Blast wave injury prediction models for complex scenarios

J.A. Teland[1], J.C.A.M. van Doormaal[2]

[1] *Norwegian Defence Research Establishment (FFI), Postboks 25, 2027 Kjeller, Norway,*
e-mail: jan.teland@ffi.no
[2] *TNO, Lange Kleiweg 137, 2288 GJ Rijswijk, The Netherlands*

Abstract

Blast waves from explosions can cause lethal injuries to humans. Development of injury criteria has been ongoing for many years, but with the main focus on free field conditions. However, with terrorist actions as a new threat, explosions in urban areas have become of much more interest. Urban areas provide a complex environment for blast wave expansion, thus increasing the difficulty of injury and lethality prediction.

TNO and FFI have examined the topic of blast injury in a complex environment to find the most appropriate injury criterion and develop a quick analysis procedure. A review of available models found the Axelsson model to be the most promising. It can predict the injury of the air-filled organs in both complex and free-field blast situations. Unfortunately, it involves a cumbersome procedure, requiring four pressure signals on a so-called Blast Test Device (BTD) as input. However, several single point (SP) methods based on Axelsson to avoid the BTD have successfully been developed.

A potential problem with the Axelsson model (both BTD and derived SP models) is that the injury prediction is only calibrated against data from very small charges (maximum 1.36 kg). To further examine the validity of the Axelsson model, results can be compared with predictions by the Bowen/Bass curves, as these formulas are calibrated to a different and much larger data set, both with explosives and in shock tubes.

Since the Bowen/Bass models are only applicable for scenarios where the subject is either in an open field or next to a reflecting wall (whereas the Axelsson model is supposed to be valid for any complex scenario), a large range of such scenarios for different charge sizes were constructed and numerically simulated to provide input to the different models.

Comparison between the injury predictions generally showed good agreement, except that the Axelsson and Bowen/Bass models diverged considerably for very short but high amplitude blast waves. The reason for this discrepancy was investigated and found to be due to uncertainties in the empirical formulas for blast wave parameters produced by a given explosive charge.

Key words : Blast wave, Injury model, Complex geometry, Blast Test Device, Single Point

1. Introduction

Blast waves from explosions can cause lethal injuries to humans. Development of injury criteria has been ongoing for many years, but with the main focus on free field conditions. However, with terrorist actions as a new threat, explosions in urban areas have become of much more interest. Urban areas provide a complex environment for blast wave expansion, thus increasing the difficulty of the injury and lethality prediction.

TNO and FFI have performed a study on the topic of primary blast injury (i.e injury to the air containing organs, particularly the lungs) in complex environments. The goal of this research was to find the most appropriate injury criterion and to develop a quick and simple analysis procedure.

2. Injury models for "open field" situations

It has been known for several hundred years that blast waves can cause injuries to humans. However, the degree of injury was not examined systematically on a large scale until after

World War 2, when the development of nuclear weapons meant that blast waves could propagate over very long distances.

2.1. Bowen

In the 1960s many animal experiments were performed at the Lovelace Foundation to examine the lethality from exposure to blast waves. In a report by Bowen et. al. [1] these were summarised and related to human injury, leading to the widely known and used "Bowen curves".

The animal experiments in total involved 2097 animals of 13 different species. The blast waves were generated either by a detonation or from a shock tube and in most experiments the animals were exposed near a reflecting surface. After scaling, this resulted in a number of curves expressing the probability of human survival as a function of maximum pressure P and blast wave duration T.

The original lethality curves of Bowen are strictly only applicable to situations where the subject is standing against a wall. However, by making a few assumptions, Bowen was able to create curves for two other scenarios as well:

- Human standing in an open field
- Prone person (with body parallell to blast wave propagation axis).

To achieve this, Bowen invented the concept of "pressure dose". He then postulated that the same curves could be used for these scenarios, but with a different "pressure dose" as input (the duration is assumed to remain the same in all cases).

- For a person near a wall, the pressure dose is the reflected pressure (as before).
- For a person in an open field, the pressure dose is the incident pressure p_s + the dynamic pressure $q = \frac{1}{2}\rho v^2 = \frac{5p_s^2}{2p_s + 14p_0}$.
- For a prone person, the pressure is just the incident pressure p_s.

2.2. Bass and Rafaels

Recently, Bass and Rafaels [2,3] have included more data in the analysis to produce updated survival curves. These curves were also extended to the open field and prone situation, but in a different way than the Bowen-curves. For a prone situation, the extension was similar with Bass assuming (as Bowen) that the pressure dose was the incident pressure p_s. Bass pointed out that there was still no data available for testing this hypothesis.

However, for an open field situation, Bass and Bowen diverge considerably in their approach. Instead of the incident pressure p_s plus dynamic pressure q, Bass states that the reflected pressure p_r from an imaginary wall (behind the subject) is the pressure dose. Consequently, for lethality, there is no difference between standing in an open field and standing near a wall.

2.3. Discussion

The Bowen/Bass curves are plotted together in Figure 1 for different orientations. We note that for the prone situation they are more or less identical, except for the dynamic regime (roughly durations of 5-50 ms). Also the near wall scenarios are almost the same except for the same region.

