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Review of blast injury prediction models

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English summary

Methods for predicting human injury from shock waves are studied in detail. The theoretical foundation of the Bowen and Bass lethality curves is examined and the basic hypotheses of the models are studied numerically. The calibration experiments for the Axelsson BTD model for injury calculation are also studied using numerical methods. The Axelsson, Bowen and Bass models are compared for various scenarios and good correspondence is found except for shock waves with short duration. Through studies of the experimental data of the Bowen and Bass models for short wave durations, the discrepancy is resolved.

Sammendrag

Aktuelle metoder for å beregne skade på mennesker fra luftsjokk studeres i detalj. Grunnlaget for Bowen og Bass-kurvene for dødelighet undersøkes og hypotesene som ligger til grunn for modellene studeres numerisk. Det eksperimentelle grunnlaget for kalibreringen av Axelsson BTD-modellen for skadenivå undersøkes med numeriske metoder. Axelsson, Bowen og Bass modellene sammenlignes på aktuelle scenarier og god overensstemmelse finnes bortsett fra for sjokkbølger med korte varigheter. Ved å studere datagrunnlaget for Bowen og Bass-modellene for korte sjokkbølger viser det seg at avviket skyldes store usikkerheter i de eksisterende empiriske modellene for varigheten av en sjokkbølge fra en gitt ladning.

Contents

1 Introduction

Explosions can cause human injury in a number of ways, in particular through blast wave interaction and fragment impact. In this report we will focus only on injuries due to blast waves. Fragment impact has earlier been studied at FFI in (1-3).

The actual blast wave injury depends on many parameters like the size and composition of the bomb, the location of the human relative to the bomb, the geometry of the surrounding area etc. Further, the exact injury mechanisms in humans are not completely understood.

In cooperation with TNO the problem of calculating injury from a given blast wave has therefore been studied intensively at FFI, resulting in the publication of three joint (FFI and TNO) papers at international conferences (4-6). This report reviews previous work that has been performed on blast injury, summarises the results obtained by FFI and TNO as well as expanding slightly on some topics. In (7) there is a summary of the work from a TNO perspective.

2 Bowen curves

It has been known for several hundred years that blast waves could 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. 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. (8) these were summarised and related to human injury, leading to the widely known and used "Bowen curves". Due to the importance of the Bowen curves in the field of human injury from blast waves, we will devote some time to examining them in detail. At FFI the work of Bowen has earlier been studied (9) with regards to implementation in the risk analysis tool AMRISK.

2.1 Experimental set-up and assumptions

The Bowen curves deal with human injuries from blast waves that have not scattered or reflected due to the surrounding geometry. We will call these "ideal blast waves" and they are characterised by the pressure amplitude P and the duration T of the positive phase. A Bowen curve is a relationship between P and T that gives the same lethality, i.e. probability of death. In principle, there is a separate injury curve for each lethality, but typically 1%, 50% and 99% are of most interest.

The Bowen curves are totally empirical in nature, being the results of many experiments where different species of animals were exposed to a blast wave. After exposure it was noted whether the animal survived or died within 24 hours. By exposing several animals to the same loading, a ratio of how many animals died within 24 hours could be found. In total 2097 experiments on 13 different animal species were performed, making it possible to obtain estimates for the probability of death from a given blast wave.

The experiments spanned a a wide range of durations. Generally the data was obtained in different ways for short and long duration.

2.1.1 Long duration experiments

Bowen relied on shock tube experiments for exposing the animals to long duration shock pulses (14-400 ms). In these experiments, the animals were placed against the end plate which closed the tube. The set-ups for two different shock tube configurations are shown in Figure 2.1.

Monkeys and larger species were held in harness and straps while smaller species were placed in specially designed metal cages that were 90% open. The blast wave parameters *P* and *T* were measured with transducers near the end plate.

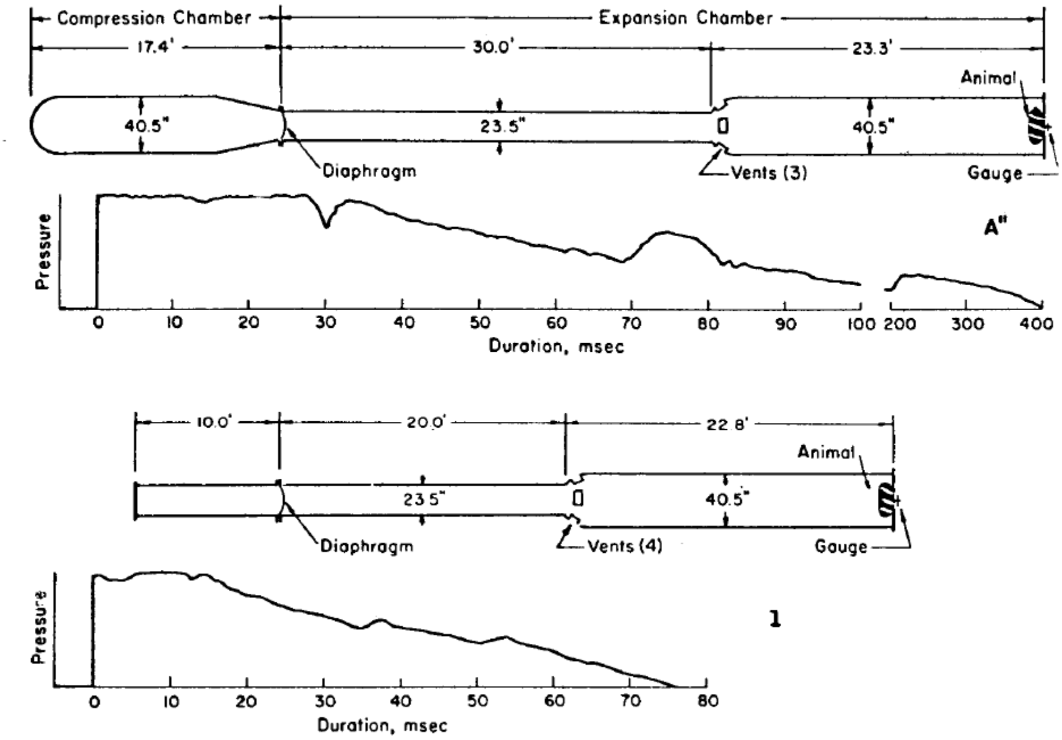


Figure 2.1 Shock tube configurations and corresponding pressure history (Figure reproduced from (10)).

2.1.2 Short duration experiments

Short duration blast waves were obtained using various explosive charges:

- RDX (14.2 g)
- Comp B (114 g)
- Pentolite (454 g)
- TNT (454 g, 3.63 kg and 29.06 kg)

In these experiments, most animals were positioned (in prone position) on a concrete pad with the charge placed overhead (See Figure 2.2). The only exception was for 9 sheep that were suspended upright with the charge placed at the level of the chest in front or behind them.

In some of the earlier experiments the sensitive element of the pressure transducer was located 1.9 cm above the reflecting concrete surface. Bowen used a correction method (12) to convert the measured maximum pressure to the actual pressure *P* at the surface. Particularly for the small charges, the correction was quite significant.

Further, the positive duration *T* was difficult to obtain from the measured pressure-time records. Instead of measurements, Bowen therefore used an empirical relationship developed by Goodman (13) in 1960 to estimate the positive duration of the blast wave. However, since the Goodman relationship had been derived for Pentolite, and Bowen mostly used TNT, Bowen had to assume that Pentolite released 10% more energy than TNT and the other explosives to apply this formula.

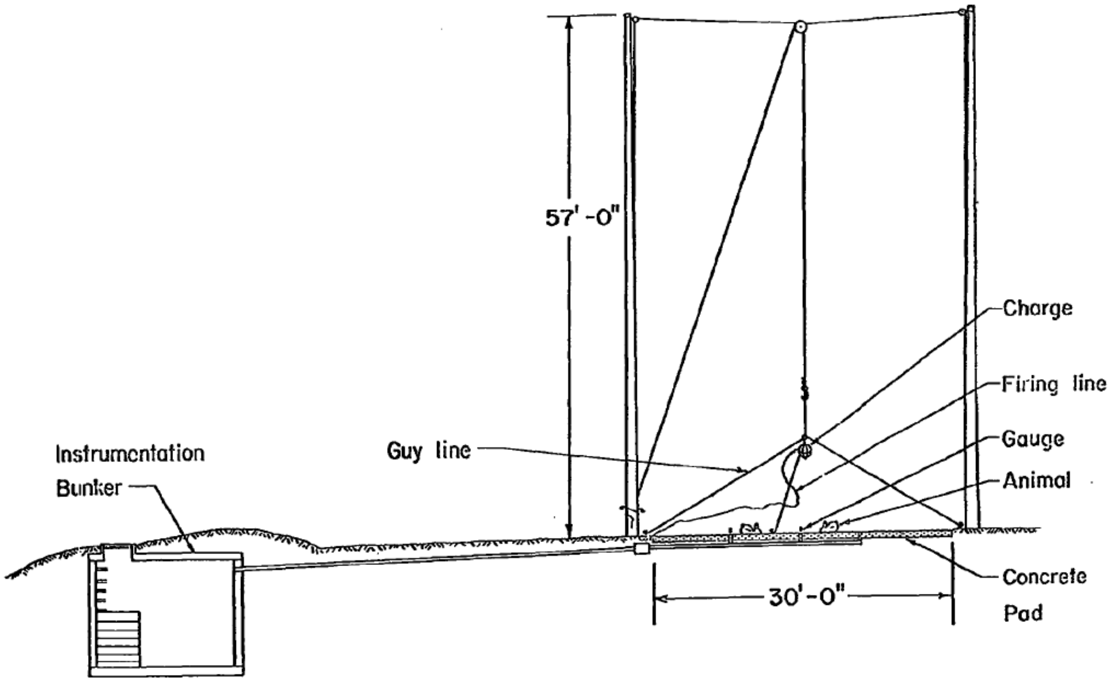


Figure 2.2 Experimental set-up for the explosive experiments. (Reproduced from (11)).

2.1.3 Scaling of experimental data

The experiments were performed for animals of different sizes. Bowen performed the following scaling of the duration t_+ for each experiment, both for body mass *m* and atmospheric pressure, to make it applicable to humans:

$$T = t_+ \left(\frac{70kg}{m}\right)^{1/3} \left(\frac{p_0}{101.225kPa}\right)^{1/2} \qquad (2.1)$$

This was justified by appealing to dimensional analysis on a single degree of freedom model of the animal thorax (14).

Also the measured reflected pressure p_r was scaled for atmospheric pressure:

$$P = p_r \left(\frac{101.225 kPa}{p_0} \right) \tag{2.2}$$

Bowen justified this scaling from shock tube experiments (15,16) performed on animals at different atmospheric pressures.

2.2 Near wall scenario

Having gathered all the experimental data, Bowen assumed that the lethality curves could be expressed on the following form:

$$P = P^* (1 + aT^{-b}) \tag{2.3}$$

and proceeded to do a statistical analysis to determine the parameters *a*, *b* and P^*. Points (P,T) on this curve correspond to a given lethality (probability of death). It is extremely important to note that in this relationship *P* is the maximum reflected pressure at the surface and not the incident pressure.

There are different parameters P^* for each lethality, but *a* and *b* remain the same. In the case of 50% lethality, Bowen found $P^* = 423\ kPa$, $a = 6.76$ and $b = 1.064$. The transformation to other lethalities rests on the assumption of a normal distribution.

