A Fast Running Model for Lethality due to Wall Debris Throw from Above Ground Magazines

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Abstract

The Klotz Group (KG) is an international group of experts on explosives safety from eight nations. The main aim of the KG is to improve the knowledge of explosion effects associated with the storage, processing and transport of ammunition and explosives, and to develop associated engineering models (computer codes) that enable the quantification of these effects as a basis for consequence and risk analysis. One of the main achievements of the KG is the development of the KG-EngineeringTool (KG-ETool) that allows a detailed calculation of debris throw from above ground structures.

Switzerland, as a founding member of the KG, uses this tool as a basis for the development of a new Fast Running Model (FRM) for the calculation of the lethality of people due to debris throw from walls of above ground reinforced concrete ammunition and explosives storage magazines (PES). This paper describes the FRM and its development. Discussed are the general methodology for developing a lethality model, the main factors influencing wall debris throw and comparisons of the output of the FRM with results from recent model and full scale tests.

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1. Background

Most ammunition safety regulations are still based on easily applicable quantity-distances (QD) concepts, taking into account deterministic criteria like a certain hazardous debris density as a decisive and sole measure, but do not focus on the actual hazard to exposed persons. Modern world solutions however, call for probabilistic risk analysis procedures focusing on the real hazards to people and allow to optimise the use of the sparse resources left in our field today, such as money, personnel or space for military activities.

However, innovative probabilistic risk analysis procedures - as the one successfully used in Switzerland since the late 70's [1] or the one described in the NATO AASTP-4 "Manual on Explosives Safety Risk Analysis" [2] - require more sophisticated explosion effect and lethality models than the ones nowadays used in QD-manuals.

In Switzerland, for performing risk analysis for above ground reinforced concrete ammunition storage magazines, a relatively simple explosion effect model was used till recently (Figure 1) [1]. However, this model already took into account the well-known fact that debris throw from the walls of a freestanding magazine is distributed in a clover-leaf shaped manner to the surrounding.

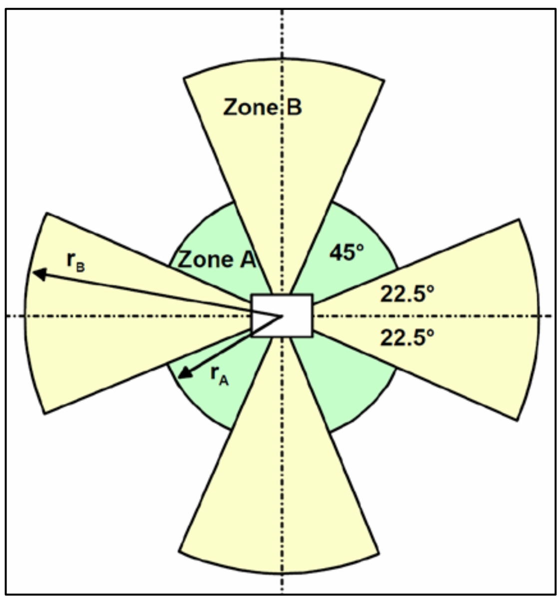

Figure 1: Current Swiss Explosion Effect Model for a Freestanding Above Ground Magazine

During the last few decades however, many tests with model and full scale freestanding above ground reinforced concrete magazines (referred to as "magazines" in this paper) were performed [e.g. 3 - 12], the results were leading to a huge database on debris throw from such structures. This data was used by the International Klotz Group to develop a sophisticated computer model - the so-called Klotz Group Engineering Tool, or short KG-ETool [13 - 15] - which allows the calculation of the distribution of concrete debris in the surrounding area in case of an explosion inside a magazine in great detail. The database from the various tests and the development of the KG-ETool made it then possible to improve the relatively simple Swiss model used until now.

This paper describes the successful development of a new Fast Running Model (FRM) for the calculation of the lethality of people staying in the open or within buildings *due to wall debris throw* from explosions in magazines, based on using the KG-ETool for calculating debris densities around a magazine and the Swiss tool LambdaT© [16 - 18] for converting debris densities into lethalities.

2. Aim

As mentioned, the Klotz Group's KG-ETool as well as the Swiss tool LambdaT© are quite sophisticated engineering tools, in the sense that a lot of knowledge is needed to input the many variables and parameters correctly. Needless to say, that the data handling and running of the tools takes some time. For performing "every day risk analysis" this proved to be not really suitable. Therefore, it was decided to try to develop a new Fast Running Model (FRM) based on these computer codes and all the test data on hand.

The following requirements for the FRM were defined:

- Common Swiss above ground magazines should be covered. A typical example of such a magazine is shown in Figure 2.
- The Model should be applicable for a lager range of charge sizes and loading densities.
- The main use of the FRM should serve as basis for performing standard risk analysis according to the Swiss regulations.
- Therefore, the input has to be limited to a number of variables and parameters that can be compiled easily from construction drawings or collected in the field from the real structure.
- The model and its use is supposed to be easily understandable.

Figure 2: Typical Swiss Above Ground Magazine for Training Ammunition

3. Methodology

Basically, lethality of people due to any type of debris throw can be calculated according to the procedure shown in Figure 4.

In a *first step*, the properties of the incoming debris at a location to be considered have to be defined. These are, for a suitable number of mass classes:

- average mass of debris pieces per class,
- areal density of debris pieces per mass class,
- impact velocity, and
- impact angle.

In a *second step*, using these properties:

- The hit probability of a piece of debris on a certain part of the body of a person (defined by a body model) can be defined, and

- the lethality of that person then can be found by a mathematical combination of the hit probability of a body part, the specific lethality of this body part (called basic lethality) and the lethality of all body parts.

Of course, in the case of a person staying inside a structure, the properties of the incoming debris, have to be modified by the protection that is given by different building materials. The whole procedure of how to calculate lethality due to debris throw is outlined in detail in the following references [17, 19].