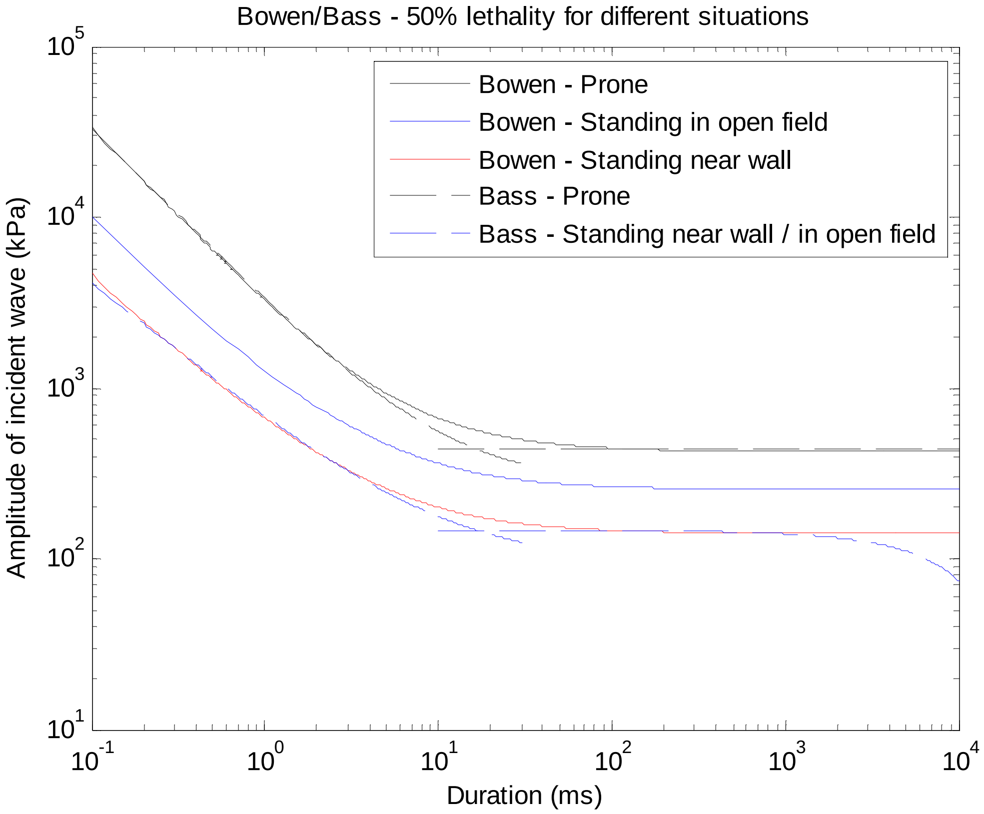


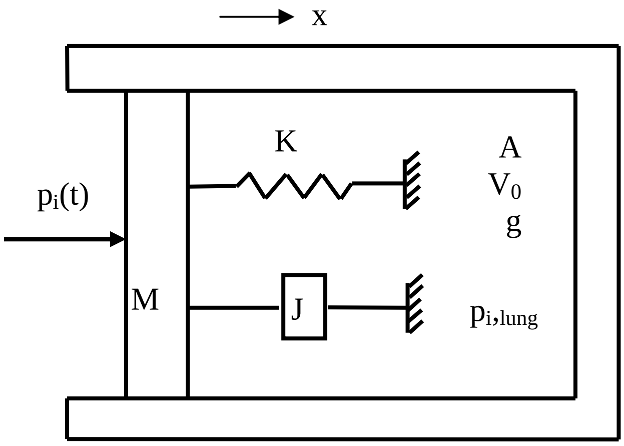
Figure 1. *Bowen 50% lethality curves compared with Bass curves for various orientations*

The big difference lies in the open field situation, which the Bass formula considers to be much more dangerous than Bowen (in fact, just as dangerous as being near a wall). Finally, the Bass curves have an odd behaviour for very long durations, but this is not too important in practise. Thus, the new experimental data included by Bass has not made all that much difference for the lethality prediction, but the different assumption on converting to an open field situation has.

Both the Bowen and Bass formulas have several limitations. First, they assume a free field blast wave and are therefore not applicable to complex blast waves that develop in a situation where the initial wave reflects against one or several walls/obstructions. Secondly, they only consider lethality (probability of death) and not the degree of injury.

3. Axelsson BTD

Axelsson [4] addressed the shortcomings of the Bowen curves by creating a mathematical model which could take input data for a blast wave of any shape and provide an injury prediction for a person exposed to this wave. The Axelsson BTD model is a single degree of freedom (SDOF) system meant to describe the chest wall response of a human exposed to a given blast wave (Figure 2). It requires pressure input data from four transducers located at 90 degrees interval around a 305 mm diameter Blast Test Device (BTD) (Figure 3), exposed to the relevant blast wave. Besides lung injury, the Axelsson BTD model also accounts for injuries to the respiratory tract, the thorax and the abdominal area. (Stuhmiller [5] has developed a similar mathematical model, but since the actual model is not public, it was not studied any further).



