Comparison of the NATO 79J hazardous fragment with contemporary blunt impact and penetration injury models

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Abstract

TNO develops the Quantitative Risk Analysis (QRA) software Risk-NL, which is used for risk assessment and licensing of munition storage depots in the Netherlands. Recently, improvements have been made on the topic of injury models for debris and fragment impact, which is an important aspect within Risk-NL.

The aim of this study is to give an overview and comparison of blunt impact and penetration injury models, develop an approach for multiple hits at the body, and conduct an impact study with selected models. A secondary aim is to describe the implications of the findings for the NATO 79J hazardous fragment criterion.

The Swiss blunt injury model was selected for implementation in Risk-NL for all types of projectiles and masses. This model has a solid empirical basis and the comparative analysis shows that the probability of lethality also sufficiently covers the penetration injury regime.

An impact study was conducted to compare lethality predictions in the surroundings of ammunition magazines for the new and existing Risk-NL models. The new model gives a smaller probability of lethality at short and mid-range. Beyond the Inhabited Building Distance (IBD), the difference disappears, because only larger projectiles reach those distances, which are always lethal.

This paper also sheds new light on the 79J hazardous fragment criterion, as used by NATO in its definition of the Inhabited Building Distance (IBD). The general understanding is that any 79J projectile represents a similar level of injury or lethality. However, realizing that 79J may mean a 1 kg, 13 m/s fragment, as well as a 1g, 397 m/s fragment, it appears that the possible injuries may span from the blunt impact regime to the penetration regime, and there are differences in expected probability of lethality. Also, with the IBD being based on minimum projectile masses that are derived from a terminal (free fall) velocity assumption, smaller but potentially lethal projectiles may be overlooked.

Introduction

TNO develops the Quantitative Risk Analysis (QRA) software Risk-NL, which is used for risk assessment and licensing of munition storage depots. In the period between 2023 and 2025, Risk-NL has been applied to over 40 ammunition depots in the Netherlands and mission areas abroad.

Risk-NL considers munition storage accidents involving the different munition Hazard Divisions (HD), and various types of Potential Explosion Sites (PES) and Exposed Sites (ES). Risk-NL is based on NATO guidelines for munition storage (AASTP-1 **[1]**) [1] and explosives safety risk analysis (AASTP-4 **[2]**), national regulations and explosion effect- and consequence models developed by TNO. A Risk-NL analysis consists of:

- Applying AASTP-1 Inter Magazine Distances (IMD) and making sure an ammunition depot is internally safe. Distances with at least a high level of protection are applied which prevents prompt propagation, and in some cases prevents any form of propagation.
- Applying the AASTP-1 exterior Quantity Distances (QD), such as the Inhabited Building Distance (IBD) to check for any infringements. According to Dutch regulations only existing infringements can be accepted when the risk is below appropriate threshold values. New infringements are never acceptable.
- Determining the location specific individual risk and group risk for the infringements. For this purpose explosion effect and consequence models for blast, projectiles and thermal effects are used. The Dutch models are described in AASTP-4 **[2]**.

Risk-NL is periodically updated to reflect the latest versions of NATO and national standards. Also, the Risk-NL effect- and consequence models are regularly updated with the latest insights from testing and

[1] AASTP stands for Allied Ammunition Storage and Transport Publication

modelling. Recently, improvements have been made on the topic of injury models for projectile impact.

The aim of this study is to give an overview and comparison of blunt impact and penetration injury models, develop an approach for multiple hits at the body, and conduct an impact study with selected models. A secondary aim is to describe the implications of the findings for the 79J hazardous fragment, as used by NATO in its definition of the IBD.

This paper is organized as follows:

- *Selection of a new model for injury due to debris and fragment impact*. For this purpose Section 2 discusses contemporary blunt- and penetration injury models. Section 3 presents a comparative analysis, followed by a selection for implementation in Risk-NL.

- *Development of an approach for multiple hits*. For this purpose a statistical treatment of the number of hits and overall lethality are discussed in Section 4. Section 5 gives attention to the possible number of fatalities in a group of people.

- *Impact study*. Section 6 shows the impact of the new versus the existing lethality- and multiple hits models with a case study.

In this paper, the term "debris" refers to concrete, and "fragments" to steel from ammunition casings. Whenever something applies to both debris and fragments, this paper adopts the word "projectiles". The main interest is on lethality risk, because this is included in the legal definitions. Nevertheless, injury is also considered for a broader understanding

Overview of blunt and penetration injury models

Current assumption in Risk-NL

The current assumption in Risk-NL is that every projectile hit is lethal, irrespective of its mass or velocity. This rather conservative assumption is to be challenged. Furthermore, it is assumed that exposed persons are always facing the hazard and are in standing position for low angle projectiles. With respect to high angle projectiles, which arrive moments later, it is assumed persons are lying down.

NATO AASTP-1 criterion for hazardous projectiles

History

NATO AASTP-1 [1] defines an impact energy equal to or greater than 79J as "hazardous". The first notion of the 79J kinetic energy level stems from 1906 (Rohne [3]) and 1907 (Journee [4]). Note that this energy level is also expressed as 8 m-kg or 58 ft-lb. Rohne states: "To remove a human from the battlefield, a kinetic energy of 8 m-kg is sufficient according to the prevailing view in the German artillery community". He also mentioned that horses need a kinetic energy of 19 m-kg to incapacitate them. Rohne, while not discussing the validity of the 79J criterion, used it to determine ranges at which various military rifles ceased to be effective.

US(ST)IWP 11-79 [5] refers to the article by Journee [4]: ''The 58 ft-lb criterion had its origin in experiments done by COL Journee, a French infantry officer, and reported in Revue d'Artillerie 70, pp 81-120 (May 1907). He fired pistol and rifle bullets of various calibers (4.5 to 21.2 mm) and various weights (3 to 56 grams) into horses and human cadavers and documented the energy levels required for wounding soft tissue and bone. For example, he noted that at least 15 ft-lb was required for penetration of soft tissue, that at 36 ft-lb human bones could be cracked, and that 115 ft-lb was required to assure fracture of large human bones such as the femur. He also related the cross sectional area of bullets to their wounding power.''