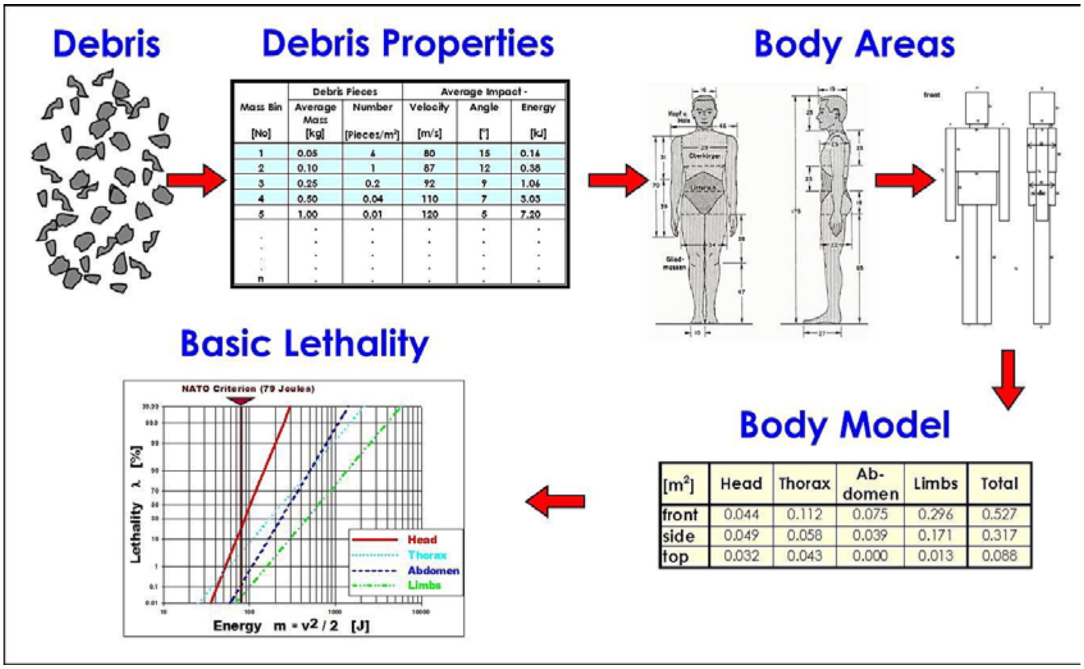

Figure 3: General Procedure for Calculating Lethalities due to Debris Throw

To calculate the properties of the incoming debris according to step 1, the *Klotz Group Engineering Tool*, KG-ETool Version 1.5.4, [13, 14] was used. Based on the input of a large number of parameters, this tool is capable to compute all the necessary debris properties to be used for the lethality calculation according to Figure 3. Typical input screens are shown in Figure 4. The output is either in graphical from (Figure 5) or for further use of the detailed debris properties in tabular form.

In the second step, the computer code *LambdaT*© is fed with the data generated by the KG-ETool. The calculation steps performed in LambdaT© are shown in the flow-chart in Figure 6. The output is the lethality of a person at a given location (distance and direction from magazine), taking into account whether the person is staying in the open or inside a building, and the body position (standing, sitting, lying) as well as the body orientation (front, side). A detailed description of this tool can be found in the following references [16 - 18].

4. Development of the Fast Running Model (FRM)

4.1 Relevant Parameters

Most important, as a starting point for the development of the FRM, was to define the relevant parameters that should be taken into account. Despite the fact that the new FRM is not a directly physics based model, it was the aim to include the most relevant physical parameters that drive wall debris throw. These are:

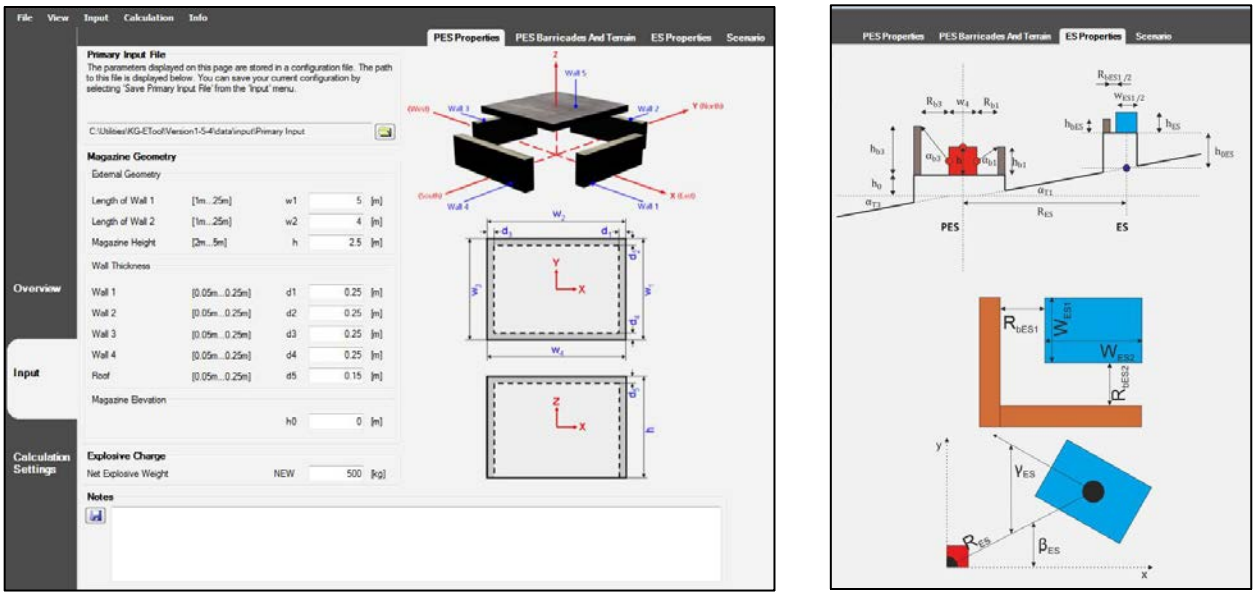

Figure 4: Typical Input Screen in the KG-ETool Version 1.5.4

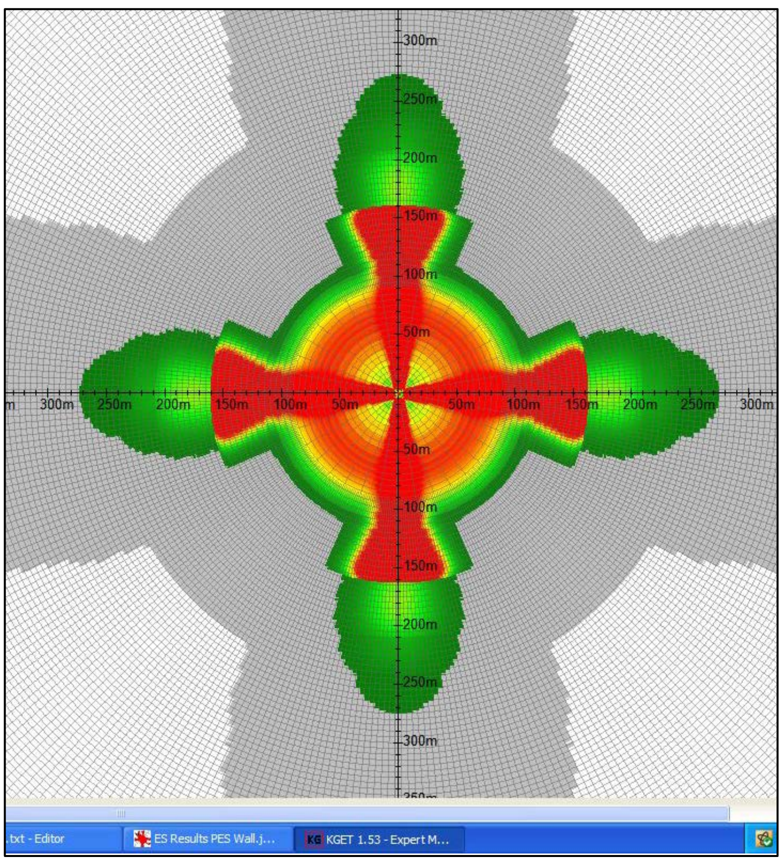

Figure 5: Typical Graphic Output from KG-ETool, Showing Wall and Roof Debris Number Densities of a Freestanding Non-Earth-Covered Magazine

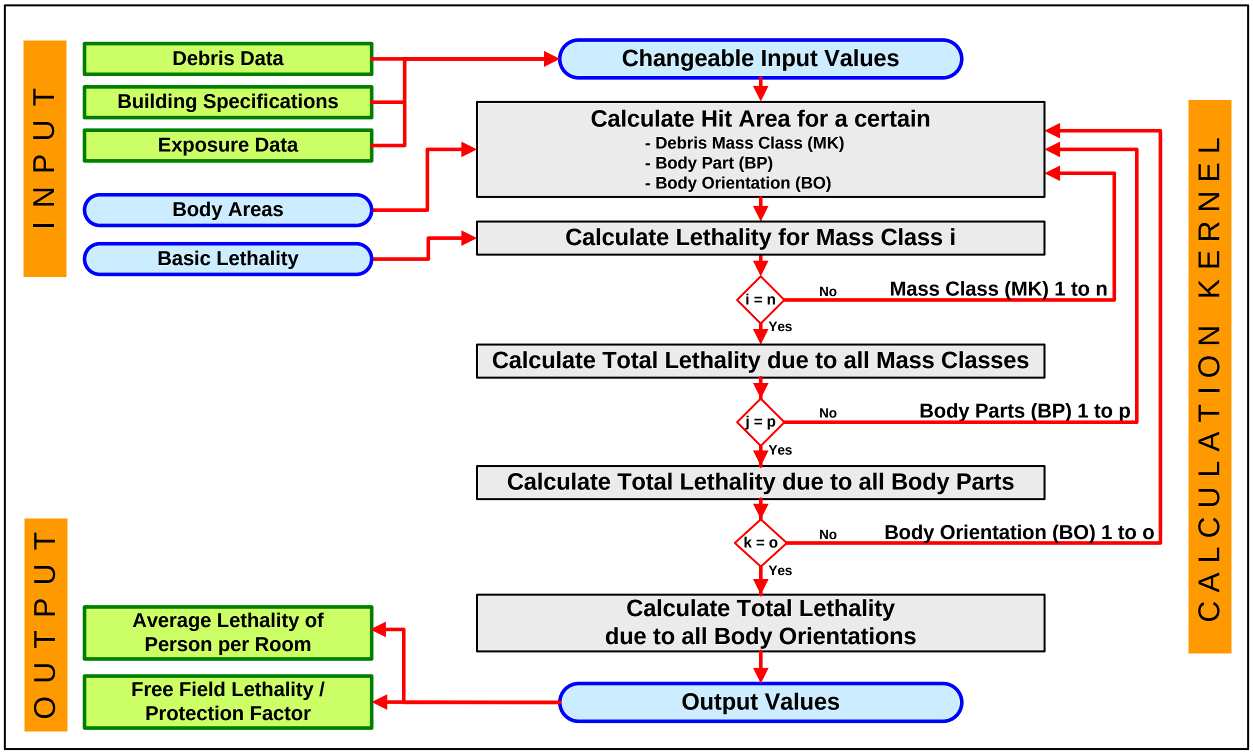

Figure 6: Flow-Chart Showing the General Calculation Procedure in LambdaT©

- The initial velocity that a piece of wall debris is accelerated to, due to an explosion in the magazine, is the so called *launch velocity*. The launch velocity is mainly dependent on the loading density of the magazine (amount of explosives divided by the inside volume of the magazine), the specific wall mass (mass per m^2), and the average length of the structural element one is looking at [20 - 22].

- The *total wall mass* that is thrown into the surroundings. This is simply the product of the wall area, the wall thickness and the specific weight of the construction material.

- The *average mass of a piece of debris* (per mass class). This value also depends mainly on the loading density.

- The so called *lost mass*. This is the part of the total wall mass that, due to the explosion forces, disintegrates in very fine dust-like pieces that are no longer safety relevant. The lost mass is again a function of the loading density.

- Finally it is obvious that the *slope of terrain* has a relevant influence on how far debris is thrown, farther in the downhill range and to a shorter distance in the uphill range.

All these parameters can now be taken into account in the new FRM, knowing the following quantities:

- outside size of the magazine (length, width, height),
- thickness of the structural elements,
- explosives charge,
- visibility of a structural element (see Chapter 5.1), and
- slope angle of the terrain.

