A model to determine the response of munitions for lower order reactions

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Abstract

Warships sail around with various types of munitions on board. To evaluate and improve combat survivability, it is important to investigate how those munitions will react, when hit by hostile weapon effects, and determine the response of the adjacent munitions (sympathetic reaction). Since these vulnerabilities are not fully known for several (naval) munitions, certainly not for the configuration as stored, TNO Defense, Safety and Security, in cooperation with the Dutch Command Materiel and IT agency (COMMIT) of the Ministry of Defense (MoD), are investigating the munition responses when subjected to, among others, small arms weapon impact, Shaped Charge Jet (SCJ) impact, and sympathetic reaction scenarios.

The investigation comprises in-service munition testing, simulations using combined munition and platform vulnerability tools, and mitigation methods research. The munitions are tested in the configuration as stored on a platform. In case of a severe response, mitigation methods, supported by computer simulations, are developed for the munitions that are a danger to personnel and/or materiel.

An engineering shock model, based on the Energy fluence parameter *E*, was developed previously and has been improved for bare explosives and flyer impact, recently. The model showed to be very useful in vulnerability as well as in lethality studies and is being implemented in several codes, such as the platform vulnerability code RESIST.

The penetration/perforation response methodology was presented previously. For this response tool, a model has been developed, that is capable to estimate the response of a munition once the internal pressure of the lower order reaction is known. Besides the velocity of the casing, driven by the internal pressure, the model is capable to estimate the fragmentation of the casing due to this fast, but lower order reaction expansion.

Introduction

In the nineties, TNO conducted research in the field of Cook-off, investigating the mechanisms of a thermal threat to munitions that can lead to a range of responses, from a mild burning to a full detonation of the article [[1[2[3]. Due to heating, decomposition of the explosive starts, degrading the explosive (and for PBX's also the crystal-binder matrix), influencing the porosity, burning surface and mechanical properties of the explosive. The production of gases of the decomposition reactions gives rise to the internal pressure and stresses the material, resulting in more damage and an increased burning surface (area) of the explosive. Once ignited, this damage and increased surface area gives rise to accelerated burning of the material and fast pressurization of the system, leading to more damage and so more surface area.

Depending on the strength of the confinement and the size of the system, which determines the so-called intrinsic confinement of the system, the severity of the reaction can range from a mild burning up to a full detonation of the munition.

Simulating such a complex mechanism, and not only the time and temperature to a runaway reaction, but also estimating the response of the reaction, requires sophisticated models and many parameters of the explosive and also a good understanding of the mechanical properties. Furthermore, the damage and the status of the explosive material at the moment of ignition and during burning and pressurisation needs to be known. That is probably the reason that a large part of the cook-off community started to investigate the mechanical properties, porosity and many other parameters in more detail, as to understand the mechanisms that lead to the response of the system, which is influenced by the increase of damage and surface area.

TNO investigated the damage phenomenon in more detail [[4[5]. Aspects as damage, mechanical and shock properties of energetic materials are not only of interest for the cook-off threats, but also for other IM-threats, such as fragment and bullet impact and for the sympathetic reaction scenario. The damaged material can be more shock sensitive, but also in a bullet or fragment penetration scenario, it gives rise to the amount of surface area after ignition. At the beginning of the new millennium, effort has been put in the understanding the thermally and mechanically induced damage to materials and the corresponding burning behaviour. This kind of research increased the insight into the mechanisms that leads to violent reactions of munition after thermal or mechanical impacts. Once the mechanisms that lead to a certain response are understood, it is easier to mitigate and control these effects.

In the scope of ship vulnerability, the code RESIST (Resilience Simulation for Ship Targets) has been developed at TNO, and is capable to simulate the physical damage to a ship as part of the Advanced Concepts for Damage Control (ACDC) simulation framework. It can simulate the primary damage due to fragments and blast caused by explosions from e.g. hostile missile attack. The secondary damage due to the spread of fire and smoke can also be simulated. Finally, the effects of fire-fighting actions can be simulated, such as the use of fire hoses, sprinklers, inert gasses, halon installations and water mist.