Bowen also calculated an injury threshold curve by assuming it to be given by 1/5 of the (reflected) pressure for the 50% lethality curve.

In Figure 2.3 we have plotted some Bowen curves for different lethalities. Note that they show the maximum reflected pressure amplitude for a standing person exposed against a wall.

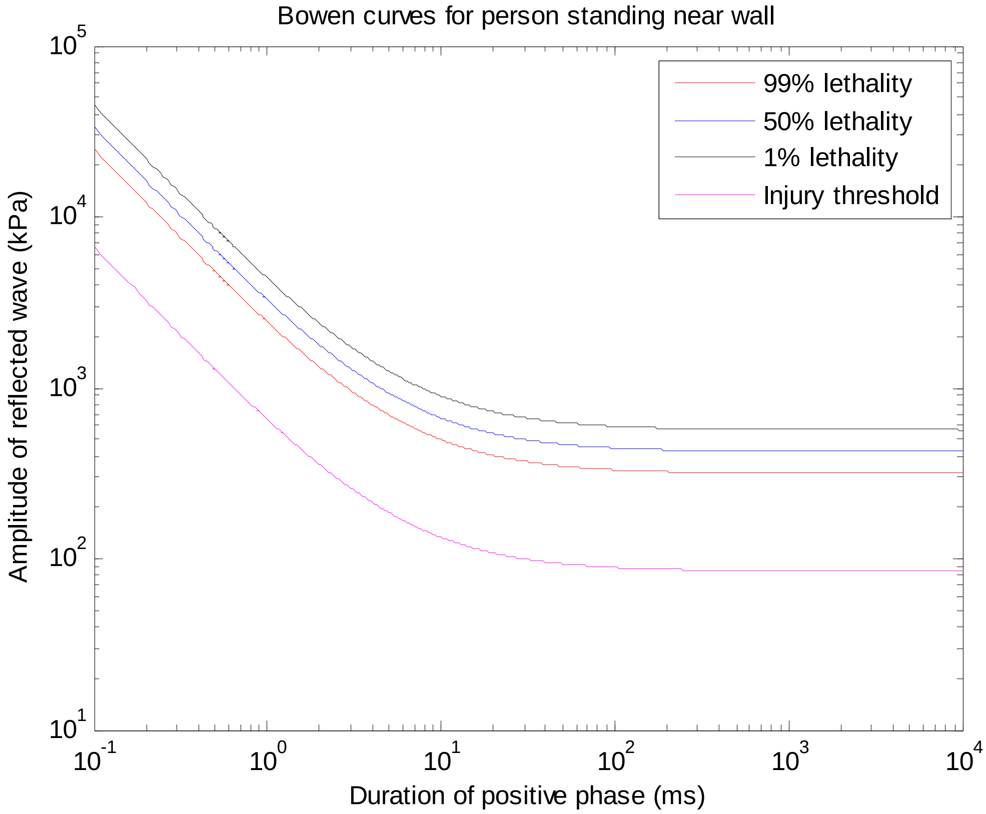


Figure 2.3 Bowen curves for various lethalities with reflected pressure as input parameter.

It is not particularly convenient to have the curves as function of the reflected pressure p_r. It would be more natural to have them as a function of the amplitude p_s of the incident wave. Fortunately, there is a very simple analytical relationship between the incident pressure p_s and the reflected pressure amplitude p_s for a plane wave that is reflected against an infinitely strong wall.

$$p_r = \frac{8p_s^2 + 14p_s p_0}{p_s + 7p_o} \tag{2.4}$$

It is trivial to solve this for p_s:

$$p_s = \frac{p_r - 14p_0 + \sqrt{196p_0^2 + 196p_r p_0 + p_r^2}}{16} \tag{2.5}$$

Applying Equation (2.5) to all points on the curves in Figure 2.3, we can express the Bowen curves as a function of the amplitude of the incident wave p_s. This is done in Figure 2.4. The transformation may not seem very exciting since the curves look identical, except for the scale on the axes, but the new curves are in a much more convenient form for practical use.

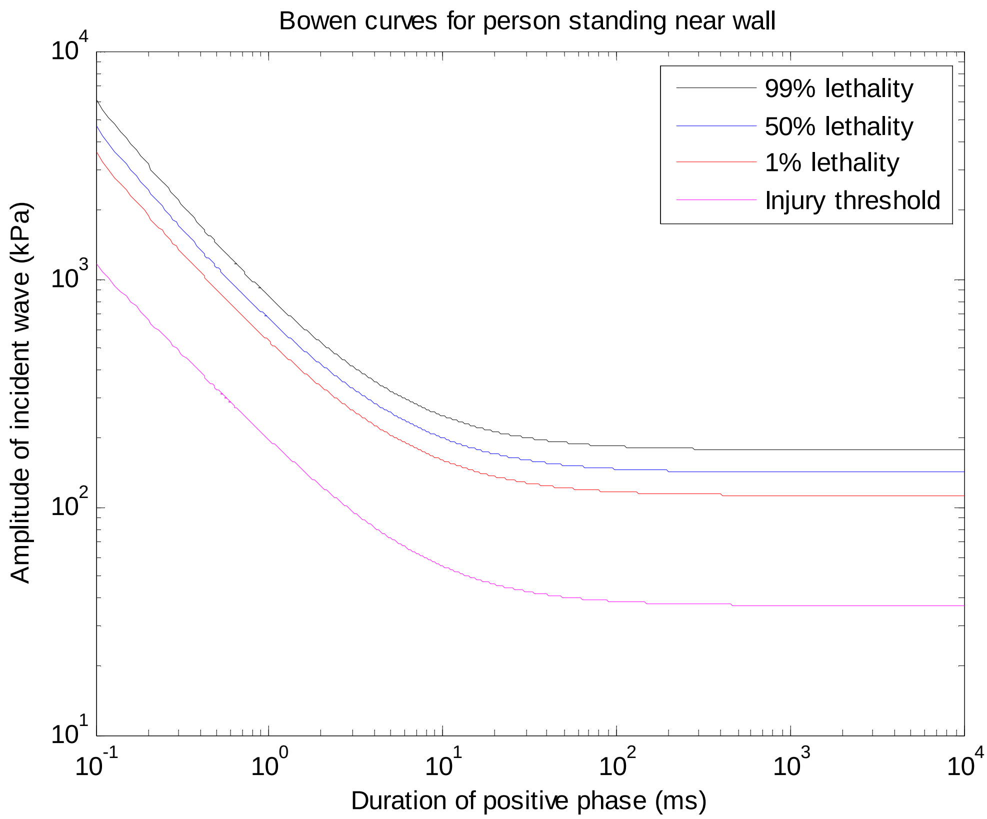


Figure 2.4 Bowen curves for various lethalities with incident pressure as input parameter.

2.3 Other scenarios

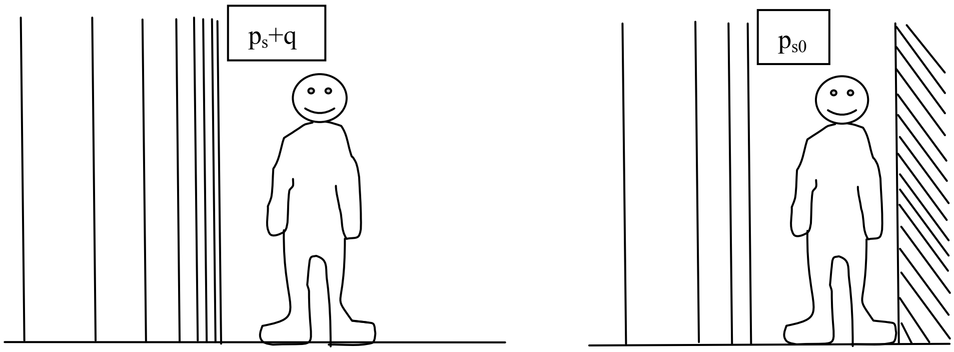
The original lethality curves of Bowen are strictly only applicable to situations where the subject is standing against a wall. However, by making a few assumptions, Bowen was able to create curves for two other scenarios as well:

- 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 $q = \frac{1}{2}\rho v^2 = \frac{5 p_s^2}{2 p_s + 14 p_0}$.
- For a prone person, the pressure is just the incident pressure p_s.

This is illustrated in Figure 2.4 for the open field case. Thus, to calculate the lethality for a person in an open field situation exposed to an incident blast wave with amplitude p_s, one has to find an imaginary blast wave p_{s0} that when reflected against a wall will give an amplitude $p_{r0}=p_s+q$. According to Bowen the lethality for these two scenarios will then be identical.



According to Bowen these situations give the same lethality as long as the reflected pressure p_{r0} caused by the blast wave with incident amplitude p_{s0} is equal to p_s+q.

Figure 2.4 Bowens "pressure dose" method for translating the lethality curves for a person near a wall to a person in an open field.

Instead of thinking of "pressure doses" it is simpler to think in terms of the incident pressure and generate new lethality curves for each of the two situations. This is shown in Figure 2.5. With curves like these, there is no need to worry about pressure doses ever again.

It is very important to note that the extensions to these geometric situations almost only rests on assumptions. Bowen and co-workers performed very few experiments in neither prone nor open field position. In fact, for the experiments which Bowen used to generate his curves, there were zero experiments in prone position and only 9 experiments with sheep out of a total 2097 (though only 351 on large animals) were in an open field.

Bowen was aware that the extension of his curves to open field and prone position was speculative and noted in (8) that it may be an oversimplification and that the supporting data was "meagre". However, to support his hypothesis, he pointed to results from some experiments with guinea pigs. Details from these experiments were never published (the reference is always given as "unpublished data by Richmond"), so it is impossible for us to investigate them any further. But, the figure, which is reproduced in Figure 2.6, apparently shows the 50% lethality for guinea pigs in different geometric configurations. Assuming that the experimental data is okay, the figure seems to show that different incident pressures lead to the same lethality for different configurations. Further, by applying Bowen's pressure dose concept, roughly the same pressure dose is seen to give the same lethality for the guinea pigs.

