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DETONATION TRANSFER - Summary report, FFI project 803.03

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b) Detonation transfer	b) Detonasjonsoverføring
c) Sympathetic detonation	c) Medfølgende detonasjon
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8) ABSTRACT

In connection with the upgrade of AMRISK, a program for risk analysis of ammunition storages, the process of detonation transfer have been studied. Based on earlier work a model for sympathetic detonation is developed and implemented. To validate the model experiments have been carried out. The agreement between the model and the experimental results is not very good. A better initiation model will probably improve the accordance. Models for detonation propagation in a stack of ammunition and between stacks have also been developed. Based on these models and a reliable model for sympathetic detonation the amount of ammunition that contributes to a mass detonation may be estimated.

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1 INTRODUCTION

1.1 Background

The AMRISK code is a tool for calculating risk values for personnel in the vicinity of military or civilian ammunition storages. The calculations take into account the complete chain from a potential accident to hazards to exposed persons.

AMRISK is the result of a joint Norwegian-Swedish development of the originally Swiss code AMMORISK, which has been used in Norway since 1985. The code has been ported from DOS to Windows, it will communicate with GIS systems and also be updated with improved physical models.

In the early stage of the project, a preferential list of the most important improvements to the code was established as follows:

1) Accident probability
2) Amount of high explosives detonating
3) Lethality
4) Physical effect models

The work on point 2) has been performed at FFI under project 803.03. This report gives a summary of the obtained knowledge.

1.2 Main problem areas

It is an empirical fact that, in many cases, only parts of the stored ammunition detonate in a storage accident. This is not taken into consideration in AMRISK or similar codes used today. On the contrary, the calculations are based on the assumption that the complete mass of high explosives detonates[1]. Because of this, the results will be overly conservative in many cases.

With the gradual introduction of class 1.4 ammunition to replace class 1.1[2], the problem of mass detonation will be reduced. Still class 1.1 ammunition will be produced, transported and stored for several years ahead. Hence, predicting the amount of high explosives that

[1] It is also assumed that the propagation of detonation is such in time and space that the generated blast wave approximates that of a single source.
[2] Classes refer to UN's hazard classes; class 1.1 is mass detonating ammunition, class 1.4 is ammunition giving moderate fire and no blast.

contributes to the effects of an ammunition accident is important to the quality of a risk analysis.

The origin of a mass detonation is a detonation in some munition. The first part of finding how the mass detonation propagates is to determine if a detonation in one munition (donor) causes a detonation in the neighbour munition (acceptor). Then the model must be expanded to include the stack (a pallet) of munitions. Finally, to estimate the amount of mass detonating ammunition in a storage, the process of sympathetic detonation between different stacks must be investigated. The progress of a mass detonation depends on the design and the contents of the storage. In addition the process will be different depending on where the detonation starts.

If the storage consists of several caves with one or a few common adits, detonation transfer between the caves is of interest. The same goes for detonation transfer between containers in a field storage.

Figure 1.1 shows the different detonation transfer processes. The work in this report covers the problems of detonation transfer between individual munitions, propagation in a stack and transfer between stacks.

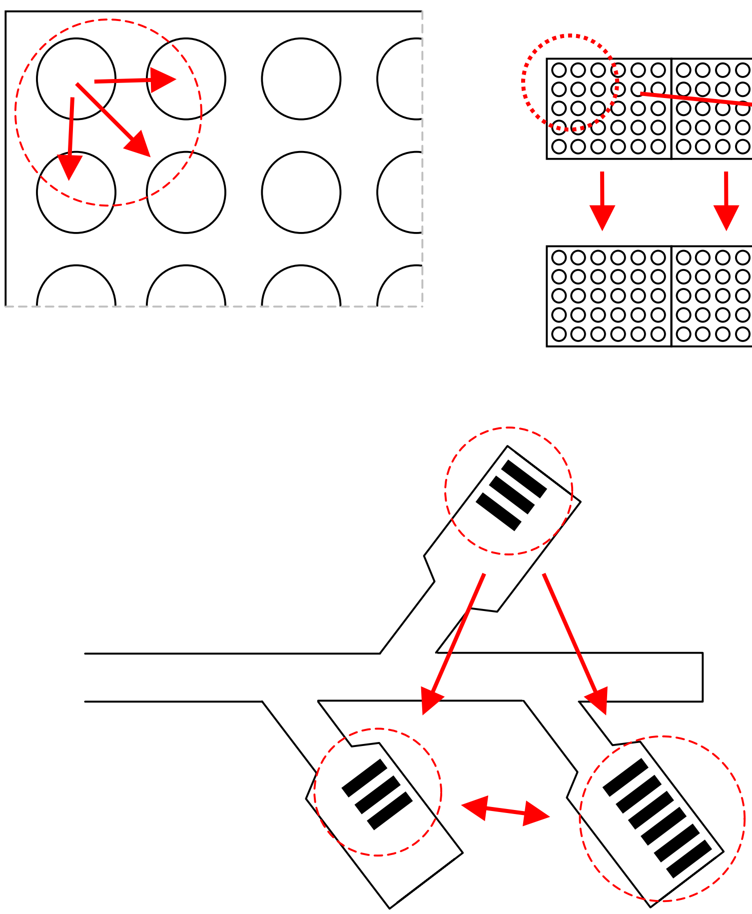

Figure 1.1 Approaches to possible detonation transfer processes in an ammunition storage

1.3 Structure of the report

Chapter 2 describes a model for predicting detonation between a single donor and an acceptor. It is based on an earlier Norwegian work, which has been re-investigated and coded in MATLAB; the original program was in Pascal. Some results are presented, and model limitations pointed out.

Chapter 3 takes the results from chapter 2 one step further by presenting a model for detonation in a stack or a pallet. The model describes one layer of munitions, and includes screening and desensitisation effects. Attempts have thereafter been made to analyse the statistics of the detonation process by a Monte Carlo procedure employing the probabilities, which are the output from the basic propagation model.

Chapter 4 gives a summary of the results of experiment carried out within the project. The trials were mainly simple donor - acceptor situations with 155 mm artillery grenades. The experimental results are compared to results from the basic propagation model including desensitisation effects.

Chapter 5 outlines a simple model describing detonation transfer between stacks or pallets. Note that this problem could be solved by modifying the model from chapter 3. However, starting out with a more basic approach was useful to investigate the statistical significance of the trials described in chapter 4.

Chapter 6 offers some conclusions of the results presented in the previous chapters. Shortcomings of the work and recommendations for future investigations are pointed out.

2 SYMPATHETIC DETONATION MODEL

2.1 Introduction

A sympathetic detonation means that a detonation in a donor initiates a detonation in an acceptor. Whether a sympathetic detonation occurs depends on the contents and shape of the munitions, their relative positions and the ambient conditions. The origin of the first detonation is considered irrelevant here. Still the mechanisms leading to the detonation may influence the conditions for further propagation of the detonation. For instance, if the initial detonation is caused by cook-off, the heating may have changed the sensitivity of the acceptors.

Three categories of initiation mechanisms may be active in a sympathetic detonation (1). The first is the shock to detonation transition (SDT) where a shock causes direct detonation in the acceptor. The shock may come directly from the donor blast wave or may be induced by fragment impacts. The second alternative is that a stimulus causes damage in the acceptor, and a subsequent shock initiates the detonation (XDT). A thermal initiation (deflagration) may also lead to a detonation (DDT), normally in predamaged or porous materials. The contributions to a mass detonation from XDT and DDT are small compared to SDT, which is the initiation mechanism considered here.

The most important cause for shock waves in cased munitions is fragment impact. After a detonation in a cased charge the casing ruptures into many fragments while the blast wave outruns the fragments. However the blast wave decays much more quickly than fragment speed. Therefore the air blast wave from the donor charge may be considered irrelevant for initiating a detonation (1),(2). Still it may cause secondary impacts and sensitisation or desensitisation of acceptors.

At secondary impacts the acceptor is accelerated by the donor effects and then hits the ground, the wall or other objects. The most important effect is probably plastic deformation of the acceptor. Hence, the influence of secondary impacts on a mass detonation is insignificant.

As a first approach we are considering cased charges only. When a fragment hits the casing, a shock wave is created and propagates into the explosive. If the shock exceeds a certain pressure threshold over a specific minimum area, it becomes a detonation wave (3). Fragments may also penetrate the casing and then pass through the warhead or stop inside. The result of a fragment staying inside can be an ignition leading to a detonation; this depends on the fragment speed and the confinement of the munition (3). This initiation mechanism is not considered here. In addition to fragments, the expanding case of a donor may cause initiation of an acceptor.

The mass, velocity and direction of fragments from a cased charge are usually described statistically. From this the probability of one or more hits of fragments with sufficient mass and velocity to initiate a detonation in the acceptor can be derived.

2.2 Model basis

The basis of our model is adopted from Strømsøe and Ingebrigtsen (4)-(6). They developed a model to predict detonation transfer between warheads. The model describes a single donor, single acceptor case.

The velocity of the fragments thrown out when the donor detonates, is a function of the angle relative to the warhead axis φ,

$$v(\varphi) = v_0 F_v(\varphi), \qquad (2.1)$$

where v_0 is found from Gurney’s formula,

$$v_0 = \frac{G}{\sqrt{\frac{C}{Q} + k_\mathrm{G}}} \,. \tag{2.2}$$

G is Gurney's constant dependent on the explosive, C is the casing mass, Q is the mass of the charge and k_G is a geometric constant; for cylinders it is ½. $F_v(\varphi)$ is the distribution function of the fragment velocity (7),

$$F_v(\varphi) = 0.6474 - 0.02636\varphi + 0.0006095\varphi^2 - 3.08 \cdot 10^{-6}\varphi^3 \tag{2.3}$$

for 5° ≤ φ ≤ 95°. For 95° < φ ≤ 185°, φ is substituted with 190° - φ.

There is also an angle distribution of fragment masses,

$$m(\varphi) = CF_\mathrm{m}(\varphi)\,, \tag{2.4}$$

where $m(\varphi)$ is the mass of fragments per angle unit at φ, and $F_\mathrm{m}(\varphi)$ is the fragment mass density function,

$$F_\mathrm{m}(\varphi) = \frac{a}{\sqrt{2\pi}} e^{-\frac{1}{2}y(\varphi)^2} \,. \tag{2.5}$$

The empirical parameter a and the function $y(\varphi)$ are different for different calibres, see Table 2.1. Included in a is the mass of fragments relative to total casing mass.

Calibre	a / deg^{-1}	y
81 mm	8.09	$0.0724(\varphi - 84.41)$
105 mm	8.84	$1.523\left(\sqrt{\varphi} - 9.30\right)$
155/175 mm	7.57	$4.08 \cdot 10^{-4}\left(\varphi^2 - 8796.56\right)$

Table 2.1 Quantities defining the mass distribution function $F_m(\varphi)$

The distribution of masses is described by the Mott-Linfoot formula,

$$N(m) = \frac{M_0}{2M_\mathrm{k}} e^{-m^{1/2}/M_\mathrm{k}} \,, \tag{2.6}$$

where $N(m)$ is the number of fragments with mass larger than m. M_0 is the total mass of fragments and may be taken from (2.4). M_k is a fragment distribution parameter expressed as (7):

$$M_{\mathrm{k}} = B\, t^{5/6} D_{\mathrm{i}}^{1/3} \left(1 + t/D_{\mathrm{i}}\right). \tag{2.7}$$

Here t is the case thickness, D_{i} is the internal diameter and B is an explosive constant.

