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

M.M. van der Voort[1], K.B. Holm[2], P.O. Kummer[3], J.A. Teland[2], J.C.A.M. van Doormaal[4], H.P.A. Dijkers[4]

[1]*Munitions Safety Information Analysis Center (NATO), B 1550, BZ S054, B-1110, Brussels, Belgium*

[2]*Norwegian Defence Research Establishment (FFI), P.O. Box 25, NO-2027 Kjeller, Norway*

[3]*Bienz, Kummer, and Partners, Langaegertenstrasse 6, CH-8125 Zollikerberg, Switzerland*

[4]*TNO, Lange Kleiweg 137, P.O. Box 45, 2280 AA Rijswijk, The Netherlands*

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.

Keywords

Blast, injury, lethality, lung, explosion, risk

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., 2014). Ammonium nitrate was also likely involved in the recent explosions in Tianjin (China) in 2015.

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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 manual. The objective of this study is to obtain a prediction method for lethality inflicted by relatively simple Friedlander blast waves (Baker, 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 Figure 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.

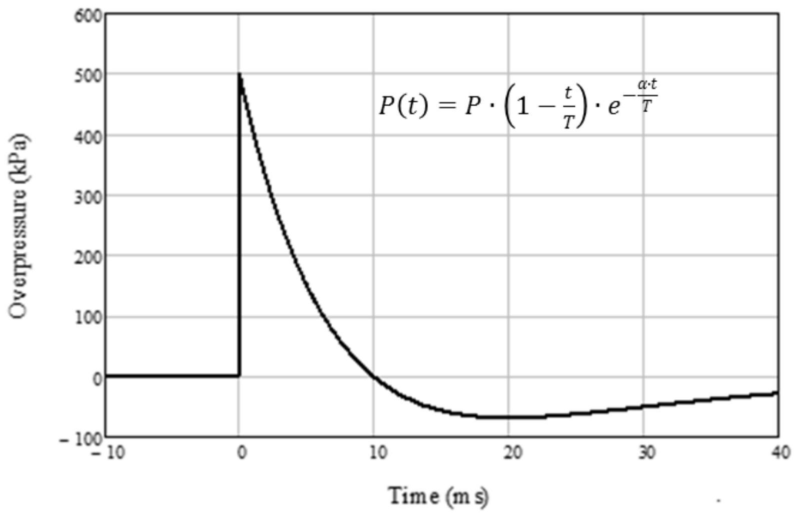

Figure 1. Illustration of a Friedlander blast wave with P = 500 kPa, positive phase duration T = 10 ms, and decay constant α = 1.

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.

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The distance up to which lung injury may be lethal, varies between just a few meters 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 1,000 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, 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 2,097 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.

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, 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), Eq. 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.

Table 1. Pressure dose concept for persons in three orientations according to Bowen (1968) and others. The symbols refer to: Reflected overpressure (P_r), Side-on overpressure (P_s), Dynamic pressure (Q), and Stagnation pressure (P_s + Q).

Person orientation/posture	Blast load Peak overpressure	
	Bowen (1968)	Bass (2006, 2008) Rafaels (2008, 2010) Panzer (2012)
In front of reflecting surface	P_r	P_r

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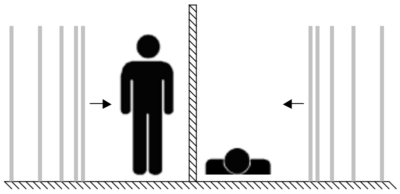
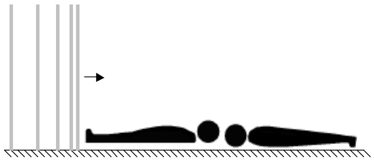
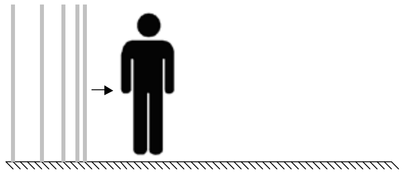
		
Prone 	P_s	P_s
Standing in the free field 	$P_s + Q$	P_r

The assumed blast loads in Table 1 are compared in Figure 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.

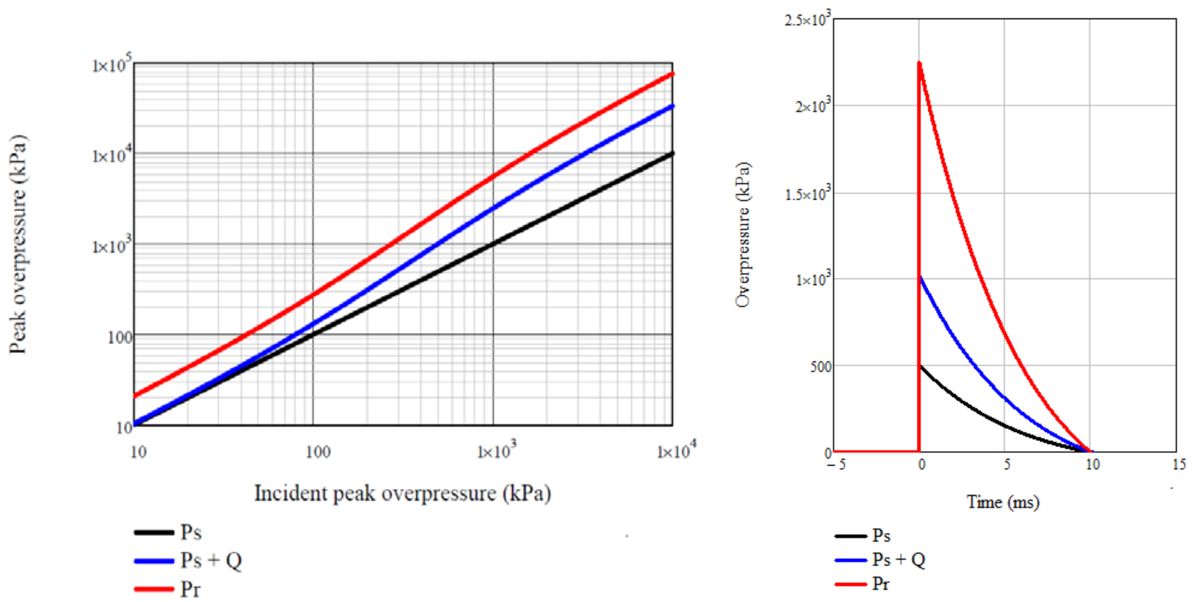


Figure 2. Left: Peak overpressures for blast loads given in Table 1 as a function of incident overpressure. Right: Overpressure as a function of time assuming the Friedlander wave shape for P_s = 500 kPa and T = 10 ms. The negative phase is left out of consideration.