Sterne [6] suggested that the 79J criterion applied to lethality rather than to a sub lethal effect. Indeed, penetrating injury research shows that lethal injuries can occur at impact energy levels significantly less than 79J. Nowadays, the term "hazardous" is used which could mean both lethal and non-lethal injury. In some of the earlier versions of AASTP-1 the 79 J energy level was rounded to 80 J, but in the most current version the original 79 J value is restored for historical reasons.

Application in Debris and Fragment Distance (DFD)

The NATO 79J criterion is used by NATO in its definition of the debris Inhabited Building Distance (IBD), which is called the Debris and Fragment Distance (DFD) since 2023 [1]. Beyond this distance, the number of hazardous projectiles per m^2 does not exceed 1 per 56 m^2. With a typical body area of 0.56 m^2, the probability of a hit by a hazardous projectile at the DFD is close to 1%[2].

Figure 1 shows the mass-velocity combinations which have a kinetic energy of 79 J, and also a larger (arbitrary) kinetic energy of 300 J.

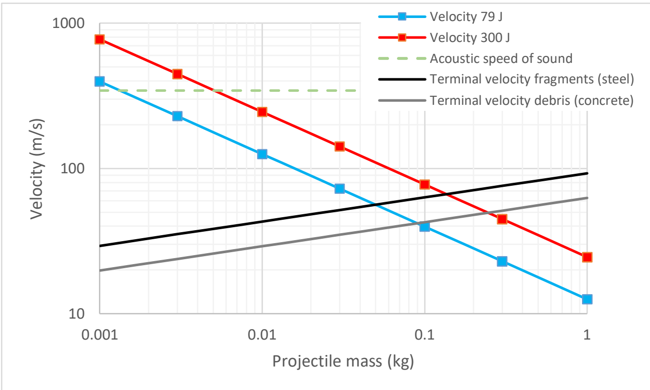


Figure 1: Velocity of 79 J and 300 J projectiles, compared with terminal velocity of debris and fragments.

In explosives testing the location of the DFD is determined from projectile pick-up data. For this purpose it is assumed that projectiles impact with the terminal (free fall) velocity. This means that, in order to have an impact energy of 79J or greater, concrete debris (2400 kg/m^3 density) should at least have a mass of 90g and steel fragments (7800

[2] This follows from 1/56 m^2 * 0.56 m^2 = 1/100 = 1%

kg/m³ density) at least a mass of 50g. This can be seen from Figure 1, where the terminal velocity has been plotted for concrete debris and steel fragments. Only projectiles with masses above these limits are collected and considered in the determination of the DFD from test data.

While this terminal velocity assumption may be valid in the far field, it will be clear that more close-in to the explosion smaller projectiles can easily have higher velocities (and hence possibly also energies above 79J). In the remainder of this paper we will therefore include the small high velocity projectiles in the analysis.

Model from "Publicatiereeks Gevaarlijke Stoffen"

The model from the Dutch PGS 2-1a [7] consists of criteria for three regimes of projectile mass (Figure 2). For each regime a probit function is specified to calculate the probability of lethality. For masses below 100 g the criterion is based on skin penetration, for masses between 100 g and 4,5 kg it is based on kinetic energy, and for masses above 4,5 kg it is skull fracture. One of the energy criteria considered is the aforementioned 79J criterion [1].

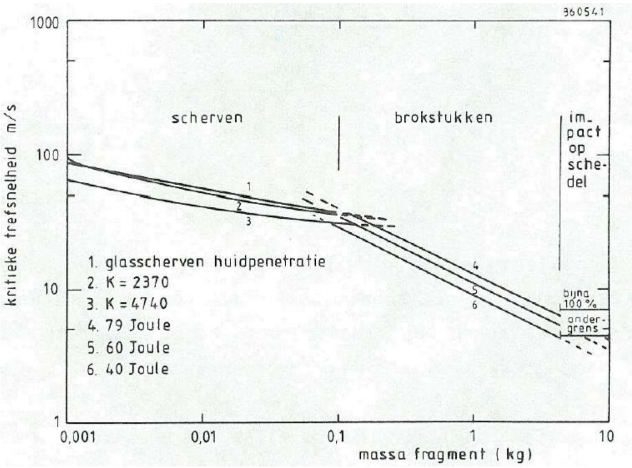


Figure 2: Lethality model from PGS 2-1a [7] with three regimes of projectile mass. "Scherven" means fragments and "brokstukken" means debris.

A more recent overview of skin perforation criteria was given by Breeze et al. (2015) [8]. In Figure 3, the velocities needed for skin perforation are presented as a function of "sectional density". The data partly has the same basis as the left part of the graph in Figure 2.

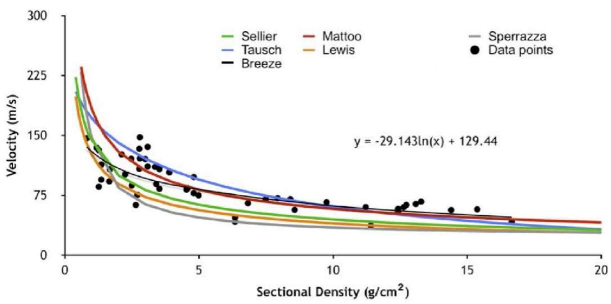


Figure 3: Overview of skin perforation criteria from Breeze et al. (2015) [8].

Swiss blunt injury model

The NATO AASTP-4 [2], Explosives Safety Risk Analysis, describes a blunt injury model, developed and used by Switzerland in their national QRA software. The model is mainly based on research performed by Feinstein [9], Kokinakis [10], White [11], and others in the period 1960 - 1980. [2]. This research focused on the impact of blunt non-penetrating objects.