The fragments will be retarded in air, and the impact velocity is given by

$$v = v_0\, e^{-\frac{c\,s}{m^{1/3}}}, \tag{2.8}$$

where s is the distance covered by the fragment. The factor c depends on the drag coefficient and shape factor of the fragments and the air density and is assumed to be constant with value 0.00465. The distance s is calculated by supposing that the fragments move along a straight line from the donor axis to the acceptor casing. The distance from the donor centre is then

$$s_{\mathrm{o}} = \sqrt{y_{\mathrm{o}}^{\;2} + (d - x_{\mathrm{o}})^2} \tag{2.9}$$

giving

$$s = s_{\mathrm{o}} - R_{\mathrm{od}}, \tag{2.10}$$

where (x_0, y_0) are coordinates of the hit point, d is the distance between donor and acceptor and R_{od} is the outer radius of the donor. x_0 and y_0 are of course connected by

$$x_{\mathrm{o}} = \sqrt{R_{\mathrm{oa}}^{\;2} - y_{\mathrm{o}}^{\;2}}, \tag{2.11}$$

when R_{oa} is the outer radius of the acceptor. Note that the distance does not depend on the polar angle φ.

The initiation criterion is defined by the least velocity giving initiation as a function of the explosive sensitivity (k_{s}), the perforation thickness (t_{p}) and the fragment mass (m) (8).

$$v_{\mathrm{i}} = \sqrt{\frac{0.00864\, k_{\mathrm{s}}\, e^{64.5 t_{\mathrm{p}}/m^{1/3}}}{\mathrm{m}^{2/3}\left(1 + 39.6\, t_{\mathrm{p}}/m^{1/3}\right)}}. \tag{2.12}$$

By using (2.8) and (2.12) the smallest fragment mass that will initiate a detonation, can be determined. (2.6) then gives the number of fragments with mass larger than this critical mass.

The ammunition is considered to be a cylinder. The acceptor warhead half cylinder is divided into n_{L} longitudinal and n_{W} latitudinal zones yielding $n_{\mathrm{L}} n_{\mathrm{W}}$ area elements for which the hit probability is computed, as can be seen in Figure 2.1.

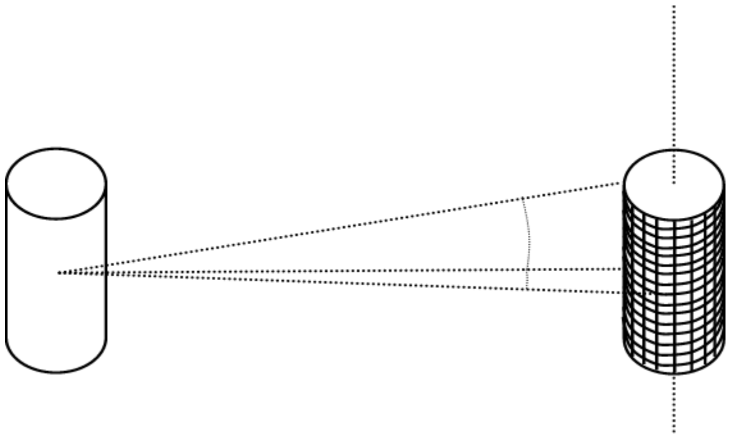

Figure 2.1 The basic geometry of the donor-acceptor model

Hit probability is not computed for segments that do not expose the high explosive core of the grenade.

When a fragment hits the casing at (x_o, y_o), it continues in the same direction, and in case of perforation, to the inner side of the casing. The distance from the donor centre to this point is

$$s_i = d' - \sqrt{d'^2 - d^2 + r_i^2}\ , \tag{2.13}$$

where

$$d' = d\,\frac{d - x_o}{s_o}\,. \tag{2.14}$$

The distance a fragment has to penetrate through a warhead casing is then

$$t_p = s_i - s_o\,. \tag{2.15}$$

(x_o, y_o) are the coordinates of the element midpoint. In the model the perforation thickness is independent of the polar angle.

For an area element (2.4) gives the mass of fragments per polar angle unit, and (2.6) gives the corresponding number of fragments larger then the critical mass. The fraction of these hitting an element is given as

$$f_i = \frac{L\alpha_i \sin^2\varphi}{2\pi n_w \left(d - R_{oa}\right)}, \tag{2.16}$$

where L is the length of the vulnerable part of the acceptor, and α_i is the angle defined by the longitudinal borderlines of the element.

In this way the number of fragments of those with sufficient mass and velocity to initiate the acceptor, that hit an area element, is determined. If these fragments are distributed uniformly across the acceptor, the number may be considered as the expectation value of a Poisson distribution. If the elements are indexed by *i* and *j*, the probability of detonation transfer becomes

$$p_1 = 1 - e^{-\sum_{i=1}^{n_L}\sum_{j=1}^{n_W} N_{ij}} . \qquad (2.17)$$

Here it is supposed that multiple impacts work independently. To allow for the effect of the reinforcement when two or more impacts are close, it is supposed that when two or more fragments with at least half of the critical mass impact the same area element, they will initiate a detonation of the acceptor. Varying the size of the elements changes the synergistic effect. With N_{ij}' as the number of fragments with mass between the half and the whole critical mass, the probability of detonation increases to

$$p = 1 - (1 - p_1)\left(\prod_{i=1}^{n_L} \prod_{j=1}^{n_W} (1 + N_{ij}') e^{-N_{ij}} \right) \qquad (2.18)$$

The model described above was originally implemented in a Pascal program. Based on this, we have programmed the calculation procedures in MATLAB code.

2.3 Results

The outcome of the model is the probability of sympathetic detonation between two warheads of a given calibre. This is shown in Figure 2.2 for different centreline distances.

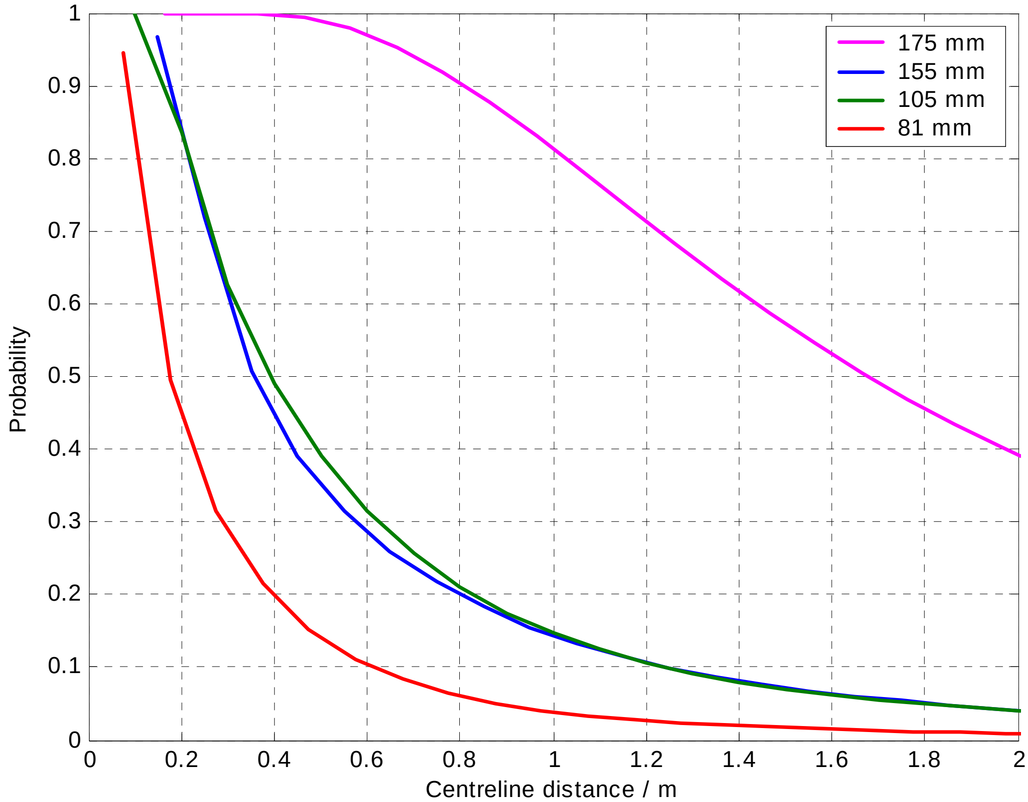

Figure 2.2 Probability of detonation transfer between two warheads with Comp B or TNT (155 mm) as a function of the distance between the warhead axes

Strømsøe and Ingebrigtsen (6) compared their results with experimental data from tests with 81 mm, 105 mm and 175 mm warheads. The agreement is best for the 175 mm grenades. In the experiments with 81 mm and 105 mm there seems to be a relatively sharp distance limit for detonation transfer, whereas the calculations predict an increase in the probability from 0 to 1 over a much longer interval.

2.4 Model limitations

Strømsøe and Ingebrigtsen (6) suggest that the deviation between experiments and calculations can be explained by the neglect of direct shock and synergism between direct shock and fragment impact. They refer to results (2) giving critical distances for sympathetic detonation induced by direct shock. The distances are 16 cm for 81 mm calibre, 22 cm for 105 mm and 37 cm for 175 mm. However, increasing the probability to 1 at these distances, only give small changes in the curves, see Figure 2.2.

A significant effect of direct shock or a previous impact may be sensitisation or desensitisation of the explosive. The sensitivity is increased when the shock breaks up the charge and makes it more porous. On the other hand a shock can close up voids in the charge and reduce the sensitivity (3). If there are sensitisation effects they may give better correspondence to the experiments at small distances.

The donor warhead is considered as a point source of fragments when the polar angle to the acceptor zones is determined. The error in this assumption is largest at short distances.

The effect of more than one fragment impacting simultaneously is treated somewhat primitively in the model. It is possible to adjust the parameters, but Strømsøe and Ingebrigtsen (5) found that the contribution from multiple impacts was minor for the warheads they studied.

The model is founded on Rindner's formula (eq. (2.12)) from 1968, which is based on large-scale experiments carried out at Picatinny Arsenal before 1960. Both the impact and the resulting initiation are comprised by the simple formula. More recent models (9), (10) for initiation of high explosives have a more physical basis and will probably be in better agreement with observed results. These models are similar in the way they describe the fragmentation, propagation of fragments, and fragment impact. The main difference is in the initiation criteria. Victor's model (9) uses a failure diameter criterion, while Annereau (10) uses a constant P^n T-value criterion for the shock initiation. Both models include corrections for cylindrical geometry and diagonal effects that are not included in the current model.

