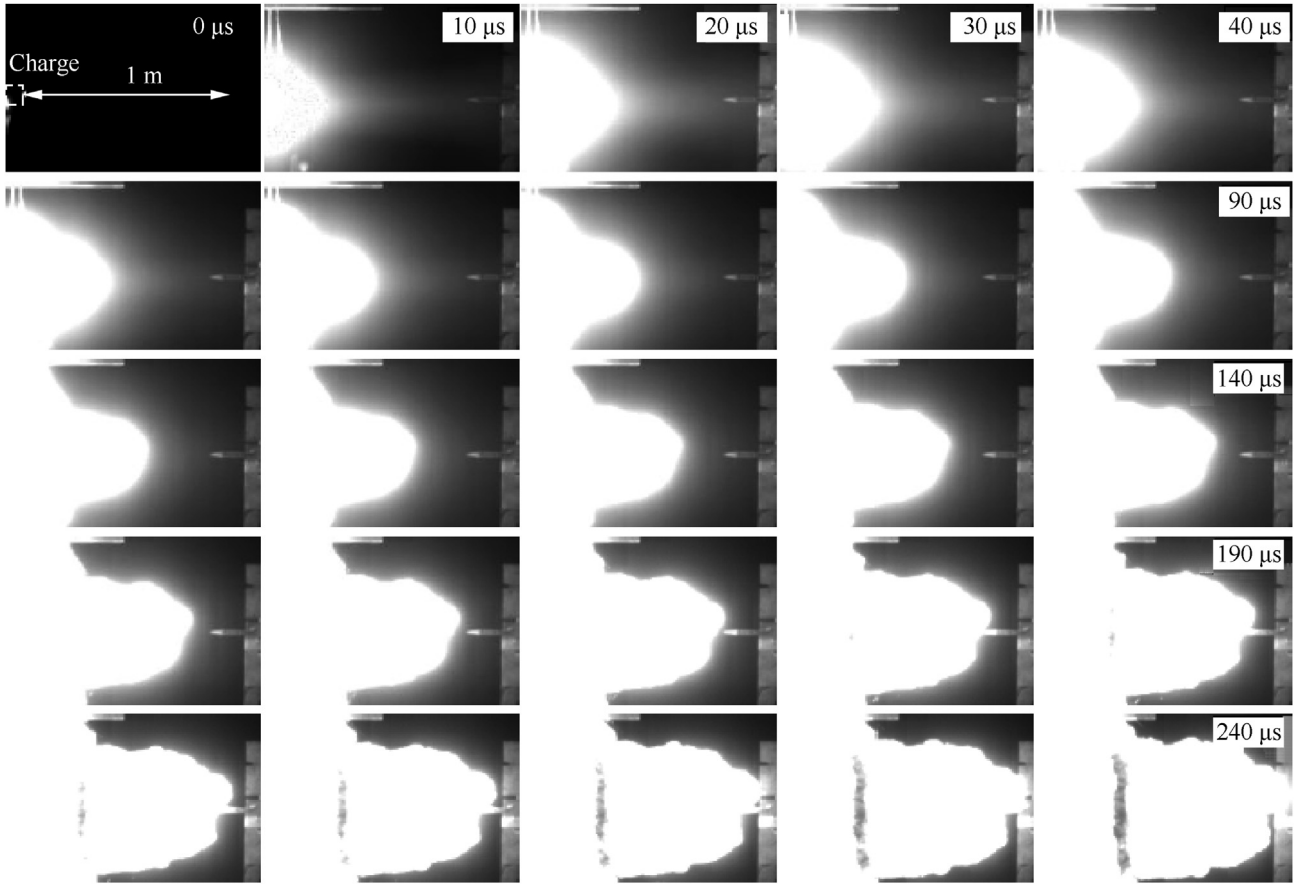


Fig. 4. Collage of pictures at 10 μs intervals of the product cloud from a 1 kg cylindrical composition B charge in the forward direction.