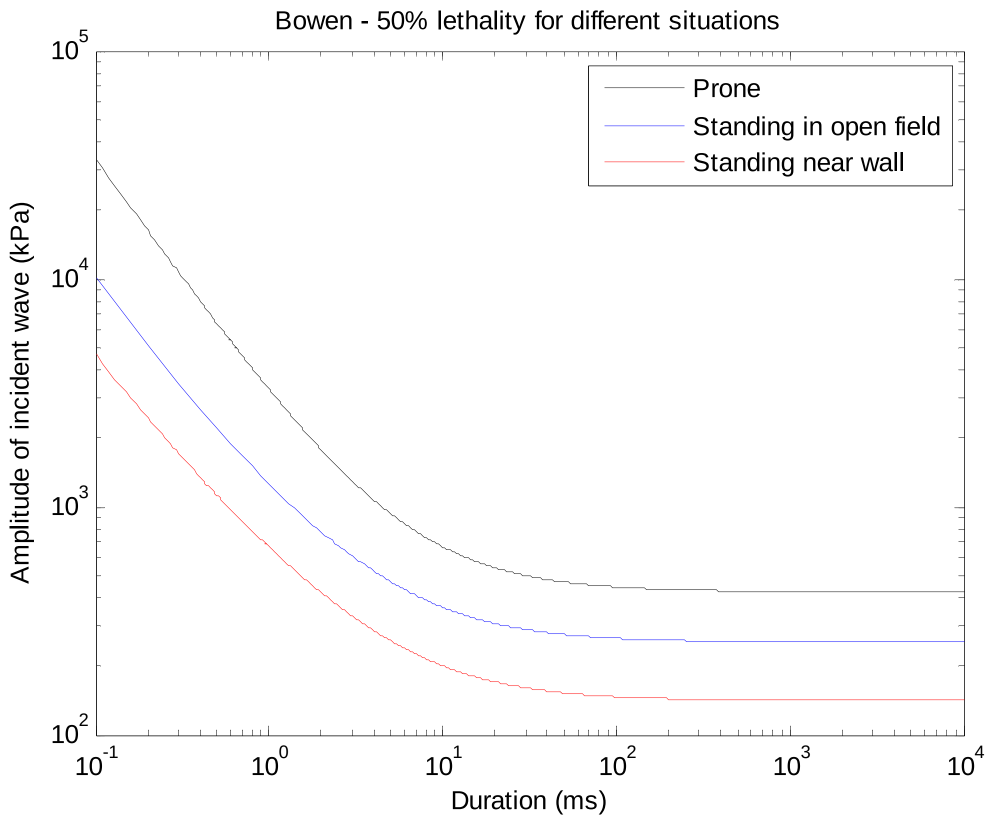


Figure 2.5   Bowen 50% lethality curves for different geometrical situations

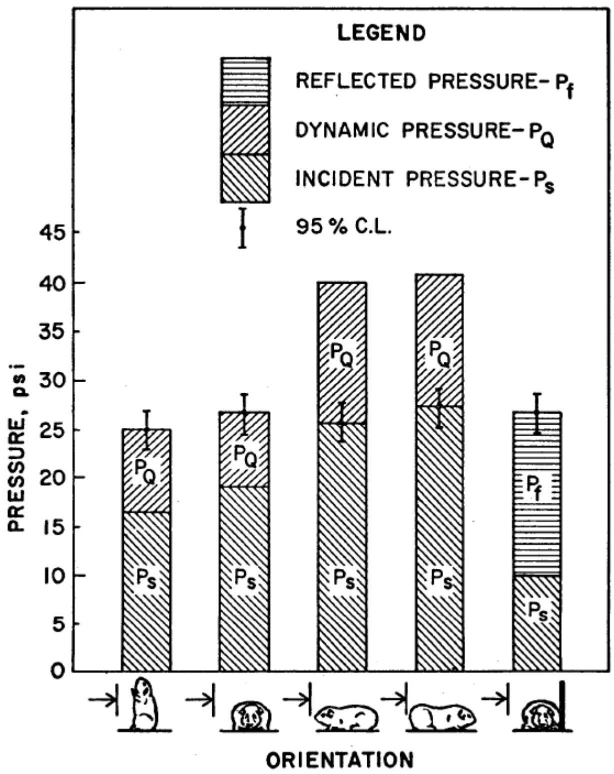


Figure 2.6   Experiments on guinea pigs exposed in shock tube indicating that the pressure dose concept of Bowen is valid. (Reproduced from (9)).

3 Bass curves

The Bowen curves were developed in the late 1960s and have been widely applied to estimate human lethality, despite never being published in peer-reviewed literature. However, recently Bass and coworkers have gathered more data in order to update and improve the Bowen curves. In total, data from more than 2550 large animal experiments (including the 351 large animals from Bowen) were used in the new calculation. According to Bass, the data came from both open field and near wall experiments.

The new curves were published in two separate articles (17,18), dealing with two different regimes: short duration waves (less than 30 ms) and long duration waves (more than 10 ms). Notice that, according to this definition, there is a great deal of overlap between the two regimes.

For short durations, and with incident pressure as input parameter, the 50% lethality takes the same form as assumed by Bowen, but with different parameters: $P^*=89.5$ kPa, $a=6.7$ and $b=0.83$. For long durations a linear relationship was used: $P=147$ kPa-$0.0072T$.

The Bass 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 diverged considerably in their approach. Instead of using the incident pressure p_s plus dynamic pressure q, Bass used the reflected pressure p_r from an imaginary wall (behind the subject) as the pressure dose. Consequently, for lethality, there is no difference between standing in an open field and standing near a wall. This is illustrated in Figure 3.1.

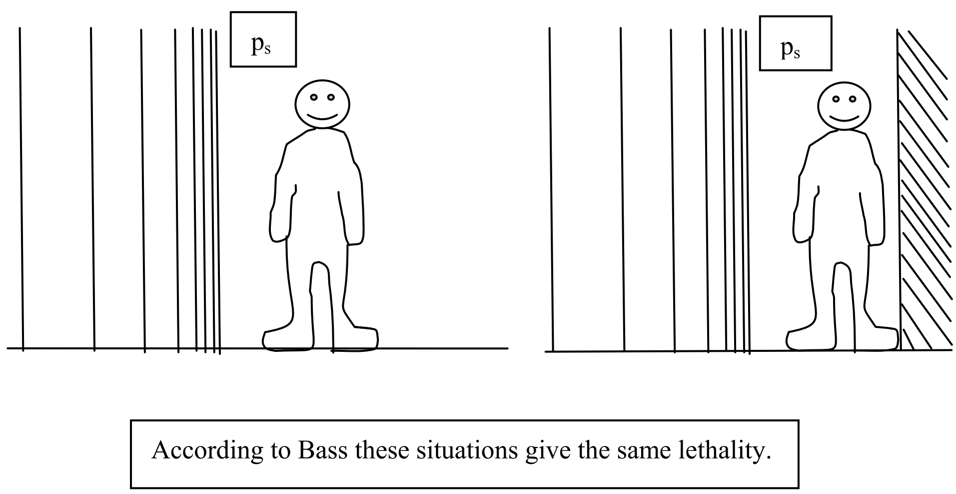


Figure 3.1 Bass claims that the "pressure dose" is the same whether a person is in an open field or near a wall.

The reason for the Bass assumption was their inability to find any experimental evidence for a statistically different tolerance for animals in an open field and near a reflecting wall. For waves less than 4 ms, Bass also had a physical argument. "*At such short durations, explosives necessary to obtain 50% lethal pressures require high overpressures at close range. So, substantial portions of a potential reflecting surface will be occulted by the presence of an attenuating body in the blast field, limiting the effect of the reflecting surface*."

Bass also used some of the experimental data to determine the injury threshold (instead of assuming that you divide the pressure by 5, like Bowen).

To avoid having to think about pressure doses, one Bass curve can be calculated for each geometrical situation, just as for Bowen. In this case, the calculation is simpler than for Bowen since, according to Bass, the situation with near wall and standing in an open field are exactly the same.

The Bowen/Bass curves are plotted together in Figure 3.2 for different orientations. We note that for the prone situation they are more or less identical, except for diverging slightly in the 5-50 ms region (actually a huge region). Also the near wall scenarios are almost the same except for the same region.

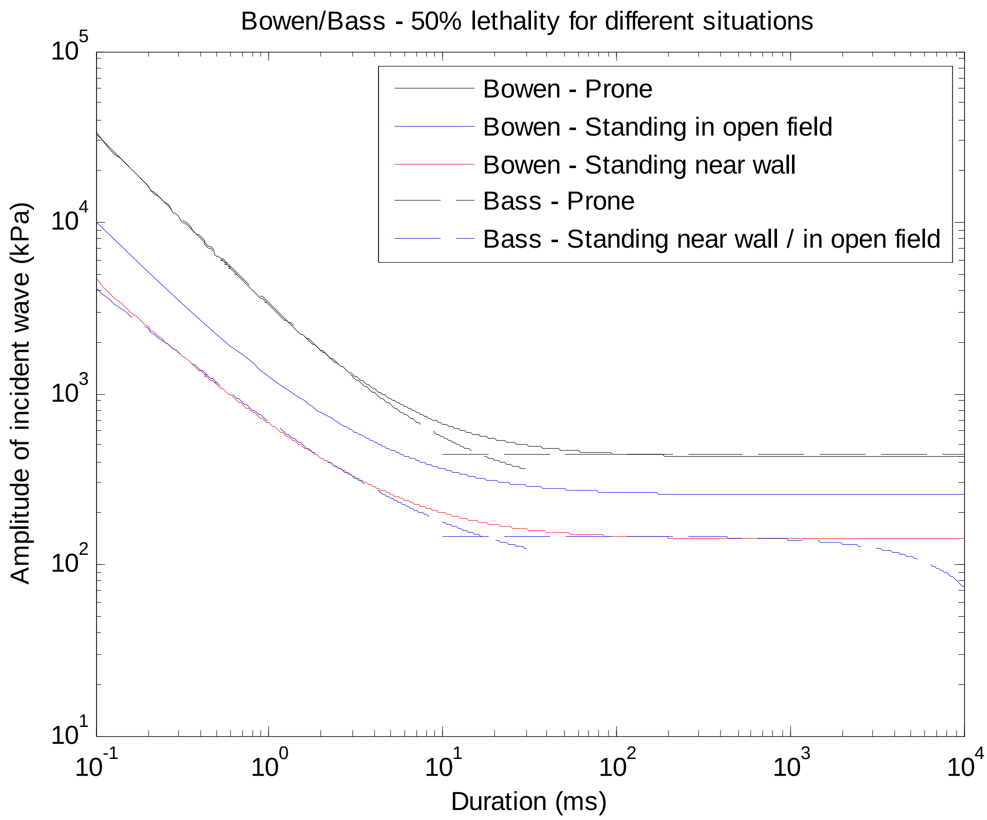


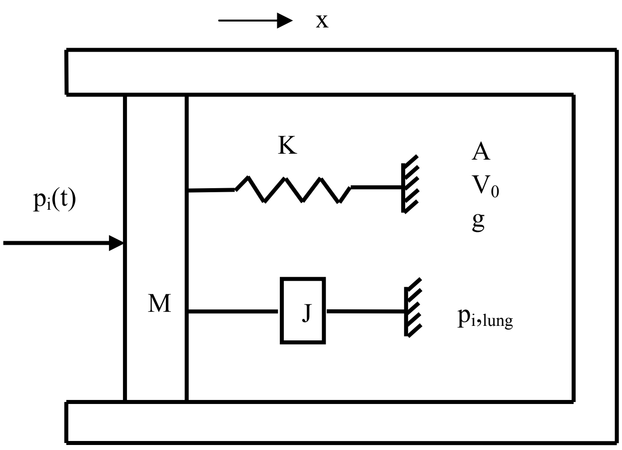
Figure 3.2 Bowen 50% lethality curves compared with Bass curves for various orientations

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 curve has 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.

4 Axelsson BTD model

The Bowen/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.

The Axelsson BTD model (19) was developed to overcome the limitations mentioned. It 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 4.1). The model requires pressure input data from four transducers located at 90 degrees interval around a 305 mm diameter Blast Test Device (BTD) (Figure 4.2), exposed to the relevant blast wave. (Stuhmiller (20) has developed a similar mathematical model[1], but since the actual model is not public, it will not be studied further here).



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 4.1 Mathematical model of the thorax according to Axelsson (19)

[1] Actually, the Stuhmiller model was initially published in open literature (20), but the original article contains at least two errors in the differential equation for the model, making it impossible to apply. In private correspondence, Stuhmiller says these errors have been corrected in later versions of the model and that the model itself has "evolved significantly" since then, though the correct differential equation remains secret for the time being.