To calculate the lethality of a person at any point you like in the surroundings of a magazine, the following quantities must be known in addition:

- distance from the magazine center on the axis of the wall, and
- lateral deviation of this point from the wall axis.

4.2 General Procedure

The development of the FRM was an iterative process and took place in several substeps. In each substep one of the parameters was investigated in detail. That included calculating lethalities of persons for a large number of locations people might stay in the surroundings of various magazine configurations. Then, based on the calculated data points, a mathematical model was developed for that parameter.

The influence of the following quantities on the lethality was investigated in detail, one after the other:

1. Size of the explosives charge
2. Volume of the magazine
3. Small loading densities (< 1 kg/m^3), how to deal with loading densities that only lead to a partial destruction of the magazine
4. Thickness of a magazine wall
5. The area of a wall that contributes to debris throw, how to deal with walls that are partially backfilled
6. Slope of terrain

It would far exceed the scope of this paper to explain each step in detail. However, two representative examples are shown (simplified) in the following chapter. In addition, the rest of the paper concentrates on lethality staying in the open on flat terrain.

4.3 Examples

Influence of the Size of the Explosives Charge

In a first step, for a reference magazine, a large number of lethalities were calculated, using KG-ETool und LambdaT©, for various charge sizes and at various distances from the magazine. This lead to the dots shown in Figure 7. Obviously, there is quite some scatter in these data points. While for lethalities below 50% normally lager charge sizes lead to greater distances for the same lethality, due to several reasons this is not the case for high lethalities.

Therefore, some assumptions had to be made for the development of the FRM, e.g. like:

- The model should be accurate for lethalities smaller than 50%.
- Larger charges should always lead to larger distances for the same lethality.
- To get relatively simple mathematical formulas, the model is required to show straight lines in a lethality-distance diagram (log-scale).
- The straight lines for various charge sizes should be parallel.

Again, to find a suitable model was an iterative process that had to be repeated several times. This led finally to the bold lines shown in Figure 7. They can be calculated by the following simple basic formula:

$$\mathbf{Pr_{(L)} = A + B * \ln(R)}$$

where:

$Pr_{(L)}$	Probit of the Lethality (for a person staying on the wall resp. magazine axis)
A	Factor that takes into account the loading density and hence the total charge size
B	Constant
R	Distance from the magazine centre (on wall axis)

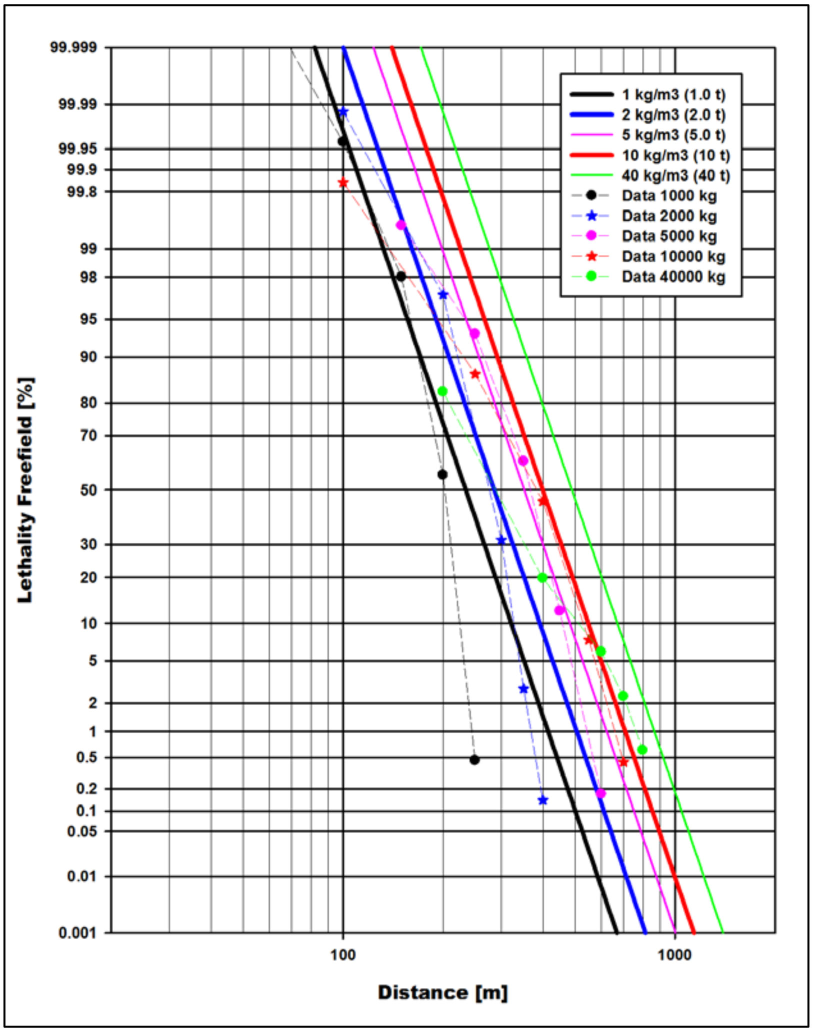

Figure 7: Model for a 1'000 m^3 Magazine and Various Charge Sizes resp. Loading Densities (on wall axis)

Influence of Wall Thickness

Basically the procedure for studying the influence of the wall thickness on the lethality at a given distance was the same as for the other parameters. Also in this case a large number of single calculations for various wall thicknesses were performed. The result is depicted in Figure 8. The bold lines show lethalities for a reference magazine with a wall thickness of 25 cm, while the thin lines represent thicker as well as thinner walls.

As can be seen, a change in wall thickness leads not to a horizontal shift of the lines as for other parameters, but to a change of the slope of the lines. This seems to be logical, as debris from thinner walls get a higher launch velocity, hence fly farther, leading to higher lethality in the far range, than debris from thicker walls. On the other hand, due to the lower total wall mass, in the near range debris densities as well as lethalities will be smaller compared to thicker walls.

An Example of the model developed for this effect is shown in Figure 9, depicting lethalities for a magazine with a wall thickness of 25 cm (bold lines) and a wall thickness of 15 cm (dashed line).