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2.2 Discussion about the pressure dose concept

Richmond (2002) analysed new test data with standing “biotargets” without a reflecting surface. Although this is not well verifiable, his conclusion was that for T > 6 to 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 and 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 Figure 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. Therefore Bass’ curves are lower than Bowen’s curves. Because Bass and Rafaels included more data and didn’t distinguish between the orientations, the spread in their model is larger than in Bowen’s model.

Bass et al. assume that Bowen’s scaling with ambient pressure is correct for long, but not for short durations. In the model for all durations (Panzer et al, 2012), a scaling factor is used that gives a continuous transition between the ranges with and without scaling. When comparing with Bowen’s model in Figure 3 an ambient pressure of 101.3 kPa is assumed. Load curves for three hemispherical charge masses based on Kingery and Bulmash (1984), have been added to Figure 3 for comparison.

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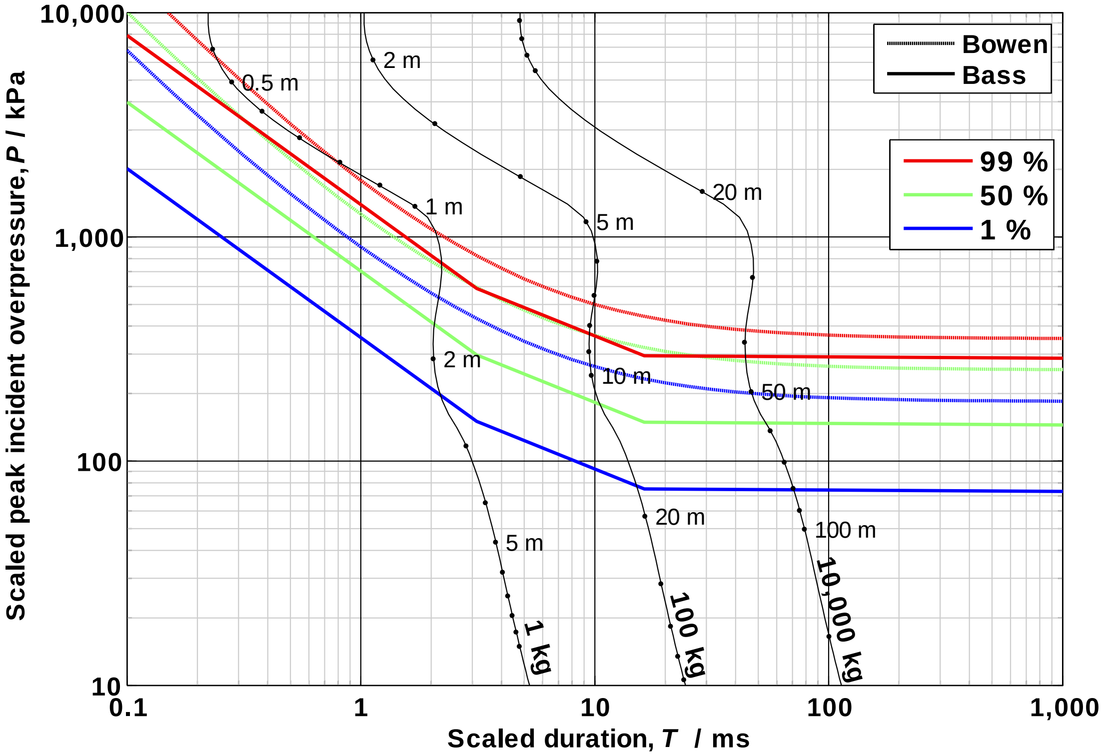

Figure 3. Scaled incident peak overpressure versus scaled duration for three lethality levels (1, 50 and 99%). Comparison of Bass and Bowen for a person standing in the free field. Load curves for a hemispherical surface burst of 1, 100, and 1,000 kg are shown as well.

Comparing the assumptions in Table 1 and their consequences in Figure 3 we conclude that even for relatively simple Friedlander blast waves consensus is still to be reached. An alternative hypothesis for the blast load on a person standing in the free field will be presented in Section 3.

3. A closer look at the blast loading of a person

Within the NATO technical working group on explosives safety risk analysis, lung injury due to blast has been a permanent agenda item for a number of years. In this group the following hypothesis has been investigated in order to improve the pressure dose concept:

For blast waves with short positive phase durations, 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, the load on a person standing in the free field is lower than for a person in front of a reflecting wall.

This hypothesis is supported by common knowledge about blast waves, and is illustrated by numerical blast simulations. A description follows in the next paragraphs.

3.1 Basic analysis

When a blast wave hits a body in the free field, the front face of the body (the side of the body facing the blast source) is first loaded by P_r. The load on the side and the rear of the body is more or less equal to the P_s of the incident wave that passes and wraps around the body. Due to the pressure difference between the front and the sides of the body, relaxation waves propagate from the edges of the front face. This reduces the load at the front from P_r to P_s + Q. The reduction is especially relevant

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when T is larger than the time required for the pressure release, also called clearing time. According to (UFC, 2008) the clearing time t_c for a human of width W_h (m) may be approximated with the expression

$$t_c(P) = \frac{2 \cdot W_h}{C(P)} \quad (3)$$

In this equation C(P) is the sound velocity (m/s) in the reflected region, which depends on the local overpressure P. We define short, intermediate, and long duration blast as follows:

Short duration: $T \leq t_c(P)$ (4)

Intermediate: $t_c(P) < T \leq 10 \cdot t_c(P)$

Long duration: $T \geq 10 \cdot t_c(P)$

The criteria for short and long duration blast are plotted in Figure 4. For W_h, we have taken representative values of 0.305 and 0.5 m. The first value is the diameter of the standard Blast Test Device (BTD) that is often used in experiments to represent the thorax of a standing person (Yu, et al., 1990). The results show that for P_s < 50 kPa the transition between short and long duration blast roughly takes place between 2 and 20 ms. This is consistent with the observations of Richmond (2002). For P_s > 100 kPa, the transition region shifts to smaller positive phase durations in the order of tenths of ms due to the significant increase of the speed of sound.