Until recently, the ship’s munition storage was not part of this simulation and was handled as a black box. A hit by a severe threat instantly led to the mass explosion of the stored munitions with catastrophic consequences. However, ship constructions have been improved and not all munitions will react sympathetically in all situations. A better methodology was needed to cover the munition storage situation and the munition response in the RESIST code.

Therefore, TNO is in the process to improve the RESIST code by implementing munition vulnerability models for predicting the probability of a violent event on a ship (or other platform), when the munition storage is hit by e.g. a bullet or fragments from a hostile attack. To obtain the proper statistical output, several millions of calculations have to be performed to obtain a probability of the reaction and its consequences. Because millions of different scenarios have to be calculated, hydrocode calculations cannot be used for this type of application, but fast and efficient engineering solutions need to be developed.

An improved shock model, used for fragment impact and sympathetic reactions calculations, was presented previously [6]. Also, the methodology for the implementation of a stochastic approach for a munition vulnerability tool into the ship vulnerability code RESIST, was explained.

The next step is the development and implementation of a tool, predicting the non-shock initiation and response reaction of munitions in cases where bullets or fragments penetrate or perforate the munitions. The approach for non-shock impact of a bullet or fragment is presented in more detail in this paper. A bullet/fragment impact flowchart was developed in this approach, to predict the response of the munition after an impact. Several steps in this approach are explained and first results are presented. Once all models have been fully developed and validated, bullet/fragment penetration/perforation can be added to the TNO munition vulnerability model library and also be implemented in the platform vulnerability code RESIST.

Approach

Scholtes and Hooijmeijer [7] presented a flowchart for a bullet/fragment and an Explosively Formed Projectile (BI/FI/EFP) reaction mechanism. This flowchart shows the different steps, decision blocks and types of calculations needed to predict the response of munition after impact of a projectile. This flow chart also handles the shock initiation of a munition as well as the reaction of the adjacent munition due to the response of the first reacting munition. The focus in this paper is on the non-shock response of the munitions. Figure 1 shows the part of the flowchart for the penetration/perforation response. This was improved in comparison to the original flowchart [7].