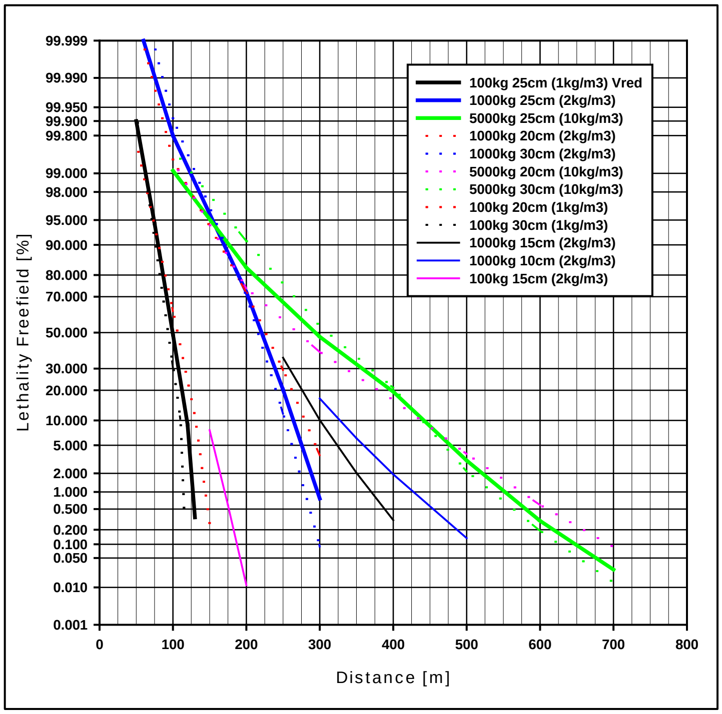

Figure 8: Calculated Distances for Various Wall Thicknesses (500 m^3 magazine, on wall axis)

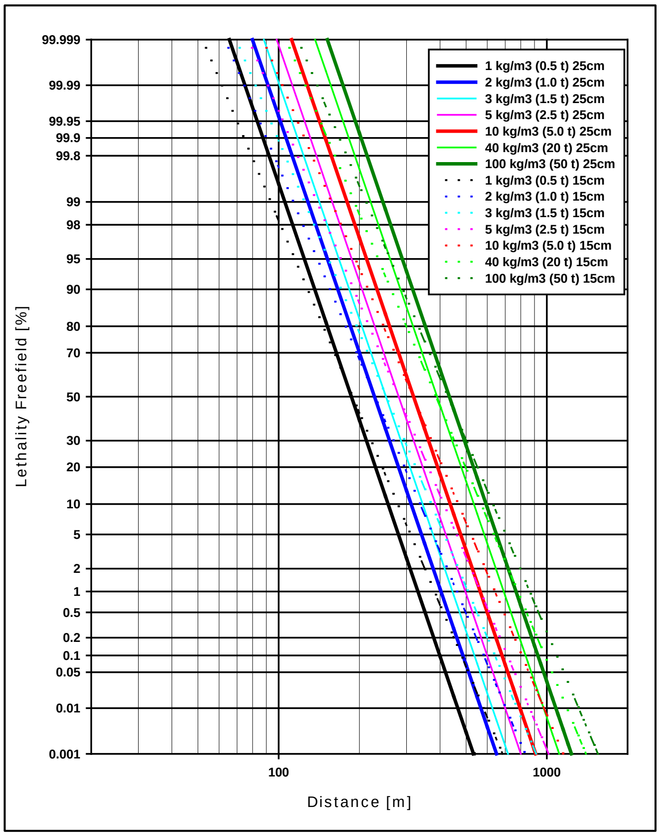

Figure 9: Lethalities for a Wall Thickness of 25 and 15 cm (500 m^3 magazine, on wall axis)

5. The Final Wall Debris Lethality Model

5.1 People in the Open on Flat Terrain

The investigation and combination of all the different influences led to the following final formula for the lethality of people, staying in the open on flat terrain, exposed to wall debris throw from above ground free-standing ammunition storage magazines:

Lethality on magazine wall axis:

$$\mathbf{Pr_{(L)} = A + B * \ln(R/f_F)}$$

where:

$A = ((26.25 + 5.53 * \ln(\gamma)) + (f_w * (2.95 + 0.68 * \ln(\gamma)))) / (1 + 0.161 * \ln(\gamma))$ [-]
$B = - 4.07 + (f_w * - 0.57)$ [-]

$f_w = (d_w - 25) / 7.5$ [-]
$f_F = (F_{eff} * f_a * f_v / 63) \wedge (^1/_3)$ [-]

A	=	Parameter A, defines the horizontal resp. vertical position of the lines in the log-scale diagrams
B	=	Parameter B, defines the slope of the lines in the log-scale diagrams
f_w	=	takes the wall thickness into consideration
f_F	=	takes into account those parts of a wall that are effectively thrown into the surroundings (normally this is the part of a wall that is visible from the outside of the magazine, e.g. those parts of a wall that are backfilled are not to be considered as they do not contribute significantly to wall debris throw)

$Pr_{(L}$	=	Probit value of the lethality (Freefield)	[-]
R	=	Distance from the magazine center	[m]
γ	=	Loading density Q/V	[kg/m^3]
Q	=	Charge size (in kg of TNT)	[kg]
V	=	Inside magazine volume	[m^3]
d_w	=	Wall thickness	[cm]
F_{eff}	=	Wall area (Average between inside and outside wall area, floor thickness not to be taken into account)	[m^2]
f_a	=	Visibility (part of a wall that is visible from the outside)	[%]
f_v		if $\gamma >= 1$ kg/m^3 = 1.0 if $\gamma < 1$ kg/m^3 = V_{red} / V_{eff}	[-]
V_{eff}	=	V = effective magazine volume (inside)	[m^3]
V_{red}	=	Magazine volume (inside) where the loading density is equal to 1 kg/ m^3	[m^3]

Lethality lateral of the magazine wall axis:

$$\mathbf{Pr_{(L,\ lateral\ of\ the\ axis)} = Pr_{(L,\ on\ the\ axis)} * \%Pr} \quad [-]$$

where:

$\%Pr$	=	$e \wedge (A + B * \alpha^{2.5})$	[-]
A	=	$\ln(100)$	[-]
B	=	- 0.00025	[-]
α	=	Lateral deviation from the axis of the magazine wall	[°]

5.2 Sloped Terrain and Lethality of People Inside Buildings

Of course, also a procedure for sloped terrain was developed. Due to the focus of this paper on flat terrain, it is not discussed here in detail. However, the general influence of sloped terrain is shown in Chapter 6 with an example. Further details are given in [23, 24, 25].