The model gives the probability of lethality due to blunt impact, as a function of kinetic energy. The model distinguishes 4 body regions: head, thorax, abdomen and limbs. The "basic lethalities" are given in Figure 4. The Swiss body model and assumed areas of body regions are given in Figure 5.

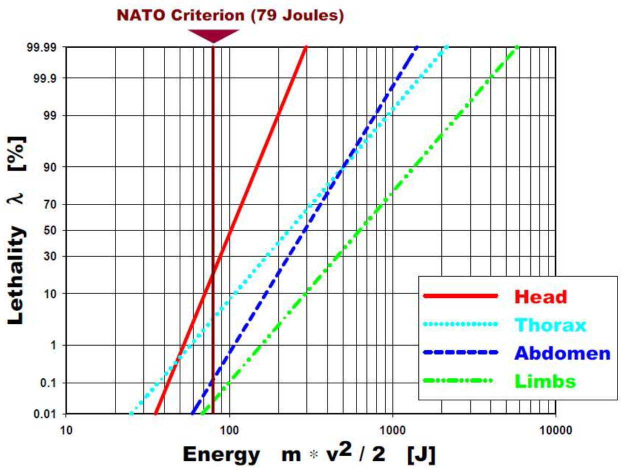
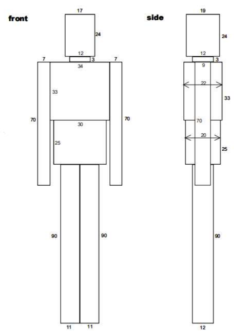


Figure 4: Swiss lethality probability as a function of kinetic energy for different body regions [2].



[m²]	head	thorax	abdomen	limbs	total
front	0.044	0.112	0.075	0.296	0.527
side	0.049	0.058	0.039	0.171	0.317
top	0.032	0.043	0.000	0.013	0.088

Figure 5: Swiss body model [2].

The "basic lethalities" are given by an error (erf)-function in Figure 6. The model description does not provide a range of validity in terms of projectile mass.

$$F_x(x;\,\mu,\sigma) = \frac{1}{2}\left[1 + erf\left(\frac{lnx - \mu}{\sigma\sqrt{2}}\right)\right]$$

	Head	Thorax	Abdomen	Limbs
Sigma	0.286	0.63	0.44	0.6
Mu	4.62	5.52	5.70	6.42
Mean (J)	106.05	304.89	330.50	735.10
Median (J)	101.80	250.01	300.01	614.00

Figure 6: Equation and constants for "basic lethalities" [2] *depicted in Figure 4. The probability is denoted as* F_x*, the kinetic energy is denoted as "x".*

US blunt injury model

The US uses a similar model as the one from Switzerland in their national QRA code SAFER. The model is also described in AASTP-4 [2], but the primary reference for this model is TP-14 rev 5 [12]. The US model uses the same equations for the "basic lethalities" as the Swiss model. An important difference is that impacts at the limbs are always considered non-lethal and are hence excluded in lethality risk calculations. Furthermore, the US also presents relations for the probability of minor and major injury.

Penetration injury model in TARVAC/Computerman

The Computerman code in the TNO TARVAC software [13] is used to assess the lethality of ballistic penetrating threats. Contrary to the Swiss and US blunt injury models, this model is not simply a function of kinetic energy, but depends on more variables such as fragment mass, velocity, density and shape. The range of application is generally below 10 to 30 grams.

TARVAC/Computerman calculates the retardation of the projectile based on the penetration of various tissues. Based on this, a penetration depth and corresponding damaged tissues are established. This is used to calculate the Abbreviated Injury Scale (AIS2005) Scores. From these injury scores, a probability of lethality can be derived. TARVAC/ComputerMan outputs a vulnerability view where each pixel reflects a projectile hit and gives the resulting AIS of that projectile using a colour code (Figure 7).

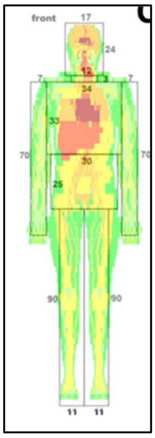


Figure 7: TARVAC/ComputerMan vulnerability view example. The numbers refer to dimensions in cm.

The AIS ranges from 0 to 6 with the injury severities displayed in Table 1. Within the context of QRA it is reasonable to assume that AIS 5 and AIS 6 are both lethal.

Table 1: AIS colour definitions and corresponding injury labels.

Colour	AIS	Label
	1	Minor injury
	2	Moderate injury
	3	Serious injury
	4	Severe injury
	5	Critical injury
	6	Fatal injury

First observations on the models

A first analysis of the various models leads to the following observations.

The model from PGS 2-1a **[7]** has been superseded by more data and analysis. The assumption that skin perforation by itself is sufficient to cause lethality is very conservative. Although skin perforation is an important prerequisite, further penetration and impact at vital organs or arteries is a further necessity for lethality to occur.

The "basic lethalities" for the different body regions in the Swiss **[2]** and US blunt injury models **[12]** have a solid empirical basis. The range of validity in terms of projectile mass is however not specified. This raises a concern whether the presented "basic lethalities" are also realistic (or at least conservative) for small projectile masses in the penetration injury regime. This has led to a comparison between blunt- and penetration injury models in Section 3.

The exclusion of limbs from the lethality calculation in the US model is not fully understood. The expectation is that in general this is an unconservative assumption, especially when applied to the general public. In practice this might be less relevant for the US, as safety arcs typically do not exit US DoD installations.

Comparison of injury models

In this section a comparison between the blunt- and penetration injury models is presented. This is done for projectiles with two kinetic energies at the lower and higher end of the lethality spectrum, 79 J and 300 J respectively. The comparison is carried out for the velocity-mass combinations that were already given in Figure 1 by the blue and red squares.