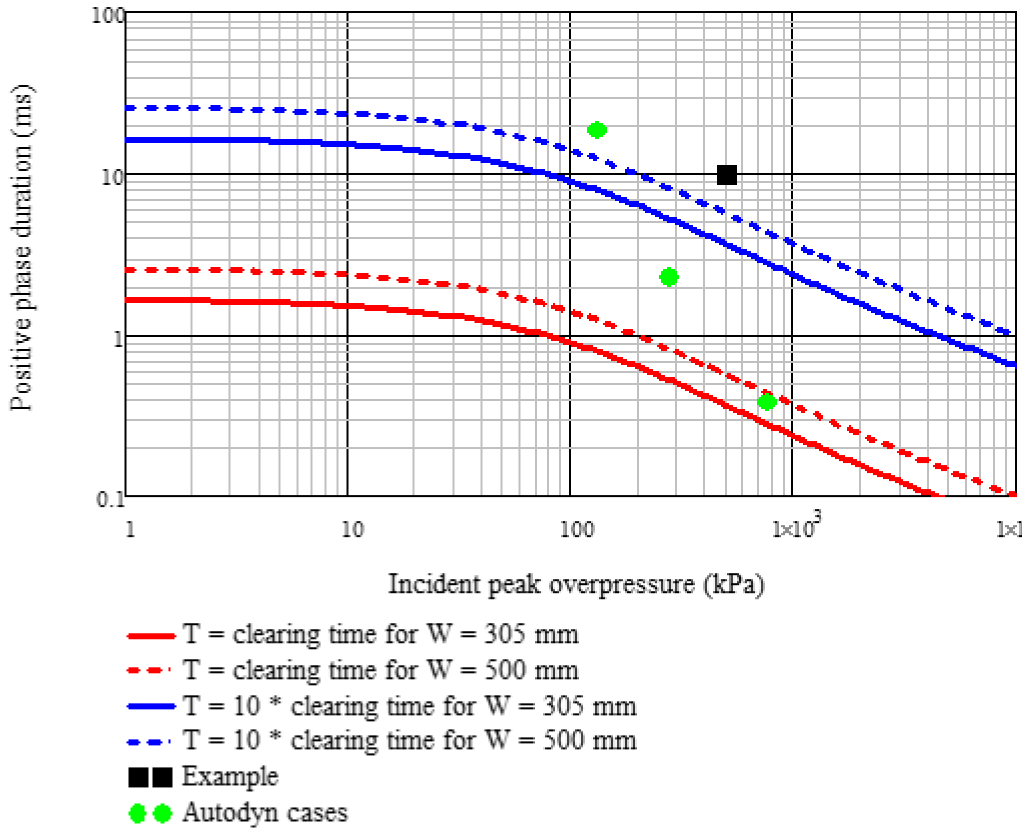

Figure 4. Positive phase duration of the incident blast wave versus incident peak overpressure. Definition of short and long duration blast based on clearing time.

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Figure 5 shows overpressure-time profiles at the front, side and rear of a BTD for a blast wave with P_s = 500 kPa and T = 10 ms. With Figure 4 (datapoint "Example") we determine that this blast wave falls in the long duration regime. Figure 5 also shows blast loads based on the assumptions of Bass (P_r) and Bowen (P_s + Q) for this situation. Based on the above description the blast load at the front of the BTD consists of a reflected overpressure spike that drops to P_s + Q due to clearing. Compared to the assumptions by Bass this greatly reduces the impulse and damage potential. For long duration blast Bowen's pressure dose concept is the most representative for the front. The blast load at the sides and rear of the body is equal to P_s, but with a slight time delay. The delay equals $\frac{W_h}{2 \cdot C(P)}$ for the side, and $\frac{W_h}{C(P)}$ for the rear.

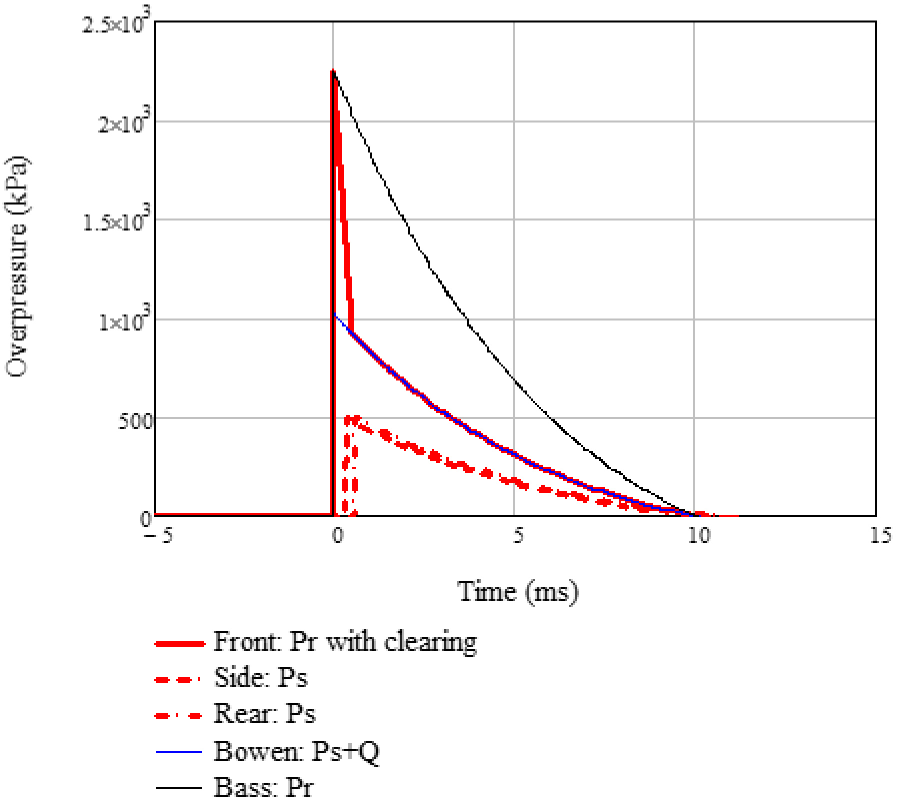

Figure 5. Overpressure as a function of time for a long duration blast load on a BTD in the free field. Results are shown for the front, side and rear, and also blast loads assumed by Bowen and Bass et al. are shown. The Friedlander wave shape has been used with an incident peak overpressure of 500 kPa and positive phase duration of 10 ms. The reflected blast load is shown with a clearing time of 0.4 ms. The negative phase is left out of consideration.