Name	Explanation
A	Effective area
M	Effective mass
V_0	Lung gas volume at x=0
J	Damping factor
K	Spring constant
p_0	Ambient pressure
$p_i(t)$	External (blast) loading pressure
$p_{i,lung}(t)$	Lung pressure
g	Polytropic exponent for gas in lungs
x	Chest wall displacement

Figure 2. *Mathematical model of the thorax according to Axelsson [4]*

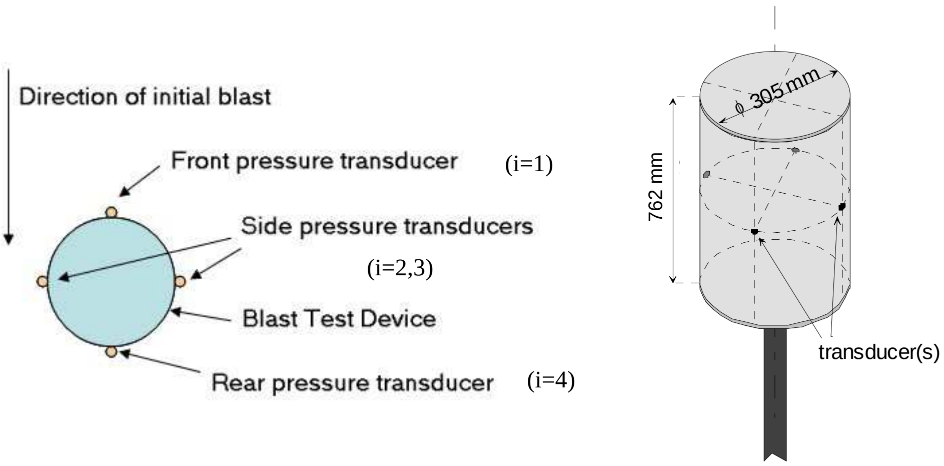


Figure 3. *Blast Test Device*

The mathematical formulas for the Axelsson BTD model are expressed by the four independent differential equations of (1).

$$M \cdot \frac{d^2 x_i}{dt^2} + J \cdot \frac{dx_i}{dt} + K \cdot x_i = A \cdot \left[p_i(t) - p_{i,lung}(t) \right] \qquad i = 1,2,3,4$$

$$p_{i,lung}(t) = p_0 \left(\frac{V_0}{V_0 - A \cdot x_i} \right)^g \qquad (1)$$

The values of the model parameters are given in Table 1. However, it is not stated anywhere in Axelssons original article [4] how these were derived.

For each of the four $p_i(t)$ pressure histories measured on the BTD, Equation (1) can be solved for chest wall positions $x_i(t)$, chest wall velocities $v_i(t)$ and lung pressure $p_{i,lung}(t)$. There are no restrictions on the input pressure histories $p_i(t)$, so the Axelsson BTD model is not limited only to free field blast waves.

Table 1: Model parameters for the Axelsson BTD model (from [4])

Parameter	Units	70 kg body	Scaling Factor
M	kg	2.03	(M/70)
J	Ns/m	696	$(M/70)^{2/3}$
K	N/m	989	$(M/70)^{1/3}$
A	m^2	0.082	$(M/70)^{2/3}$
V_0	m^3	0.00182	(M/70)
g		1.2	

Axelsson found the following quantity, called the Chest Wall Velocity Predictor (V), to provide the best correlation as a measure for injury:

$$V = \frac{1}{4}\sum_{i=1}^{4} \max\left(v_i(t)\right) \tag{2}$$

Johnson [6] performed experiments using small explosive charges (57g – 1361g C4) with anesthetized sheep in closed containers with BTDs as prescribed by the Axelsson BTD model to record the pressure histories. After the experiments, the injuries of the sheep were assessed and quantified with an ASII-number indicating the injury level in each case. Evidently the experiments showed huge scattering, but by using data from 177 of the 255 sheep, Axelsson used curvefitting of these data to derive Equation (3) for the correlation between ASII and V:

$$ASII = (0.124 + 0.117V)^{2.63} \tag{3}$$

The correlation between injury level, ASII and V, is shown in Table 2. We see that the various regimes are overlapping due to the large uncertainties.

Table 2. Correlation between injury level, ASII and V**.**

Injury Level	ASII	V (m/s)
No injury	0.0-0.2	0.0-3.6
Trace to slight	0.2-1.0	3.6-7.5
Slight to moderate	0.3-1.9	4.3-9.8
Moderate to extensive	1.0-7.1	7.5-16.9
>50% Lethality	>3.6	>12.8

The Axelsson BTD model solves the problems mentioned with the Bowen/Bass approach, but unfortunately the price is added complexity. The BTD procedure complicates things considerably since each experiment or simulation can only predict injury at the BTD location. Fortunately, a variety of single point (SP) models have been developed to address this problem.

4. Single Point models

In this chapter, we will briefly outline some SP models for blast injury prediction. All these models are based on the Axelsson BTD model, but by making various assumptions they are able to give an injury estimate without the need for a BTD. For those SP models, only the side-on pressure history at the relevant location is required.

4.1. Weathervane SP

The Weathervane SP model [7] is an approach that tries, based on the single point (SP) field pressure, to estimate what the pressure would have been for the four sensors if a BTD had been present.

A fundamental assumption in the Weathervane SP model is that one of the (non-existing) pressure sensors always faces directly towards the blast wave. Given that, the procedure to estimate what the four sensors would have measured is as follows:

Sensor facing blast wave $p_1(t)$: Maximum pressure and total impulse are assumed equal to the reflected blast load on a rigid infinite wall. These values can easily be found analytically.

The full pressure history $p_1(t)$ is then represented by a modified Friedlander form for the pressure wave. The decay parameter μ is found by an iteration procedure until the total reflected impulse is correct.

Side sensors $p_2(t)$ and $p_3(t)$: Assumed equal to the field (side-on) pressure.

Rear sensor $p_4(t)$: Assumed equal to the ambient pressure p_0.

These pressure histories are then used as input to the Axelsson BTD model (Equation (1)) for calculation of the chest wall velocity predictor V.