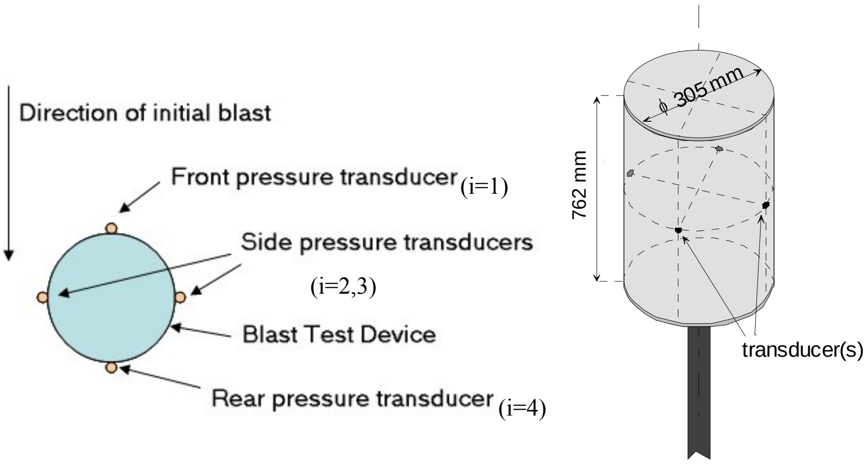


Figure 4.2 Blast Test Device (19)

The mathematical formulas for the Axelsson BTD model are expressed by four independent differential equations:

$$M \cdot \frac{d^2 x_i}{dt^2} + J \cdot \frac{dx_i}{dt} + K \cdot x_i = A \cdot \left[p_i(t) - p_{i,lung}(t) \right] \qquad i = 1,2,3,4$$
$$p_{i,lung}(t) = p_0 \left(\frac{V_0}{V_0 - A \cdot x_i} \right)^g \tag{4.1}$$

The values of the model parameters are given in Table 4.1. However, it is not stated anywhere in Axelssons original article how he arrived at these parameter values, so their derivation is a mystery for the time being.

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	

Table 4.1 Model parameters for the Axelsson BTD model

Input to the model are the four $p_i(t)$ pressure histories measured on the BTD. With this input, the differential equations can be solved for chest wall positions $x_i(t)$, chest wall velocities $v_i(t) = \frac{dx_i}{dt}(t)$ and lung pressure $p_{i,lung}(t)$. We see that 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.

To relate the chest wall motion to actual human injury, Axelsson started by examining the Bowen data. In the cases where the body was parallell to the direction of propagation of the blast wave, the blast load on the body should be almost equal to the incident blast wave, and the same for all four gauge points. Axelsson estimated the pressure histories $p_i(t)$ for many different blast waves on the same Bowen curves and solved Equation (4.1) with this as input. He noticed that the maximum inward chest wall velocity was reasonably constant for different combinations of *P* and *T* on the same Bowen curve. Since all these *P* and *T* combinations should give the same injury probability, this led Axelsson to assume that the maximum inward velocity was a good indicator of injury.

For the more general case, where the body is not parallell to direction of the incoming blast wave (and the various $p_i(t)$ therefore are different), Axelsson proposed the following quantity, called the Chest Wall Velocity Predictor (*V*), as a measure of injury:

$$V = \frac{1}{4}\sum_{i=1}^{4} \max\left(v_i(t)\right) \tag{4.2}$$

To calibrate his model to actual injury, Axelsson used experimental data from Johnson (21). These experiments were performed using small explosive charges (57g – 1361g C4) with anesthetized sheep in closed containers and with BTDs, as prescribed by the Axelsson BTD model, to record the pressure histories.

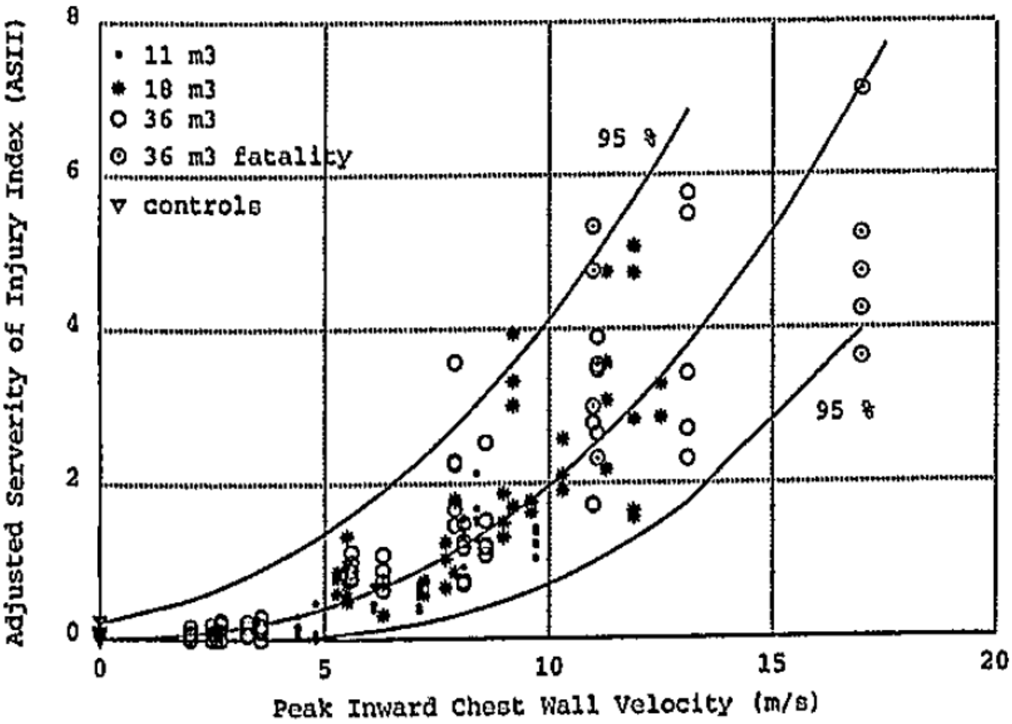


Figure 4.3 Correlation between measured ASII and Chest wall velocity (reproduced from (19)).

After exposure, the injuries of the sheep were assessed and external lesions, fractures, burns, and trauma to the pharynx/larynx, trachea, lungs, heart and hollow abdominal organs were assigned numerical values depending on the severity of the injury. The individual values were then summed to obtain the Adujsted Severity of Injury Index (ASII) as a measure of the degree of injury. From measurements on BTDs in sheep position, Axelsson found pressure input to his differential equation and was able to calculate the Chest Wall Velocity Predictor *V*.

Evidently the experiments showed huge scattering, but by using ASII data from 177 of the 255 sheep, Axelsson applied curvefitting to derive Equation (4.3) for the correlation between ASII and V. On plotting the corresponding *V* and ASII points in the same diagram, Figure 4.3 was obtained.

$$ASII = (0.124 + 0.117V)^{2.63} \qquad (4.3)$$

The correlation between injury level, ASII and V are shown in Table 4.2. We see that the various regimes are overlapping due to the large uncertainties.

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

Table 4.2 Correlation between injury level, ASII and V.

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. However, several single point (SP) models, needing only the side-on pressure as input, have been developed to simplify things.

5 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 most SP models, only the side-on pressure history at the relevant location is required.

5.1 Weathervane SP

The Weathervane SP model (22) 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 found by assuming a modified Friedlander form for the pressure wave and iterating the decay parameter μ 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 (4.1)) for calculation of the chest wall velocity predictor *V*.

5.2 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 at each point in time. This will be called the Modified Weathervane model.

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.

5.3 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 $V = \max(v_1)$.

5.4 TNO SP

TNO has developed an approximation procedure of the Axelsson BTD model. The method is fully described in (23). 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 5.2). An exact pressure-time curve is not necessary. The full equations for V as a function of the blast characteristics are quite complicated and are therefore not repeated here.

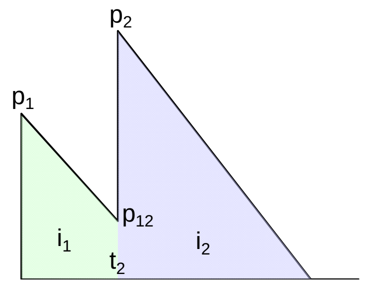


Figure 5.2 Relevant characteristics of an arbitrary shock wave with two peaks, used for the approximation procedure of TNO (12)

5.5 Comparison of SP methods

In (4,24) 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 particularly suited for use in numerical simulations. Comparison of the results given by the models for a few scenarios are shown in Figure 5.3. For a more complete discussion, the reader is referred to (4,24).

However, the mentioned studies did not examine the foundation of the Axelsson BTD model itself. They only found that if, in fact, the Axelsson BTD model was (reasonably) accurate, the SP models would be (reasonably) accurate as well. Nor was the relationship between Axelsson BTD and Bowen/Bass studied. In the next chapter we will therefore look more critically at the derivation of the Axelsson model.

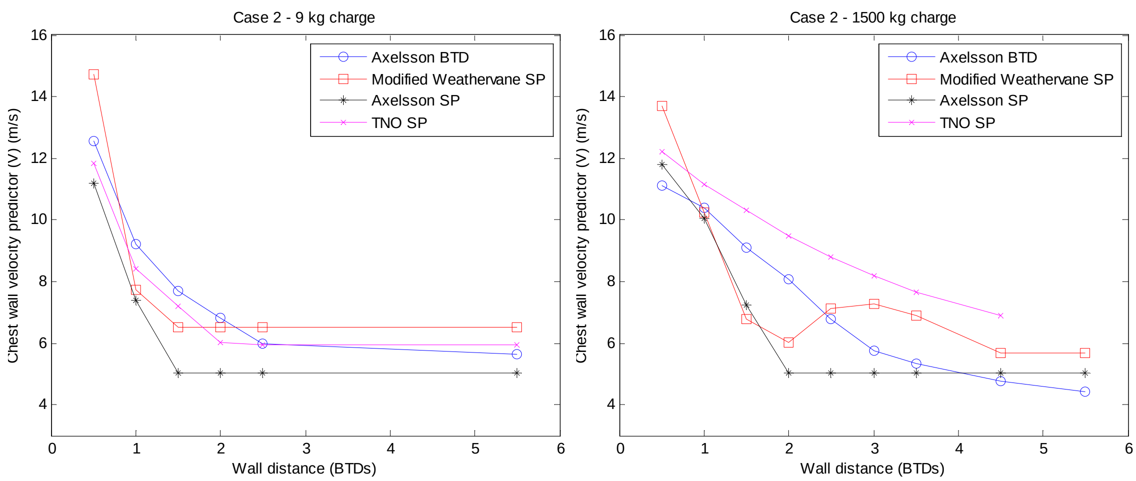


Figure 5.3 Chest wall velocity predictor for the different approaches (Case 2: 50% survivability according to Bass), based on 3D AUTODYN simulations

6 Johnson experiments

As mentioned, the Axelsson ASII(V) formula is calibrated against a set of experiments performed by Johnson et. al. (21). In these experiments sheep were placed inside chambers, charges were detonated and the sheep injury assessed to give the injury parameter ASII.

The calibration experiments were performed with three different chambers:

- A (3.05 m x 2.44 m x 2.44 mm)
- B (same as A but with an open door)
- C (4.88 m x 3.05 m x 2.44 m)
- D (3.05 m x 1.52 m x 2.44 m)

Typically a spherical charge was detonated in the middle of the chamber, except for a few A-scenarios where it was detonated either in a corner or at a wall. In a couple of A-scenarios there were also two charges detonated simultaneously. The sheep were always positioned right side-on to the charge.