For a short duration blast wave the clearing process is too slow to take effect, and the load on the front of the body is P_r, which is consistent with Bass' assumptions. It should be realized that the sides and rear of the body are again loaded with the side-on overpressure, but with a time delay.

The process of blast loading a body in front of a reflecting surface is initially the same as in the free field. First a reflection forms at the front, which then starts to clear and propagate to the sides. However, this process is disturbed by the reflecting wall. After a time delay of $\frac{W_h}{C(P)}$, a reflected wave starts travelling back, which can be observed in the loads as a second pressure peak on top of the incoming blast wave. This phenomena is investigated in more detail with numerical blast simulations in Paragraph 3.2.

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3.2 Detailed analysis with numerical simulation

A more detailed analysis has been made by numerical simulations with a BTD in the free field and in front of a reflecting surface (near wall). Simulations have been performed with the code Autodyn for three different charge mass-distance combinations (Teland, 2012, Teland and van Doormaal, 2012, the first case has not been published previously). The charge was spherical, and the distance was measured between the centre of the charge and the centre of the BTD. The three cases give P_s and T values within the short, intermediate and long duration regime. The values just before the blast wave arrives at the BTD have been added to Figure 4 ("Autodyn cases"). The simulation results are shown in Figure 6 and 7. For symmetry reasons the two side gauges of the BTD always give the same results.

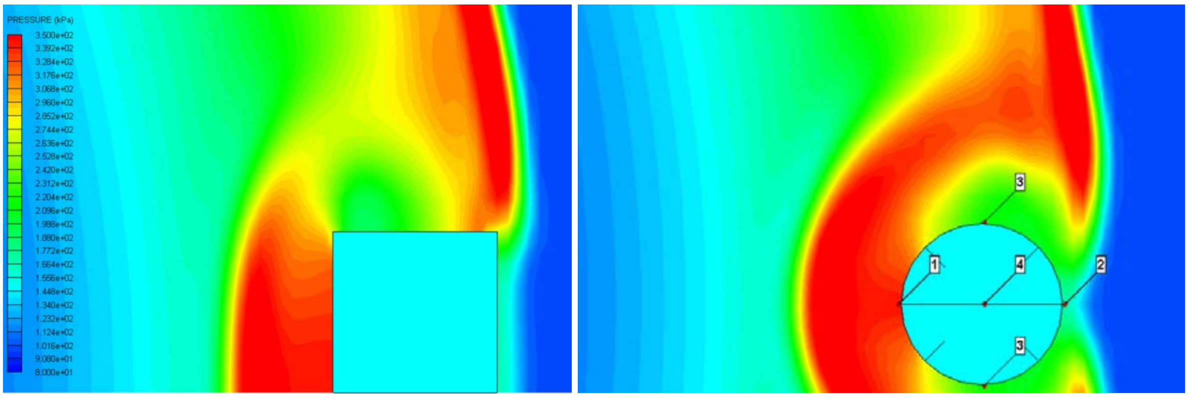
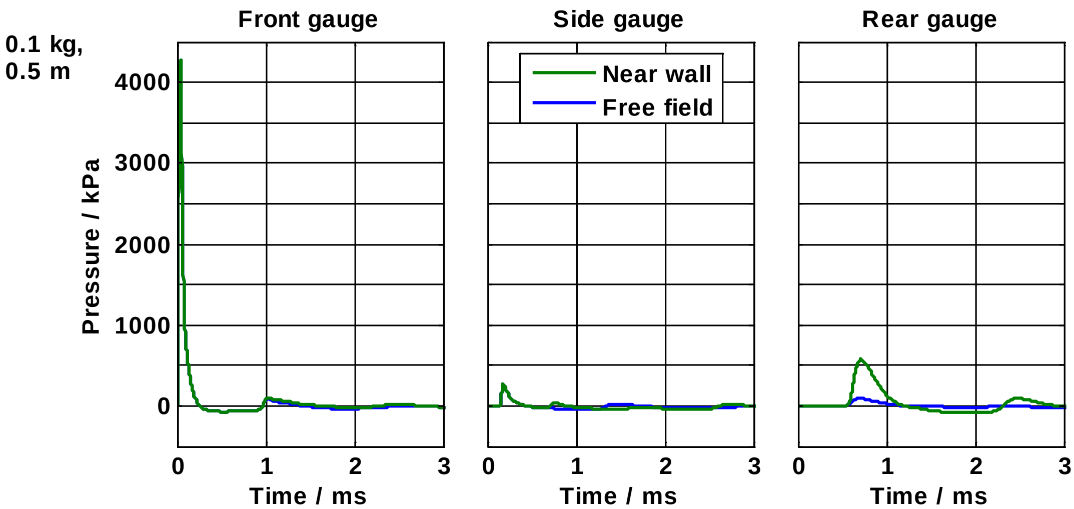


Figure 6. Simulation overpressure result for 9 kg at 3.4 m from a BTD in the free field. Side view (left), top view (right). The shock propagates from left to right. The location of pressure gauges on the front (1), sides (3) and rear (2) have also been indicated.