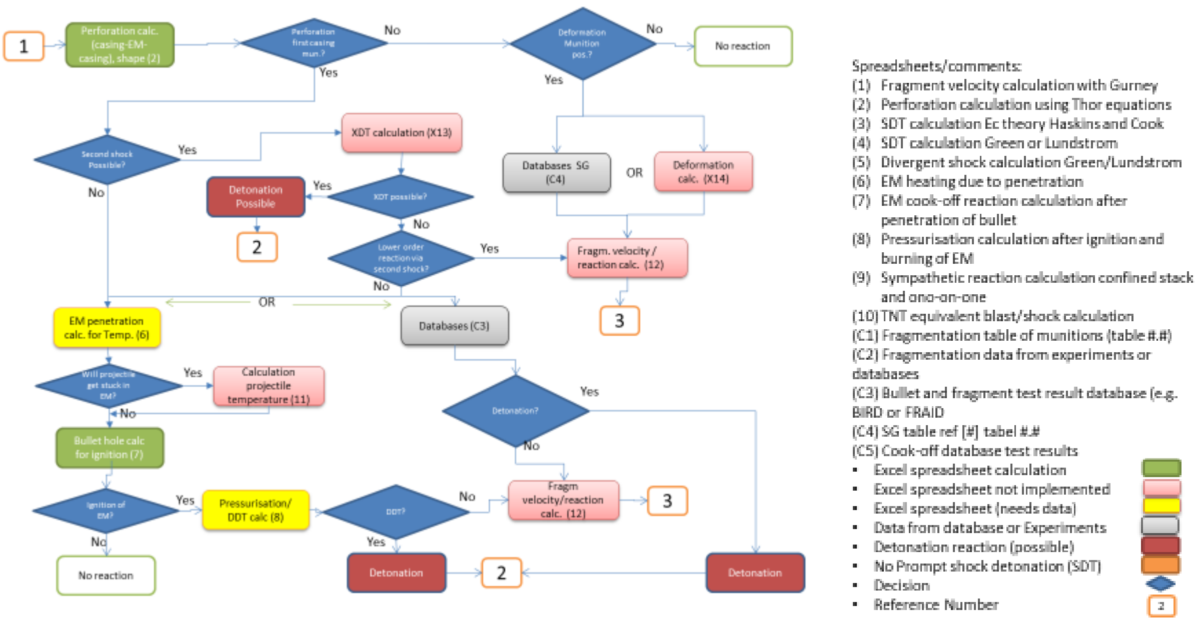

Figure 1: Penetration/perforation part of the projectile impact flowchart.

The green, light-red and yellow rectangles are calculation blocks that give an answer to the question in the blue diamond shaped form. The grey rectangles are used when data from literature or experiments are used. A red block indicates that a detonation reaction is highly possible. The rectangular blocks with a number refer to another part in the flowchart. In case that no reaction takes place, this is indicated by a green open block.

The main processes that need to be determined in the penetration/perforation response mechanism are:

- Heating of the projectile before impacting a munition and during perforation of a barrier and the acceptor casing;
- The heating of the energetic material (EM) and the probability of ignition of the EM due to shear friction of the projectile with the EM, in case of the perforation through the munition, or heating of the EM due to a stuck projectile inside the munition (partial penetration);
- Burning reaction of the EM after ignition, with one or two venting holes and the pressure inside the casing just before fragmentation of the casing starts;
- Response of the munition in the form of the maximum fragment velocity and the fragment size distribution.

These main processes are divided in several subprocess steps. For each of these steps engineering equations have to be found, developed and sometimes amended. All these steps have to be combined to estimate the overall response of the munition after impact of a projectile. The status of each of two of these subprocess steps is described in the following chapters.

Details of models for some of the individual steps

Introduction

In the previous conference [[15], a few models were already presented such as a model for the bullet temperature before impact, the temperature of a fragment from a detonating charge, and the heating and ignition of an Energetic Material (EM) due to perforation of the projectile. However, the heating of EM was not yet completely understood and needed further investigation.

Also the equations for the burning and accelerated burning and pressurization of the munition were explained and result in a pressure before fragmentation starts. With this pressure and the model of Baker et al. [[10, [11], the case expansion velocity can be estimated. However, the fragment mass distribution equation still needed to be investigated in more detail.

In the following paragraphs the heating of the EM is explained in more detail as well as the steps taken to understand this problem and the calculation results are presented.

After ignition, the EM starts to burn. Due to the burning of the EM the vessel is pressurized and at a certain moment the casing starts to expand due to the internal pressure and leads to a certain expansion velocity and fragmentation of the confining casing. For several pressures, i.e, the detonation pressure of Comp B and pressures 10 and 100 times lower than the detonation pressure of Comp B, the response was determined and is presented.

First the model of Baker is used to estimate the casing expansion velocity and with the model described, the fragment mass distribution of the steel confinement was determined.