The same applies for the lethality of people staying inside buildings. The general procedure is described in reference [19], and the result is shown in [24, 25].

5.3 Range of Validity

The model described in Chapter 5.1 is generally applicable within the following boundaries:

- type of exposure: free field
- type of magazine: above ground, reinforced concrete, non-earth covered
- charge size: starting from a few kg up to 50 t, depending on size of the magazine
- loading density: approx. 0.1 kg/m^3 up to 40 kg/m^3
- volume of magazine: from approx. 5 m^3 up to over 1000 m^3 (on one or two storyes)
- wall thickness: from approx. 10 cm up to approx. 35 cm (depending on magazine size)
- slope of terrain: from approx. -50^O up to +90^O
- lethality: from 99.99… % to 5 * 10^{-5} %

However, not all combinations lead to meaningful results. E.g. a combination of a very small magazine with very thick walls, in combination with a low loading densities situation, might lead to no debris throw at all. But based on the sensitivity analysis performed, it can be assumed, that all calculable combinations lead to results that are safe sided.

6. Comparison with the Current Swiss Model, Test Data and Calculations with the KG-ETool

In a last step, the new FRM was compared with the current Swiss lethality model, actual test data and calculations with the KG-ETool. While a direct comparison with the current Swiss lethality model was easily possible, only an indirect comparison with test data and the KG-ETool output can be made as they only show debris densities and not lethality. Therefore, an interpretation of the results was necessary. Overall however, the comparisons made showed remarkable good agreement with calculations and data. The following sections show some of the comparisons made.

Comparison with the Current Swiss Model

Despite the fact that a comparison with the current Swiss model does not prove anything (as the basis for this model was weak), it was important to see that the new FRM does not lead to very much larger lethality zones than compared to the old model. Otherwise, risks would have been underestimated and an immediate recalculation of all the risk calculations done so far would have been necessary.

Summarizing, the new FRM shows larger lethality zones for high lethalities while for a lethality of 1 %, what approximately can be compared to an Inhabited Building Distance (IBD), the new zones are only slightly larger. This effect is more pronounced for small loading densities compared to high loading densities.

Comparison with Test Data

As mentioned above, during the last decades many tests with magazines were performed with the aim of studying debris throw. Quite recently all these tests were reevaluated by NATO / MSIAC concerning the IBD [26, 27]. The result of this effort is depicted in Figure 10.

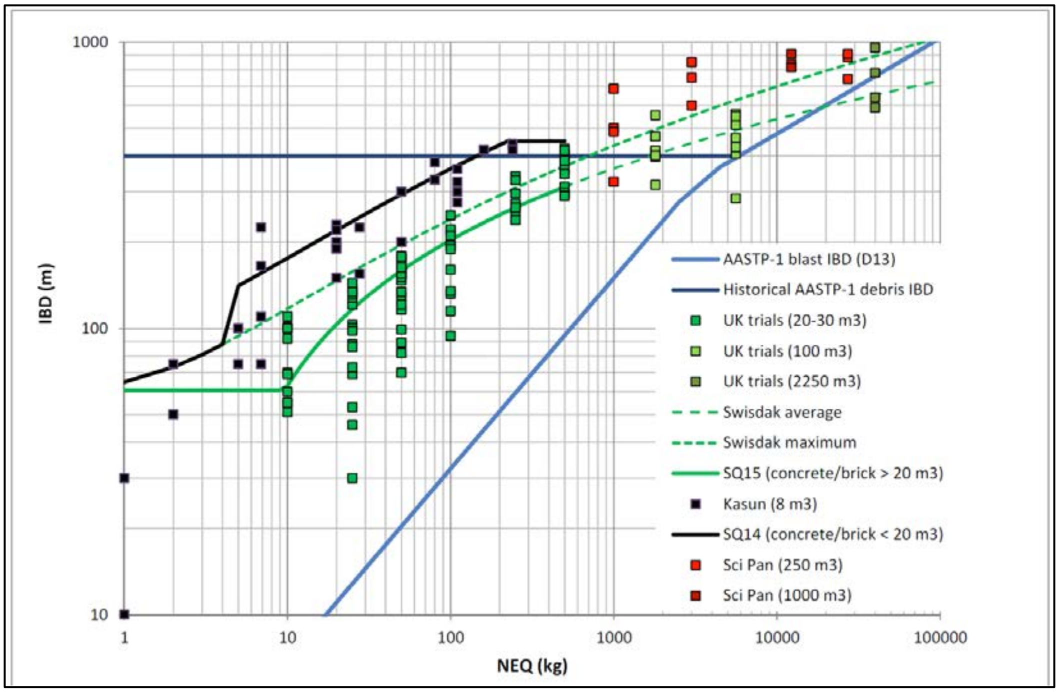

Figure 10: Collection of IBD's from Recent Test Series [3 - 12]

The following remarks to Figure 10 have to be made:

- Each dot represents an Inhabited Building Distance (IBD) according to NATO, AASTP-1 [28].
- IBD is defined as the distance where the hazardous debris (HD) density is 1 HD / 56 m^2.
- A piece of debris is considered to be hazardous in case its energy is 79 J or more.
- The susceptible area of a standing person is assumed to be 0.5 m^2.
- Hence, it is assumed that at the IBD the lethality of a person is approx. 1%.

At least some of these tests were evaluated in detail and compared with the new FRM. Lethality was calculated for 1, 10 and 50 %. An example is shown in Figure 11. The calculated data points (stars) were then inserted in the NATO / MSIAC diagram.

Figure 12 shows the comparison with the KASUN (black squares) [3 - 6] and SciPan (red squares) [7 - 10] tests, while Figure 13 depicts the comparison with the UK brick and reinforced concrete magazine trials (green squares) [11 - 12].