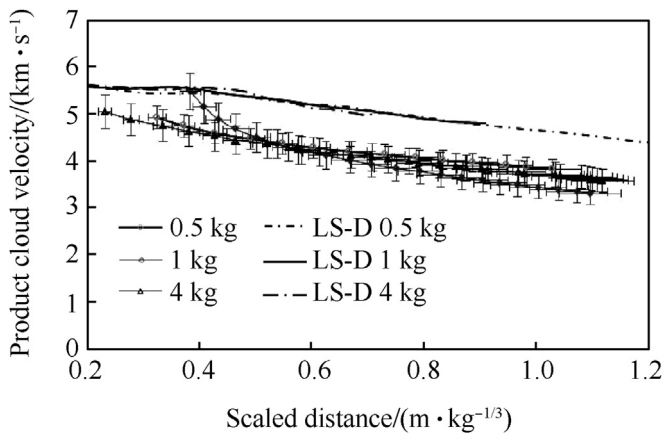


Fig. 5. Velocity of the product cloud from cylindrical composition B charges in the forward direction, as a function of scaled distance.

contained environments. Two examples of experiments conducted are highlighted.

### 2.3.1. Confined VLIP tests

The effect of RDX based charges containing various percentage of aluminium powder was investigated experimentally in various containment scenarios. In one specific test a 1.5 m diameter heavily confined instrumented cylindrical chamber of  $L/D = 1$ , was used to study two sets of charges of total mass of approximately 300 g and 900 g [27]. On the top of the chamber a heavy plate, with a

calibrated mast fixed to it, was loosely positioned so that it could be vertically propelled by the blast impulse. The bottom of the chamber was left open to vent the detonation products and the chamber was suspended approximately 400 mm from the ground level. The charges were hung centrally in the chamber and a high-speed video camera captured the motion of the plate and the mast. This allowed the measuring of the momentum of the plate as a function of time. Photographs of the setup and video frames from a firing sequence are shown in Fig. 6.

Two series of tests with identical charges of varying aluminium content were conducted. The only difference in the setup for the two series was that the trench that was dug for entry into the chamber to arm the charges was covered by a steel plate for all the firings in the second test series. The VLIP scaled impulse data from the two test series is summarised in Fig. 7.

Each data point in Fig. 7 is the average result of two different test firings and the error bars reflect the maximum difference (approximately 6%) obtained between any two results of the firings.

The interesting aspect of the data in Fig. 7 is that the small change in the venting arrangement at the bottom of the chamber (i.e. the covering of the trench in the second series) had an equally large impact on the impulse of the plate compared to the after-burning behaviour of the explosive products in this particular chamber volume. This illustrates the importance of minor containment detail in quantifying the blast loading on a structure.

### 2.3.2. Compound pendulum tests in the semi-confined blast chamber

There are three loading regimes from explosive blast waves, i.e.

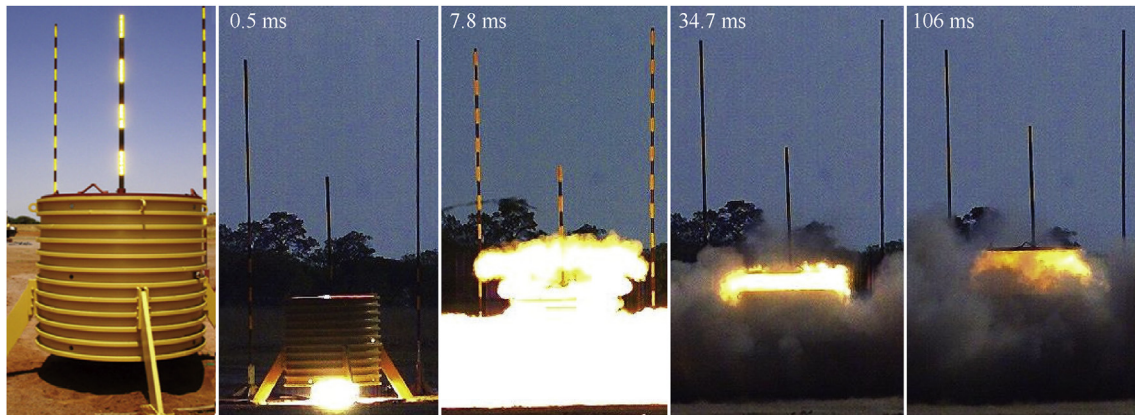


Fig. 6. The confined VLIIP setup and examples of the HSV footage at different times.