As noted before, the results for the Swiss (and US) blunt injury models only depend on kinetic energy. The results are summarized in Table 2.

Table 2: Probability of lethality for 79 J and 300 J projectiles based on Swiss model (US model excludes the limbs).

Body region	79 J	300 J
Head	20%	99.9%
Thorax	5%	70%
Abdomen	0.1%	50%
Limbs	0.01%	10%
Weighted average	2.8%	37%

The probability of lethality at 79J weighted over the total body area is 2.8%. This means that projectiles, currently included to determine the DFD, have a probability of lethality of at least 2.8% (possibly up to 100%). Together with the earlier mentioned hit probability of about 1% at DFD, this would suggest an overall probability of lethality between 0.028% and 1% at DFD.

TARVAC results were generated under the assumption that debris and fragments have a cube shape. The TARVAC results have been averaged for each of the body regions as used by the Swiss model (Figure 5), enabling direct comparison between the two approaches.

As a first check of the penetration capacity, the 79J projectiles are compared against the skin penetration criterium set by Breeze et al. [8] in Figure 8. This figure shows that 79J projectiles below approximately 30 grams can potentially penetrate the skin as they lie above the combined skin perforation relation (black line). This implies that TARVAC/Computerman results for 79J are only relevant below approximately 30 grams. In a similar fashion it can be concluded that 300 J fragments are only relevant below about 100 grams.

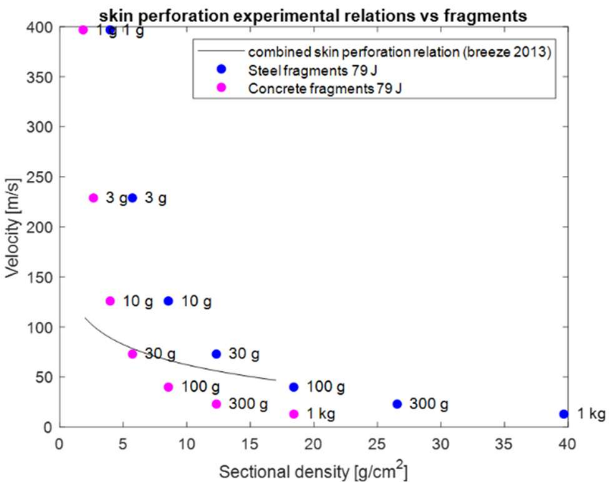


Figure 8: Comparison of the 79 J fragment combinations with the skin perforation from Breeze et al. (2015) [8]*. Fragment with a mass below 30 grams could potentially perforate the skin.*

Figure 9 compares the lethality predicted by TARVAC/ Computerman with the Swiss model from AASTP-4. It shows results for respectively 79J steel, 79J concrete, 300J steel and 300J concrete. Results are presented per body region and as a weighted average ("total body"). For TARVAC/Computerman, results are only shown within the applicable range, i.e. below 10 to 30 grams.

Among the TARVAC/Computerman results, lethality is largest for penetration of the thorax, followed by the head, abdomen and limbs. On the other hand, the Swiss model from AASTP-4 for blunt impact always give the largest lethality for the head followed by the thorax, abdomen and limbs. Steel fragments always cause a larger lethality due to penetration than concrete debris. This is caused by the higher density of steel fragments resulting in a smaller presented area and thus a higher penetration capacity.

When the impact energy increases from 79J to 300J, the lethality due to blunt impact (right column) increases significantly whereas lethality due to penetration (left columns) increases only moderately. In quantitative terms, the lethality increase for blunt impact is at least a factor of 5, whereas the lethality increase for penetration is a few tens of percent at most. When penetration into a certain body region has taken place, a further increase of impact energy will apparently not increase lethality dramatically.

The probability of lethality due to penetration decreases with fragment mass (given a constant kinetic energy). For masses above 3 to 10 grams, the probability of lethality due to penetration always drops below the value for blunt impact, and hence these masses are not depicted in the figure. For 300J projectiles, lethality due to penetration is always lower than due to blunt impact. For 79J projectiles of 1 and 3 g, the lethality due to penetration is somewhat larger than for blunt impact. This is mainly caused by the thorax area.