4.2. Modified Weathervane SP

A problem with the Weathervane model is that finding the front pressure $p_1(t)$ is not straightforward, but involves a cumbersome iteration process to find the correct impulse. For implementation in a hydrocode this is inconvenient. To get around this, an alternative approach is possible, where the Friedlander waveform is not used, but instead the estimated sensor pressure $p_1(t)$ is assumed equal to the reflected pressure from a wall. This will be called the Modified Weathervane model [8,9].

Thus, the estimates for $p_2(t)$, $p_3(t)$ and $p_4(t)$ are exactly the same as in the original Weathervane model, only $p_1(t)$ changes.

4.3. Axelsson SP

The Axelsson SP model is just the Axelsson model without the BTD, but using the single point (SP) field pressure (i.e non-BTD) in the given location as input to the Axelsson differential equations. The four differential equations are then identical, so that $V = \max(v_1)$.

In [10] the relationship between ASII and V was recalibrated for the Axelsson SP model

$$ASII_{SP} = 0.175 \cdot V_{SP}^{\ 1.205}$$

4.4. TNO SP

TNO has developed an approximation procedure of the Axelsson BTD model. The method is fully described in [11]. Instead of solving the four differential equations, the Axelsson chest wall velocity predictor V is estimated from the main blast characteristics: peak pressures, the impulses, and the points in time of the different peaks (see Figure 4). An exact pressure-time curve is not necessary. The calculation procedure consists of a set of equations and a selection procedure (if – then relations). This method is particularly appropriate in combination with semi-empirical load prediction. Also for this SP-approach a specific relationship between ASII and V has been determined.

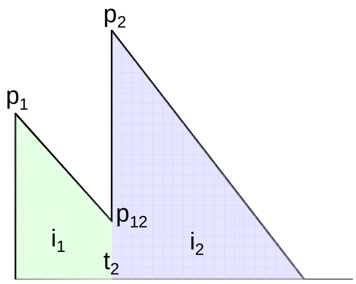


Figure 4: *Relevant characteristics of an arbitrary shock wave with two peaks, used for the approximation procedure of TNO [11].*

4.5. Comparison of SP methods

In [8,9] these SP approaches were compared and shown to agree quite well with the Axelsson BTD model for a wide range of scenarios (different charge sizes (9 kg – 1500 kg) and distances from a wall). In particular, the Axelsson SP model was suited for use in numerical simulations. Comparison of the results given by the models for a few scenarios are shown in Figure 5.

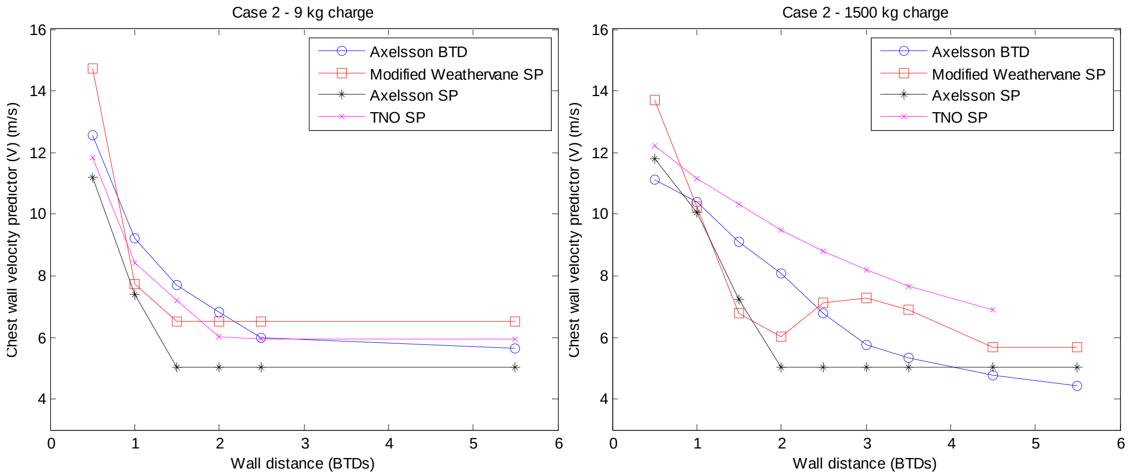


Figure 5: *Chest wall velocity predictor for the different approaches (Case 2: 50% survivability according to Bass), based on 3D AUTODYN simulations*

5. Comparison between the Axelsson models and the Bowen and Bass curves

The Axelsson BTD (and derived SP formulas) have been based exclusively on experiments with relatively small charges (56 g – 1361 g). An interesting question is how they compare with the Bowen/Bass formulas which rely on a much bigger database of experiments.

Since these formulas are quite different from the Axelsson formulas it is not trivial to compare them. The Bowen/Bass curves give probability of death, while Axelsson gives the degree of injury. Further, Bowen/Bass can only be used for ideal detonations with subjects either located in an open field or near a wall, whereas Axelsson, in principle, (if correct) should work for any scenario.

So, to compare the formulas, we need to relate the Axelsson ASII to probability of death. According to Axelsson [4], an ASII=3.6 corresponds to 50% lethality. Assuming that this criterion is correct, we can use numerical simulations to compare predictions for a subject standing in free field or next to a wall for Axelsson BTD, Axelsson SP, Bowen and Bass.