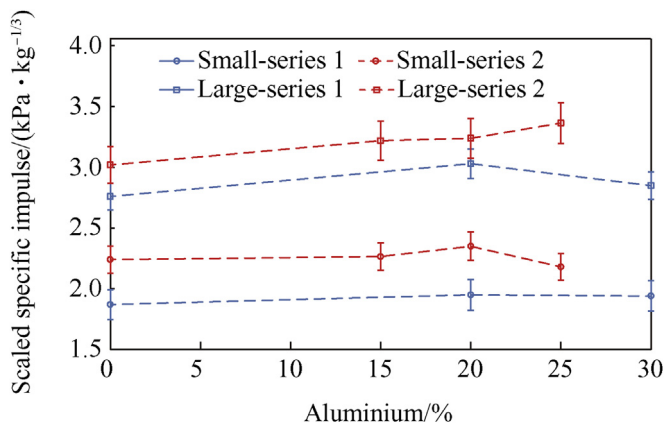


Fig. 7. Scaled specific impulse of the VLIIP from detonation of small (300 g) and large (900 g) RDX charge containing aluminium powder.

the impulsive load from the pressure wave, the dynamic loading of the blast wind and static loading from the build-up of static pressure due to containment around the event. In order to research the loading of a structure in a large-scale confinement, the blast chamber discussed in section 2.1 was furnished with heavy compound pendulum of 5tons on its open end. The pendulum area ratio to the area of the open end was 0.52. A photograph of the pendulum addition to the chamber is shown in Fig. 8.

In one specific test series with this experimental arrangement, it was of interest to see what the effect of directional loading of cylindrical charges would be on the loading of the pendulum in this semi-confined arrangement. For this test series, 0.5 kg and 1 kg charges were hung from a wire-cradle in the centre of chamber, 2 m from the chamber wall and 2 m from the pendulum. The charge axis was varied from horizontal (on the symmetry axis of the chamber) and vertical (perpendicular to the symmetry axis). The charges were detonated in the direction of the pendulum and in the opposite direction of the pendulum for the horizontal case, and downward in the vertical case. Pressure measurements were obtained from face-on sensors in the chamber wall directly perpendicular to the charge position for up to 50 ms. In Table 1, the scaled specific impulse is shown for composition B charges of 0.5 kg, 1 kg and 1.5 kg as well as a 1 kg RDX based charge containing 20% aluminium, in various firing orientations. In the second last column, the impulse calculated directly from the pendulum motion (which includes diffraction loading) is shown, while in the last column, the impulse calculated from integrating the reflected pressure

recordings are depicted. Each result is the average of two charges and the difference between the two firings are indicated as the measuring error margin.

At the hand of the very small differences measured between similar firings it is concluded that the initial impulsive loading contribution to the total loading for different firing orientations is only significant for small charges where the detonation product volume generated is small. For the larger charges, the dynamic loading and static pressure build up due to reactive behaviour in the chamber overrides the effect of the firing orientation observed in the free field case.

#### 2.4. Blast mitigation

For obvious reasons, The field of blast mitigation is the most studied sub-discipline in blast protection research. The field can be sub-divided into two areas that present different challenges. These areas are passive mitigation and active mitigation.

##### 2.4.1. Passive mitigation of blast

This study field focus on the inherent ability of materials and substances (or combinations thereof) with different geometries, morphologies and internal properties, that can lower either the peak pressure or the blast impulse when placed between the explosive threat and the target [28–33]. The use of a passive blast mitigation solution is the preferred option in blast protection applications due to the simplicity of fitment and functionality [28].

Many areas of interest have been identified in this study field and the challenge is to assimilate the fundamental knowledge into cost effective and practical concepts that covers a particular requirement. Progress is made in the field of low density or granular material additions to barriers [33,34] that can attenuate parameters of the blast wave, but in some cases, the application limits require further investigation [35]. Progress has also been made in investigating materials and manufacturing methodologies in construction that can provide mitigation against blast for buildings [36–40].

The protection of armoured vehicles presents an additional challenge over and above blast protection, in the sense that protection against ballistic threats is equally important. The metallic V-hull design for passive mitigation of mine detonations partially fulfils this requirement and is still successfully applied in MRAP designs. Adaptations have been suggested to enhance the geometrical passive blast mitigation effect [39]. Blast mitigating seats have also been introduced for armoured vehicles [40].