In the experimental report (19), Johnson notes about the gauges on the BTD: "*Gauge 3 of the instrumentation cylinder was directly face-on to the blast and the amplifier gain was set low to accommodate the reflected spike. The resulting records were of little value because of the poor resolution and were not used* " (p. 22-23). Despite this, it appears that Gauge 3 was used by Axelsson in creating the relationship between ASII and V of Equation (4.3), although Axelsson does not state this explicitly.

For example, let us look at the configuration A6, shown in Figure 6.1.

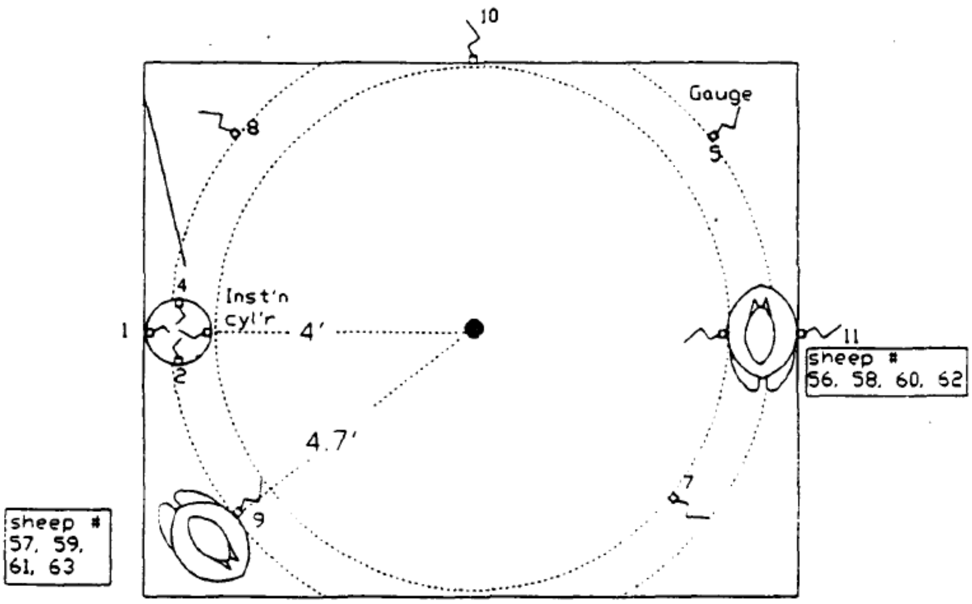


Figure 6.1 Scenario A6 in the Johnson experiments. Cross section of the chamber. Distances are given in feet. Reproduced from (21)).

The results for pressure amplitudes of the various BTD-sensors and measured ASII for a sheep in a similar position, reported by Johnson are given in Table 6.1.

A6	**Front (kPa)**	**Rear (kPa)**	**Side (kPa)**	**Measured ASII**
114 g	497	995	422 / -	0.08, 0.56, 0.20
227 g	892	1388	672 / 475	0.45, 0.11, 0.71
454 g	2084	1171	879 / 609	1.53, 1.32, 1.12
907 g	2936	1957	769 / 980	2.44, 5.74, 2.90

Table 6.1 Results from Configuration A6.

Inspection reveals some surprising results for the pressure amplitudes. First the two side gauges differ quite considerably, despite the situation being symmetrical. Further, the rear amplitude for 227 g C4 is larger than for 454 g, one of the side gauges gives a higher reading for 454 g than for 907 g, as well as for 227 g and 454 g. All the mentioned results seem quite counterintuitive, indicating that there may well be some big uncertainties in the measurements. Similar anomalies are seen for most of other the configurations.

These observations are potentially quite important because if the pressure data is as unreliable as it appears from Johnson, the chest wall velocities V calculated by Axelsson may be unreliable as well. This may then possibly have resulted in Axelsson calculating an incorrect relationship between ASII and V.

7 Summary of human blast injury models

Having reviewed the available blast injury models, we now summarise the status in Table 7.1.

We see that there are both advantages and problems with the different methods. The Bowen and Bass curves are based on a big experimental database, but only works for a few geometric scenarios. The Axelsson based methods are only calibrated to experiments with small explosive charges, and there are indications that even this set of pressure data was of poor quality. In addition, the BTD method is cumbersome to use. The SP models suffer from the same problems as the BTD approach, but are potentially very useful if the BTD model could be further validated.

Let us now look more in detail at the uncertainties surrounding the various injury models and try to see if the situation can be improved.

Injury model	Shock wave	Scenarios	Input	Output	Advantages	Disadvantages
Bowen	Ideal	Prone, Open field, Near wall	P and T	Lethality	Easy to apply, requires only P and T. Developed from large experimental database	Only ideal blast waves Only tested near wall, other scenarios almost purely based on assumptions Some experimental data not measured but estimated from empirical formulas Differs from Bass for open field scenario
Bass	Ideal	Prone, Open field, Near wall	P and T	Lethality	Easy to apply, requires only P and T. Developed from very large experimental database	Only ideal blast waves, Data from open field did not give lethality Some experimental data not measured but estimated from empirical formulas Differs from Bowen for open field scenario
Axelsson BTD	Any	Any	Four p(t) on a BTD	ASII (degree of injury)	Works for any shock wave.	Cumbersome, requires four pressure histories measured on a BTD Based on questionable pressure measurements Only based on experiments with small charges
Weathervane SP	Any	Any	p(t) in one point	ASII (degree of injury)	Works for any shock wave	Cumbersome iteration method needed Based on questionable pressure measurements Only based on experiments with small charges
Modified Weathervane SP	Any	Any	p(t) in one point	ASII (degree of injury)	Works for any shock wave	Accurate enough? Based on questionable pressure measurements Only based on experiments with small charges
Axelsson SP	Any	Any	p(t) in one point	ASII (degree of injury)	Works for any shock wave	Accurate enough? Based on questionable pressure measurements Only based on experiments with small charges
TNO SP	Multi-peak	Any	p_i, T_i	ASII (degree of injury)	Simple, does not even require full pressure history	Accurate enough? Based on questionable pressure measurements Only based on experiments with small charges

Table 7.1 Blast injury model status

8 Numerical simulations of Johnson experiments

We saw that there were uncertainties regarding the pressure data in the Johnson experiments, which was used to develop the ASII(V) relationship in the Axelsson BTD model. If we don't know how good the data was, it may not be a good idea to trust this model.

One possible way of (in)validating the Johnson data would be to perform numerical simulations and compare with the experimental pressure data. This should give us some further indications about whether the results by Johnson/Axelsson are trustworthy. Each experiment is carefully documented in detail in (21), and in all cases the geometry is extremely simple to model. Further, there are no unknown material models, so unless the numerical code is all wrong, there should be no reason for the simulations to give wrong results. It was therefore decided to perform simulations of all the Johnson experiments using the ANSYS AUTODYN 13.0 hydrocode (25).

The Johnson experiments were simulated in two stages. The detonation of the charge and the initial propagation of the blast wave was modelled in 1D as long as the situation remained spherically symmetric (i.e. before the blast wave reached a chamber boundary). This was achieved using a "wedge" in a 2D Euler-Godunov mesh. Previously, this method has been shown to give accurate results for spherical explosions as long as the grid resolution is fine enough (26). In our case the resolution was around 0.2 mm.

The final state of the 1D-simulation was then remapped to a 3D Euler-FCT grid (Figure 8.1). The 3D-stage of the simulations was typically run for 30 ms, quite a long period, which was necessary since the calculated maximum chest wall velocity, sometimes occurred after several reflections.

The chamber was modelled using an Euler-FCT grid without any boundary conditions. This implies perfect reflection at the grid boundary, as from an infinitely strong wall. This is a good approximation of the steel chamber, since very little of the total energy is transmitted through the walls. For many configurations, symmetry considerations were exploited, enabling us to model only 1/8th of the chamber. The grid size varied between configurations, but a typical simulation had around 1 million cells and a resolution of around 5-7 mm in the most relevant areas. The few B-scenarios with open doors in the container were modelled using a "flow out" boundary condition on the boundary cells corresponding to the door. Most experimental configurations had several sheep inside the chambers together with the BTD, although usually these were positioned away from the BTD. This was therefore ignored in the simulations.

To calculate the Axelsson injury parameter V from each experiment a user subroutine written at FFI and implemented in AUTODYN was used. Details of the subroutine is described in (27) but it has later been updated and expanded to also include the Modified Weathervane model.

The only materials involved were air and C4. Air has an ideal gas EOS that is well known. A density of 1.0421 g/cm^3 and an initial pressure of 83.0 kPa was used for the undisturbed air, corresponding to the conditions of the experiments as described by Johnson (21). The explosive C4 was modelled using the JWL EOS from the AUTODYN material library. (See Appendix A for full material models).

The BTD was modelled as rigid, thus only acting as a boundary to the Euler grid. Numerical gauge points were placed in the Eulerian cells nearest to the BTD. For most configurations, the position of the BTD was accurately given in (21). In cases where the position was slightly ambiguous, we tried to estimate the position as accurately as possible according to the illustrations.

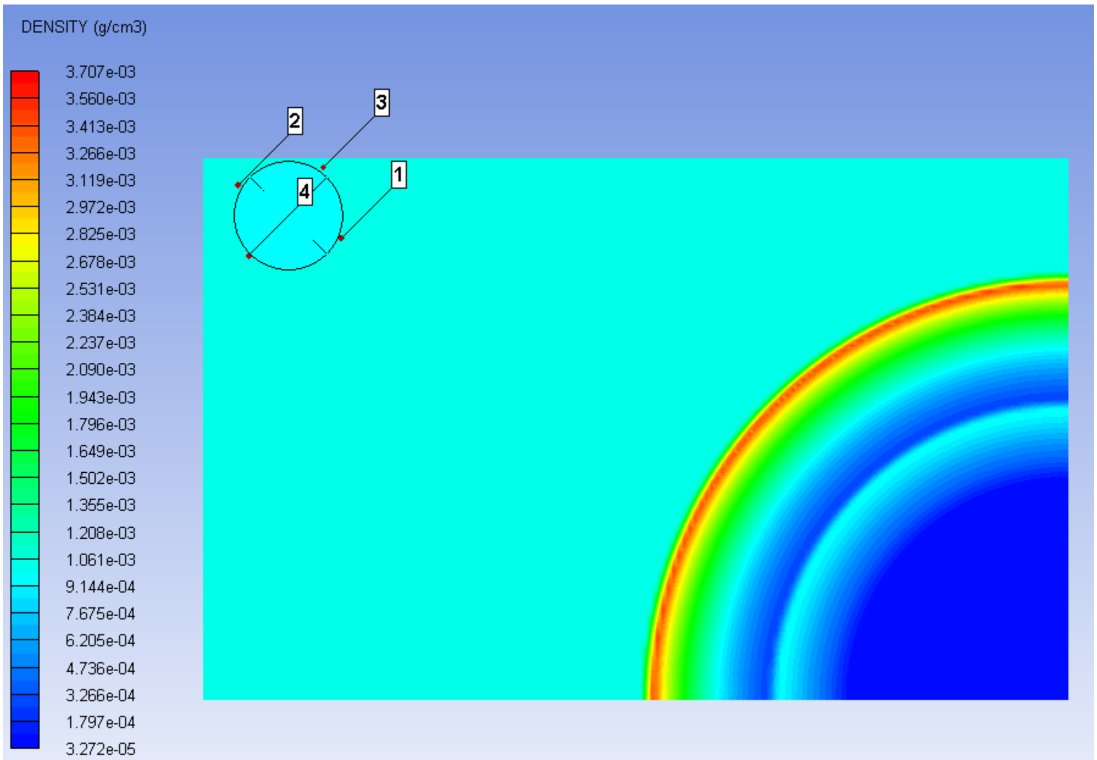


Figure 8.1 Initial state (cross section through the center) for the 3D simulation (remapped from 1D) of scenario C1 (907 g). Location of the gauges are shown. Due to symmetry, it is enough to model 1/8 of the container.