As regards the fragment mass distribution there are alternatives (11)-(16) to Mott's formula. The influence on the model output from changing to another formula remains unexplored. Another point that may be considered is that rotating fragments probably cause smaller shocks (17). They penetrate the casing more easily, however, and can initiate deflagration.

3 PROPAGATION OF DETONATION IN A STACK

When the probability of detonation transfer between one donor and one acceptor is established, the next step is to find what will happen in a stack of ammunition, see for instance Figure 3.1.

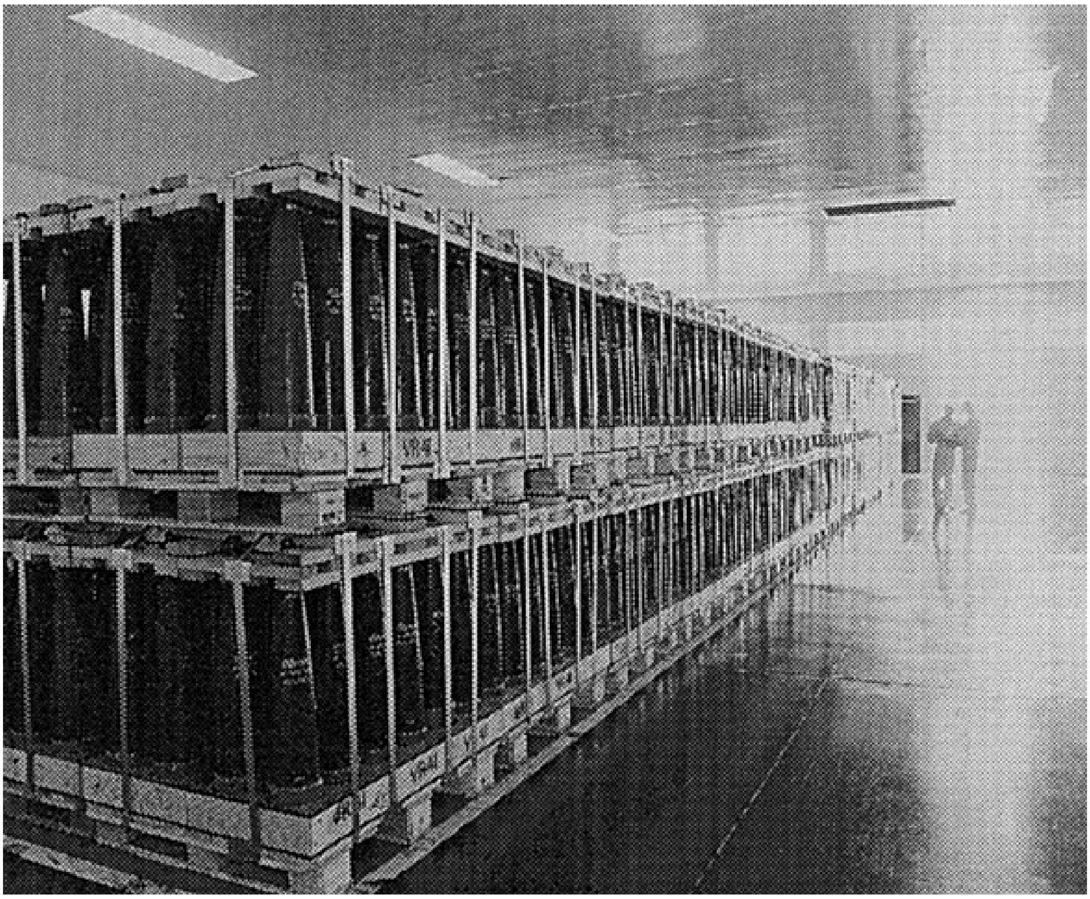

Figure 3.1 155 mm projectiles awaiting delivery

3.1 Simulation model

A simple 3D discrete-event model for sympathetic detonation in a layer of cylinders representing grenades in an ammunition stack has been established. The stack is modelled as a single layer of ammunition. To improve the prediction of sympathetic detonation in a stack, periodic border conditions should be imposed. This means that the fragment distribution from other layers is modelled by allowing the single layer to be initiated from above by fragments thrown out below by the single layer. A typical stack configuration is shown in Figure 3.2.

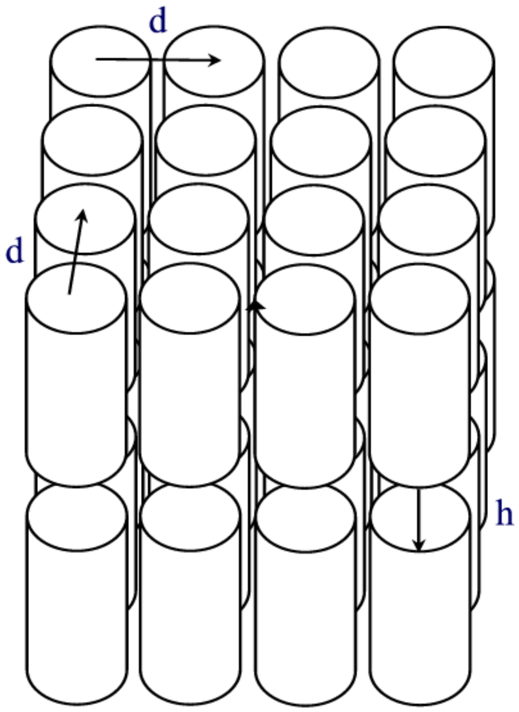

Figure 3.2 A stack of ammunition

The ammunition in the stack closest to the donor will screen out ammunition further away from the donor. At close stacking distances the screening will be total and only the closest ammunitions will be exposed. As the detonation propagates through the stack, the screening effect will diminish. The initial exposed area for different ammunitions is shown in Figure 3.3.

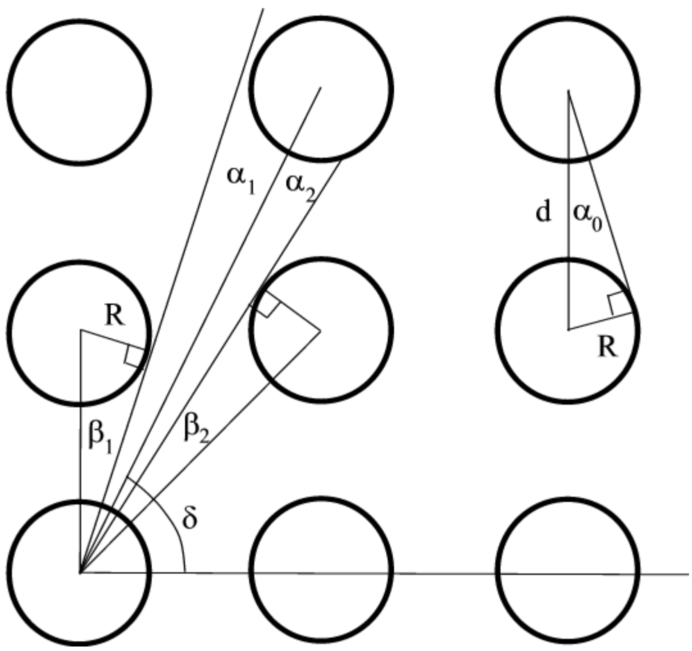

Figure 3.3 Parameters used for calculating screening effects

First we consider the fragment trajectories projected on a plane normal to the grenade axes. After a detonation the fragments travel radially out from the donor centre.

The donor is assigned coordinates (0,0), and the acceptor has coordinates (i_A,j_A). The size of the angle in which the donor fragments must be sent to strike the acceptor when there are no grenades between, is

$$2\alpha_0 = 2\arcsin\left(\frac{1}{2\sqrt{i_A^{\;2}+j_A^{\;2}}\,(1+k)}\right) \tag{3.1}$$

where

$$k = \frac{d}{2R} \tag{3.2}$$

In Figure 3.3 $d/2R$ = 0,67, so $i_A = 2$ and $j_A = 1$ give $2\alpha_0 = 15.4°$.

In a stack grenades between the donor and the acceptor may reduce the angle that leads to hit. The angle at the left side of the line between the donor centre and the acceptor centre, where the fragments propagate unobstructed, is denoted α_1. The angle at the right side is α_2. The size of the angle of departure of the fragments hitting the acceptor thus becomes

$$\alpha = \min(\alpha_0,\alpha_1) + \min(\alpha_0,\alpha_2) \tag{3.3}$$

α_2 is calculated as

$$\alpha_2 = \arctan\left(\frac{i_A}{j_A}\right) - \arctan\left(\frac{i_2}{j_2}\right) - \arcsin\left(\frac{1}{2\sqrt{i_2^{\;2}+j_2^{\;2}}\,(1+k)}\right) \tag{3.4}$$

where (i_2, j_2) are the coordinates of the grenade closest to the line between (0,0) and (i_A, j_A):

$$(i_2, j_2) = \max_{i,j}\left(\frac{i}{j}\right) \in \frac{i}{j} < \frac{i_A}{j_A} \wedge j \le j_A \tag{3.5}$$

With $i_A = 2$ and $j_A = 1$, (0,1) and (1,1) satisfy the conditions. Thus (i_2, j_2) = (1, 1) and $\alpha_2 = 6.2°$.

For α_1 the corresponding expressions are

$$\alpha_1 = \arctan\left(\frac{j_A}{i_A}\right) - \arctan\left(\frac{j_1}{i_1}\right) - \arcsin\left(\frac{1}{2\sqrt{i_1^{\;2}+j_1^{\;2}}\,(1+k)}\right) \tag{3.6}$$

$$\left(i_1, j_1\right) = \max_{i,j}\left(\frac{j}{i}\right) \in \frac{j}{i} < \frac{j_{\mathrm{A}}}{i_{\mathrm{A}}} \wedge i \le i_{\mathrm{A}} \tag{3.7}$$

In our example only (1,0) satisfies the conditions, and α_2 becomes 9.1°, yielding $\alpha = \alpha_0 + \alpha_1 =$ 16.8°.

3.2 Desensitisation effects

Desensitisation effects are reported by several sources (18)-(21). Homogeneous explosives require stronger shocks to detonate than heterogeneous. Shock loads below initiation threshold may reduce heterogeneities. The data reported does not allow detailed modelling of the effect. In the current model a simplified representation of the effect has been tested. Desensitisation is assumed to take effect for stacking distances that are smaller than the fragmentation limit for the casing of the ammunition.

3.3 Simulations

Previously attempts have been made to analyse the statistics of the detonation process without addressing the temporal properties of the process (22). In our model we have simulated detonation in a stack using a discrete-event model. The process starts with detonation in one donor. For each step the probabilities of detonation transfer from donors to possible acceptors are calculated. The acceptors getting initiated are picked randomly by a Monte Carlo procedure. Detonated grenades are removed.

The simulation code given in appendix A may briefly be described by the following pseudo-code:

Initiate the first donor ammunition
Calculate the first hit probabilities
While acceptors are being initiated
    Find detonated ammunition and change the screening
    Find desensitised ammunition
    Acceptors that are not desensitised and not already detonated may be initiated
    Calculate new hit probabilities
    Select at random acceptors to be initiated the next cycle
Compile statistics

In Figure 3.4 the results are shown as the fraction of ammunition that has detonated.