This can be done by defining blast wave scenarios, either in open field or near a wall, which according to Bowen or Bass would give 50% lethality. For the Axelsson models to be in agreement with Bowen or Bass, the predicted ASII for all these situations should be as close to 3.6 as possible. (However, remember that both methods have huge error bands, so exact agreement should not be expected.)

5.1. Definition of 50% lethality scenarios

We will use the same range of charges (9 kg – 1500 kg TNT) as in [8,9], where a study was performed comparing predictions of Axelsson BTD and SP. Additionally we will include 500 g and 1 kg TNT.

The scenarios were defined using the computer program CONWEP. This code uses empirical formulas from the American manual TM-5-855-1 to estimate blast wave parameters for a given charge. For each charge we made iterations with CONWEP until we obtained a distance from the charge that corresponded to a point (P,T) that was on the relevant 50% lethality curve.

We used the 50% lethality curves for both open field and standing near wall for both Bowen and Bass. The final scenarios are given in Table 3. Note that since the Bass approach predicts no difference between standing in an open field and near a wall, the scenarios are exactly the same in both cases. In contrast, the Bowen scenarios differ for the two cases. Also note that for small charges, the Bowen and Bass reflecting wall scenarios are the same, and there is not much difference for bigger charges either. This could, of course, be expected from the comparison between Bowen and Bass in Figure 1.

Table 3: Scenarios that were studied. The distance is from center of the charge and to the rear of the BTD.

	Bass (50%) – open field	**Bowen (50%) – open field**	**Bass (50%) – near wall**	**Bowen (50%) – near wall**
0.5 kg	1.01 m	0.78 m	1.01 m	1.01 m
1 kg	1.35 m	1.06 m	1.35 m	1.35 m
9 kg	3.40 m	2.65 m	3.40 m	3.40 m
20 kg	4.90 m	3.62 m	4.90 m	4.70 m
200 kg	12.40 m	8.85 m	12.40 m	11.65 m
400 kg	16.60 m	11.48 m	16.60 m	15.10 m
1500 kg	26.60 m	18.60 m	26.60 m	24.50 m

5.2. Numerical set-up

The numerical simulations were performed using the ANSYS AUTODYN 13.0 hydrocode [12]. The following set-ups were compared in the simulations:

- Axelsson BTD (3D-simulation involving a BTD, with four gauges at 90 degrees interval).
- Modified Axelsson SP (3D-simulation without BTD and only a single pressure gauge where the BTD centre would have been located).

In all cases, the simulations were run using the following procedure: The detonation and ensuing blast wave propagation was initially spherically symmetric, enabling us to calculate everything in 1D using a grid resolution of 7 mm. The output from this 1D-simulation was then mapped into a coarser Euler Multi-material 3D grid when the situation was no longer spherically symmetric, i.e. when the blast wave reached the BTD. For the 3D-simulations, a graded grid with a resolution of 7 mm around the BTD was used, but a coarser grid further away. The gauge points for the BTD were placed in the Euler grid right outside the BTD.

The air and detonation products were modelled using an Euler Multi-material grid, whereas the BTD was modelled as a rigid boundary on the Euler grid. The standard air and TNT models from the AUTODYN material library were used. Thus, air was modelled as an ideal gas and the TNT was modelled using the JWL-equation.

Example pressure plots from the 3D simulations are shown in Figure 6. The gauge locations on the BTD are also indicated.

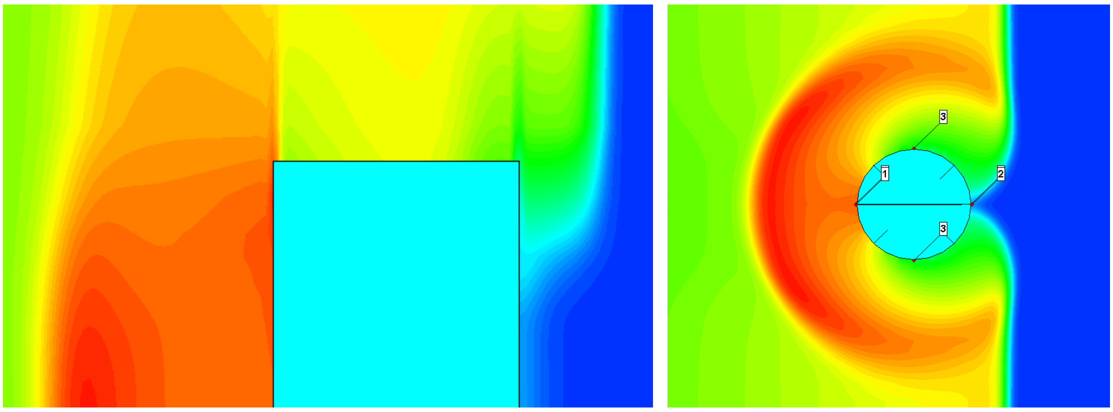


Figure 6: *Pressure plots in the 200 kg simulation from two different viewing angles (side and top)*

5.3. Numerical results for Bass scenarios

The results for the Bass scenarios are plotted in Figure 7. Along the x-axis we have the positive phase duration for the given scenario, along the y-axis the ASII-score. The black horizontal line indicates the 50% lethality level according to Axelsson.