9 Comparison with experimental data

The raw pressure data from the Johnson experiments have not been preserved, making it impossible to systematically compare the simulations and the experiments. However, in Axelssons original article (19) some experimental data from Johnson has been reproduced, including pressure histories for the front and rear sensor (corresponding to Gauges 1 and 2 in Figure 8.1) in the C-1 (corner) configuration with a 907 g charge. These plots were digitized and compared with the results of the numerical simulations in Figure 9.1.

In particular for the rear gauge the agreement is pretty good. According to Johnson, the front gauge gave results of “little value”, but the agreement with the numerical simulation still looks quite accurate. There is a tendency for the measurement and the simulation to become slightly “out of sync” after a while, in particular for the front gauge. The reason for this is not clear, but for the calculation of the chest wall velocity predictor V, it happens too late to have much impact.

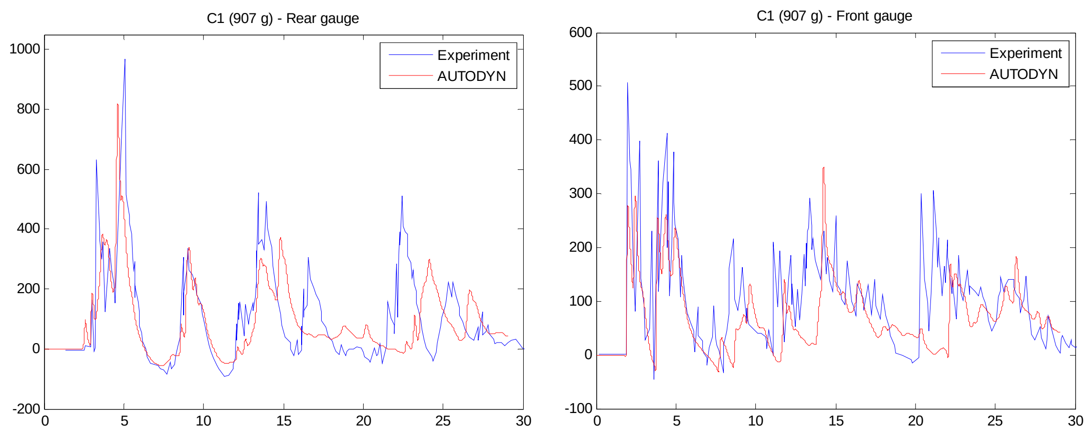


Figure 9.1 Comparison between experiment and numerical simulation for the rear gauge (left) and the front gauge (right) in the C-1 scenario (907 g).

Axelsson (19) also included the computed chest wall velocities for each of the sensors in the C-1 (907 g) scenario, as well as average results for the C-1/2 (short wall) and C-1/4 (long wall) scenarios. These are compared with the corresponding AUTODYN results in Tables 9.1 and 9.2. The agreement is in general very good. In the C-1/2 case there is some difference of around 10% between simulation and experiment, but compared with C-1/4 the numerical result in C-1/2 actually looks much more reasonable since the cylinder is much closer to the charge in the C-1/4 case.

Sensor	V computed from experimental data	V computed from numerical data
Front	7.9	6.77
Rear	17.6	16.95
Side 1	15.5	14.26
Side 2	11.5	12.04
Average	13.1	12.51

Table 9.1 Comparison between experiments and numerical simulations for C-1 (907 g)

Scenario name	Charge mass (g)	V computed from experimental data	V computed from numerical data
C-1	907	13.1	12.51
C-1	1361	17.0	16.88
C-1/2	1361	11.0	9.97
C-1/4	1361	11.1	11.38

Table 9.2 Correlation between injury level, ASII and V for four scenarios

10 Numerical results of Johnson simulations

Axelsson used 177 of 255 sheep experiments in his analysis to obtain Equation (4.3), without providing any details in (18) on how the relevant sheep were selected. Inspection of the experimental report (21) did not provide us with any particular reason to exclude parts of the data. Therefore simulations were run for every single scenario and configuration in (21).

In addition to simulating the experiments with the BTD at the correct position in the chamber, simulations were also performed without the BTD, but with a single point (SP) sensor at the location where the center of the BTD would have been. The idea behind the SP simulations was to further investigate the results obtained in (4,24), and briefly described in Chapter 5, that the SP models were good approximations of the Axelsson BTD models. In particular we wanted to examine whether the Modified Weathervane SP and Axelsson SP would fit equally well with the experimental data in these closed-chamber experiments.

For each scenario, the numerical chest wall velocity V was calculated using the Axelsson BTD, Modified Weathervane SP and Axelsson SP method. These results were then related to the measured ASII from the Johnson experiments (21). (Note that similar to Axelsson, but opposite to Johnson, we did not multiply the ASII by a factor 2 for the cases where the sheep died).

The final results are shown in Figures 10.1-10.3, where we have plotted the numerically calculated V together with the corresponding measured ASII for the different methods. The symbols show which configuration the data points correspond to, while the colours show if the BTD was located near a corner (red), near a wall (blue) or centrally (black, defined as more than 1 BTD size from the nearest wall).

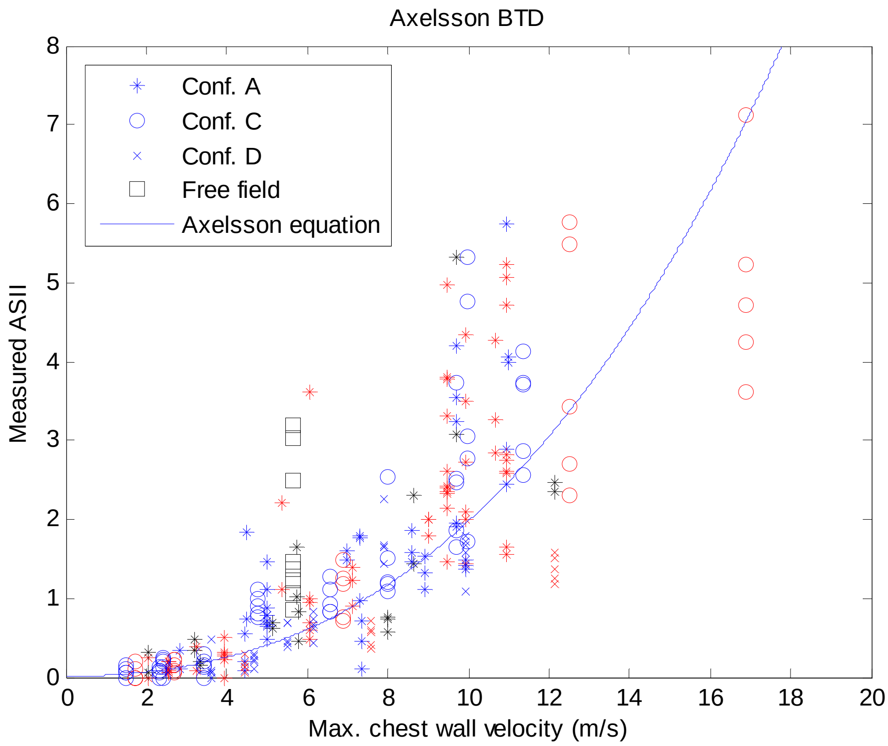


Figure 10.1 The experimentally measured ASII plotted together with the numerical results for V for the Axelsson BTD model. (Red = Near corner, Blue = Near Wall, Black = Central) (Should be compared with Figure 3.3).

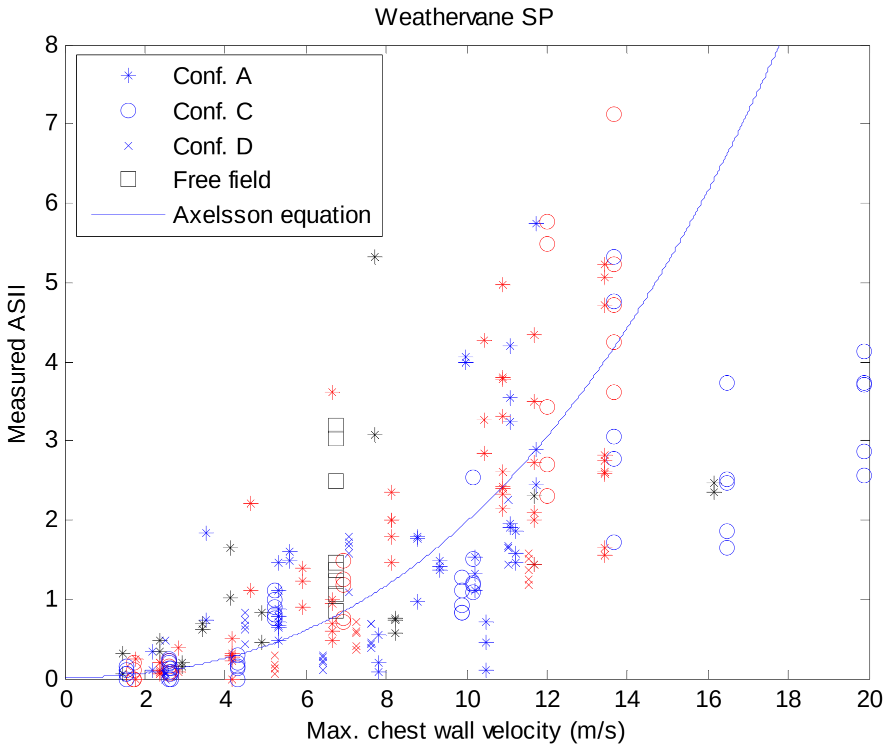


Figure 10.2 The experimentally measured ASII plotted together with the numerical results for V for the Weathervane SP model. (Red = Near corner, Blue = Near Wall, Black = Central)

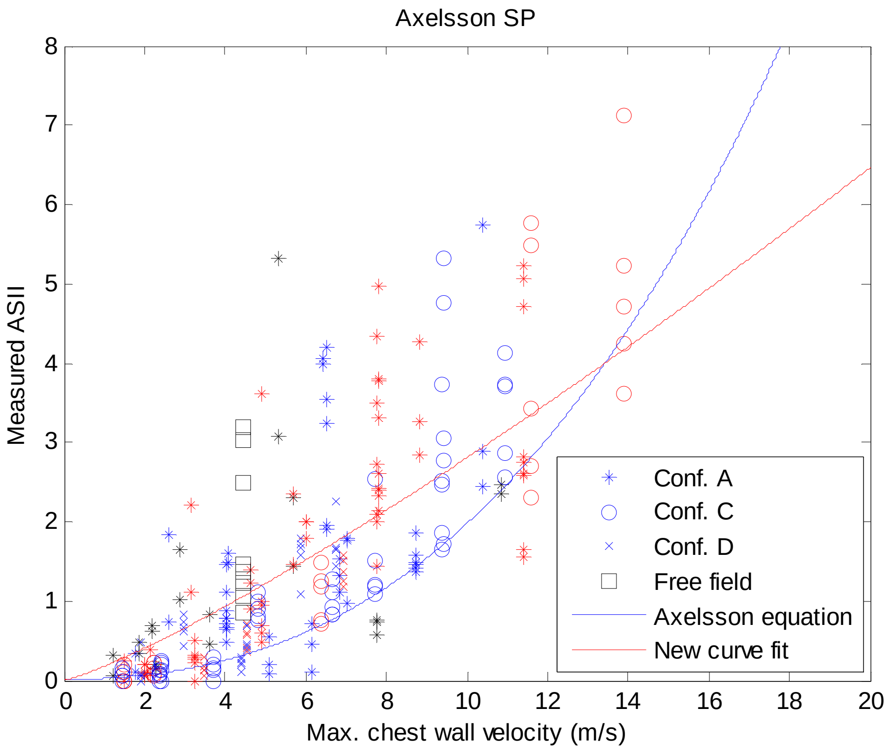


Figure 10.3 The experimentally measured ASII plotted together with the numerical results for V for the Axelsson SP model. (Red = Near corner, Blue = Near Wall, Black = Central)

11 New Axelsson SP single point injury formula

Several interesting observations can be drawn from Figures 10.1-10.3. First, the original Axelsson equation for ASII as a function of V still looks as a good fit to the numerical data from the Axelsson BTD method. This may indicate that the results of the front gauge were not quite as poor as Johnson indicated, or at least that this low quality data did not affect the final results too much.