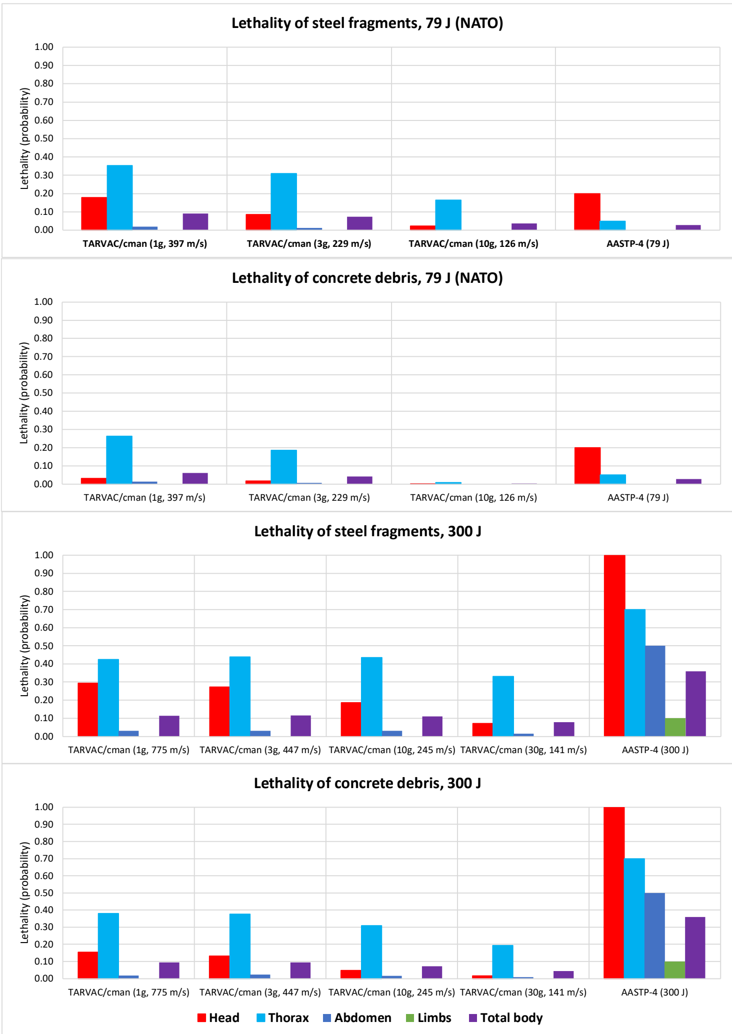


Figure 9: Comparison between TARVAC/Computerman (left) and Swiss/US models from AASTP-4 (right). From top to bottom: 79J steel, 79J concrete, 300 J steel, 300J concrete. Relevant masses for penetration injury are shown, i.e. 1-30 g.

Projectiles with a mass below 3 g will however rapidly decelerate due to air drag. Figure 10 shows results from a trajectory calculation for small steel fragments with a natural shape that are launched with 1000 to 2000 m/s. This shows that the impact energy for 3 g steel fragments is only above 79J for distances below 50 to 80 m.

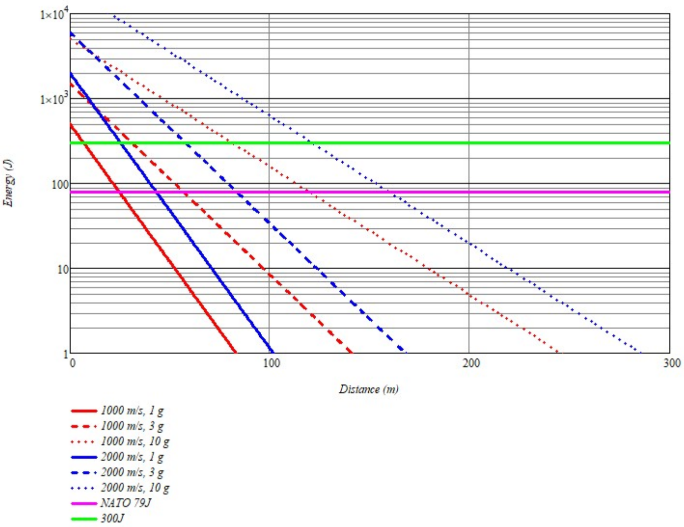


Figure 10: Impact energy versus distance for 1, 3 and 10 g steel fragments launched with 1000 and 2000 m/s.

Based on the above, the Swiss model for blunt injury was selected for implementation into Risk-NL for all types of projectiles and masses. For small masses in the penetration regime this will generally yield conservative results and in an exceptional case a slightly unconservative result. The latter will only take place below distances of 50 to 80 m and for small mass and impact energy projectiles. However, due to the many lethality mechanisms that play a role at such short distances (e.g. multiple hits, blast and thermal injuries) the overall probability of lethality is already close to 100%, and the proposed approach will not lead to underestimation of risk.

Number of hits and overall probability of lethality

The injury models discussed above are valid for a given (single) projectile hit at the human body. However, the overall probability of lethality also depends on the probability of that single hit, or possibly multiple hits, occurring. In this section we explore “multiple hits” with a statistical treatment.

Projectile number density

The analysis starts by considering the projectile (number) density (Φ), which is the number of projectiles that impacts per square meter. Risk-NL has analytical models for 6 types of projectile densities, which are illustrated in Figure 11 and described in AASTP-4 [2] and [14]. They consist of debris (solid lines) and fragments (dashed lines), launched around the horizontal (blue and red) and vertical direction (black) and impacting through a horizontal or vertical plane[3]. The models make use of empirical relations for projectile mass-, velocity- and launch angle distributions, as well as trajectory calculations. Besides projectile density, the models also give a prediction of impact velocity and energy.

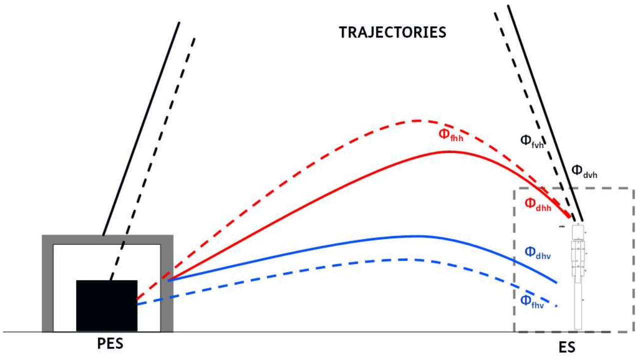


Figure 11: Illustration of Risk-NL projectile sources. Debris (solid lines) and fragments (dashed lines), launched around horizontal (blue and red) and vertical (black) direction and impacting through a horizontal or vertical plane.

An example is given for the Sci Pan 1 test [15] in Figure 12. In this test 12.249 kg of bare explosives was detonated in a concrete building. The figure shows the variation of the debris density with distance for wall and roof debris. The Risk-NL debris model shows a good correspondence with the test data. The colour coding used in Figure 12 corresponds to that in Figure 11.

[3] The projectile density in a horizontal plane is used to calculate hits at the top of the human body, the vertical plane for the front.