Heating of the EM due to perforation of the munition

The heating of the EM by a perforating bullet is nothing more than solving the “heat equation” in cylindrical coordinates (without flow) and adding a shear heat source term to the decomposition reaction term. Victor [8] reports a method for calculating the heating of an EM due to these shear forces of a projectile. The main equation has the following form:

$$\rho C_p \frac{\partial T}{\partial t} = \lambda \cdot \overline{\nabla}^2 \mathrm{T} + \varphi_s , \qquad (12)$$

and in a 1-dimensional cylindrical setup this has the following form:

$$\frac{\partial T}{\partial t} = \frac{K}{\rho\, C_p}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \frac{\dot{Q}}{C_p} + \frac{\dot{W}}{\rho\, C_p} \qquad (13)$$

With *T* the temperature, *t* the time, *K*, *ρ* and C_p the thermal conductivity, density and heat capacity of the energetic material, respectively, *r* the depth perpendicular to the hole left by the projectile, *Q* the heat of decomposition per unit mass. *W* covers the frictional heating part of the equation. Victor [8] also derived an equation, based on the work of Frey [9], for the temperature (°C) of a thin boundary layer that is heated by the friction between the bullet having a velocity V_r and the energetic material for an HTPB/AP propellant and has the form:

$$T = 25 + 0.4V_r + 0.003{V_r}^2 \qquad (14)$$

Once the temperature of that boundary layer is known (and its thickness), a simple (bullet hole) cook-off model can be used to calculate the time to ignition, as well as the minimum temperature and velocity required to achieve ignition. These results are shown in Figure 2 and Figure 3, respectively.

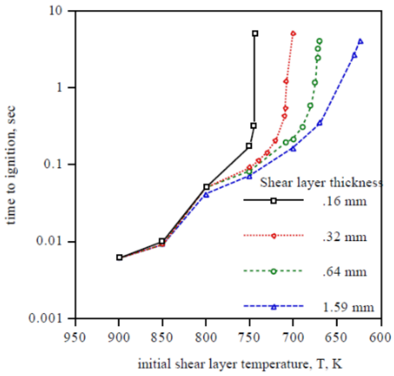

Figure 2: Initiation delay for AP/HTPB propellant as a function of the initial temperature and shear layer thickness [8].

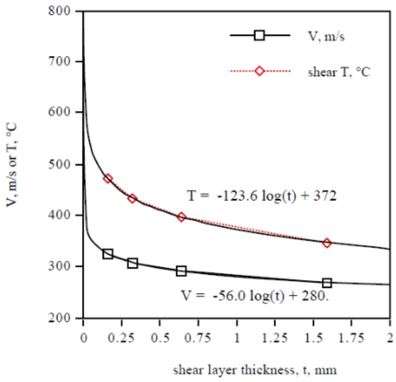

Figure 3: Minimum temperature and velocity as a function of the shear layer thickness required to initiate AP/HTPB propellant [8].

It appears that Victor's equations are not generic. The temperature equation is based on work by Frey [9], but Victor does not report how the equation is derived. Frey's work focuses on TNT and includes melting, which is a completely different material than AP/HTPB propellant. Instead of using Victor's AP/HTPB-specific equation, an attempt was made to derive a more generic equation. Frey [9] set up a heat equation, with terms for conduction, chemical reaction, and shear heating by a passing projectile.

To investigate the problem more thoroughly, several calculations were performed with AP/HTPB perforated by a bullet at certain velocities. Figure 4 shows the temperature in the EM, at a certain depth, as a function of time for decreasing time steps. It shows that the value converges to a stable solution for decreasing time steps (indicated by the arrows). Actually the problem seems to be conditional consistent. Only for a time step Δt << Δx, the solution converges to the analytical solution. This resulted in a time step of 35 ns. Therefore, the calculation was divided into 2 steps, the first one with a time step of 35 ns and after the bullet has passed, the time step is increased to a value to fulfill the stability criterion for a pure explicit heating equation solver ($\alpha' = \frac{K\,\Delta t}{\rho\, C_p\, \Delta x^2} <$ 0,5). For our system the value is about 40 μs.