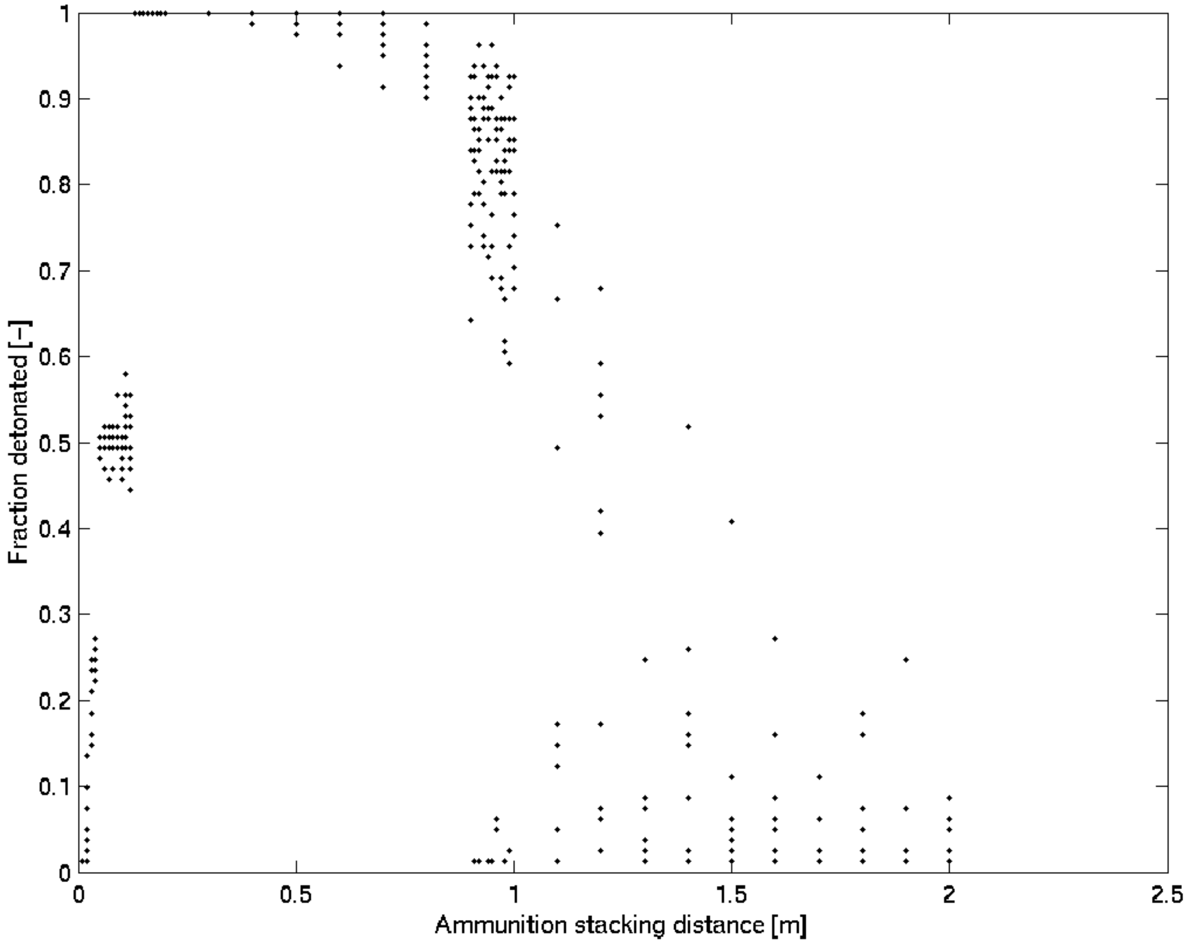

Figure 3.4 Fraction of ammunition detonated as a function of the stacking distance (between casing surfaces) for 9 x 9 TNT filled 155 mm artillery grenades

With typical stacking distances the resulting fraction detonated is found to be in the area between 10% and 30%. This would give considerable reductions in the effects from the explosion. A typical detonation pattern for a stacking distance of 25 mm is shown in Figure 3.5.

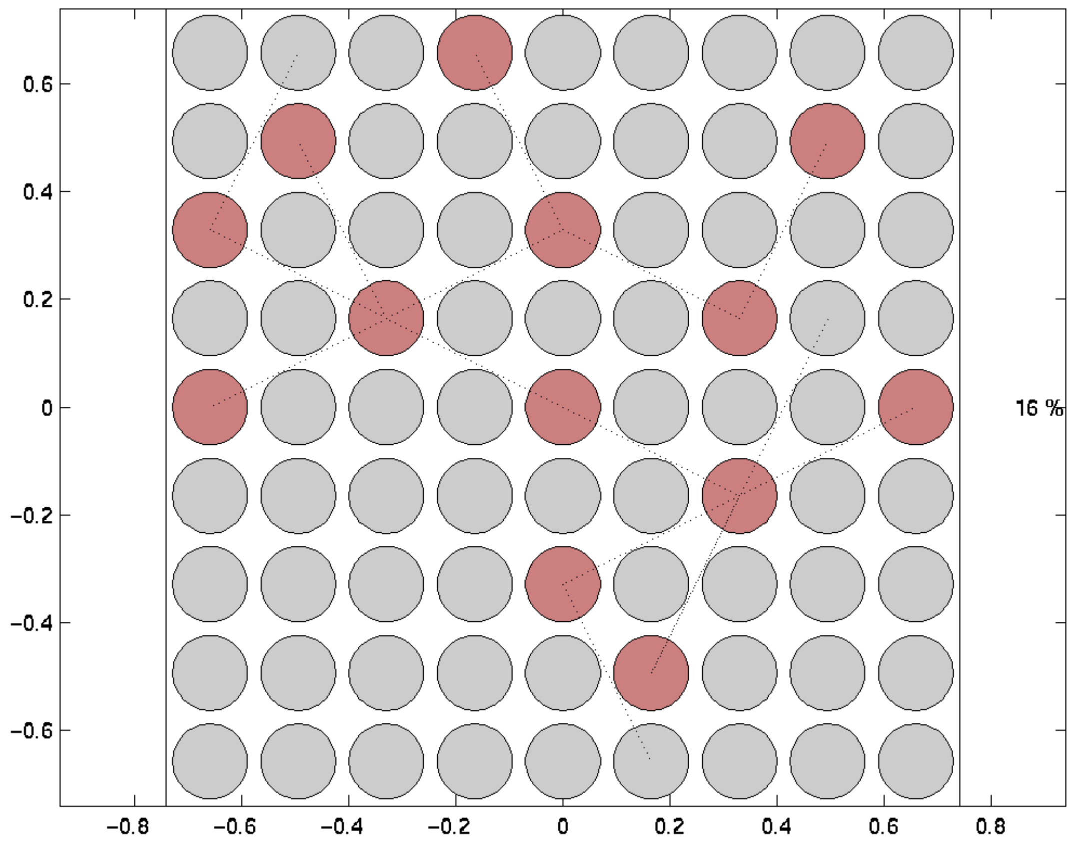

Figure 3.5 Detonation pattern for a stacking distance of 25 mm

Figure 3.5 is an example of results from the simulation model. It should be noted that the validity of the results depends heavily on the sympathetic detonation model including desensitisation effects.

4 EXPERIMENTS

To investigate detonation transfer between grenades, and particularly the sympathetic detonation model, a series of full-scale experiments were carried out (23). Witness plates, pressure transducers and video were used to document the results.

In addition to calibration and demolition bursts 33 test explosions with 70 NM28 (155 mm) grenades were made. For each of the case distances 0 mm and 25 mm 10 tests were accomplished, and all of them gave detonation in the acceptor. Of the nine tests with 150 mm distance, eight lead to deflagration and one to partial detonation. One test was made with the acceptor at 86 mm distance, and this resulted in detonation. 345 mm distance was also tested once without any reaction.

Moreover, two special tests were conducted. In the first the donor was initiated sideways as opposed to the others where the initiation was at the nose. The result was detonation in the acceptor. In addition there was a test to investigate the effect of deflagration in a donor 25 mm from the acceptor. The deflagration was initiated by detonating a grenade 150 mm from the donor. There was no reaction in the acceptor as a result of the deflagration in the donor.

Based on the experiments the probability of detonation transfer can be estimated to 1 at casing distances of 0 mm and 25 mm and to 0.1 at 150 mm. The casing distances of 0 mm, 25 mm and 150 mm correspond to centreline distances of 0.155 m, 0.180 m and 0.305 m. The uncertainty of these estimates can be expressed by their confidence interval. The ten tests at each of the three distances are a binomial test series. When the estimate is 1 the interval is one-sided, otherwise it is two-sided. In Figure 4.1 the experimental estimates are compared with the probabilities calculated by the basic propagation model.

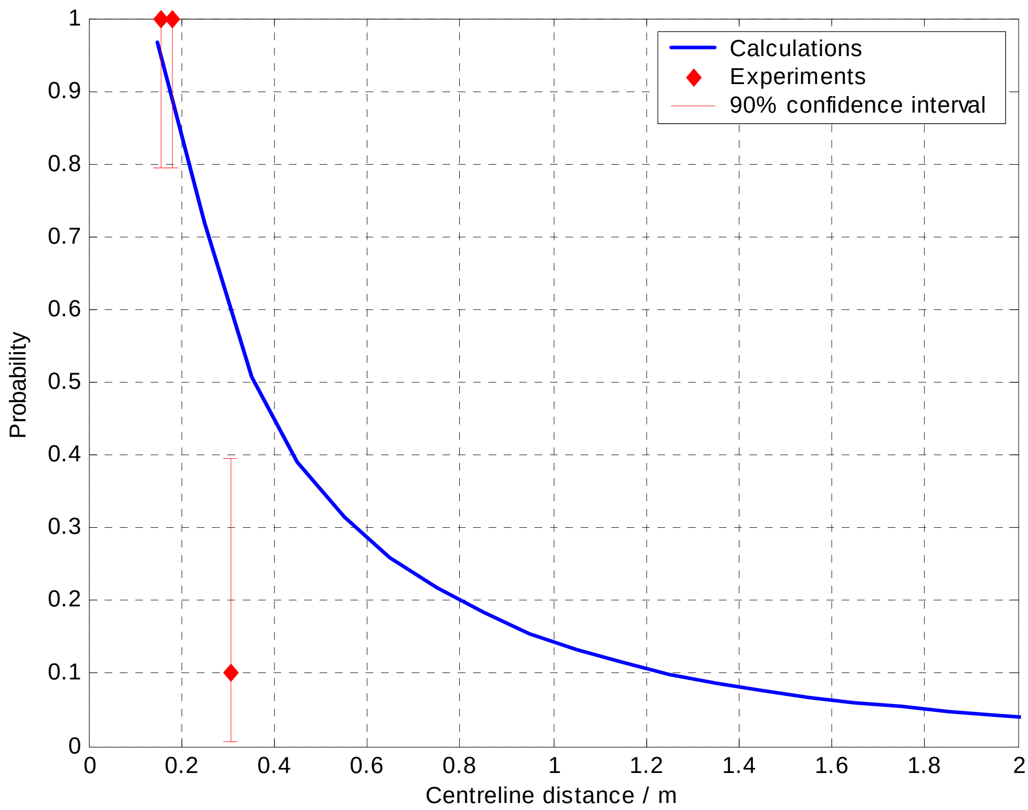

Figure 4.1 Experimental estimates with 90 % confidence intervals of probability of detonation transfer between two 155 mm warheads compared with values from the sympathetic detonation model

The agreement with the experimental results is poor at the largest distance. As pointed out in section 2.3, the calculated probability decays too slowly. Figure 4.1 also shows that the 90 % confidence intervals become quite large when they are based on no more than 10 trials.