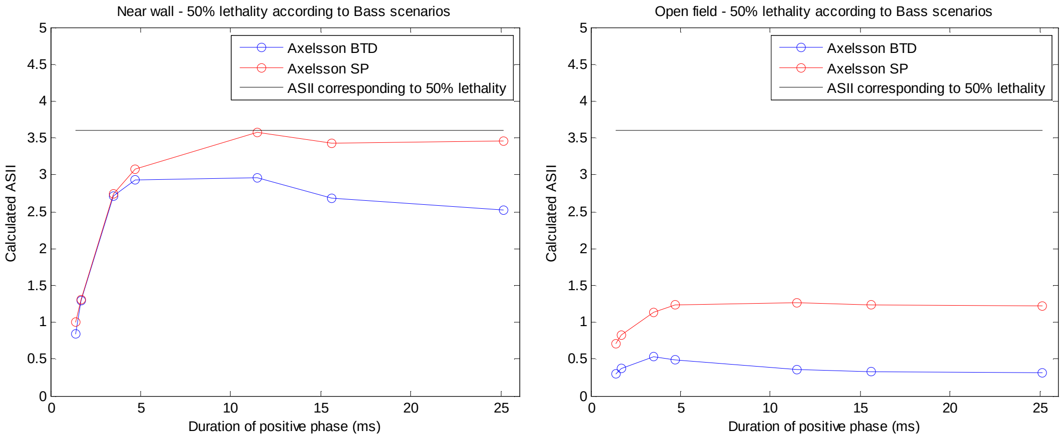


Figure 7: *Applying the Axelsson BTD and SP models to scenarios that according to the Bass injury model should give 50% lethality. (Near wall (left) and Open field (right))*

We note that for the ”near wall” situation there is relatively good agreement between both Axelsson BTD, Axelsson SP and the Bass formula for durations of around 5 ms and upwards. This corresponds to the charges in the range 9 kg – 1500 kg. In contrast, for the “standing in free field” situation, agreement is very poor for all the scenarios. This is due to the Bass injury model predicting that standing near a wall should give the same lethality as standing in an open field, a result which the Axelsson based models are unable to reproduce.

Also note that for the two small charges 500 g and 1 kg TNT (i.e. short positive phase duration), the Axelsson models predict much less injury than the Bass approach, even for the near wall scenarios.

5.4. Numerical results for Bowen scenarios

In Figure 8 we have plotted the results from using the Axelsson BTD and SP models on the Bowen scenarios for 50% lethality.

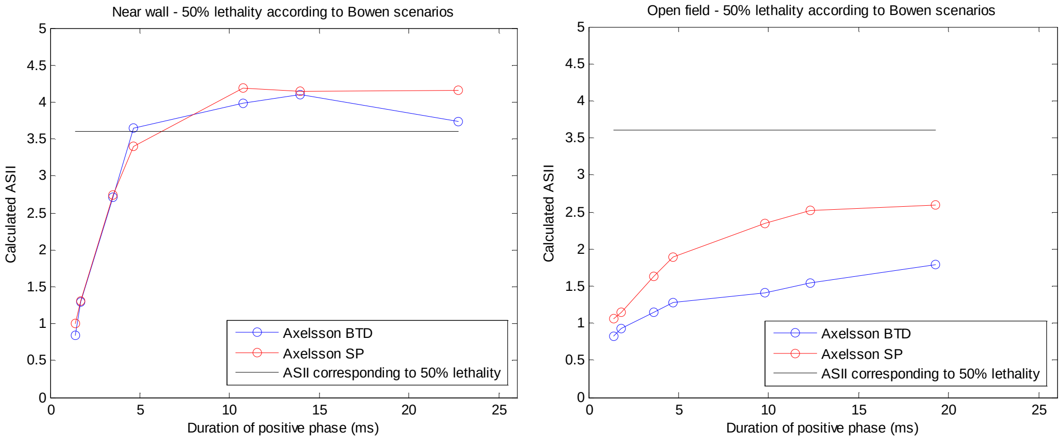


***Figure 8**: Applying the Axelsson BTD and SP models to scenarios that according to the Bowen injury model should give 50% lethality.(Near wall (left), Open field (right))*

Again the agreement is very good for the situation near a wall for a duration of around 5 ms and upwards, corresponding to charges in the range 9 kg – 1500 kg. This is not surprising because the Bowen criterion is almost the same as the Bass criterion for this situation. In an open field, the agreement between Axelsson and Bowen is not equally good, but clearly better than for the Bass scenarios. Further, there is the same tendency of poor agreement for short duration blast waves as for the Bass scenarios.

5.5. Main observations

In both cases there is good agreement between Axelsson BTD and SP, reinforcing our earlier conclusion that Axelsson SP provides a good estimate of Axelsson BTD.

It is interesting to note that the Axelsson model compares particularly well in the near wall scenario, which is exactly the kind of experiments which Bowen and Bass are based on. As mentioned earlier, the lethality curves for open field scenarios are mostly based on assumptions and very few relevant open field experiments have actually been performed.

One open question is why there is so large discrepancy between Axelsson and Bowen/Bass for short durations. In these cases Axelsson suddenly predicts significantly less injury than Bowen and Bass, even for the near reflecting wall scenarios. It may be somewhat surprising that the inconsistency occurs for small charges, which are exactly the charges (56 g – 1361 g) used to calibrate the Axelsson model. If the Bowen and Axelsson models were incompatible, it would have been more natural to expect discrepancies for large charges where the Axelsson model has not been calibrated to data at all. But, instead, the agreement is almost surprisingly good for these charges!