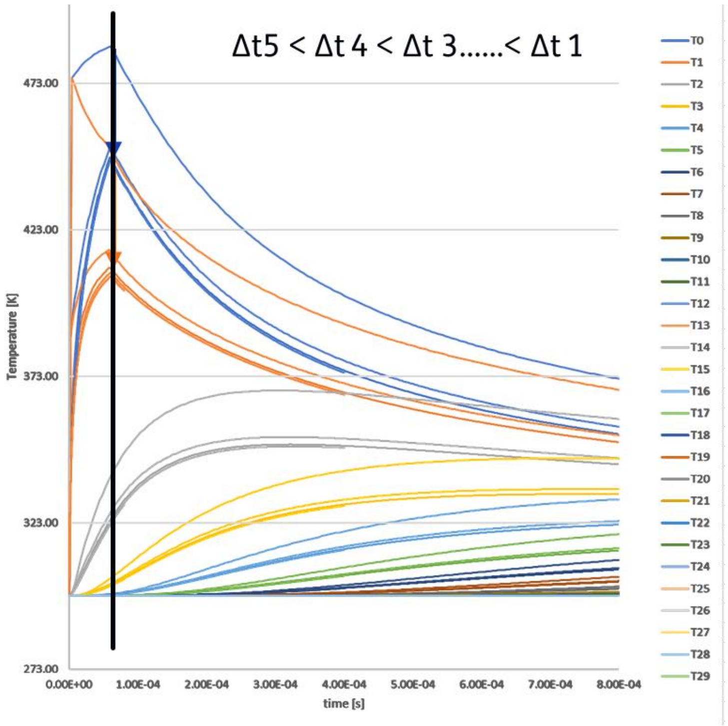

Figure 4 *Temperature as a function of time in the shear band and rest of the EM for decreasing time steps. The black line shows the moment the bullet passed the heated shear band and the only source term is the decomposition reaction of the EM.*

Figure 5 shows the results of a combined calculations for a bullet with a velocity of 720 m/s. For a bullet with a tip length of 15 mm, the time to pass by is s/V = 0.015/720= 20.8 μs (indicated by the vertical black line in the left graph (also indicated in Figure 4). Due to the shear heating, the temperature in the second part of the calculation is high enough to induce a thermal runaway reaction and ignition of the EM.

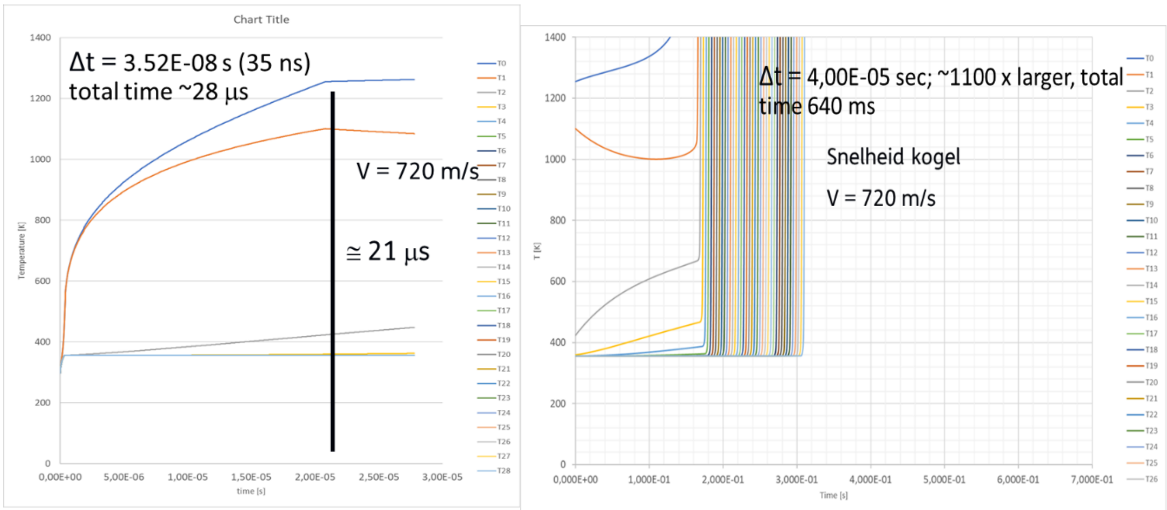

Figure 5 *Time – temperature graphs for a two-step calculation for a bullet velocity of 720 m/s.*

Fragment mass distribution of lower order reactions

The next step is the fragment mass distribution as a function of the casing expansion velocity which depends on the internal pressure at the moment fragmentation starts. In the SPLIT-X documentation [[13], a method is described to estimate the average fragment mass.

