FFI RAPPORT

AMRISK version 2.0
Reference Manual

HOLM Knut B., ELFVING Carl (FORTV, Sverige), ØYOM Hans
(FLO/S/SBL/AMS)

FFI/RAPPORT-2006/01863

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

REPORT DOCUMENTATION PAGE

1) PUBL/REPORT NUMBER FFI/RAPPORT-2006/01863 1a) PROJECT REFERENCE FFI-V/328501/130	2) SECURITY CLASSIFICATION UNCLASSIFIED 2a) DECLASSIFICATION/DOWNGRADING SCHEDULE -	3) NUMBER OF PAGES 50

4) TITLE

AMRISK version 2.0
Reference Manual

5) NAMES OF AUTHOR(S) IN FULL (surname first)

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6) DISTRIBUTION STATEMENT

Approved for public release. Distribution unlimited. (Offentlig tilgjengelig)

7) INDEXING TERMS

IN ENGLISH:	IN NORWEGIAN:
a) Quantitative risk analysis	a) Kvantitativ risikoanalyse
b) Ammunition	b) Ammunisjon
c) Storage	c) Lager
d) Reference Manual	d) Referansemanual
e)	e)

THESAURUS REFERENCE:

8) ABSTRACT

AMRISK is a tool for Explosives Safety Quantitative Risk Analysis in Norway and Sweden. It calculates risk for persons in the vicinity of ammunition storages. The calculations include probability of an accidental explosion, physical effects from the explosion, lethality caused by the effects, expected number of persons exposed to the effects and resulting risk values. The Reference Manual describes the calculation procedures.

9) DATE	AUTHORIZED BY This page only	POSITION
2006-06-26	Bjarne Haugstad	Director of Research

ISBN 82-464-1025-3

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE
(when data entered)

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Reference Manual

1 INTRODUCTION

1.1 The AMRISK code

AMRISK is a software tool for quantitative risk analysis of ammunition storages. The analysis covers the event sequence from an accidental explosion to fatal injury to exposed persons. Results from each stage of the calculations are available, including isorisk contours. AMRISK is used for storage approvals in Sweden and Norway.

AMRISK is the result of a joint Norwegian-Swedish development work on the basis of AMMORISK, a program adopted as a risk analysis tool in Norway in 1985. The development includes code conversion from DOS to Windows, functions for data exchange with GIS applications and improved physical models. Still, most of the models in AMRISK 2.0 are identical to the AMMORISK models documented in (1). During the period AMMORISK was in operation, an extra model for blast from underground installations was implemented. Some adjustments and improvements of existing models were also made. In AMRISK 2.0 the models for air blast from freestanding and earth-covered magazines are new. AMRISK version 2.0 was released in 2005.

AMMORISK was based on a Swiss code, and its models are for the most part in accordance with Swiss Standards as defined in (2) and (3). Description of the models and their basis can be found in (2), (4) and (5). The Swiss models are applicable within the range of charges, magazine volumes and loading densities listed in appendix A.

This manual shows the mathematical models employed by AMRISK for estimating risk values. The structure of the code is described in the Programmer's Manual. The User's Guide (6) gives a description of the input parameters and explains how to use the program. The User's Guide and the Programmer's Manual are included in the code as help files.

1.2 Risk analysis

Risk is a measure of the danger an undesired event represents to people, environment and economy. For ammunition storages the undesired event is an explosion in the storage, called a potential explosion site. Quantitatively risk is defined as the product of the likelihood and the consequence of the possibly dangerous event. Consequence or risk can be measured in several ways. For explosion effects the number of fatalities is normally used, this also applies to AMRISK.

The likelihood of the event is measured as the probability of an explosion in a year. This is estimated by the event analysis.

The consequence analysis is carried out in several steps. In the effects analysis the different physical effects that may cause damage to people are determined. These may be blast, debris and ground shock. The effects depend on the storage type and content. Then for each of the effects, the probability of lethal damage is estimated by the related lethality criteria, taking into account if the affected persons are in the open, in a building or in another type of exposed object. By the exposure analysis the expected number of people at exposed objects at different times is established. Multiplying these numbers with the lethality gives the expected number of fatalities.