Sensitisation effects could influence the results at distances where the direct shock wave reaches the donor before the fragments. The results indicate that desensitisation is not a dominating effect for this ammunition type.

Critical distance for deflagration is considerably smaller than supposed.

Because of the quite weak correlation between the experimental and theoretical results, the Management Group of the AMRISK upgrade project decided to terminate the efforts to implement a model for detonation transfer in the AMRISK code.

5 PROPAGATION OF DETONATION BETWEEN STACKS

In this chapter an outline of a procedure for calculating detonation transfer between stacks in an ammunition storage is drawn up. These considerations do not include the model for detonation in a stack. However it should be straightforward to combine the models at a later stage.

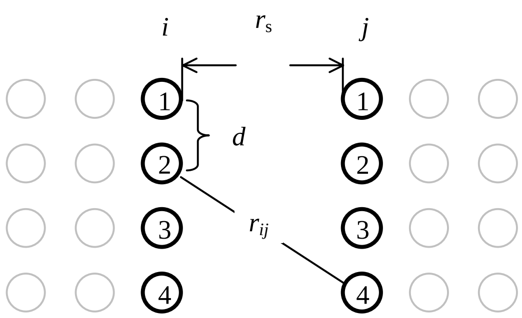

Figure 5.1 Two stacks of ammunition

We consider two stacks of grenades where the distance between is r_s. The vertical distance between the stack layers is d, and the grenade calibre is $2R$.

Here all the grenades in the left stack are supposed to detonate. We want to find the probability of detonation in the right stack or the probability of at least one detonation transfer from the left to the right. Only the grenades in the outer layers are considered.

The fragment velocity is assumed constant and does not depend on the distance from the donor or the direction. Likewise the fragment masses are supposed to be uniformly distributed. The fraction of fragments causing initiation is then independent of direction and distance. The probability of detonation transfer depends on the number of fragments hitting the acceptor grenades, and this number is proportional to the solid angle defining the acceptor's hit area.

The fragments from a grenade are supposed to be sent from one point. When the problem is reduced to two dimensions, as in Figure 5.1, the number of fragments sent in the direction given by the angle ϕ is

$$n = N\frac{\phi}{2\pi}, \tag{5.1}$$

where N is the number of fragments sent out in the observed plane and able to initiate a detonation, and

$$\phi = \frac{2R}{r}, \tag{5.2}$$

when r is the distance between donor and acceptor. Hence the specific hit point on the acceptor is not considered.

Again n is interpreted as the expectation value of a Poisson distribution. The probability of at least one fragment hit is then

$$p = 1 - e^{-\frac{NR}{\pi r}}. \tag{5.3}$$

The value of N is not known. However if the value of p at a given distance is p_0, i.e. $p(r = r_0) = p_0$, the expression may be written

$$p = 1 - \left(1 - p_0\right)^{\frac{r_0}{r}}. \tag{5.4}$$

In the experiments presented in chapter 4 a partly detonation was initiated in one of the ten experiments with the acceptor 15 cm from the donor. Accordingly the transfer probability at this distance is estimated to 0.1 with 90 % confidence interval [0.005 0.39].

The distance between two grenades at positions i and j can be written as

$$r_{ij} = \sqrt{r_s^{\,2} + (i-j)^2 d^2}. \tag{5.5}$$

When the probability of detonation transfer between those is denoted p_{ij}, the probability of no detonation transfer becomes

$$\begin{aligned} p &= 1 - \prod_{i=1}^{n}\prod_{j=1}^{n}\left(1 - p_{ij}\right) \\ &= 1 - \prod_{i=1}^{n}\prod_{j=1}^{n}\left(1 - p_0\right)^{\frac{r_0}{\sqrt{r_s^{\,2} + (i-j)^2 d^2}}} \end{aligned} \tag{5.6}$$

If any of the grenades in the left stack does not detonate, the corresponding factors are left out ($p_{ij} = 0$). That is not assumed to be the case here. The results are as shown in Figure 5.2 for $p_0 = 0.1$.

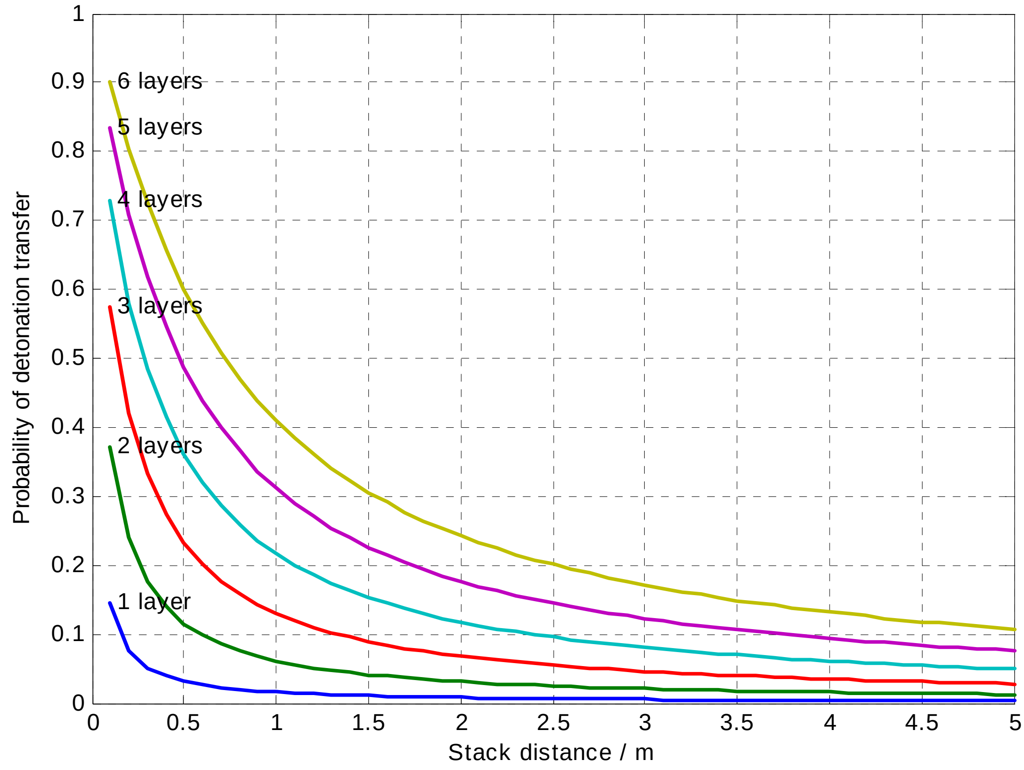

Figure 5.2 *Probability of detonation transfer with p_0 = 0.1 as a function of stack distance for different number of layers*

Setting p_0 to the lower limit of the confidence interval, 0.005, gives the results shown in Figure 5.3.

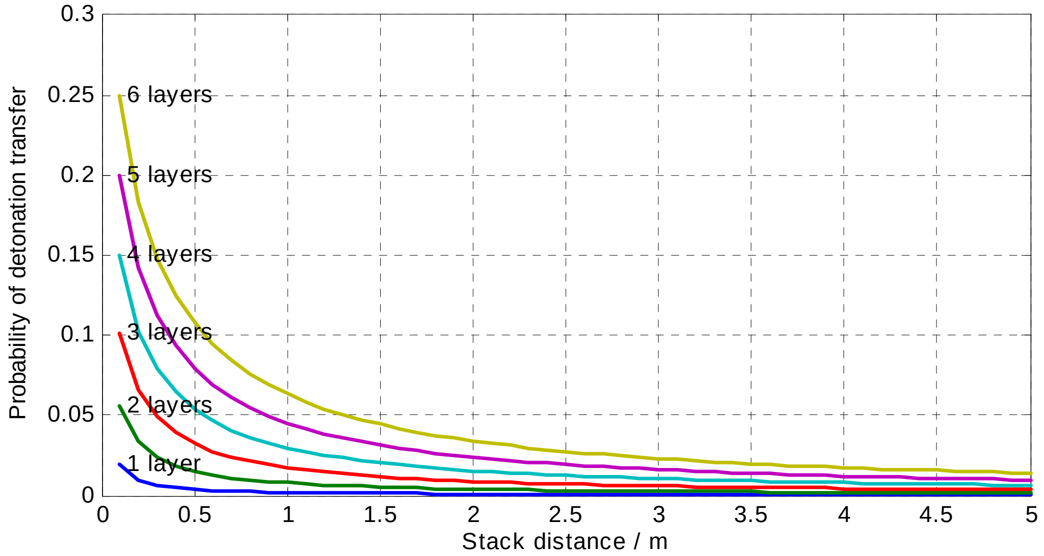

Figure 5.3 *Probability of detonation transfer with p_0 = 0.005 as a function of stack distance for different number of layers*

Using the upper limit for p_0, 0.394, the results become as Figure 5.4 shows.

