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A new standard for predicting lung injury inflicted by Friedlander blast waves

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ABSTRACT

An important blast injury mechanism is the rupture of the lungs and the gastrointestinal tract. In explosives safety studies and threat analysis the empirical model of Bowen is often used to quantify this mechanism. The original model predicts the lethality for a person in front of a reflecting surface caused by simple Friedlander blast waves. Bowen extended the applicability to persons in prone position and standing in the free field by making assumptions about the pressure dose at these positions. Based on new experimental data, some authors recently concluded that the lethality for a person standing in the free field is the same as for a person in front of a reflecting surface, contrary to Bowen's assumptions.

In this article, we show that only for a short duration blast wave, the load on a person standing in the free field is comparable to that on a person in front of a reflecting surface. For long positive phase durations, a safe and conservative assumption is that the load on a person standing in the free field is the sum of the side-on overpressure and the dynamic pressure. This hypothesis is supported by common knowledge about blast waves and is illustrated with numerical blast simulations.

In a step by step derivation we present a new standard for the prediction of lethality caused by Friedlander blast waves, which will be included in the NATO Explosives Safety Manual AASTP-4. The result is a comprehensive engineering model that can be easily applied in calculations.

1. Introduction

Accidental explosions involving ammunition, explosives and pyrotechnics are occurring quite frequently. The most notable recent ones took place at a naval base in Cyprus in 2011, killing 13 people, and at an ammunition disposal plant in Bulgaria in 2014 with 15 fatalities. Accidents also occur during storage and transport of commercial explosives and fertilizers, in particular ammonium nitrate. Examples are the disasters at fertilizer plants in Toulouse, France, in 2001, and West, Texas (US), in 2013, where 30 and 15 people were killed respectively (Pittman et al., 2014; Han et al., 2015). Ammonium nitrate was also likely involved in the recent explosions in Tianjin (China) in 2015.

The causes of fatality and injury due to an explosion may range from impacts of fragments and debris, to thermal effects and blast loading of the human body. Blast related injuries include ear drum rupture, traumatic brain injury, acceleration of the body followed by blunt impact, and injury to the air filled organs like the lungs and the gastrointestinal tract. Understanding these phenomena is essential to define appropriate safety distances and to minimize the risk of handling explosives. The knowledge is also important to design protection measures for civilians and military against deliberate explosive attacks.

Within NATO, the AC/326 SG C develops policy and guidelines for ammunition transport and storage safety. Scientific support regarding explosion effects, consequences and risk analysis is provided by a technical working group. The main objectives of this working group are to compare and harmonize models, and to keep the NATO Explosives Safety Manual AASTP-4 (2008) up to date. Blast injury to the air-filled organs, in this study referred to as lung injury, has been a permanent agenda item for a number of years. The current paper presents a new standard for the prediction of this phenomenon, which is to be included in the next version of the

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manual. The objective of this study is to obtain a prediction method for lethality inflicted by relatively simple Friedlander blast waves (Baker et al., 1983). Lethality in complex blast wave environments is a relevant subject as well, but falls out of the scope of the NATO manual and so of this study.

An illustration of the overpressure-time profile of a Friedlander blast wave is given in Fig. 1. At the arrival of the shock wave at $t = 0$ s, a discontinuous jump to the peak overpressure (P) takes place. An exponential decay brings the overpressure back to zero after the positive phase duration (T), followed by a negative pressure phase.

This profile can be measured by a pressure transducer at some distance from a high explosive charge, well away from any reflecting surface. It is the blast load experienced by a surface parallel to the blast wave direction, the so-called incident or side-on overpressure (P_s). Both the positive and the negative phase may influence the lethality. In tests and accidents the blast wave is often characterised by the positive phase duration and peak overpressure. Therefore we discuss the relation between lethality and the positive phase of the blast. In this article we will also refer to the positive phase impulse, which is the area below the overpressure-time curve.

The distance up to which lung injury may be lethal, varies between just a few metres and about 100 m for hemispherical surface bursts between 1 and 10,000 kg TNT. Fragments from ammunition shells and/or debris generated after break-up of a storage structure will typically reach much larger distances, in some cases over 1000 m. This means that lung injury is only a dominant phenomenon at the close-range and in particular in directions where debris and fragments are scarce or absent. This is the case for a bare explosive charge (i.e. without a fragmenting casing), or for a person standing behind a protection wall or in a pit.