The risk can be measured for an individual or for a group of individuals. For the collective risk it is possible to take aversion into account. Aversion implies that one event affecting many people is perceived stronger in the public than many events affecting few.

Figure 1.1 gives an outline of the components of the risk calculation in AMRISK.

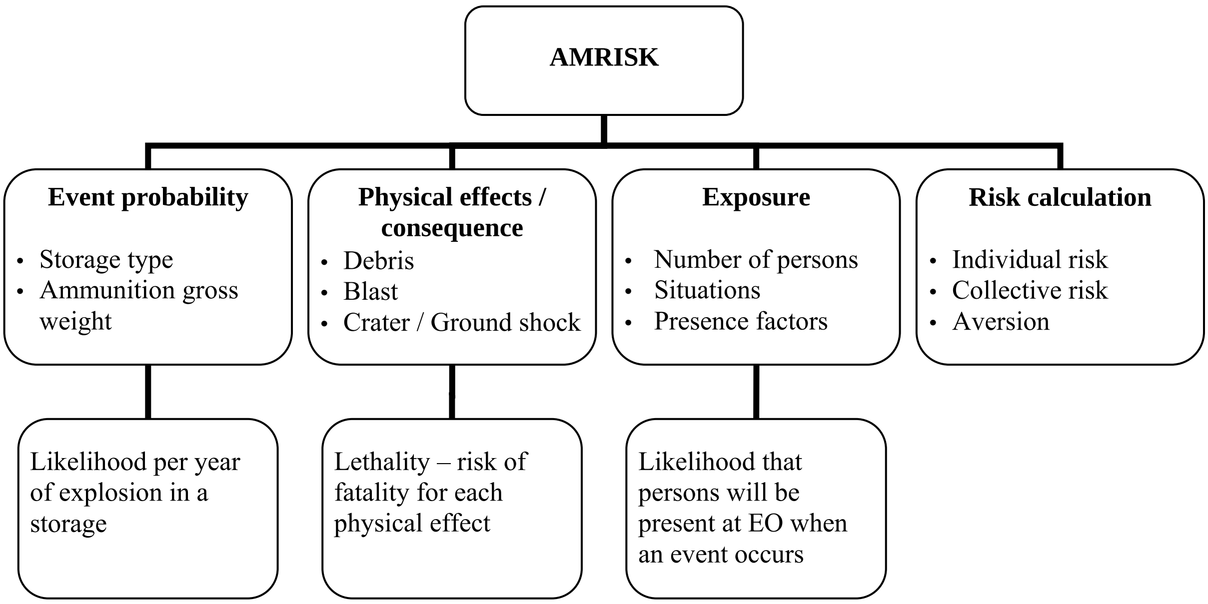
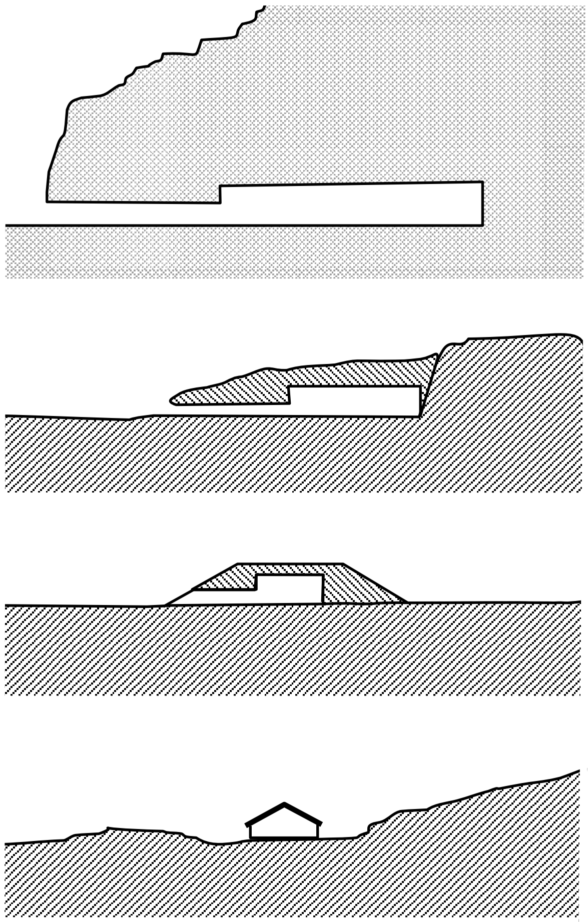