Side-blast incidents due to large IEDs present a major challenge



Fig. 8. 5-Ton compound pendulum fitted to the open end of the semi-confined blast chamber.

Table 1

Scaled specific impulse for different charges in various firing orientations.

Composition	Mass/kg	Orientation	Scaled specific impulse/(kPa · kg <sup>-1/3</sup> )	Scaled specific impulse (pressure) <sup>c</sup> /(kPa · kg <sup>-1/3</sup> )
Composition B	0.5	Vertical	0.34 (only one firing)	–
Composition B	0.5	Horizontal <sup>a</sup>	0.40 ± 0.00	0.76 ± 0.03
Composition B	1	Horizontal <sup>a</sup>	0.73 ± 0.02	1.04 ± 0.05
Composition B	1	Horizontal <sup>b</sup>	0.74 ± 0.01	1.05 ± 0.05
RDX/Al	1	Vertical	1.01 ± 0.05	–
RDX/Al	1	Horizontal <sup>b</sup>	1.4 ± 0.05	1.37 ± 0.01

<sup>a</sup> In the direction of the pendulum.

<sup>b</sup> Opposite direction of the pendulum.

<sup>c</sup> Average of two reflected pressure records integrated up to 50 ms. Transducer positions in the chamber wall across the charge and perpendicular to the chamber symmetry axis.

to armoured vehicles in recent times and several passive blast mitigation methodologies are investigated [41,42] that does not compromise the ballistic protection or mobility of the vehicle. Ongoing research in this area is required to counter continually changing threat characteristics.

#### 2.4.2. Active mitigation

In contrast with other structures, the restriction in adding additional mass complicates the application of passive methodologies in blast protection on vehicles. The concept of active mitigation systems for blast threats in military theatres evolved naturally from fire suppression systems and mitigation systems for explosions in other spheres [43]. Active blast mitigation methodologies, mostly using water deluge systems, have been considered in the mining sector for some time [44,45].

An active blast mitigation system is lucrative from the perspective that it can be deployed on demand (only when the threat is activated) which has positive implications for armoured vehicles in terms of mass and spatial requirements. There are two distinct regimes where mitigation system can be functional:

- mitigation the incoming blast wave, i.e. reducing the blast pressure, impulse or temperature,
- mitigation of the effect of the blast load on the vehicle, i.e. compensating for the impulse effect on the vehicle or countering structural effects.

The complication with active blast mitigation in the armoured vehicle domain is that usually the encounters take place at relatively short distances and therefore deployment time is severely constrained. Three major challenges are presented for deployment of active methodologies on armoured vehicles:

- sensing and positively confirming the existence of the blast threat,
- determining the location and action envelope of the threat,
- deploying the active mitigation method in time for it to counter the threat.

Despite the perceived complexities in the application of active blast mitigation systems in practice, several ideas have been investigated [46,47]. Furthermore, active mitigation systems have recently been introduced in armoured vehicle systems [48,49]. The CSIR investigated a momentum cancellation concept based on the firing of counter charges on small scale and intermediate scale [50]. Promising results were achieved and the concept is under further investigation.

#### 2.5. Other fields

There are several fields of blast protection which are equally (if not more) challenging, that is not covered in this paper. Some of these fields are blast protection in marine environments, blast protection for individuals and soldiers, combined protection for blast and penetration effects and protection against the high temperature environment associated with some blast scenarios. All these fields are relevant in the context of real world scenarios and warrants investigation.

### 3. Summary

Some of the challenges identified in the blast protection environment have been reviewed at the hand of knowledge assimilated from open literature and experimental investigations conducted at the CSIR. The complexity of real world blast events imposes

stringent requirements on practical blast protection solutions and this complexity warrants in-depth experimental methodologies to complement or validate modelling results.

## Acknowledgements

The author dedicates this paper to two colleagues in the year of their retirement, Dr Izak Snyman and Marius Olivier, who have contributed greatly to the research efforts over the years. The defence research and development board is acknowledged for funding research efforts and Rheinmetall-Denel Munitions is acknowledged for contributions in collaboration experiments.

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