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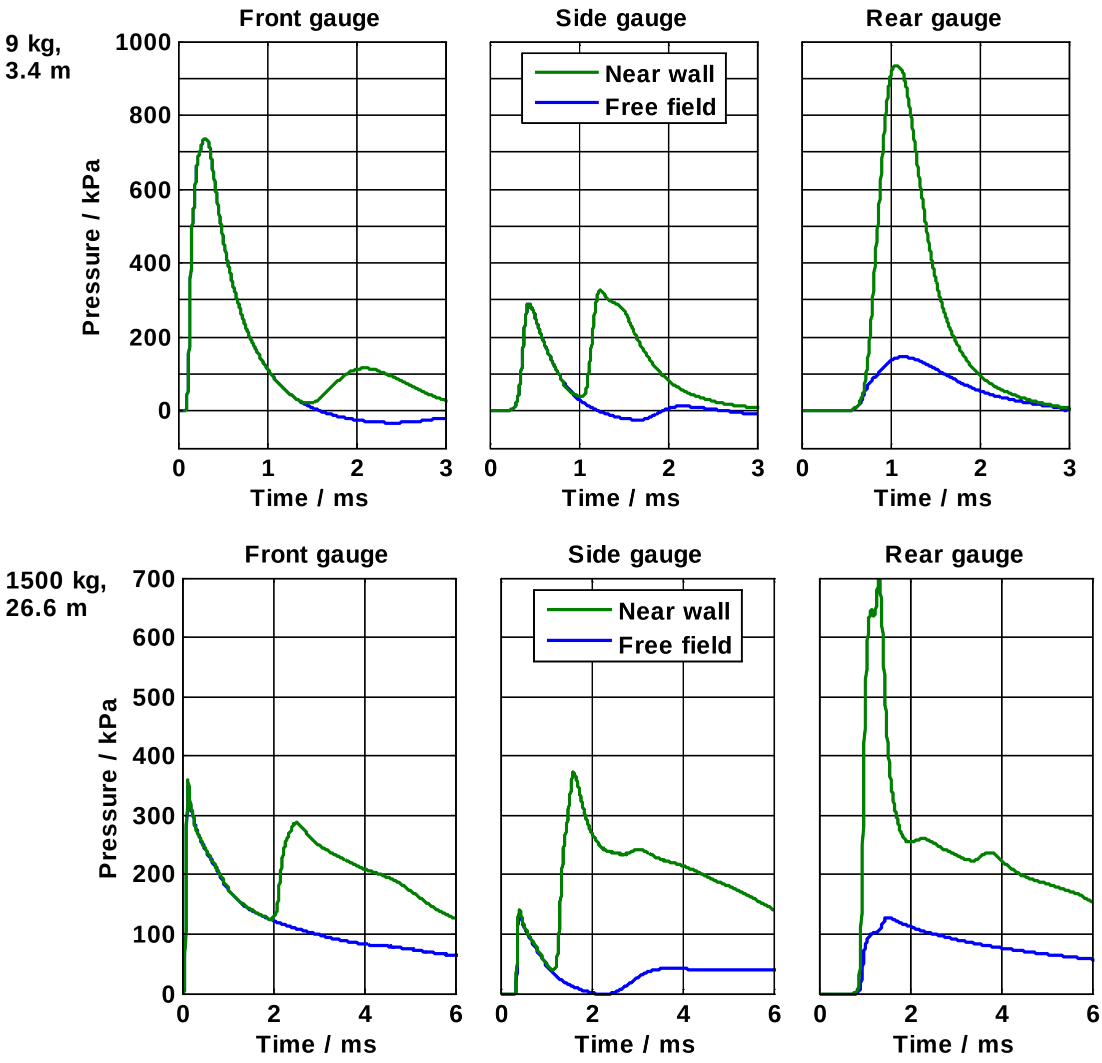

Figure 7. Overpressure versus time for front, rear and side pressure gauges of a BTD placed near a surface and in the free field. Results for three cases (Teland, 2012, Teland and van Doormaal, 2012, the first case has not been published previously).

The four pressure-time signals measured at the BTD have been used as input to the Axelsson model (1996). This model represents the human thorax as a mass-spring system, and gives an injury prediction, defined as the Adjusted Severity of Injury Index (ASII), as output. The ASII values as well as their meaning are shown in Table 2. The results show the difference between the injury predicted for the free field and near a wall.

Table 2. ASII predictions based on the Axelsson model for the three cases and for the free field and near wall situation.

Case	Charge mass (kg)	Distance (m)	ASII			
			Free field		Near wall	
1	0.1	0.5	0.17	No injury	0.32	Trace to slight injury
2	9	3.4	0.53	Slight injury	2.7	Moderate to extensive injury
3	1500	26.6	0.31	Trace to slight injury	2.5	Moderate to extensive injury

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Case 1 (0.1 kg at 0.5 m)

For case 1 Autodyn gives P_s = 758 kPa and T = 0.38 ms, and therefore falls in the short duration regime. The largest overpressure is measured at the front of the BTD independent of the presence of a wall. In this regime the BTD (or body) itself acts as a reflecting surface, consistent with the remarks made by Bass, et al. The overpressure at the front gauge and the two side gauges in the free field and near wall scenario are more or less identical, whereas the rear gauge has a higher overpressure for the near wall scenario. The Axelsson model therefore predicts a slightly higher ASII for the near wall scenario (see Table 2). However, given that three of the four gauges are very similar and that the difference in the fourth gauges is not dominant, it seems reasonable to say that for short durations, the injury for near wall and free field are approximately the same.

Case 3 (1500 kg at 26.6 m)

For case 3 Autodyn gives P_s = 131 kPa and T = 18.6 ms, and therefore falls in the long duration regime. The blast loads in the near wall scenario are all comparable to a reflected blast load, with the the largest overpressure observed at the rear of the BTD. At the side the reflection that propagates back is significantly larger than the incoming blast wave. At the front the two peaks are of the same order. The blast load is much larger in the near wall scenario than in the free field scenario, and as a result the Axelsson model (see Table 2) predicts a much larger injury. The blast loads in the free field scenario are more or less consistent with the basic analysis for long duration blast presented in Paragraph 3.1. At the front a reflected spike forms an addition to the P_s + Q load. The impulse, and hence the damage potential of this spike is however limited. At the sides and rear the load is better represented by a P_s load. At the sides a wake takes place that was not identified in the basic analysis. This wake can also be noted as the green areas on the sides of the BTD in Figure 6. As a result the blast impulse is relatively low at these locations. The formation of the wake depends on the assumed shape of the body. In reality the shape will deviate from the cylindrical BTD, but nevertheless a wake and associated pressure drop will occur. This is an important phenomenon that will occur in all long duration cases. The authors expect that the combined effect of the spike at the front and the lower overpressures at the sides are best represented by a blast load equal to P_s + Q or less. Therefore taking P_s + Q as the representative blast load for long duration blast is a safe and conservative assumption. A large amount of numerical simulations would be required to generate a more realistic long duration blast load. This is far beyond the scope of the current study. There are no valid arguments to deviate from Bowen's assumption for long duration blast, particularly as these are supported by some experimental results.