We also note that there seems to be no major difference between data points derived from a corner scenario, near wall scenario or central scenario. There is no tendency that one of the scenario types consistently gives different injury predictions than the others. This is a good indication that the Axelsson model actually provides a reasonable description of the injury process. (Or rather, this was one thing which could possibly have falsified the Axelsson model, but this did not happen.)

The Axelsson SP model in Figure 10.3 shows slightly more scattering than Axelsson BTD but the results are still quite good. The modified Weathervane SP model in Figure 10.2 also gives more scattering than Axelsson BTD and does not seem to be any particularly better than Axelsson SP. In the following we therefore focus on Axelsson SP.

The original Axelsson equation seems to be slightly lower than what curve fitting to the numerical data would give for Axelsson SP. This is in agreement with (4,24) where it was seen that Axelsson SP provided a good approximation to Axelsson BTD for a wide range of scenarios, though usually giving slightly lower injury estimates.

With the results from the new simulations it is now possible to perform a new curve fit for Axelsson SP to find a new ASII(V) equation for even better agreement with the Axelsson BTD model for estimating ASII from a given scenario. There are many possible curvefits, but it was decided to try the form $ASII = aV^b + c$. Also, since it is known physically that *ASII(V)=0*, we put c=0. MATLAB's (28) curve fitting tool then gives *a=0.175* and *b=1.205* as the best curve fit using default fitting options.

Thus, the modified Axelsson SP injury prediction formula is given by:

$$ASII_{SP} = 0.175 \cdot V_{SP}^{\ 1.205} \tag{11.1}$$

where V is calculated using the Axelsson SP approach and not with the BTD. The new curve fit is also plotted in Figure 10.3 and is seen to fit the data much better than the original Axelsson BTD equation. From now on we will use Equation (11.1) to calculate ASII with the Axelsson SP method.

The numerical simulations of the Johnson experiments have brought us a large step forward. It has more or less removed the uncertainty surrounding the calibration of the Axelsson BTD model to experimental data. As a consequence, all the SP models (which depend on the Axelsson BTD model being accurate) also now rest on much more solid ground.

12 Comparison with the Bowen and Bass curves

The Axelsson BTD and 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 type of wave and scenario.

So, to compare the formulas, we need to relate the Axelsson ASII to probability of death. According to Axelsson (19), an ASII=3.6 corresponds to 50% lethality. Assuming that this criterion is correct, we can use AUTODYN 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.)

12.1 Definition of 50% lethality scenarios

We will use the same range of charges (9 kg – 1500 kg TNT) as in (4,22), 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. These equations are also implemented in the Norwegian manual, Håndbok i Våpenvirkninger (HiV).

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. (In principle, AUTODYN could also have been used for this task, but since each simulation takes several hours, and many iterations are required to find the right distance, it was far simpler to use CONWEP).

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 12.1. 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 3.2.

	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

Table 12.1 Scenarios that were studied. The distance is from center of the charge and to the rear of the BTD.

12.2 Bass scenarios

The results for the “near wall” and “standing in free field” for scenarios defined according to Bass 50% lethality are plotted in Figure 12.1. Along the x-axis we have the positive phase duration for the given scenario.

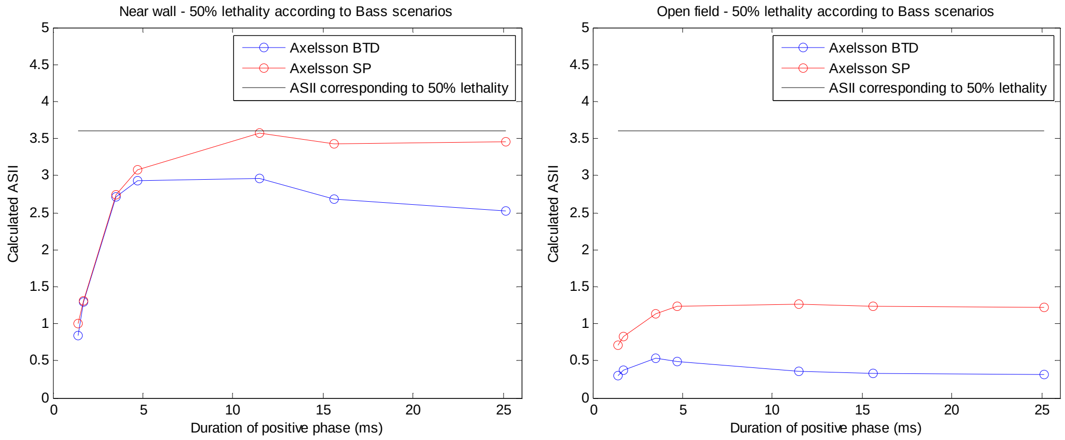


Figure 12.1 Applying the Axelsson BTD and SP models to scenarios that according to the Bass injury model should give 50% lethality. (Near wall (left) and Open field (right))

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.

12.3 Bowen scenarios

In Figure 12.2 we have plotted the results from using the Axelsson BTD and SP models on the Bowen scenarios for 50% lethality.

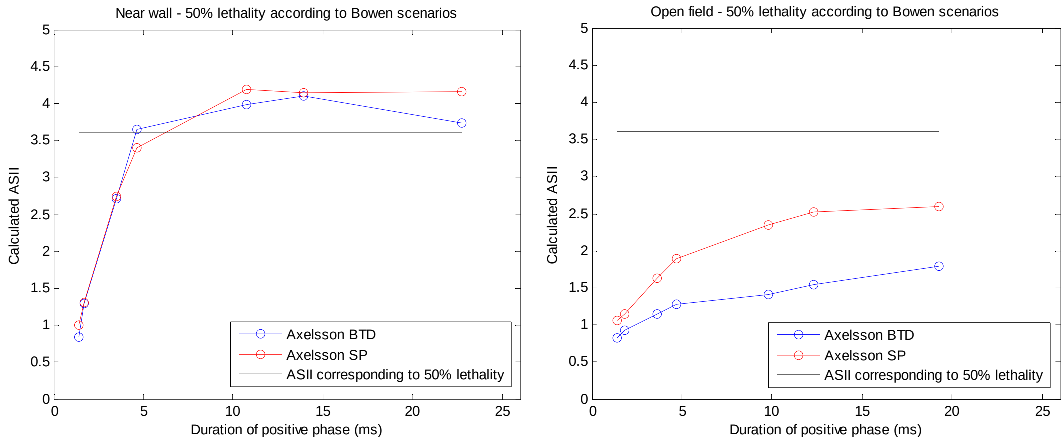


Figure 12.2. Applying the Axelsson BTD and SP models to scenarios that according to theBowen injury model should give 50% lethality.(Near wall (left), Open field (right))

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.

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

It is interesting to note that the Axelsson formulas compare 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.

While partly encouraging, the comparison between Axelsson, Bowen and Bass leaves us with a few open questions:

- Which injury model is best for detonations in an open field? Axelsson, Bowen or Bass?
- Why is there so poor disagreement between Axelsson and Bowen/Bass for short duration blast waves?

The next chapter will examine these questions in some detail.

13 Open field injury models

We will start with the first question of what is the appropriate injury model for an open field situation. From Figures 12.1 and 12.2 it is clear that the Bass model predicts more injury than Bowen which again predicts more injury than Axelsson.

There is a fundamental disagreement between Bass and Bowen, owing to the different assumptions made when extending the formulas from near wall to open field. It seems that neither assumption is quite consistent with Axelsson, but Bowen is closer than Bass. This is a question which really could only be answered experimentally, but not many relevant open field experiments have been performed.

Let us examine the arguments put forward by Bowen and Bass for their assumptions. As mentioned earlier, Bowen pointed to the guinea pigs experiments (Figure 2.6) that seemed to support his "pressure dose" theory. Basically, Bass argued (17) that while Bowen's assumption "*may be appropriate for "long" duration blasts, it may not be for short durations, especially durations less than approximately 4 ms..... So, substantial portions of potential reflecting surface will be occulted by the presence of an attenuating body in the blast field, limiting the effect of the reflecting surface*."

This physical argument by Bass that the body will shield the reflected blast wave can be checked using numerical simulations. As an example of a short blast wave, let us use the 9 kg TNT case. The BTD will be used as a substitute for a human. After all, it is the foundation of the Axelsson theory that measurements on a BTD is similar to on a human.

Thus, let us examine the pressure as a function of time at the various gauges (front, rear and side) when the BTD is in an open field and near a wall. If Bass's hypothesis is correct, there should not be too much difference between the two situations. The actual results are shown in Figure 12.3.

We note that for the front gauge there is almost no difference. The pressure is identical for a long time until the reflected wave returns at around 1.5 ms. For the rear gauge there is a huge difference in amplitude, while for the side gauge there is a reflected wave arriving at around 1.0 ms of approximately the same amplitude as the incident wave.

These results seem to contradict the hypothesis of Bass. The only way to rescue the hypothesis is to conjecture that only the pressure on the body facing the blast wave matters to the injury. This is perhaps theoretically possible, but seems like a rather odd assumption.

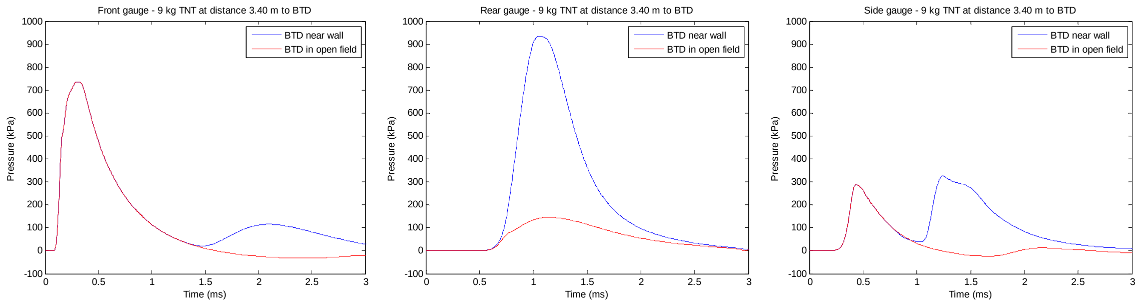


Figure 12.3 Comparison of the pressure history for BTD near a wall and in an open field

However, Bass backed up his hypothesis by claiming that the experimental data suggested no difference between standing next to a wall and in an open field. To investigate this further, all references from which Bass gathered experimental data were examined. The open field data all seem to come from one paper by Dodd et.al. (29). However, it turned out that the experiments described in this paper only focused on the injury threshold and consequently weak blast waves were used and not a single animal fatality occurred. Thus, it is hard to understand how these experiments can be used in predicting 50% lethality. Private correspondence with Karin Rafaels (co-author of the Bass paper) also failed to clear this up (30).