Lethality	**FRM**	Test Data		MSIAC	KG-ETool	
[%]	Range [m]	Debris [No/56m2]	Range [m]	Range [m]	>79 J [m]	all [m]
1	263	1	290 - 315	320 - 380	260	260
10	192	10	240 - 270		200	220
50	130	56	-		60	170

Figure 11: Evaluation of the KASUN Test with Q = 80 kg [4]

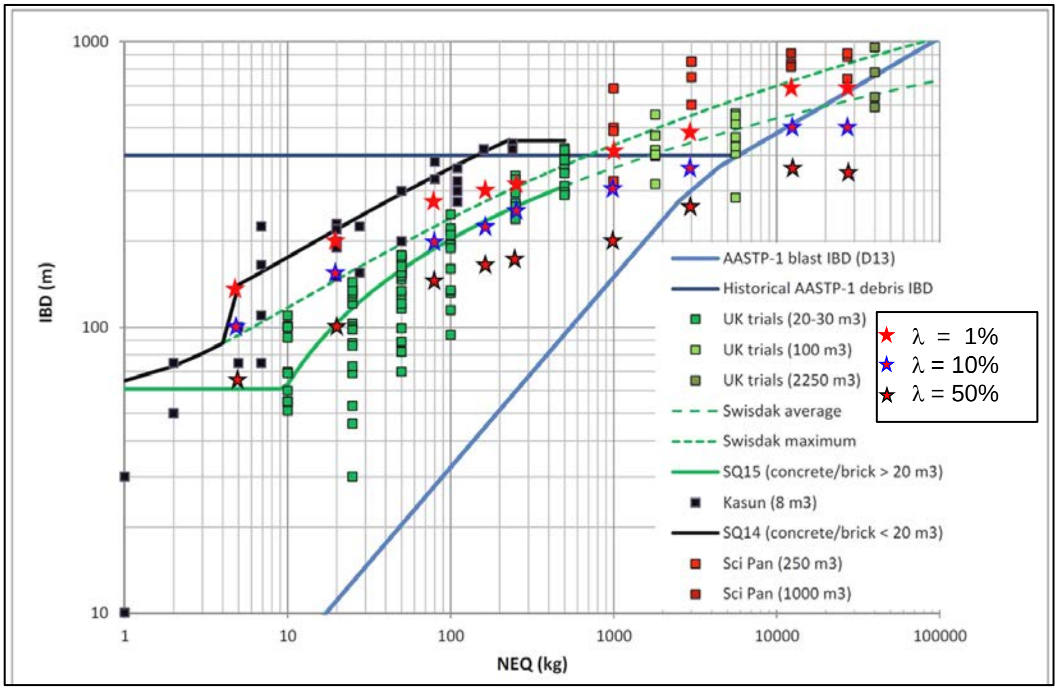

Figure 12: Comparison of the KASUN und SciPan data (black and red squares) with the FRM

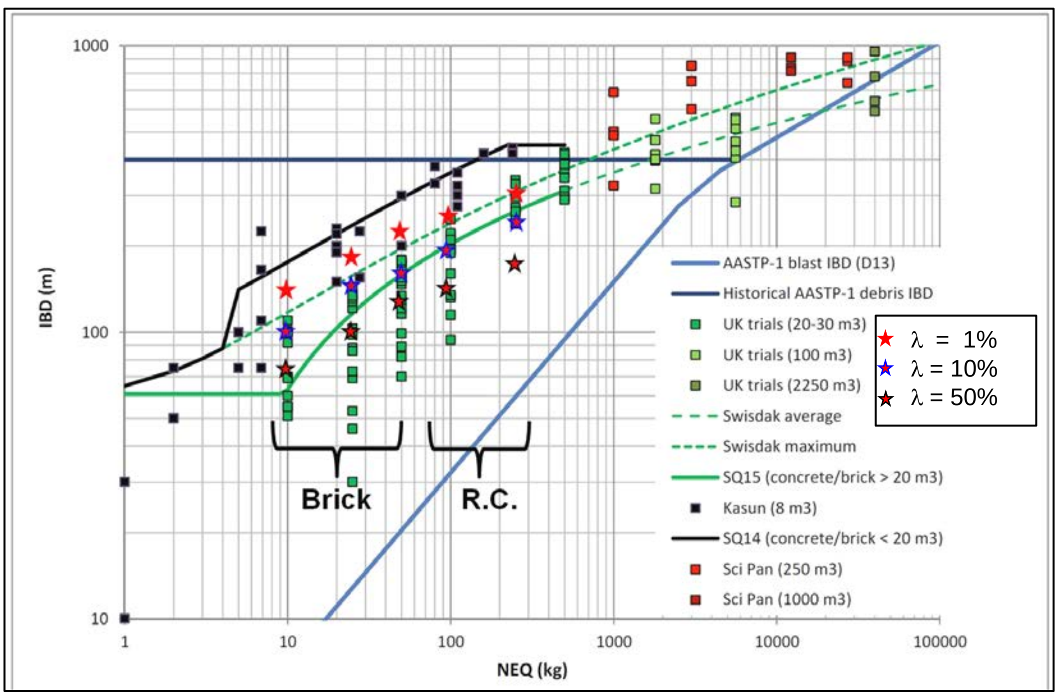

Figure 13: Comparison of the UK trials (green squares) with the FRM

This comparison shows the following:

- The new FRM leads consistently to shorter distances for a 1 % lethality than the calculated IBD's from the tests, with the exception of the UK brick magazine tests. This was to be expected, as it could be shown, already some time ago, that at IBD the lethality could be considerably less than 1 % according to the Swiss lethality model, as:

  - The susceptible body area against debris impact is depicted more realistically in the Swiss lethality model (smaller than 0.5 m^2) than in the NATO model.
  - The impact of a piece of debris with an energy of 79 J does not lead to a 100 % lethality according to the Swiss lethality model, especially if only an arm or a leg is affected.
  - The new FRM is based on actual debris densities and not on the so called PTN (pseudo trajectory normal) densities as shown in the diagrams above for the various tests.

- The FRM seems not to be applicable for brick magazines, as the FRM overestimates the lethality distances

- The calculated distances with the FRM, also for higher lethalities, compare well with test data in general, indicating the FRM takes the relevant parameter into account.