The SPLIT-X theoretical manual describes natural fragmentation and gives an overview of parameters influencing the fragmentation:

Geometry of the warhead:

- fragments tend to have a size relatively close to the case thickness;
- larger warheads have relatively smaller fragments;
- the ratio of the mass of the casing and the mass of the explosive determine the fragment size due its amount of deformation.

Metallurgical parameters:

- influence of crystal structure;
- influence on brittleness of the casing due to for instance impurities and carbon content.

Explosive parameters:

- higher detonation velocities and pressures lead to smaller fragments, This is also the reason that deflagrations or lower order reaction result in larger fragments.

As a rule of thumb, copper tends to start fragmentation at about 2.0 - 2.2 times the original radius of the warhead, aluminum around 1.8-2.0 and steel around 1.4 – 1.8.

When a warhead explodes, a number of fragments is produced, say N^{e0}. The masses of the fragments m_i with $m_1 \geq m_2 \geq m_3 \dots \geq m_{Ne0}$ are decreasing in mass. The total mass of all fragments is given by:

$$M_{e0} = \sum_{m_i \geq 0} m_i$$

The median mass $m_{1/2}$ is defined as the fragment mass that splits the mass distribution in such a way that the total mass of all fragments having a mass smaller than $m_{1/2}$ is the same as the total mass of all fragments having a mass larger than $m_{1/2}$. So both parts have a total mass of ½ M_{e0}.

Also a dimensionless mass is defined:

$\mu = m/m_{1/2}$

The manual describes several types of distribution functions. The most commonly used and well-known distribution is the Mott [12] distribution. Also the exponential and the so-called Payman distribution are described in the manual. The Mott and exponential distribution are both special cases of the Generalized Mott distribution having the following form:

$$P_{GM}^{\lambda} = Q(1 + \frac{1}{\lambda}, (c_\lambda \mu)^\lambda)$$

With μ the dimensionless mass and Q(a,x) the so-called incomplete gamma Function:

$$Q(a,x) = \frac{1}{\Gamma(a)} \int_x^{\infty} e^{-t}\, t^{a-1} dt \qquad (a > 0)$$

The parameter λ is the parameter that characterizes the distribution. For λ = 1 we get an exponential distribution with $c_1 = 1.678$.

With M^{e0} the total mass of the casing, the mass distribution function has the following form:

$$M_{exp}(\mu) = M^{e0}(1 + c_1\mu)e^{-c_1\mu}$$

and the distribution for the number of fragments has the form:

$$N_{\exp}(\mu) = \frac{c_1 M^{e0}}{m_{1/2}} e^{-(c_1\mu)}$$

For λ = ½ we get the classical Mott distribution equation with $c_{1/2} = 7.149$

$$M_{Mott}(\mu) = \frac{M^{e0}}{2}(2 + 2\sqrt{c_{1/2}\mu} + c_{1/2}\mu)e^{-\sqrt{c_{1/2}\mu}}$$

And for the number of fragments the following is obtained:

$$N_{\mathrm{Mott}}(\mu) = \frac{c_{1/2} M^{e0}}{2m_{1/2}} e^{-\sqrt{c_{1/2}\mu}}$$

To estimate the mass distribution function, the number of fragments and what often is an important parameter, the most credible fragment mass, the theory developed by Grady and Hightower is used [[13]. The fragmentation energy E_{frag} is a material property that can be determined through experimental measurements. There are two dominant modes in fracture during a fast expansion of the casing. The first one is the tensile fracture and the second one the shear fracture. In the tensile fracture mode, the fracture line is perpendicular to the expansion direction, while the shear fracture line has an angle of 45 degree to the expansion direction.