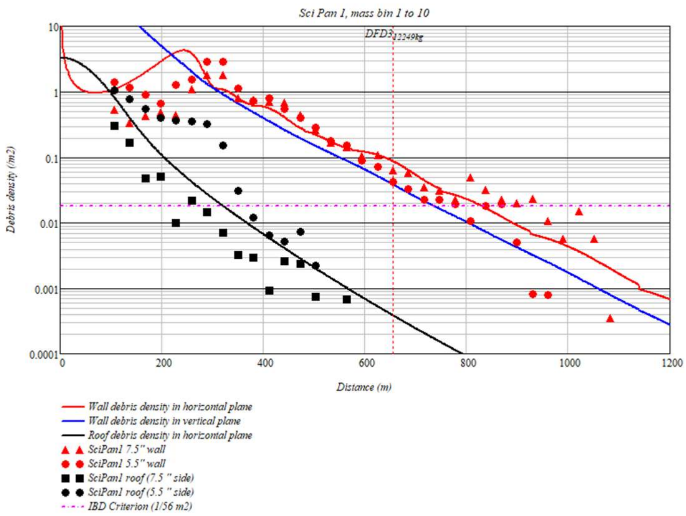


Figure 12: Debris density (number of impacting debris per m²) versus distance for the Sci Pan 1 test [15]*. Results for debris from wall and roof over the full range of debris masses, in the wall normal direction. Test data versus Risk-NL model results.*

Statistical analysis

The number of hits (n = 0, 1, 2, 3, ..) at the human body can be regarded as a Poisson process, where the projectile density (Φ), times the area of the body (A) acts as a “rate parameter”[4]. At this stage we consider only one type of projectile density and we do not distinguish between body regions.

The probability of n hits is given by:

$$P_{hit}(n) = \frac{(\Phi \cdot A)^n \cdot e^{-\Phi \cdot A}}{n!} \qquad \text{Eq 1}$$

The expected number of hits equals:

$$E(n) = \Phi \cdot A \qquad \text{Eq 2}$$

Based on this equation we can calculate the probability of receiving at least 1 hit (this is 1 minus the probability of no hits, n=0):

$$P_{hit}(\geq 1) = 1 - e^{-\Phi \cdot A} \qquad \text{Eq 3}$$

This equation is frequently used in risk models, but has the disadvantage that it does not distinguish between 1, 2, 3 or more hits, and hence disregards the effect of multiple hits. In the current Risk-NL model the same approach is taken, but the equation above is further simplified as:

$$P_{RiskNL,hit} = \min(1, \Phi \cdot A) \qquad \text{Eq 4}$$

[4] Other examples of Poisson processes are the number of customers calling a help center, visitors to a website, action potentials of a neuron and radioactive decay.

An approach which better acknowledges multiple hits is to separately calculate the probability of 1, 2, 3, etc. hits, using Eq. 1.

$$P_{hit}(1) = \Phi \cdot A \cdot e^{-\Phi \cdot A},$$

$$P_{hi}(2) = \frac{(\Phi \cdot A)^2 \cdot e^{-\Phi \cdot A}}{2},$$

$$P_{hi}(3) = \frac{(\Phi \cdot A)^3 \cdot e^{-\Phi \cdot A}}{6}, \text{ etc.} \qquad \text{Eq 5}$$

The various probabilities have been plotted in Figure 13 as an illustration.

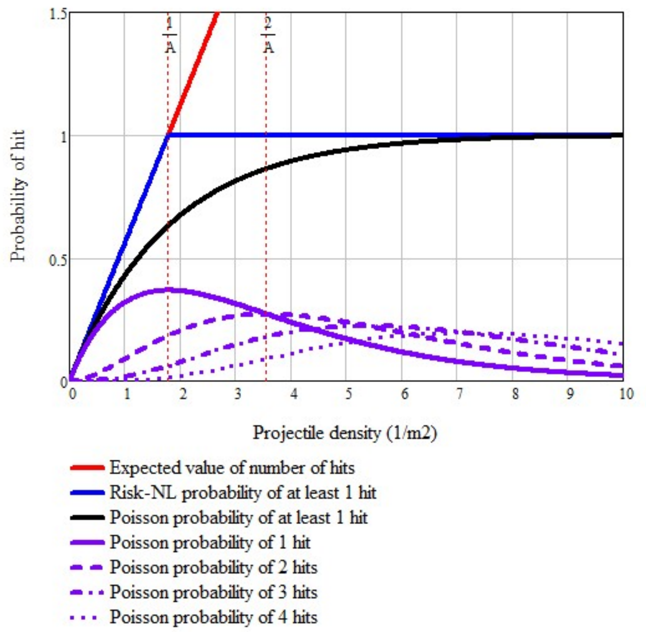


Figure 13: Probability of 1 or more hits based on the Poisson distribution and as implemented in Risk-NL. A=0.56 m².

Figure 13 shows that for low projectile densities, the hit probability (black curve, Eq 3) is well approximated by Risk-NL (blue curve, Eq 4), but becomes overly conservative for higher debris densities. The purple curves for the separate number of hits add up to the match the black curve.

Next, each of the separate probabilities for 1, 2, 3, etc. hits (Eq 5) should be multiplied by the probability of lethality due to 1, 2, 3, etc. hits, and then would need to be accumulated. When a person is hit by multiple projectiles the probability of lethality may add up in a non-trivial fashion, e.g. lung damage may have worse effects if there is also a loss of blood due to a penetration injury in a another body region. Medical experts could judge whether e.g. two hits of 10% lethality add up to 20% or perhaps to a larger value. At the same time the probability of lethality can obviously not exceed 100%.

When we consider the fact there are different types of projectile densities and different body regions, the analysis becomes even more complex. From a theoretical perspective it is very well possible to e.g. calculate the probability of receiving 1 hit at the head, 2 hits at the thorax and zero at limbs and abdomen:

$$P_{hit}(1, A_{hea}\ ) \cdot P_{hit}(2, A_{thora}\ ) \cdot P_{hit}(0, A_{limbs}) \cdot P_{hit}(0, A_{abdomen})$$

Due to the enormous amount of possible outcomes, this approach is not considered feasible. The limitation is not in the mathematics, but more so in the required effort and the knowledge gap in the medical field.