Case 2 (9 kg at 3.4 m)

Case 2 falls in the intermediate regime. It shows phenomena and trends that are between the short and long duration regime. Further details are omitted for this case.

4. Derivation of new standard for lung injury

In this section we derive a new standard for prediction of lung injury for a person in front of a reflecting surface, prone, and standing in the free field. The new standard is based on Bowen's original equation, the pressure dose concept and the results from Section 3.

As a first step we reformulate Bowen's original equation in terms of P_s for the three orientations, by using Eq. 1 and 2.

For a person standing in front of a reflecting surface we can write:

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$$P_r = 2 \cdot P_s + \frac{(\gamma+1)\cdot P_s^2}{2\cdot\gamma\cdot P_0+(\gamma-1)\cdot P_s} = P_{sw} \cdot e^{c\cdot(y-5)} \cdot \left(1 + a \cdot T^{-b}\right) \qquad (5)$$

The parameters (P_{sw} = 424 kPa , a = 6.76, b = 1.064, c = 0.1788) are the fit parameters in Bowen's original equation, and y is the probit value which is directly related to a probability. This equation can be rewritten with just the side-on overpressure on the left hand side, and a new set of parameters (indicated with accents).

$$P_s = P_{sw}' \cdot e^{c'\cdot(y-5)} \cdot \left(1 + a' \cdot T^{-b'}\right) \qquad (6)$$

The new parameters have been determined by fitting Eq. 6 to Eq. 5, for the 0.1, 1, 10, 50, 90 and 99 % curves, and are given in Table 3. In Figure 8 both equations are plotted showing an excellent agreement.

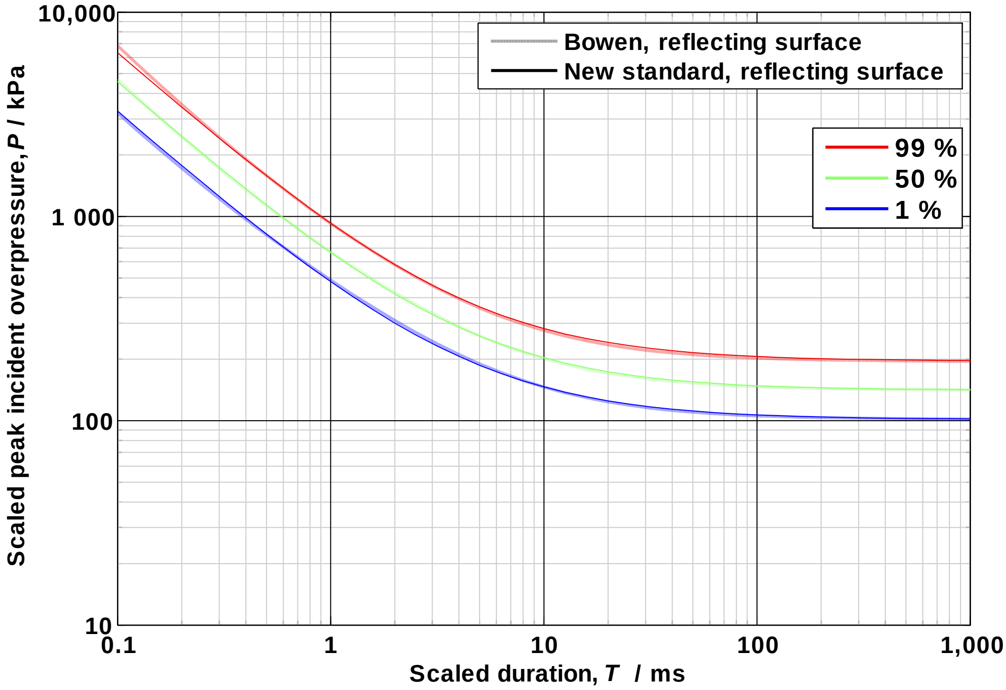

Figure 8. Scaled incident peak overpressure versus scaled duration for three lethality levels (1, 50 and 99%). Refitting of Bowen's original model for a person in front of a reflecting surface.

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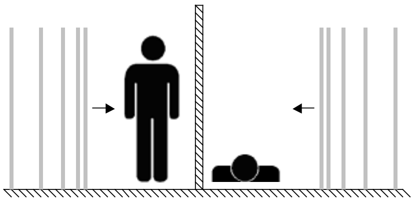
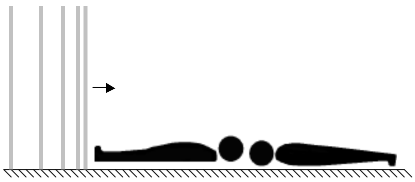
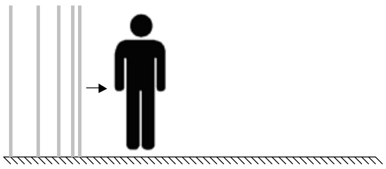
Table 3. New standard for lung injury due to blast.

Person orientation	P_s is the side-on overpressure!			
	P_{sw} (kPa)	a	b	c
In front of reflecting surface 	141	3.727	0.9249	0.1414
Prone 	424	6.76	1.064	0.1788
Standing in the free field 	255	1.771	0.9269	0.1376

For a person in prone position a similar approach means that the reflected pressure in Bowen's equation is replaced with the side-on overpressure, and hence the fit parameters are identical to the original values determined by Bowen.

For a person standing in the free field the new standard (Figure 9: "New standard, standing in the free field") is based on the hypothesis presented in Section 3, and the appropriate blast load transitions between 2 and 20 ms from P_r (Figure 9: "Bowen, reflecting surface") to P_s + Q (Figure 9: "Bowen,

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standing in the free field").