$E_{frac,tension}$ can be determined with the following equation:

$$\mathrm{E}_{frac,tension} = \frac{K_c^2}{2E}$$

With K_c the material fracture toughness and E the elastic modulus of the casing material. The $E_{frag,\ shear}$ part of the fragmentation can be determined with:

$$E_{frac,shear} = \frac{\rho c}{\alpha}\left[\frac{9\rho^3 c^2 \chi^3}{Y^3 \alpha^2 \dot{\gamma}}\right]^{\frac{1}{4}}$$

With $\dot{\gamma}$ the shear strain rate, c the specific heat and ρ the density of the material. χ is the thermal diffusion coefficient, α the softening coefficient and Y the ultimate strength of the casing material.

A dimensionless parameter f_m was defined to characterize the fracture model with t_f the thickness of the casing at the moment of fracture.

$$f_m = 1 - Q\left[a, \frac{a-1}{bt_f}\left(\frac{K_c}{Y}\right)^2\right]$$

The constants *a* and *b* have values of 10 and 0.25 respectively. The effective fracture energy per unit area is defined as:

$$E_{frac,total} = f_m E_{frac,shear} w_{shear} + (1 - f_m) E_{frac,tensile} w_{tensile}$$

With the weight factors w_{shear} and $w_{tensile}$ having the values of 180 and 90.

The characteristic mass $m_{1/2}$ of this distribution can be determined by:

$$m_{1/2} = \rho t_f \left(\frac{E_{frac,total}}{\rho \dot{\varepsilon}^2} \right)^{2/3}$$

Now that $E_{frac,total}$ and the density ρ are known, the only two parameters that have to be determined are the casing thickness at the moment of fracture t_f and the strain rate $\dot{\varepsilon}$.

Peugeot et al. [14] provide an equation for the casing thickness t_f at the moment of fracture:

$$t_f = R_f - \sqrt{\left[{R_f}^2 - 2(R_o + t_c)t_c + {t_c}^2 \right]}$$

With t_c the original thickness of the casing (at rest), R_o the original inner radius of the warhead casing and R_f the outer radius of the warhead at the moment of fracture, which is about 1.4-1.8 times the original radius of the casing of steel. In the Split-X manual, there is another method described to determine t_f as well as the multiplication factor to determine R_f. However, for first order calculations the equation above gives a good estimate.

The value for the strain rate $\dot{\varepsilon}$ can be estimated by $\dot{\varepsilon} = \frac{v}{R_f}$

With R_f the outer radius of the casing at the moment of fracture and the expanding velocity v of the casing. Since this velocity is determined by the method of Baker [[11], the fragment mass $m_{1/2}$ can be determined and with that the mass distribution for a (lower order) reaction.

Once the value of $m_{1/2}$ is determined the total number of fragments can be obtained by setting $m=0$ for both distribution types. The value of the exponential function is 1 and N_{total} is:

$$N_{Mott,total} = N_{\mathrm{Mott}}(0) = \frac{c_{1/2} M^{e0}}{2 m_{1/2}} \text{ and}$$

$$N_{Exp,total} = N_{\mathrm{Exp}}(0) = \frac{c_1 M^{e0}}{m_{1/2}}$$

The total mass of the casing M^{e0} and the constant $c_{1/2}$ and c_1 are known.