Nevertheless, two alternative formulas were developed for the total probability of lethality. Both options have the property that the probability does not exceed 1. The first is based on a non-linear addition of probability of lethality

$$P_{let,tot,alt} = P_{let} \cdot P_{hit}(1) + \sum_{n=2}^{\infty}(1 - e^{-n \cdot P_{let}}) \cdot P_{hit}(n) \quad \text{Eq 6}$$

The second is based on a linear addition with rounding.

$$P_{let,tot,alt2} = \sum_{n=1}^{\infty} \min(1, n \cdot P_{let}) \cdot P_{hit}(n) \quad \text{Eq 7}$$

Furthermore, there is the model from Switzerland [2], which takes a different approach:

$$P_{let,tot} = 1 - e^{-\Phi \cdot A \cdot P_{let}} \quad \text{Eq 8}$$

Eq 8 resembles Eq 3, but with a different exponent. $\Phi \cdot A \cdot P_{let}$ can be interpreted as the expected value of the number of times a person can get killed (p = 0,1,2,…) from being struck by a number of projectiles $\Phi \cdot A$, each with a probability of lethality P_{let}. This interpretation is somewhat problematic because a person can only get killed once. For example, consider a person with standard body area A=0.56 m^2, a high debris density of 10/m^2 and a probability of lethality of 50% per projectile. The result is that the person would get killed 2.8 times on average.

Figure 14 shows the three alternatives, Eq 6, 7 and 8, and their results are fairly close. Based on the above, the simpler Swiss model (Eq 8) was selected for implementation into Risk-NL, because it suffices for the current purpose.

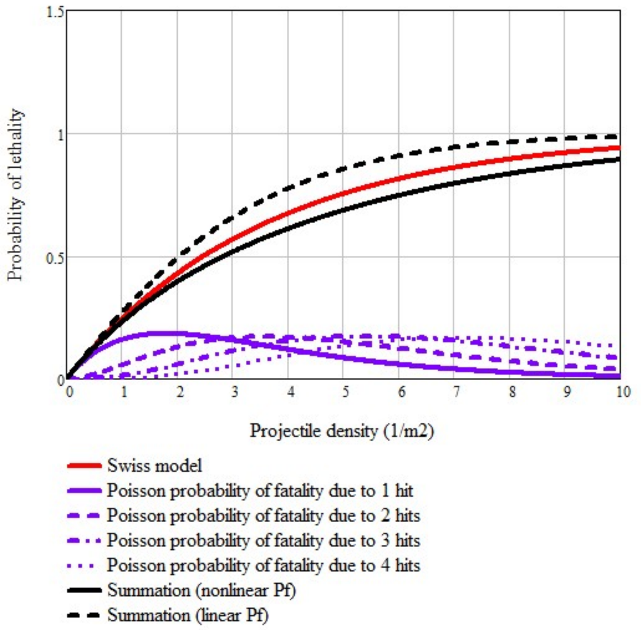


Figure 14: Probability of lethality according to Swiss model or two alternative formulations. P_{let} = 0.5. A=0.56 m^2.

Within the context of Risk-NL, Eq 8 is further generalized by realizing there are 6 different sources of projectiles (k=1-6), projectile mass bins (i=1-10), impacting at different body regions (j=1-4):

$$P_{let,tot}(r) = 1 - e^{-\sum_{ijk} \Phi_{ik}(r) \cdot A_j \cdot P_{let\,j}(E_i(r))} \quad \text{Eq 9}$$

With:

$\Phi_{ik}(r)$ Projectile density from source k and mass bin i

A_j Area of body region j (choice for front, side or top)

$P_{let\,j}$ Probability of lethality for body region j

$E_i(r)$ (Kinetic) energy decay with impact distance for mass bin i

Number of fatalities in a group of people

Another non-trivial aspect is what a certain probability of lethality means for a large group of people. Let's consider a group of 100 people at a location around the DFD where the debris density is hence about 1/56 m^2. As mentioned earlier, with a typical body area of 0.56 m^2, the probability of a hit by a hazardous projectile at this distance is around 1%.

On average, the explosive event leads to 1 person within this group getting impacted by hazardous debris[5]. In risk analysis it is this average value which is often used for group risk calculations. The distribution of possible outcomes follows however a binomial

[5] This follows from 1% * 100 = 1

distribution. The probability of k out of K people getting hit as a result of a hit probability P is:

$$P_{hit}(k) = \frac{K!}{k! \cdot (K-k)!} \cdot P^k \cdot (1-P)^{n-k} \qquad \text{Eq 10}$$

Figure 15 shows that 1 person getting hit indeed has the largest probability (37%). Perhaps counterintuitive is that none of the people being hit is almost as likely (36.6%). Furthermore, larger numbers are also very well possible and have significant probabilities, e.g. 18.5% for 2 people, 6.1% for 3 people and 1.5% for 4 people getting hit.

The example shows that the distribution is surprisingly broad. This is relevant information since group risk acceptance criteria are in some nations progressively stricter for larger numbers of fatalities [16].

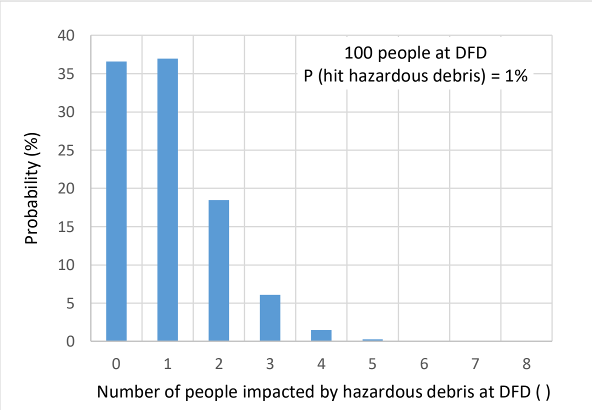


Figure 15: Probability of the number of people impacted by hazardous debris at DFD (debris IBD). 1% lethality and 100 people.