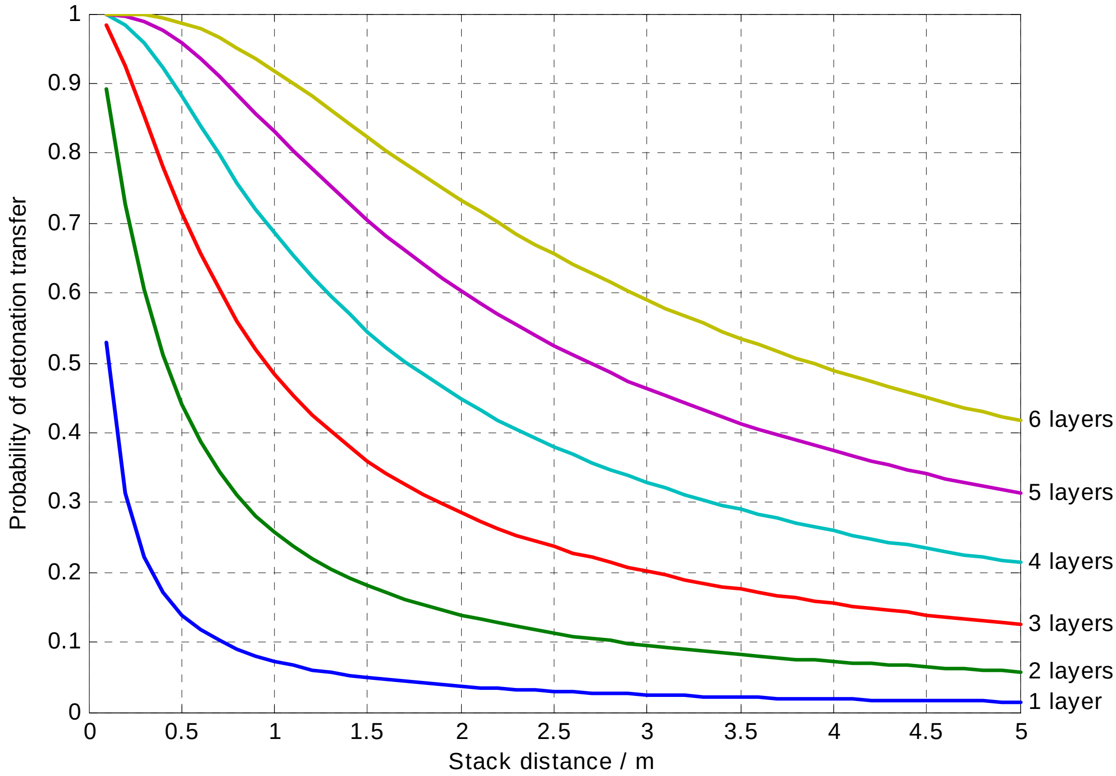

Figure 5.4 *Probability of detonation transfer with p_0 = 0.394 as a function of stack distance for different number of layers*

The probability of p_0 inside a given interval is the same as the probability of p being within the values calculated using the limit values of p_0. With six layers and a stack distance of 1 m the probability of detonation transfer is estimated to 0.41, and the 90 % confidence interval is [0,02 0,92]. Hence, the uncertainty gets quite large when the estimates are based on such a few results.

It can also be useful to calculate the distance giving a certain critical probability. Figure 5.5 shows the distances giving probability 0.1 as a function of number of layers. In addition to values calculated with p_0 = 0.1 the figure shows results using the limits of the chosen confidence interval for p_0.

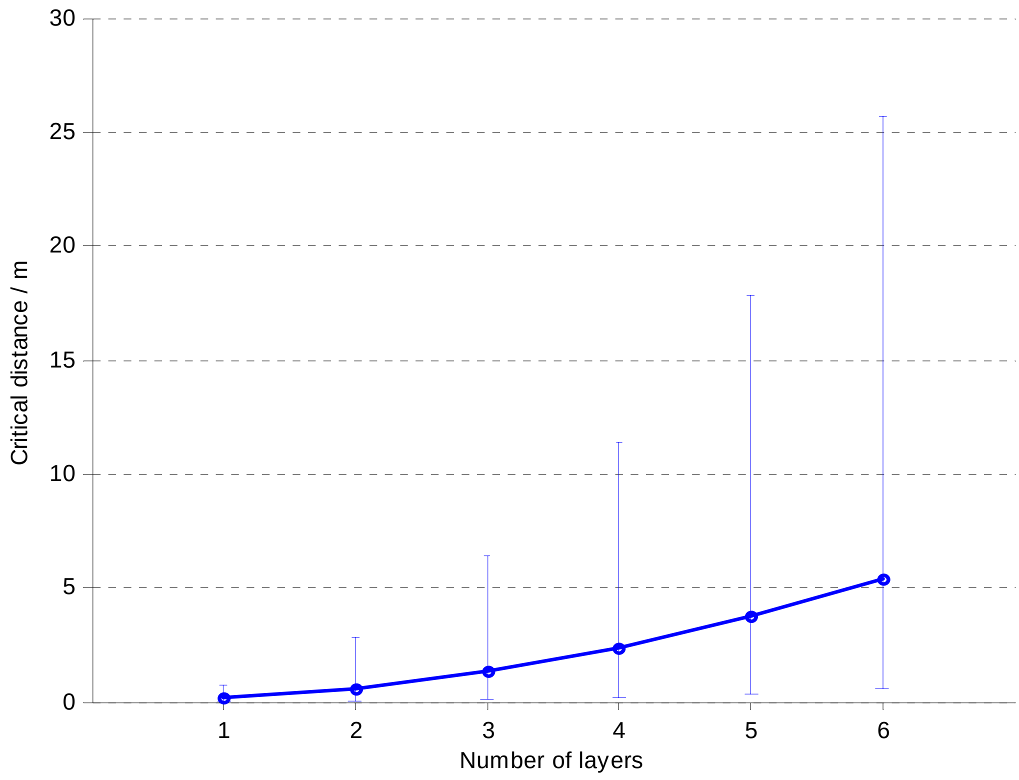

Figure 5.5 *Stack distances giving 10 % probability of detonation transfer with p_0 = 0.1, and with upper and lower limits corresponding to the 90 % confidence interval of p_0*

The results show the need for more experiments to get better estimates for the probability of detonation transfer between munitions. An alternative to using experimental results is to make use of calculated values of (r_0, p_0) with an improved single donor/single acceptor model.

Then this model for detonation propagation between stacks can be combined with the model for propagation in a stack. The resulting model can also be applied to several stacks. It is of course essential to validate the model against experiments.

An obvious alternative to this procedure is to extend the discrete-event model for detonation propagation in a stack to propagation between stacks. Essentially this only requires an expansion of the considered geometry. It should be kept in mind that the experiments indicate (chapter 4) that at a fairly short distance deflagration is a very probable event, the propagation in time may therefore also be important. This is not considered in the model described in this chapter, in contrast to the discrete-event model.

6 CONCLUSIONS

A model for predicting the amount of explosives in an ammunition storage contributing to a mass detonation remains uncompleted. Still the main elements are developed on which it is a manageable task to build up the overall model.

The experiments carried out indicate that detonation transfer takes place only at short distances between the donor and the acceptor. The upper limit for the 155 mm grenades is approximately 15 cm, and at this distance deflagration clearly seems to be a more probable outcome. The experiments also indicate that a deflagrating munition does not initiate its neighbours. Further experimental studies are needed to establish more certain estimates of the results after a detonation in a donor.

A comparison of the model for sympathetic detonation with experiments shows that the model is not good enough. The shortcomings seem mainly due to the initiation model, which is very simple. Better models are described in the literature and should be implemented in the sympathetic detonation model.

Another aspect of the model, which should be subject to further investigation, is sensitisation or desensitisation. A desensitisation model is included, but experiments do not confirm that this is in correspondence with real effects. At short distances between donor and acceptor an increase in sensitivity would give better correspondence with experiments.

Models for detonation propagation in a stack and between stacks are developed. When a new model for detonation transfer between a single donor and acceptor has been verified experimentally, these models could be implemented. The model results will most likely be a probability distribution of the amount of explosives detonated in a number of stacks. The extension to an entire ammunition storage requires treatment of more ammunition types. This should be followed by experimental verification in full-scale.