Example calculations for detonation pressure, and 10 and 100 times lower pressures

To show the influence of the pressure and the casing velocity on the fragment mass distribution for a 5 inch steel cylinder (casing thickness 17 mm) filled with composition B, calculations were performed. The casing velocity for the three pressures 29.5, 2.95 and 0.295 GPa, respectively, were determined. The results of these calculations are shown in Table 1. The estimated velocities of the casing for these pressures are 1109, 506 and 153 m/s using Bakers' methods. With these velocities $m_{1/2}$ are determined and are 43, 140 and 842 grams, respectively. Once these values are known, the fragment mass distributions can be determined. Figure 6, shows the overview of these results for the Mott and Exponential distributions for the three pressures. It is obvious that the number of fragments drops for decreasing pressures, while the average masses increase. Besides the casing velocity V_{casing} and the characteristic $m_{1/2}$ mass for the M(ott) and E(xponential) distribution, the total number of fragments N_{tot}, the average mass m_{avg} and the most credible fragment mass (mmc, at 99% confidence) are shown.

Table 1 Overview of the example calculations for 3 different pressures

P[GPa]	V_{casing}[m/s]	$m_{1/2}$[g]	N_{tot},M	N_{tot},E	m_{avg},M	m_{avg},E	mmc,M	mmc,E
29.5	1109	43.1	1148	539	12.1	25.7	128	118
2.95	506	140.4	352	165	39.3	83.7	417	386
0.295	153	841.8	59	28	235	501.7	2497	2310

Figure 6, shows the results of these three pressures showing the Mott and exponential cumulative mass distribution functions as a function of fragment mass. It is obvious that for the lower pressure the number of large fragments is higher than for the highest pressure, which is a detonation pressure.

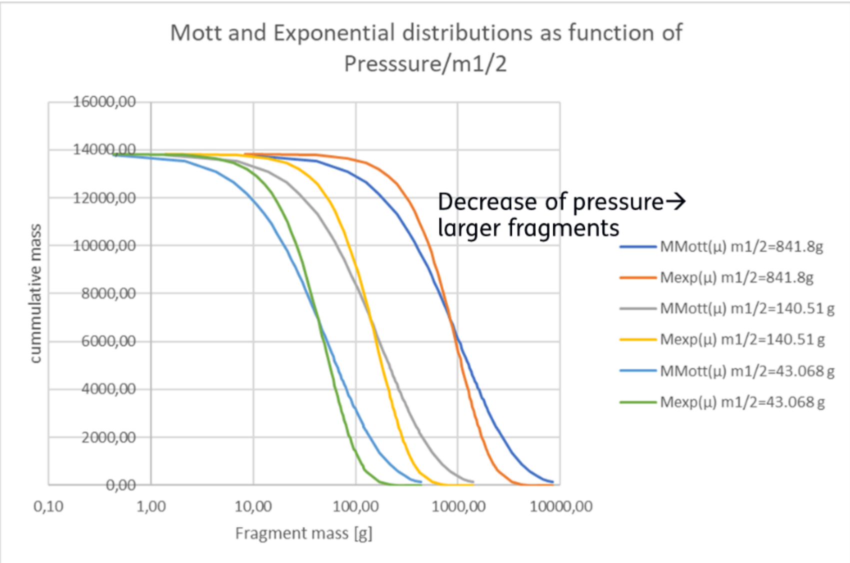

Figure 6 Mott and exponential fragment mass distribution for a 5” steel cylinder at a pressure of 29.5, 2.95 and 0.295 GPa at the moment of fragmentation.

Summary and future developments

The main process steps to predict the response of munitions when penetrated or perforated by a projectile, were identified. These process steps were split into several smaller process steps and models were developed, derived or combined and implemented in an Excel spreadsheet or, in case of more complex sets of equations, in codes like Python or Mathcad.

Most process steps, in the method to predict the response of a munition after penetration or perforation of a projectile, were explored or investigated. For most of these process steps, a model was found, developed or improved and implemented in a spreadsheet or other computer code. Some of these models work quite well and show realistic answers. Other models still need more investigation. Ultimately, the combination of these process steps and models will give an estimate of the response of the munitions that can to be compared with experimental results obtained from in-service munitions' test series.

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