Section 2 presents an overview of the most important literature on lung injury due to blast. In Section 3 we take a closer look at blast loading of the body, and we present a new hypothesis for the blast load on a person in the free field. A step by step derivation of the new standard for the prediction of lung injury is presented in Section 4, followed by guidance for its application in Section 5. Conclusions follow in Section 6.

2. State-of-the-art

2.1. Bowen's model and the pressure dose concept

The empirical model of (Bowen et al., 1968) for lung injury due to blast is widely recognized and used in explosives safety studies and threat analysis. The model predicts the lethality for a person in front of a reflecting surface. The model is based on 2097 tests with 13 animal species mostly in front of a reflecting surface and both with a shock tube and high explosive charges. The reflected peak pressure and positive phase duration are the characteristics that the lethality is correlated to. Scaling was employed to account for differences in ambient pressure and the mass of the various animal species and a human.

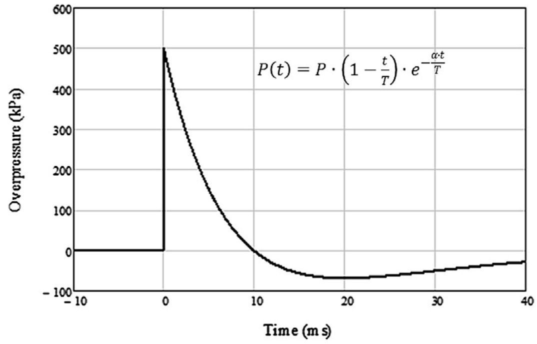

Fig. 1. Illustration of a Friedlander blast wave with $P = 500$ kPa, positive phase duration $T = 10$ ms, and decay constant $\alpha = 1$.

The so-called pressure dose concept was developed to extend the applicability of Bowen's model to a person in prone position (long axis of the body parallel to the blast wave direction) and a person standing in the free field. The assumptions are given in the second column of Table 1.

Q and P_r can be expressed in terms of P_s using elementary shock wave physics (Kinney and Graham, 1985):

$$Q = \frac{P_s^2}{2 \cdot \gamma \cdot P_0 + (\gamma - 1) \cdot P_s} \tag{1}$$

$$P_r = 2 \cdot P_s + (\gamma + 1) \cdot Q \tag{2}$$

In these equations γ is the ratio of specific heats of air with a value of about 1.4, and P_0 the ambient pressure (101.3 kPa at sea level). For very large side-on overpressures (>10 MPa), Eqs. (1) and (2) underestimate the dynamic pressure and the reflected overpressure (TM5-855-1, 1998). Since the lethality is practically 100% for these high overpressure levels, the underestimation does not significantly influence the lethality data.

The assumed blast loads in Table 1 are compared in Fig. 2 and presented as a function of the incident overpressure. This figure shows that P_r is at least twice as large as P_s, but it increases to a factor of about 8 for higher overpressures. The dynamic pressure does not give a substantial contribution below about 50 kPa side-on overpressure, but for higher overpressures it may be two times larger than the side-on overpressure. This comparison shows that there is a substantial difference between the blast loads, and thus in the probability of lethality for the three orientations.

2.2. Discussion about the pressure dose concept

Richmond (2002) analysed new test data with standing "bio-targets" without a reflecting surface. Although this is not well verifiable, his conclusion was that for $T > 6$–10 ms the data is in good agreement with Bowen's pressure dose concept. For $T < 2$ ms, Bowen's lethality criterion underestimates the lethality in the free field, leading to an unsafe prediction.

Based on new experimental data, Bass, Rafaels, and Panzer recently concluded that the lethality for a person standing in the free field is the same as for a person in front of a reflecting surface (see Table 1). Initially their research focussed on short duration blast ($T < 30$ ms). Many more animal test data were used than in Bowen's and Richmond's analysis; regarding the larger animals: 1100 versus 350. Bass et al. (2006, 2008) claimed that in the short duration regime the body itself acts as a reflecting surface. He concluded that "the pressure dose for both bodies against a reflecting surface and bodies parallel to the blast for short durations is assumed to be the reflected pressure." Rafaels et al. (2008) reported that for long duration blasts ($T > 10$ ms) the difference between the two orientations is statistically significant. However, in 2010 Rafaels reached the opposite conclusion. Panzer et al. (2012) combined short and long duration data and did not further consider differences in orientation.

The consequences of the different assumptions for a person standing in the free field can be observed in Fig. 3. In this figure, the lethality curves predicted by Bowen and Bass have been plotted with P_s on the vertical axis. Bass' assumption of a reflected blast load implies that lethality already occurs at a low value of P_s.