Comparison with Debris Density Calculations with the KG-ETool

Figure 14 shows a comparison between the FRM and a magazine with a charge size of 1'000 kg (size similar to the SciPan4 test). The solid lines in the figure in the right hand side sector of the magazine are calculated with the FRM. This comparison - and also numerous other comparisons made - shows the good agreement with regard to the lethality one would expect at the calculated debris densities with the KG-ETool. In addition, the figure shows that the shape of the zones calculated with the FRM match the calculated debris distribution with the KG-ETool.

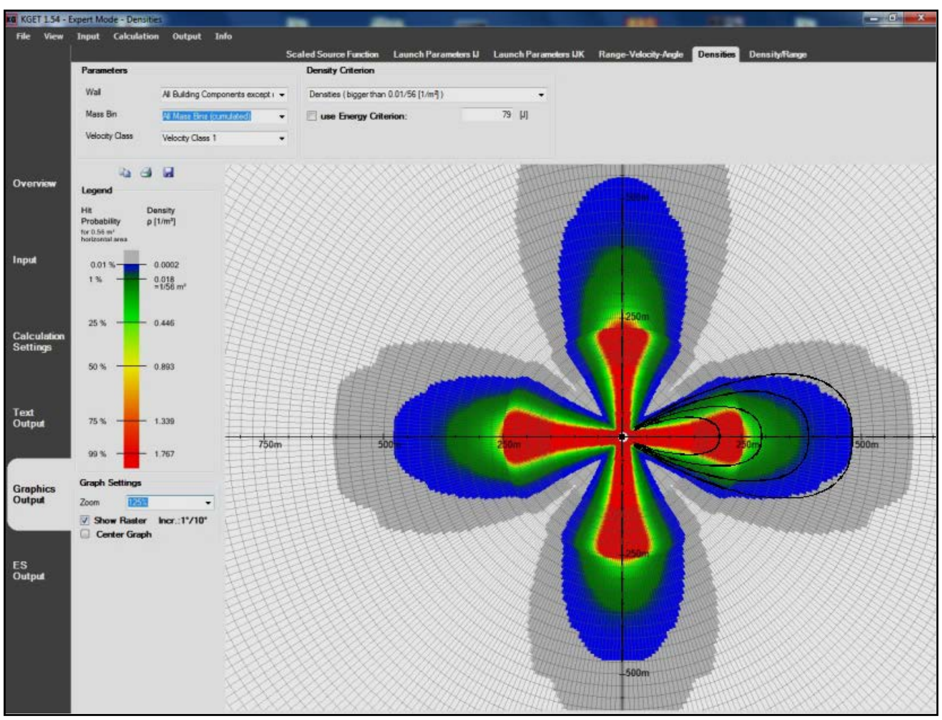

Figure14: Comparison Between KG-ETool and the FRM, Q = 1'000 kg, all Debris, and Lethality Zones of 50%, 10%, 1% und 0.1%

Although not discussed in detail in this paper, Figure 15 shows a comparison between the KG-ETool and the FRM for sloped terrain. As can be seen, the calculations match well again.

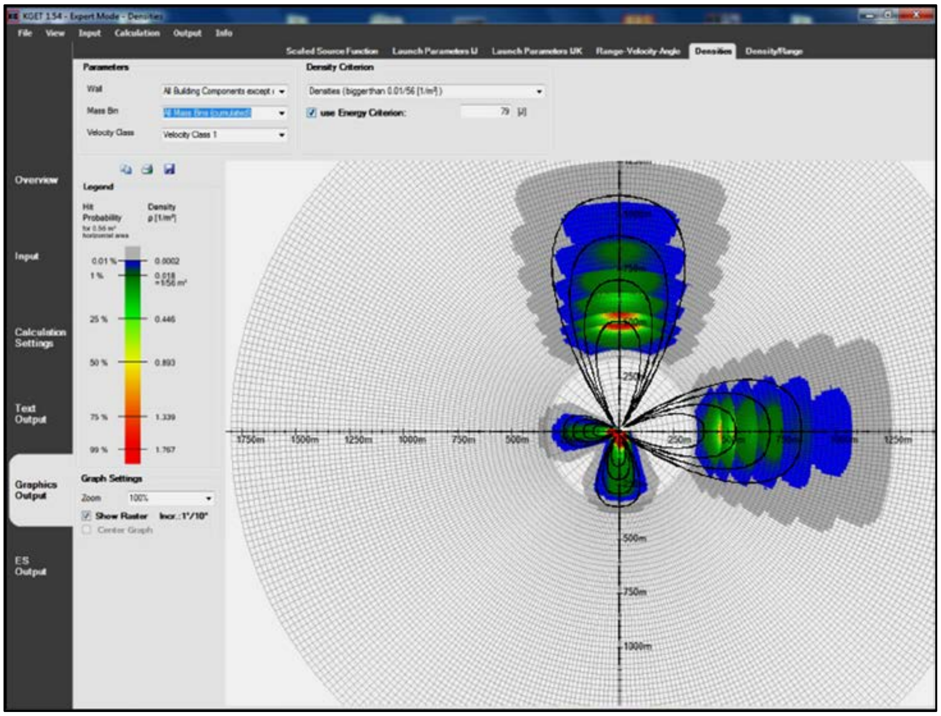

Figure 15: General Comparison between the KG-ETool and the FRM for sloped Terrain (slope angle +/- 20% in this example).

7. Summary and Future Work

It has been shown that it is possible to develop a Fast Running Model (FRM) for the calculation of lethalities caused by wall debris throw from above ground freestanding reinforced concrete ammunition storage magazines, using existing data and computer tools. It is planned to include the whole model - including sloped terrain and lethality inside buildings - in one of the next releases of the NATO Manual on Explosives Safety Risk Analysis, AASTP-4.

In addition, it is planned to develop a similar model for debris throw from the roof of such magazines, and in case the explosives charge size is large enough to create a crater under the magazine, also for crater debris throw. To make the picture complete, in a risk analysis for such magazines furthermore debris throw from inert material present inside the magazine (e.g. packing material, inert ammunition components) as well as primary fragments have to be considered. Models for those types of debris do not exist yet and will still have to be developed.

Acknowledgements

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