6. Short blast wave durations

The derivation of the Axelsson model has been scrutinized earlier in [10,11] and, despite some uncertainties, no major problems were found. Let us now look closer at how the Bowen curves were derived. One important point is that for short durations (where there seems to be a problem), Bowen did not actually measure the blast wave duration, but instead relied on an old empirical formula for Pentolite by Goodman [14]. In applying this formula to TNT and some other explosives, Bowen assumed that Pentolite had the same behaviour, except that Pentolite releases 10% more energy. Could the use of this old empirical formula possibly have caused problems?

Inspection of the original report by Goodman [14] revealed some intriguing facts. Goodman collected blast wave data (pressure amplitude and duration) from various different sources. He writes that the measurement of positive phase duration was not as precise as the side-on pressure measurements. The data points show quite a bit of scatter and Goodman therefore did not make any least squares curve fit to the data. However, one curve was “drawn by eye” and tabulated in his report. Presumably this tabulation is where Bowen collected the duration data.

Later, new pressure and duration data have been collected by Kingery and Bulmash [15] to create updated curves for the duration (and other airblast parameters). The empirical formulas developed by them are implemented into TM5-855-1 (and consequently CONWEP) and are widely used today.

However, inspection of the original report by Kingery and Bulmash [15] revealed something quite interesting. The authors expressed severe doubts about the interpretation of the experimental data for the positive duration phase:

“When recording overpressures in the range of 10 000 kPa and a negative pressure of less than 100 kPa, then it is very difficult to determine the time of which the overpressure changes to an underpressure. There can be large variations in the individual interpretations of the positive duration of the blast wave”.

In fact, the problems were so significant that Kingery and Bulmash did not base their empirical formula for duration on the relevant data at all. Instead their equation was based solely on hemispherical data using a 1.8 reflection factor. Further investigation revealed the hemispherical data to consist of only 4 tests, each with huge bombs (5, 20, 100 and 500 tons TNT). On comparing this with the (uncertain and not used) free field spherical data, the empirical curve of Kingery and Bulmash did not fit the data at all.

Scaling the experimental results of Goodman and Kingery/Bulmash according to charge mass, we can plot them together with AUTODYN results [13] in the same diagram for comparison. This is done in Figure 9.

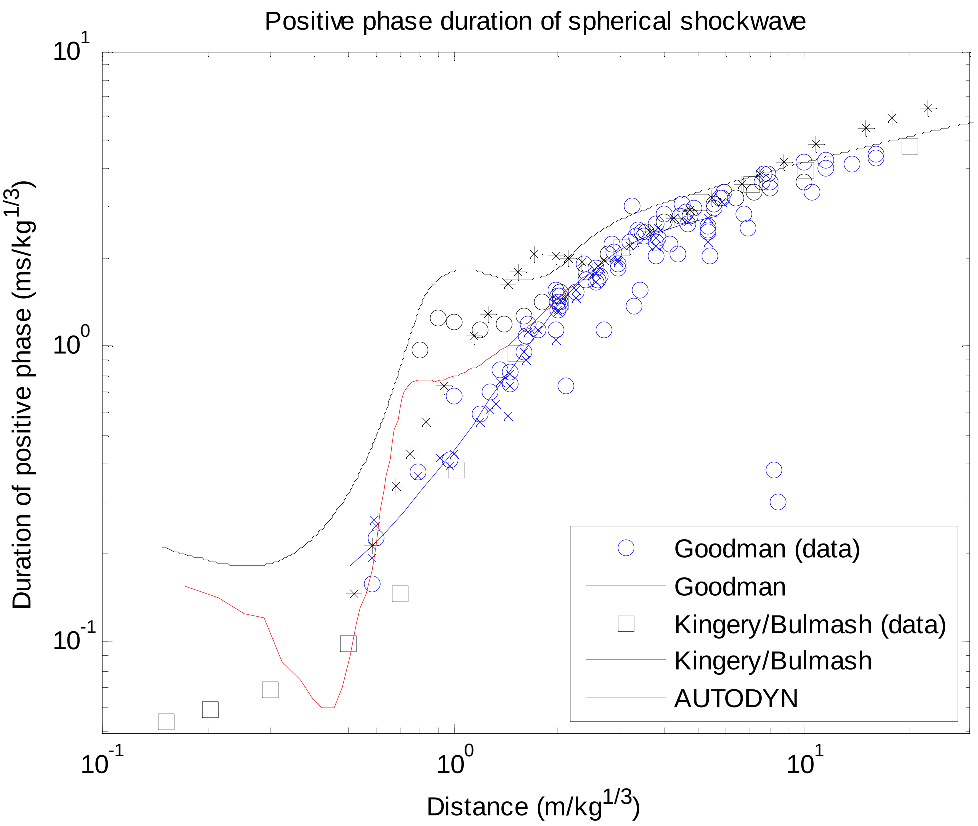


Figure 9: *Comparison of experimental data and predictions of positive phase duration*

There are several aspects of Figure 9 worth commenting on. As already mentioned, the widely used Kingery and Bulmash equation does not fit the experimental data. Most importantly, there is substantial difference between Goodman and Kingery/Bulmash for short distances, whereas they seem to more or less converge for larger distances. This is probably due to it being much more difficult to actually measure duration at short distances. With this insight, we look once more at what happens with the injury prediction formulas for short duration blast waves.

7. **Bowen revisited**

Let us look more closely at the tests Bowen used to obtain his formula, especially those with small charges close to the animal, which therefore gave short blast wave duration. The 12 sheep tests in Bowen's Group 128 are a good example. (According to Bowen 9 of these 12 sheep were exposed in free field, though the reflected pressure is given, either measured or calculated, against an imaginary wall behind the sheep). The charge was 454 g pentolite (which makes it equivalent to a 500 g TNT scenario if pentolite is assumed to release 10% more energy). There were 2 fatalities among the 12 sheep.