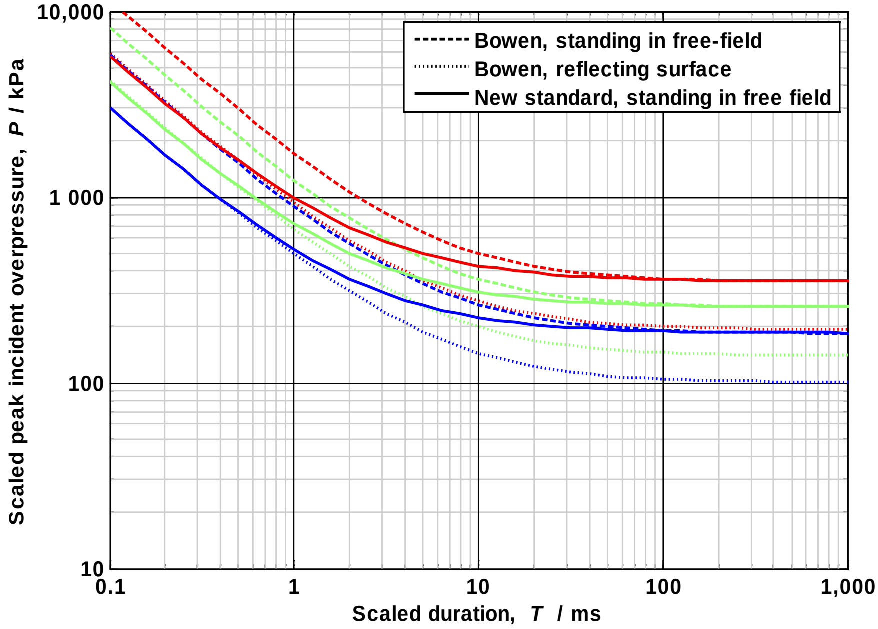

Figure 9. Scaled incident peak overpressure versus scaled duration for three lethality levels (1, 50 and 99%). New standard for a person standing in the free field which consists of a transition between 2 and 20 ms from Bowen's model (reflecting surface) to Bowen's model (standing in free field).

Figure 10 shows a comparison of Bass, Bowen, and the new standard for a person standing in the free field. For this purpose overpressures and positive phase durations have been calculated based on Kingery and Bulmash (1984) for three hemispherical charge masses. The figure shows that for the largest charge mass of 10,000 kg TNT, the lethal distances predicted by the new standard and Bowen's model are virtually identical. For smaller charge masses of 100 and 1 kg TNT, the lethal distances predicted by the new standard move towards the model predictions of Bass, et al.. For even smaller charge masses, the new standard does not approach the model by Bass, et al. asymptotically, because of the larger spread in Bass' overpressure-time curves.

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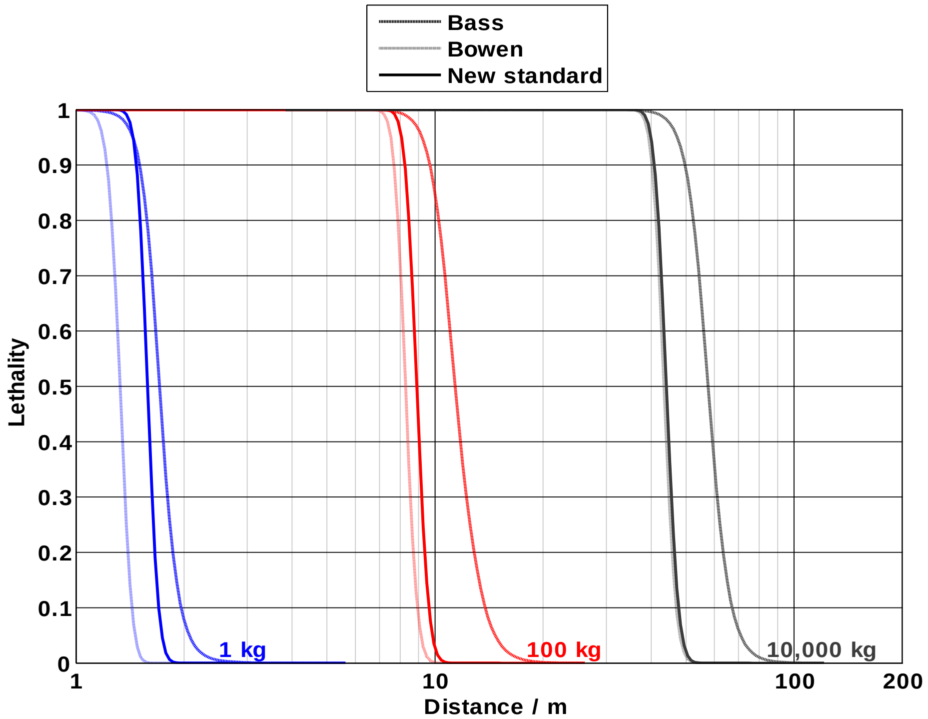

Figure 10. Lethality versus distance. Comparison of Bass, Bowen, and the new standard for a person standing in the free field for charge masses of 1, 100, and 10,000 kg TNT.

5. Guidance for application of the new standard

In this section we give guidance for the application of the presented new standard. The following steps have to be taken:

1. Determine the overpressure-time profile of a blast wave just before it impacts the person of interest. In principle this can be done by measurement or calculation[1].
   - Verify if the overpressure time profile resembles the Friedlander blast wave shape. When the deviation is large, more detailed calculation methods are required, e.g. (Axelsson, et al., 1996) or (van Doormaal et al., 2012).
   - Determine the side-on peak overpressure P_s (kPa) and positive phase duration T (ms).
2. Register the orientation of the person of interest (in front of a reflecting surface, prone or standing in the free field).

The lethality can now be determined as follows:

3. Determine the probit value (y), using Eq. 7 and the appropriate parameters in Table 3.

$$y = 5 + \frac{1}{c} \cdot ln\left(\frac{P_s}{P_{sw} \cdot (1 + a \cdot T^{-b})}\right) \quad (7)$$

[1] An example is the model by Kingery & Bulmash (1984) for blast from a (hemi)spherical TNT charge. It is a safe and conservative approach to apply the distance measured between the centre of the charge and the nearest point of a standing person. Because Bowen's model is based on overpressure measurements in a reflecting surface behind an exposed animal it is defendable to apply the distance measured between the centre of the charge and the furthest point of a standing person.

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4. Determine the lethality (L) using Eq. 8 or alternatively a table that translates probit values to probability:

$$L = \int_{-\infty}^{y-5} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2} dx \quad (8)$$

Less accurately, the lethality can also be read from Figure 11. The determined P_s and T can be directly applied to the vertical and horizontal axis respectively. The resulting data point in the chart can then be compared with the lethality curves for the appropriate orientation.