APPENDIX

A PROGRAM CODE FOR THE MODEL FOR DETONATION PROPAGATION IN A STACK

```
function [SD]=sim_det(Nmax,d,xip,yip,tm,DTYPE,ATYPE);

%
% function [SD]=sim_det(Nmax,d,RY,xip,yip,tm,DTYPE,ATYPE);
%
% Example >>[SD]=sim_det(5,0.2,5,5,100e-6,155,155);
%
% 2*Nmax-1 is the number of ammunitions in each side of the stack
%
% d is the distance between the surfaces of the ammunitions in the stack
%
% d_space is the maximum centre to centre separation distance at which
% desensitisation occurs
%
% Initiation point [xip,yip]
%
% Average time for detonation transfer tm
%

clear

global BLENG LSONER BSONER RI RY MNULL KF k2

%
% Data to be preserved in between calls to fsolve to speed up the simulation

global fsolve_ix fsolve_param fsolve_Mcrit

%
% Create *.avi file for later

mov = avifile('sim_det.avi','COLORMAP',[0 0 0; 1 1 1; 0.8 0.8 0.8; 0.8 0.5 0.5])

%
% Keep track of the run time

C1=clock;

%
% Radial limit for fragment attack (fragmentation distance).

d_space=0.26;

%
% Resolution for the cylindrical representation of acceptor ammunitions

LSONER = 4;  % number of length zones
BSONER = 16; % number of width zones

% gets other geometrical and explosive data
[MK,VNULL] = data(DTYPE, ATYPE);

%
% Init fsolve data

fsolve_ix=1;
fsolve_param={};
fsolve_Mcrit(:,:,1)=ones(LSONER,BSONER);
```

```
%
% Initiate fixed random series (or series seeded by the clock)

rand('state',0);
%rand('state',sum(100*clock));

%
% Generate mesh grid for ammunition stack coordinates (NB: swap XY to allow
% convention (x,y,z) to be used in matrix indexing.

k = d/(2*RY);
g = 2*RY+d;

[Y,X]=meshgrid([-(Nmax-1).*g:g:(Nmax-1).*g],[-(Nmax-1).*g:g:(Nmax-1).*g]);
xp=g.*(xip-Nmax);
yp=g.*(yip-Nmax);
X=X-xp;
Y=Y-yp;
GRID_D=sqrt(X.^2+Y.^2);
DSENS=GRID_D<d_space;

D=zeros(size(GRID_D));
D(xip,yip)=1;
SAV(1).D=D;

%
% Graphics initiation

clf;

%
% The outline of the ammunition-stack is plotted

dd=(2*RY+d)/2;
xy=(2*Nmax-1)*g/2;

plot([-xy,xy],[-xy,-xy],'k-');
hold on
plot([xy,xy],[-xy,xy],'k-');
plot([-xy,xy],[xy,xy],'k-');
plot([-xy,-xy],[-xy,xy],'k-');

axis equal;

for ix=1:2*Nmax-1
   for jx=1:2*Nmax-1
      xp=g.*(ix-Nmax);
      yp=g.*(jx-Nmax);
      fillcircle(xp,yp,RY,[0.8 0.8 0.8]);
   end
end

%
% The initiation point is marked red

xp=g.*(xip-Nmax);
yp=g.*(yip-Nmax);
fillcircle(xp,yp,RY,[0.8 0.5 0.5]);

sx=1;

%
% The subsequent detonation points are found. A logical variable is generated
% for all grid points, indicating whether the probability is above or
% below the p(d) value (This is the Monte Carlo-step).

disp(sprintf('iteration: %d  initiated at  : %d %d \n',sx,xip,yip));
```

```
init_det=(vuln(GRID_D, matrix(X,Y,xip,yip,D,d,GRID_D), DTYPE, ATYPE))>rand(size(D));

%
% Detonated points (D) and points at which detonation has been initiated (ID)
% are set

ID=and(init_det,~DSENS);

%
% Fragment path indications
%

linecircle(xp,yp,X+xp,Y+yp,ID);

%
% Desensitisation is initiated
for ix=1:2*Nmax-1
   for jx=1:2*Nmax-1
      if ID(ix,jx)
         [Y,X]=meshgrid([-(Nmax-1).*g:g:(Nmax-1).*g],[-(Nmax-1).*g:g:(Nmax-1).*g]);
         xp=g.*(ix-Nmax);
         yp=g.*(jx-Nmax);
         X=X-xp;
         Y=Y-yp;
         GRID_D=sqrt(X.^2+Y.^2);
         DSENS=or(DSENS,GRID_D<d_space);
      end
   end
end

%
% Store a list with the number of new detonations each turn

SD(1)=1;

%
% Initial configuration in movie file

F = getframe(gca);
mov = addframe(mov,F);

%
% Loop while new points are still initiated and while all ammunition is not
% initiated

while max(max(ID))~=0 & min(min(ID))~=1

   NID=zeros(size(GRID_D));
   NDSENS=zeros(size(GRID_D));

   % Double loop through the mesh to find points that are detonated this turn
   for ix=1:2*Nmax-1
      for jx=1:2*Nmax-1

          % Points that are detonated this turn may detonate nabours the next turn

          if ID(ix,jx)
             [Y,X]=meshgrid([-(Nmax-1).*g:g:(Nmax-1).*g],[-(Nmax-1).*g:g:(Nmax-
1).*g]);
             xp=g.*(ix-Nmax);
             yp=g.*(jx-Nmax);
             X=X-xp;
             Y=Y-yp;
             GRID_D=sqrt(X.^2+Y.^2);
             NDSENS=or(NDSENS,GRID_D<d_space);
             disp(sprintf('iteration: %i  sub ammunition: %i %i fsolve_ix: %i
\n',sx+1,ix,jx, fsolve_ix));
```

```
            init_det=(vuln(GRID_D, matrix(X,Y,ix,jx,D,d,GRID_D), DTYPE,
ATYPE))>rand(size(D));
            NID=and(or(NID,init_det),~or(NDSENS,DSENS));
            fillcircle(xp,yp,RY,[0.8 0.5 0.5]);
            linecircle(xp,yp,X+xp,Y+yp,and(init_det,~or(NDSENS,DSENS)));

             F = getframe(gca);
             mov = addframe(mov,F);

          else
             disp(sprintf('iteration: %i  sub ammunition: %i %i \n',sx+1,ix,jx));
          end
      end
   end

   % Overlay the points detonated on the mesh containing the points detonated so far
   D=or(ID,D);

   % Advance the points to be initiated the next turn to the currently initiated
   ID=NID;

   % Overlay the points desensitised on the mesh containing the points desensitised
   % so far
   DSENS=or(NDSENS,DSENS);

   % Increment the turn counter and store the number of points detonated
   sx=sx+1;
   SAV(sx).D=D;
   SD(sx)=sum(sum(D));

end

SAV(sx+1).D=or(ID,D);

%
% Fill the last acceptors

for ix=1:2*Nmax-1
   for jx=1:2*Nmax-1
       if ID(ix,jx)
          [Y,X]=meshgrid([-(Nmax-1).*g:g:(Nmax-1).*g],[-(Nmax-1).*g:g:(Nmax-1).*g]);
          xp=g.*(ix-Nmax);
          yp=g.*(jx-Nmax);
          X=X-xp;
          Y=Y-yp;
         fillcircle(xp,yp,RY,[0.8 0.5 0.5]);
       end
   end
end

%
% Establish the time axis

T=ones(size(SD));
T=tm*cumsum(T);

%
% Compute the run time

C2=clock;

CS=C2(6)-C1(6)+60.*(C2(6)<C1(6));
CM=C2(5)-C1(5)+60.*(C2(5)<C1(5))-(C2(6)<C1(6));
CH=C2(4)-C1(4)+24.*(C2(4)<C1(4))-(C2(5)<C1(5));
CD=C2(3)-C1(3)+30.*(C2(3)<C1(3))-(C2(4)<C1(4));

display(sprintf(' %i days : %i hours : %i minutes : %i seconds' ...
        ,CD,CH,CM,round(CS)));
```

```
%
% Save results

save sim_det.mat

%
% Display the percentage detonated

msg=sprintf('%d %%',round(100*sum(sum(D))/((2*Nmax-1).^2)));
text(Nmax.*g+dd,0,msg);

%
% Add the last frame and close movie file

F = getframe(gca);
mov = addframe(mov,F);

mov = close(mov);
hold off

pause;

%
% Plot the number of detonations each turn as a function of time

plot(T,horzcat([1],diff(SD))./tm);

%
% Display the percentage detonated, and mark the initiation point green

xlabel('t [s]');
ylabel('Detonations per unit time [Hz]');

F = getframe(gca);
imwrite(frame2im(F),'sim_det_f.tif','tif');

pause;

%
% Plott the cumulative number of detonations as a function of time

plot(T,SD./(2*Nmax-1).^2);
xlabel('t [s]');
ylabel('Mass fraction detonated [-]');

F = getframe(gca);
imwrite(frame2im(F),'sim_det_mf.tif','tif');
```

```
function [ANGLE_EXP]=matrix(X,Y,xip,yip,DET,d,GRID_D)

global BLENG LSONER BSONER RI RY MNULL KF k2

g = 2*RY+d;
IA=round(X./g);
JA=round(Y./g);
k = d/(2*RY);
Nmax=(length(DET)+1)/2;

% Compute the [-pi:pi] angles for the line between donor and acceptor
ANGLE=atan2(Y,X);

% Store necessary values inside a representation of the matrix that can be sorted
% and manipulated (a meta matrix).
iz=1;
meta=[];
for ix=1:2*Nmax-1
   for jx=1:2*Nmax-1
      meta(iz,1)=ANGLE(ix,jx);
      meta(iz,2)=GRID_D(ix,jx);
      meta(iz,3)=DET(ix,jx);
      meta(iz,4)=IA(ix,jx);
      meta(iz,5)=JA(ix,jx);
      iz=iz+1;
   end
end

% Remove donor from the meta matrix
meta=meta([meta(:,4)~=0 | meta(:,5)~=0],:);

% Sort according to angle and distance
[meta,imeta]=sortrows(meta,[1,2]);

% Concatenate with self to account for periodicity
meta_p=meta([meta(:,1) < 0],:);
meta_p(:,1)=meta_p(:,1)+2*pi;
if isempty(meta_p)
   meta_p=meta([meta(:,1) > 0],:);
   meta_p(:,1)=meta_p(:,1)+pi/2;
end
meta_n=meta([meta(:,1) >= 0],:);
meta_n(:,1)=meta_n(:,1)-2*pi;
meta=vertcat(meta_n, meta, meta_p);

% Remove all detonated ammunition
meta=meta([meta(:,3)~=1],:);

% Prepare arrays to receive exposed angles from above and below
Angle1=zeros(size(DET));
Angle2=zeros(size(DET));

% If there are undetonated sub ammunitions and screening is relevant

if ~isempty(meta)

% Check only between -pi and pi
iz=1;

while meta(iz,1)<-pi
   iz=iz+1;
end

while meta(iz,1)<pi

   % Keep current acceptor
   cmeta=meta(iz,:);
```

```
   % Check above and below separately and keep acceptors with the same screening
   % angle as the current acceptor for further investigation
   screen_a=meta([meta(:,1)>cmeta(1)],:);
   screen_b=meta([meta(:,1)<cmeta(1)],:);
   screen_c=meta([meta(:,1)==cmeta(1)],:);

   % Only those acceptors that are closer to the donor than the current acceptor can
   % participate in the screen
   screen_a=screen_a([screen_a(:,2)<cmeta(2)],:);
   screen_b=screen_b([screen_b(:,2)<cmeta(2)],:);
   screen_c=screen_c([screen_c(:,2)<cmeta(2)],:);

   % Compute the unscreened angle
   alpha_0=asin(1./(2.*sqrt(cmeta(4).^2+cmeta(5).^2).*(1+k)));

   % Select the acceptors with angles that are closest to the current acceptor from
   % above, compute their exposed angle, to be used for computing the screening
   % angle, and generate logical index for selecting the dominant screening acceptor
   % (the one that is closest to the donor).
   alpha_a=screen_a([screen_a(:,1)==min(screen_a(:,1))],:);
   betha_a=asin(1./(2.*sqrt(alpha_a(:,4).^2+alpha_a(:,5).^2).*(1+k)));
   la=[alpha_a(:,2)==min(alpha_a(:,2))];

   % Repeat the procedure for acceptors that are closest from below
   alpha_b=screen_b([screen_b(:,1)==max(screen_b(:,1))],:);
   betha_b=asin(1./(2.*sqrt(alpha_b(:,4).^2+alpha_b(:,5).^2).*(1+k)));
   lb=[alpha_b(:,2)==min(alpha_b(:,2))];


   % Depending om the initiation point the logical indexes may be empty. This
   % depends on whether there are any acceptors above or below the donor.
   if isempty(la) & isempty(lb)
      alpha1=alpha_0;
      alpha2=alpha_0;
   elseif isempty(la) & ~isempty(lb)
      alpha1=alpha_0;
      alpha2=min(alpha_0, cmeta(1)-min(alpha_b(lb,1))-min(betha_b(lb,1)));
   elseif isempty(lb) & ~isempty(la)
      alpha1=min(alpha_0, -cmeta(1)-min(alpha_a(la,1))-min(betha_a(la,1)));
      alpha2=alpha_0;
   else

      % The angle is equal to the minimum of the unscreened and the screening angle,
      % and the screening angle is selected as the largest among the ones in the
      % same direction
      alpha1=min(alpha_0, -cmeta(1)+min(alpha_a(la,1))-min(betha_a(la,1)));
      alpha2=min(alpha_0, cmeta(1)-min(alpha_b(lb,1))-min(betha_b(lb,1)));

      % When there are acceptors closer to the donor than the current acceptor, the