The measured (or calculated from an imaginary wall) reflected pressure is given by Bowen as 8681 kPa. This corresponds to an incident shock amplitude to be 1392 kPa. The distance from the charge to the rear of the animal was 68.63 cm according to Bowen. To find the positive phase duration, Bowen consulted the Goodman formula for this distance and obtained a duration of $T=0.288$ ms. This gave Bowen one data point for his analysis: For (0.288 ms, 1392 kPa) there were 2 fatalities in 12 tests.

Bowen had no other choice than to use the Goodman data since the duration measurements were not accurate and no other empirical equation existed at the time. But, if CONWEP (Kingery/Bulmash) had been available for him to use, what would he have found? It turns out that CONWEP gives a duration of $T=1.26$ ms for the same scenario, which is an enormous difference from Goodman. This would have given Bowen a very different data point for his analysis: For (1.26 ms, 1392 kPa) there were 2 fatalies in 12 tests.

Similarly, if Bowen could have used the AUTODYN curve in Figure 8, he would have obtained a duration of $T=0.59$ ms. Clearly the differences in duration estimates are not just of academic interest, but they have a major influence on the Bowen curves.

From Figure 9 we see that Goodman consistently gives smaller durations than the Kingery/Bulmash formula. If Bowen had used CONWEP in constructing the injury curves, the calculated durations would always have been longer for the same lethality. This means that the injury curves would have been shifted to the right, or equivalently we could say they would have been shifted upwards for a given duration. In any case, this implies that for a given duration *T*, a higher pressure *P* is needed to achieve the given lethality.

This would have a major impact on the definition of our scenarios in Table 3. Now a more dramatic scenario is needed to give 50% lethality. If the Axelsson models are applied to such a scenario, they would return a higher ASII value, thus moving them closer to ASII=3.6. It is likely that this explains the disagreement between Bowen and Axelsson for small charges.

Note that since there is less uncertainty for longer duration, a modification of the Bowen curves is not necessary in that range, meaning that the good correspondence between Bowen and Axelsson for large charges will remain. Thus the Axelsson model seems quantitatively OK for long duration loads and probably for short duration loads as well.

8. Summary

The most important available blast injury models are the Bowen curves, the Bass curves, Axelsson BTD and various Axelsson based single point (SP) models.

The Bowen and Bass injury models are totally empirical lethality curves based on animal tests, where the subjects were mostly exposed to blast waves near a reflecting surface. While Bass added new data to the Bowen analysis, it was seen that this did not make all that much difference to the 50% lethality curve. The major difference between the Bowen and Bass curves was due to different assumptions being used for extending them to the open field situation.

Unfortunately, the Bowen and Bass models only work for blast waves with a clearly defined amplitude and duration. Thus, they can not be applied to situations with complex geometry where the blast wave may have several peaks due to reflection. The Axelsson BTD model was developed to solve this problem. However, this model required input from four pressure sensors on a Blast Test Device (BTD), making it cumbersome to apply in a practical situation.

To overcome this problem, several Axelsson based single point (SP) models have been developed. Typically, in these models only the pressure in the relevant location is needed to determine the degree of injury from a blast wave. In previous studies [8,9] the SP models were shown to generally provide a good approximation of the Axelsson BTD model.

The Axelsson models have only been calibrated to experiments with small charges. To see if they could be extended to large charges, we systematically compared Axelsson BTD and Axelsson SP models with the injury curves of Bowen and Bass. This was done by selecting

50% lethality scenarios from the Bowen and Bass models, which were supposed to give an ASII of 3.6 when applied to the Axelsson models. The results were almost surprisingly good considering that the Axelsson models have not been calibrated to large charges at all. Especially for the near wall situation there was very good agreement, while for the open field situation, where little experimental data is available and everything rests on assumptions, there was some discrepancy but within the uncertainty range.

However, the comparison revealed a large difference between the Axelsson and Bowen models for blast waves with short duration. Since the Axelsson model is calibrated to small charges this was surprising. To find the reason for this discrepancy, the foundation of the Bowen curves was studied in detail. It turned out that when the calibration experiments of Bowen were performed nearly fifty years ago, the pressure measurement equipment was not good enough to experimentally measure short durations. Therefore Bowen relied on an old empirical relationship from Goodman for duration input to his model. Further investigation showed there to be enormous differences in the estimates for short duration blast waves between Goodman and the newer Kingery/Bulmash formulas that are implemented in CONWEP. If the Bowen model was corrected with Kingery/Bulmash duration data, or if Bowen was used with Goodman's equation, it would have lead to better agreement between Axelsson and Bowen also for these charges.

However, yet further inspection revealed the widely used Kingery/Bulmash relationship for blast wave duration to be very uncertain. It was only based on four experimental tests with huge hemispherical charges and did not fit the experimental data for spherical charges at all. Therefore, until better duration data is available, there will always be some uncertainty in the Bowen/Bass curves for short durations. Possible further work could include performing experiments to obtain such blast wave data.

While total agreement can not be expected in this field, the Axelsson model so far seems to be consistent with all available experimental data. With the various Axelsson based SP models described earlier, simple but accurate procedures are available for predicting human injury from blast waves in complex scenarios.

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