In Figure 12 lethality has been plotted versus distance for three charge masses and the three orientations, assuming a hemispherical surface burst (Kingery and Bulmash, 1984).

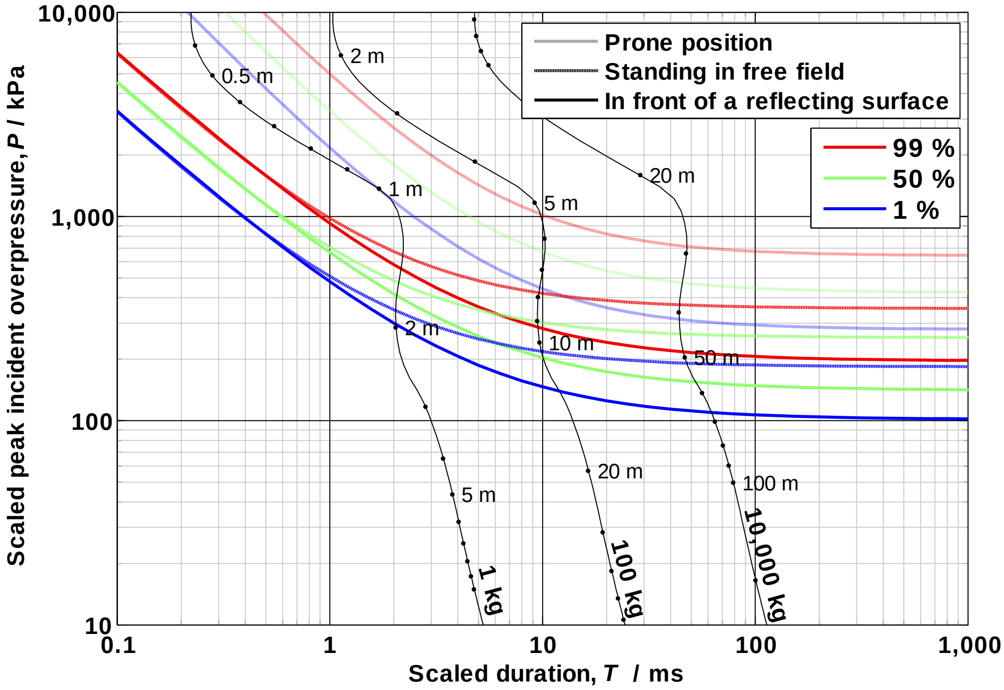

Figure 11. Scaled incident peak overpressure versus scaled duration for three lethality levels (1, 50 and 99%). New standard for a person in front of a reflecting surface, prone and standing in the free field. Load curves for a hemispherical surface burst of 1, 100, and 10,000 kg TNT are shown as well.

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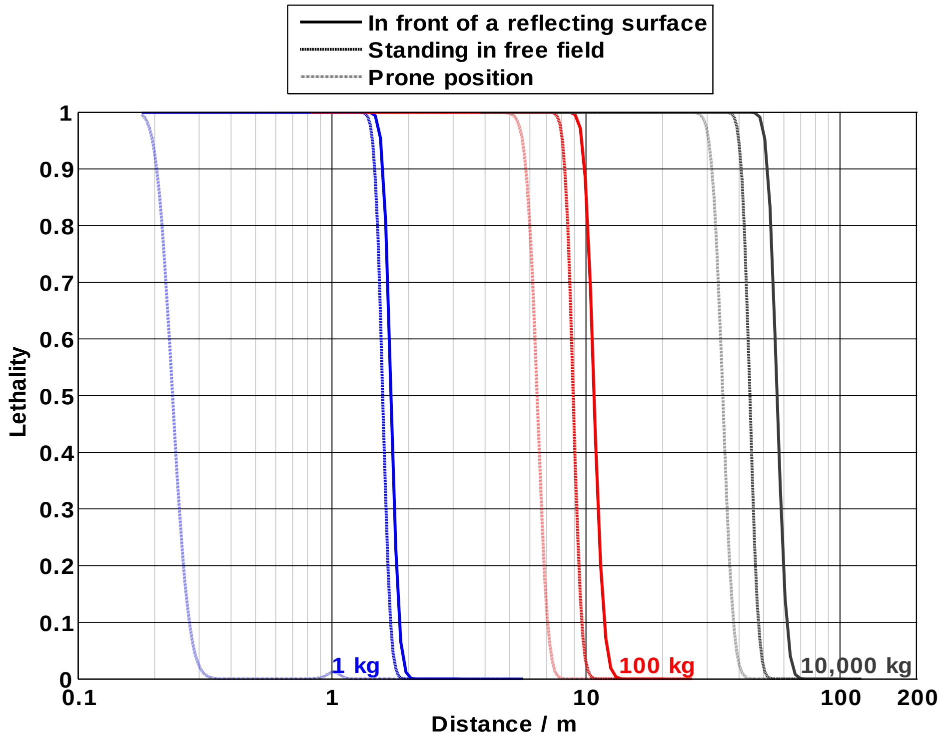

Figure 12. Lethality versus distance determined with the new standard for a person in front of a reflecting surface, prone, and standing in the free field, for charge masses of 1, 100, and 10,000 kg TNT.

6. Conclusions

An important blast injury mechanism is the rupture of the lungs and the gastrointestinal tract. 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 for the blast load on a person standing in the free field is the sum of the side-on overpressure and the dynamic pressure.

A new standard has been developed 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. This is in line with the ambition of the AASTP-4 Working Group to harmonize explosion effect and consequence models in the field of explosion safety risk analysis.

Possible future improvements to the modelling of lethality due to blast can be made by analysing the large amount of experimental data that was obtained after 1968 in line with the findings in this paper. The use of the mass-spring models of the human thorax may also help to understand the response to blast, and possibly extend models to non-lethal injury and more complex blast waves.

Another topic for future studies would be the prone position. In this and many other studies, the focus was on the free field and the effects of a reflecting wall.

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The authors do not support animal testing for this research topic. In this study only existing animal data was employed to draw conclusions about vulnerability to blast and to support the development of protection measures.

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