      % current will be screened out
      alpha1=alpha1.*isempty(screen_c);
      alpha2=alpha2.*isempty(screen_c);
   end

   % The exposed angles are inserted into the matrixes Angle1 and 2.

   Angle1(meta(iz,4)+xip,meta(iz,5)+yip)=alpha1;
   Angle2(meta(iz,4)+xip,meta(iz,5)+yip)=alpha2;

   iz=iz+1;

   %display(sprintf('matrix  %d %d %d %d \n',iz,meta(iz,1),length(meta),pi));

end

ANGLE_EXP(:,:,1)=Angle1;
ANGLE_EXP(:,:,2)=Angle2;
```

```
else


alpha_0=asin(1./(2.*sqrt(cmeta(4).^2+cmeta(5).^2).*(1+k)));

ANGLE_EXP(:,:,1)=alpha_0;
ANGLE_EXP(:,:,2)=alpha_0;

end

%
%
SIGN_SCREEN=[sum(ANGLE_EXP,3)>0];
ANGLE_EXP(:,:,1)=ANGLE_EXP(:,:,1).*SIGN_SCREEN;
ANGLE_EXP(:,:,2)=ANGLE_EXP(:,:,2).*SIGN_SCREEN;
```

```
function [MK,VNULL] = data(DTYPE,ATYPE)

% The constants MK and VNULL depend on the properties of the grenades.
% The parameters DTYPE and ATYPE can have the values 175, 155, 105 or 81 which
% correspond to four grenade types.
% The explosive properties are valid for TNT.

global RI RY BLENG KF MNULL k2

switch DTYPE

case 175     % 175 mm artillery grenade

       DRI = 0.067056;      % donor inner radius (m)
       DRY = 0.08128;       % donor outer radius (m)
       MNULL = 46689;       % total fragment mass (grams)

       G = 2370;     % parameter for calculating VNULL (m/s), Gurney's energy
                     % constant
       B = 0.3;      % explosive constant
       EVEKT = 1630; % density

case 155     % 155 mm artillery grenade

       DRI = 0.060452;
       DRY = 0.0762;
       MNULL = 35154;

       G = 2370;
       B = 0.3;
       EVEKT = 1630;

case 105 % 105 mm artillery grenade

       DRI = 0.041148;
       DRY = 0.052070;
       MNULL = 10965;

       G = 2370;
       B = 0.3;
       EVEKT = 1630;

case 81      % 81 mm mortar grenade

       DRI = 0.031242;
       DRY = 0.03683;
       MNULL = 2092;

       G = 2370;
       B = 0.3;
       EVEKT = 1630;

end

DONORDI = DRI * 2;          % donor diameter
DONORTY = DRY - DRI;        % donor case thickness

T = DONORTY * 39.37;        % donor case thickness (in)
D = DONORDI * 39.37;        % donor diameter (in)

MK = B * T ^ (5/6) * D ^ (1/3) * (1 + T / D ); % fragment distribution parameter
(oz^1/2)
MK = MK * 5.32447; % (g^1/2)

EKSPMAS = pi * DRI ^ 2 * BLENG * EVEKT; % explosive mass (kg)
STALMAS = pi * ( DRY ^ 2 - DRI ^ 2 ) * BLENG * 7840; % case mass (kg)

% VNULL = maximum fragment velocity (polar angle = 95) (m/s), Gurney formula
```

```
VNULL = G * (( EKSPMAS/STALMAS)/(1 + ( EKSPMAS / ( 2 * STALMAS )))) ^0.5;

switch ATYPE

case 175     % 175 mm artillery grenade

      RI = 0.057404;      % acceptor inner radius (m)
      RY = 0.07493; % acceptor outer radius (m)
      BLENG = 0.6477;     % acceptor length (m)

      KF = 8600000; % initiation criterion
       k2 = 0.0874887;

case 155     % 155 mm artillery grenade

      RI = 0.051562;
      RY = 0.06985;
      BLENG = 0.43688;

      KF = 8600000;
       k2 = 0.0874887;

case 105 % 105 mm artillery grenade

      RI = 0.035814;
      RY = 0.04826;
      BLENG = 0.29972;

      KF = 8600000;
       k2 = 0.133428;

case 81      % 81 mm mortar grenade

      RI = 0.029464;
      RY = 0.03556;
      BLENG = 0.1829;

      KF = 8600000;
       k2 = 0.1998197;

end
```

```
function P = vuln(AVST, ANGLE, DTYPE, ATYPE)

%
% function P = vuln(AVST, ANGLE, DTYPE, ATYPE)
%
% Vuln calculates probability of detonation transfer between donor of type DTYPE and
% acceptor of type ATYPE
%
% AVST is the 2D matrix giving the distances from the donor to the acceptors
% ANGLE is the 3D matrix giving the exposed angles for the acceptors. The
%       angles are separated in two components due to asymetries in the
%       screening effect. The dimensionality is ANGLE(:,:,1:2) where the last
dimension
%      is used to indicate angle 1 or 2.
% DTYPE is the donor ammunition type
% ATYPE is the acceptor ammunition type
%


%
% BLENG length of ammunition
% LSONER number of length zones
% BSONER number of width zones
% RI, RY inner and outer radius
% MNULL mass of the casing
% KF explosive dependent sensitivity constant
% k2

global BLENG LSONER BSONER RI RY MNULL KF k2

%
% Data to be preserved in-between calls to fsolve to speed up the simulation

global fsolve_ix fsolve_param fsolve_Mcrit

%
% Reset the probability of hit matrix

P = zeros(size(AVST));

%
% gets geometrical and explosive data

[MK,VNULL] = data(DTYPE, ATYPE);

%
% Double loop to investigate 2D stack

for i = 1:length(AVST)
   for j = 1:size(AVST,2)

      A = AVST(i,j);

      %
      % The hight array and the polar angles for the zones

      X = BLENG / BSONER;
      IANT = BSONER / 2;
      C = [1:IANT];
      HOEYDE = X * (C - 1/2);
      FIMERK = atan( HOEYDE / ( A - RY ) );
      FIMERK = FIMERK * 180 / pi;
      FIVINK = [90-fliplr(FIMERK) 90+FIMERK];

      %
      % Setting fragment distribution parameters according to
      % equ. 3.7 and Appendix A in FFI/RAPPORT-86/4002
```

```
      switch DTYPE
      case {175, 155}
         Y = 4.08E-04 * ( FIVINK.^2 - 8796.56 );
         a = 0.708;
      case 105
         Y = 1.523 * ( sqrt(FIVINK) - 9.30 );
         a = 1.18;
      case 81
         Y = 0.0724 * ( FIVINK - 84.41 );
         a = 1.513;
      end
      NORFUNK = a / (( 2 * pi )^ 0.5 ) * exp(- (Y.^2/2));

      %
      % Velocity distribution according to equ. 3.3 and 3.4 in FFI/RAPPORT-86/4002

      L = FIVINK > 95;
      XVINK = L .* (190 - FIVINK) + ~L.*FIVINK;
      FUNK = 0.6474 - 0.02636 * XVINK + 0.0006095 * XVINK.^2 - 3.08E-06 * XVINK.^3;

      %
      % Establish velocity and mass distributions

      V0 = VNULL * FUNK;
      M0 = MNULL * NORFUNK;

      %
      % Reset accumulators for probability of initiation by one large or two small
fragments

      PEN=[];
      PTO=[];

      %
      % For all acceptors the exposed angle, as seen from the donor, has to be
utilized
      % separately to compute the probability of hit. This is due to asymetry.

      for iangle=1:2

       %
       % If the acceptor is exposed the fraction of fragments hitting
       % the acceptor zones is computed

       if ANGLE(i,j,iangle)~=0

          %
          % The resolution in the width direction is determined by the exposed angle

          DELTA = min(RY, A.*tan(ANGLE(i,j,iangle))) / LSONER;
          Y = DELTA * [1:LSONER]';
          X = sqrt(RY^ 2 - Y.^2);
          BETA = atan( Y ./ ( A - X ) ) * 180/pi;

          %
          % Angle interval array in degrees and angle in the width direction in
radians

          alfa1 = [BETA(1); BETA(2:LSONER) - BETA(1:LSONER-1)];
          vink = FIVINK * pi / 180;
          [VINK, ALFA] = meshgrid(vink, alfa1);

          F = BLENG * ALFA .* (sin(VINK).^2) ./ ( 360 * BSONER * ( A - RY ) * k2);

          %
          % Thickness of the wall a fragment must penetrate in acceptor
```

```
        Youter = Y - DELTA/2;                % height to the middle of the zones
        Xouter = sqrt(RY^ 2 - Youter.^2);           %
        alfa2 = atan( Youter ./ ( A - Xouter ));    % angle to the zones in y-
direction
        b = 2 * cos(alfa2) * A;              % calculation variable

        SS = Youter./sin(alfa2);                             % distance between donor
centre and outside acceptor wall
        %   SS = (b - sqrt(b.^2 - 4 * (A^2 - RY^2)))/2;
        SMERK = (b - sqrt(b.^2 - 4 * (A^2 - RI^2)))/2;    % distance between donor
centre and inside acceptor wall

        r = b.^2 - 4 * (A^2 - RI^2) > 0;     % condition for real thickness value
        Tykk = r .* (SMERK - SS);            % penetration length
        S = r .* (SS - RY);                  % fragment track length

        TYKK = Tykk*ones(1,BSONER);

        [V0M,SM] = meshgrid(V0,S);

        %
        % Check if the calculation has been carried out before

        lfound=logical(0);
        if ~isempty(fsolve_param)
           for ifound=1:fsolve_ix-1
              if (fsolve_param(ifound).tykk==TYKK & fsolve_param(ifound).v0m==V0M &
fsolve_param(ifound).sm==SM)
                 lfound=logical(1);
                 break;
              end
           end
        end

         %
         % If calculation has been carried out with the same parameters
previously, the previous result is used
         % otherwise the calculation is carried out with the last Mcrit as the
first approximation.

         if lfound
            Mcrit = fsolve_Mcrit(:,:,ifound);
         else
            fsolve_param(fsolve_ix).tykk=TYKK;
            fsolve_param(fsolve_ix).v0m=V0M;
            fsolve_param(fsolve_ix).sm=SM;
            Mcrit = fsolve('vd',fsolve_Mcrit(:,:,max(1,fsolve_ix-
1)),optimset('TolX',1e-4,'Display','off'),TYKK,V0M,SM);
            fsolve_Mcrit(:,:,fsolve_ix)=real(Mcrit);
            fsolve_ix=fsolve_ix+1;
         end

        Mcrit = (TYKK > 0) .* real(Mcrit);

        % Number of dangerous fragments
        M0M = ones(LSONER,1)*M0;
        N = M0M/(2*MK^2).*exp(-((Mcrit*1000).^0.5)/MK);    % number of fragments
with mass > Mcrit
        NHALV = M0M/(2*MK^2).*exp(-((Mcrit*500).^0.5)/MK);% number of fragments
with mass > Mcrit/2

        L = Mcrit > 0;
        SPLINT = L .* N .* F;   % fraction of N that hit the zones
        SPLHAL = L .* NHALV .* F;     % fraction of NHALV that hit the zones

        SPLSUM = sum(SPLINT,2);
        SHASUM = sum(SPLHAL,2);
```

```
          % Probability of detonation transfer
          KLADD = SPLHAL - SPLINT;
          PMERK = (1 + KLADD) .* exp(-KLADD);  % probability of max one hit of a
fragment with mass between Mcrit/2 and Mcrit
          PTO(iangle) = 1 - prod(prod(PMERK)); % probability of initiation by
fragment witn mass between Mcrit/2 and Mcrit

          SU = sum(SPLSUM);
          PEN(iangle) = 1 - exp(-SU);          % probability of initiation by
fragment with mass > Mcrit
       else
          PTO(iangle) = 0;
          PEN(iangle) = 0;
       end

      end

      P(i,j) = 1 - ( ( 1 - sum(PEN) ) .* ( 1 - sum(PTO)) ); % probability of
initiation

   end
end
```

```
function DELV = vd(MASSE,T,V0M,SM)

% Vdiff gives the difference between the critical velocity and the fragment impact
velocity.

global BLENG LSONER BSONER RI RY MNULL KF k2


SPHAST =
sqrt(0.008637*KF*exp(64.465*T./MASSE.^(1/3))./(MASSE.^(2/3).*(1+39.615*T./MASSE.^(1/
3))));
REHAST = V0M .* exp ( -0.00456 * SM ./ MASSE.^(1/3));

DELV = SPHAST - REHAST;
```

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