Impact studies

The impact of the selected Swiss models (the one for lethality and one for addition of multiple hits) has been investigated by implementing them in a Risk-NL research code. Figure 16 and 17 present results for the SciPan 1 test (same test as in Figure 12). Curves are shown for:

- The current assumption in Risk-NL (all hits are lethal)
- Swiss model
- US model = Swiss model excluding limbs

In the analysis it is assumed, as before, that exposed persons are facing the hazard and are in standing position for low angle projectiles, and assumed lying down for high angle projectiles. Figure 16 reflects the actual test which was unbarricaded. In this case all wall and roof debris is taken into account. In Figure 17 the effect of a barricade is simulated by excluding all wall debris.

The results indicate that the Swiss and US model significantly reduce the probability of lethality. This is caused by the fact that the impact velocity and - energy of the smaller debris drops below lethality criteria.

For the larger distances, the current Risk-NL and Swiss lethality prediction are however the same. This is caused by the fact that only the larger debris reaches those distances and their impact is always lethal. The lethality predicted by the US model is smaller for all distances, which is caused by the effectively smaller body area as a result of excluding the limbs.

The distance with a probability of lethality of 1% reduces significantly, and hence this could support a reduction of IBD/DFD.

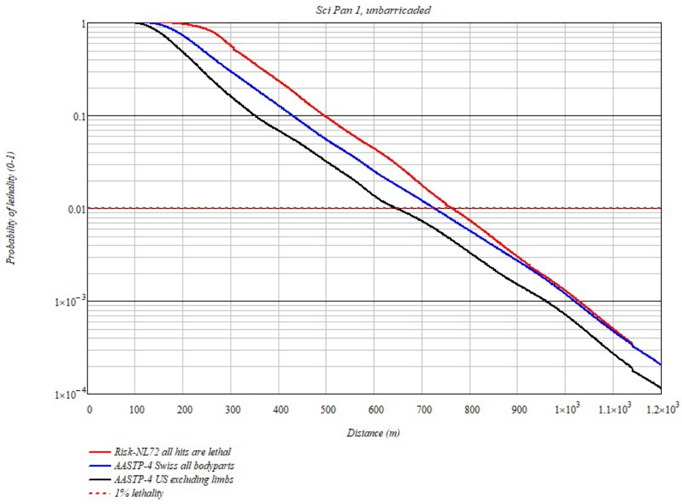


Figure 16: Probability of lethality according to Risk-NL (current assumption: all hits are lethal), AASTP-4 Swiss model (all body regions) and AASTP-4 US (excluding limbs). SciPan 1 test, unbarricaded situation.

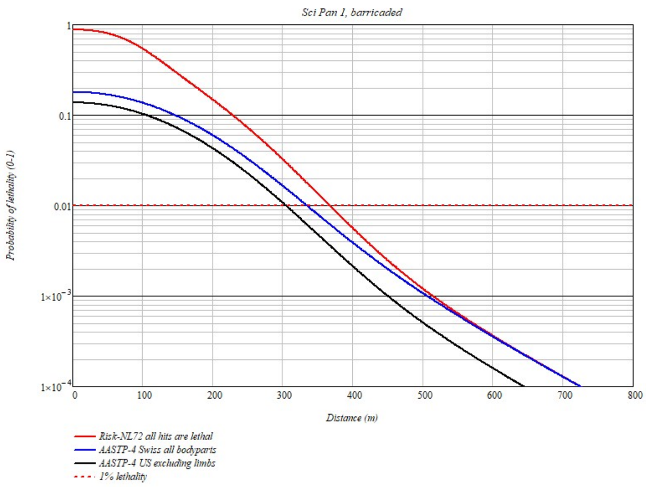


Figure 17: Probability of lethality according to Risk-NL (current assumption: all hits are lethal), AASTP-4 Swiss model (all body regions) and AASTP-4 US (excluding limbs). SciPan 1 test, barricaded situation.

Conclusions

This paper has compared various blunt impact and penetration injury models.

Models which assume that skin perforation by itself is sufficient to cause lethality are highly conservative. Although skin perforation is an important prerequisite, further penetration and impact at vital parts is a further necessity for lethality to occur.

The Swiss blunt injury model was selected for implementation in Risk-NL for all types of projectiles and masses. However, the validity of this model for small projectile mass in the penetration injury regime was not entirely clear. Comparative analysis has shown that the probability of lethality, predicted by the model, is nearly always conservative when compared to penetration injury criteria. In rare cases where penetration injury would yield greater probability, this only happens very close-in to the explosion.

Furthermore, the effect of multiple hits at the human body has been studied, based on the Poisson distribution. Using this distribution, concise relations can be derived for the probability of receiving a specific number of hits. However, due to lack of medical knowledge regarding the physiological consequences of multiple impacts, further exploration in this direction was not pursued. A simplified approach was chosen to quantify the effect of multiple hits. Furthermore, it was shown that the possible number of fatalities due to projectile impact at a group of people follows a binomial distribution.

A case study was conducted to compare lethality in the surroundings of ammunition magazines for the new and existing Risk-NL lethality model. The new model gives a smaller probability of lethality at short and mid-range. Beyond the Inhabited Building Distance (IBD), the difference disappears because only larger projectiles reach those distances, which are always lethal.

This paper also sheds new light on the 79J hazardous fragment criterion, as used by NATO in its definition of the IBD. The general understanding is that any 79J projectile represents a similar level of injury or lethality. However, realizing that 79J may mean a 1 kg, 13 m/s fragment, as well as a 1g, 397 m/s fragment, it appears that the possible injuries may span from the blunt impact regime to the penetration regime, and there are differences in expected probability of lethality. Also, with the IBD being based on minimum projectile masses that are derived from a terminal (free fall) velocity assumption, smaller but potentially lethal projectiles may be overlooked.

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