Currently it therefore looks like the assumption of Bass, that an open field situation is equally dangerous to a near wall situation, is not supported by neither experimental evidence nor theoretical analysis. The corresponding Bowen assumption, while having little experimental evidence, also looks theoretically more correct. At the moment there is really not enough experimental evidence to say whether the Bowen or Axelsson models are correct for open field situations, but the Bass model should probably not be relied on for such cases.

14 Short blast wave durations

We now turn our attention to the other open question: What happens for short wave durations (small charges) where Axelsson suddenly predicts significantly less injury than Bowen and Bass, even for the near reflecting wall scenarios? It may be somewhat surprising that the inconsistensies occur 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!

The derivation of the Axelsson model has been scrutinized earlier in this report and, despite some uncertainties, no major problems were found. Let us now look closer at how the Bowen curves were derived. Remember 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 by Goodman. 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 report by Goodman (13) 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 has been collected by Kingery and Bulmash (31) 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 FHV and are widely used today.

However, inspection of the original report by Kingery and Bulmash (31) 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.

This may give further insight into some previously unexplained results. In (26), Bjerke compared the blast wave parameters from a spherical explosion (1630 kg TNT) calculated by AUTODYN with HiV (Kingery/Bulmash). While there was good agreement for the maximum pressure, AUTODYN consistently predicted a shorter duration of the positive phase than Kingery/Bulmash. No explanation was found at the time, but it now seems likely to have been caused by Kingery/Bulmash not necessarily being correct.

Scaling the experimental results of Goodman and Kingery/Bulmash according to charge mass, we can plot them together with the AUTODYN results from Bjerke in the same diagram for comparison. This is done in Figure 14.1.

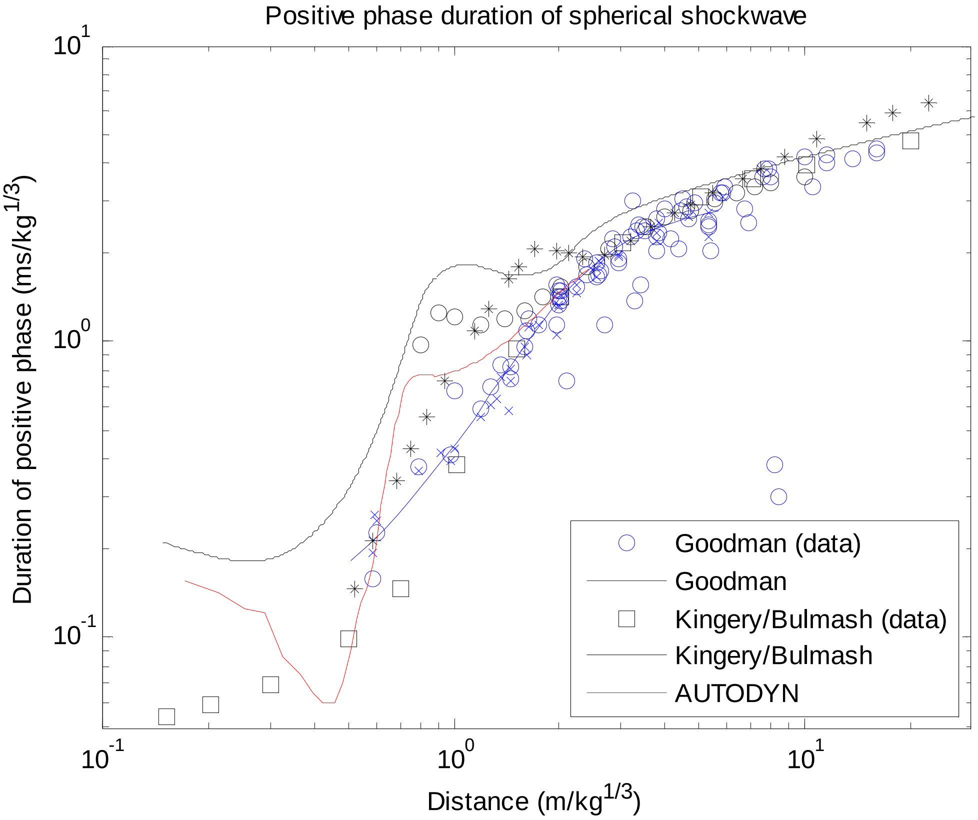


Figure 14.1 Comparison of experimental data and predictions of positive phase duration

There are several aspects of Figure 14.1 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, let us look one more time at what happens with the injury prediction formulas for short duration blast waves.

14.1 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 sheep had an average mass of 52.6 kg. Since the tests were performed at high altitude, atmospheric pressure was 83 kPa. This gives a scaling factor of $T=0.994t_+$ according to Equation (2.1), thus in reality no scaling was needed.

The measured (or calculated from an imaginary wall) reflected pressure is given by Bowen as 8681 kPa. Using Equation (2.5), we then find the 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 m/s*. 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 by Bjerke in Figure 14.1, he would have obtained a duration of *T=0.59 ms*. Clearly the differences in duration estimates are not just of academical interest, but they have a major influence on the Bowen curves.

From Figure 14.1 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 Chapter 12. 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.

One way to proceed further would be to modify the Bowen curves by using duration data from Kingery and Bulmash. However, as we have seen there is also large uncertainty regarding the accuracy of the Kingery and Bulmash formula, being only based on four hemispherical detonations of huge bombs. In fact, nobody really knows how to calculate durations for short blast waves accurately! Until more accurate data for short durations is available, there seems to be no point in modifying the Bowen curves. However, care should be taken when applying them to situations with short duration blast waves.

15 Summary

The state of the field of human blast injury has been reviewed. The most important available 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 model. The major difference between the Bowen and Bass curves was due to different assumptions being used for extending them to the open field situation. Using numerical simulations, we found that the Bass assumption seemed implausible, and thus the Bowen curves were preferred for the open field scenario.

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 side-on pressure in the relevant location is needed to determine the degree of injury from a blast wave. In a previous study the SP models were shown to generally provide a good approximation of the Axelsson BTD model.

However, the SP models rely on the Axelsson BTD model being accurate. Inspection of the experimental report for the calibration tests of this model revealed that the original researchers had grave worries about the data quality of their pressure measurements. Numerical simulations were therefore performed to investigate the foundation of the Axelsson BTD model. Good agreement was found between numerical and experimental results and it therefore seems likely that there is no inherent problem in the calibration of the Axelsson model.

Further, the Axelsson SP model worked almost as well as the more cumbersome Axelsson BTD model, especially after a new Axelsson SP injury formula was produced from curvefitting to the numerical simulations.

The Axelsson models have only been calibrated to experiments with small charges. To see if they could be extended to large charges as well, we systematically compared Axelsson BTD and Axelsson SP models with the injury curves of Bowen and Bass. This was done by creating scenarios with the Bowen and Bass models that 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 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 and FHV. If Bowen was corrected with Kingery/Bulmash duration data, it would lead to better agreement between Axelsson and Bowen also for these charges.

However, yet further inspection revealed that even the widely used Kingery/Bulmash relationship for blast wave duration was 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. Fortunately, it looks likely that better data would lead Axelsson to be more consistent with Bowen and Bass.

Table 15.1 summarises the current status of the various human injury prediction models after our comprehensive review and analysis. It is indicated in which situations the various methods have their strengths and weaknesses.

Without obtaining additional experimental data, this is probably as far as it is possible to come in the study of injuries to humans from blast waves. To improve the Bowen curves it is absolutely necessary to find reliable data for short duration blast waves. Possible further work could include performing experiments to obtain such blast wave data.

Injury model	Shock wave	Scenarios	Input	Output	Status
Bowen	Ideal	Prone, Open field, Near wall	P and T	Lethality	Good for ideal shock waves. Open field scenario not experimentally validated Should be careful when applying to short duration waves
Bass	Ideal	Prone, Open field, Near wall	P and T	Lethality	Good for ideal shock waves near reflecting wall Do not use for open field scenarios Should be careful when applying to short duration waves
Axelsson BTD	Any	Any	Four p(t) on a BTD	ASII (degree of injury)	Best and most versatile method Requires cumbersome BTD input Not validated for short duration waves in open field
Weathervane SP	Any	Any	p(t) in one point	ASII (degree of injury)	Good alternative to Axelsson BTD but unfortunately a cumbersome iteration method is needed
Modified Weathervane SP	Any	Any	p(t) in one point	ASII (degree of injury)	Gives good approximation to Axelsson BTD. Perfect for hydrocode simulations
Axelsson SP	Any	Any	p(t) in one point	ASII (degree of injury)	Gives good approximation to Axelsson BTD Perfect for hydrocode simulations
TNO SP	Multi-peak	Any	p_i, T_i	ASII (degree of injury)	Gives good approximation to Axelsson BTD for certain scenarios Perfect for simple estimates when full p(t) input is not known.

Table 15.1 Status of blast injury prediction models

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Appendix A Material models

Material Name - AIR

Equation of State	Ideal Gas
Reference density	1.22500E-03 (g/cm3)
Gamma	1.40000E+00 (none)
Adiabatic constant	0.00000E+00 (none)
Pressure shift	0.00000E+00 (kPa)
Reference Temperature	2.88200E+02 (K)
Specific Heat	7.17600E+02 (J/kgK)

Material Name - C4

Equation of State	JWL
Reference density	1.60100E+00 (g/cm3)
Parameter A	6.09770E+08 (kPa)
Parameter B	1.29500E+07 (kPa)
Parameter R1	4.50000E+00 (none)
Parameter R2	1.40000E+00 (none)
Parameter W	2.50000E-01 (none)
C-J Detonation velocity	8.19300E+03 (m/s)
C-J Energy / unit volume	9.00000E+06 (kJ/m3)
C-J Pressure	2.80000E+07 (kPa)
Burn on compression fraction	0.00000E+00 (none)
Pre-burn bulk modulus	0.00000E+00 (kPa)
Adiabatic constant	0.00000E+00 (none)
Auto-convert to Ideal Gas	Yes
Additional Options (Beta)	None
Reference:	"LLNL Explosives Handbook" Dobratz B.M & CrawfordP.C. UCRL-52997 Rev.2 January 1985

Material Name - TNT

Equation of State	**JWL**
Reference density	1.63000E+00 (g/cm3)
Parameter A	3.73770E+08 (kPa)
Parameter B	3.74710E+06 (kPa)
Parameter R1	4.15000E+00 (none)
Parameter R2	9.00000E-01 (none)
Parameter W	3.50000E-01 (none)
C-J Detonation velocity	6.93000E+03 (m/s)
C-J Energy / unit volume	6.00000E+06 (kJ/m3)
C-J Pressure	2.10000E+07 (kPa)
Burn on compression fraction	0.00000E+00 (none)
Pre-burn bulk modulus	0.00000E+00 (kPa)
Adiabatic constant	0.00000E+00 (none)
Auto-convert to Ideal Gas	Yes
Reference:	JWL Equations of State Coeffs. for High ExplosivesLee Finger & Collins. UCID-16189. January 1973