Figure 1.1 General description of the structure of AMRISK

1.3 Potential explosion sites

Ammunition storages or potential explosion sites (PES) are classified as freestanding (FS), earth-covered (EC), earth-buried (EB) or underground (UG) installations, see Figure 1.2.



Underground installation

Earth-buried installation

Earth-covered installation

Freestanding installation

Figure 1.2 Construction types of ammunition installations (4)

The freestanding, earth-covered and earth-buried magazines are called aboveground magazines, and they are made of brick or concrete. The cover on the earth-covered magazine is between 0.5 and 1 m thick, and on the earth-buried between 1 and 2 m.

The underground installations are of three types: UG1, UG2 and UG3. All these models describe a chamber containing ammunition, and the incident tunnels. The difference between UG1 and UG3 is that UG3 assumes there is a block device that closes the chamber exit after an explosion. UG2 assumes blast traps at the chamber and the tunnel exit. The model is valid for loading densities less than 50 kg/m^3 while UG1 and UG3 are best suited for high loading densities.

The effects from different magazines are treated independently, also when they are in the same installation.

1.4 Exposed objects

People exposed to explosion effects are connected to objects of a specified type and shape. The lethality caused by an effect at a specific point depends on the object type, whereas the location of the persons at an object is given by the geometric shape.

The types of exposed objects are free-field (FF), light building (BL), normal building (BN) and strong building (BS), car (CR) and train (TR). Free-field is outdoors. Light buildings are buildings of light materials as thin steel plates or with windows covering large parts, normal buildings are houses of brick, light concrete or wood and strong buildings are buildings of reinforced concrete.

A special case of free-field objects and buildings is defined when they are surrounded by forest. A forest is supposed to have at least 1 tree of minimum 10 m height per 25 m^2 area. Similarly cars and trains can be at unfavourable conditions as when the road or railway goes on a bridge, in steep terrain or in a forest. The symbol NF (no forest) is used for normal conditions and FO for forest and unfavourable conditions.

The alternative object shapes are point fixed (PF), limited area (AL), unlimited area (AU), linear free-field (LF), linear road (LR) and linear train (LT). Accordingly, the people at an object are at one point or distributed over a line or an area. Except for linear train the line and area shapes assume a uniform distribution. For road and train the distribution depends on the velocity and frequency of the means of transport.

2 EVENT ANALYSIS

The probability of an explosion in a storage during a year, P_{E}, is calculated as

$$P_{\mathrm{E}} = P_0 + k_P W \qquad (2.1)$$

where W is the gross weight in metric tons of the ammunition in the magazine, and P_0 and k_P are constants depending on storage type and type of ammunition, see Table 2.1.

Table 2.1 Parameters for calculating event probability

Storage type		P_0	k_P / tons^{-1}
Freestanding	Concrete elements	$1.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-7}$
	Brick	$5 \cdot 10^{-5}$	$1.5 \cdot 10^{-7}$
	Concrete	$1.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-7}$
Earth-covered		$1.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-7}$
Earth-buried	Mix A	10^{-6}	$1.5 \cdot 10^{-7}$
	Mix B	10^{-6}	$1.5 \cdot 10^{-8}$
Underground	Mix A	10^{-6}	$1.5 \cdot 10^{-7}$
	Mix B	10^{-6}	$1.5 \cdot 10^{-8}$

Mix A is ammunition of all hazard groups, and Mix B is ammunition without mass-reacting items. Figure 2.1 shows the resulting probabilities.

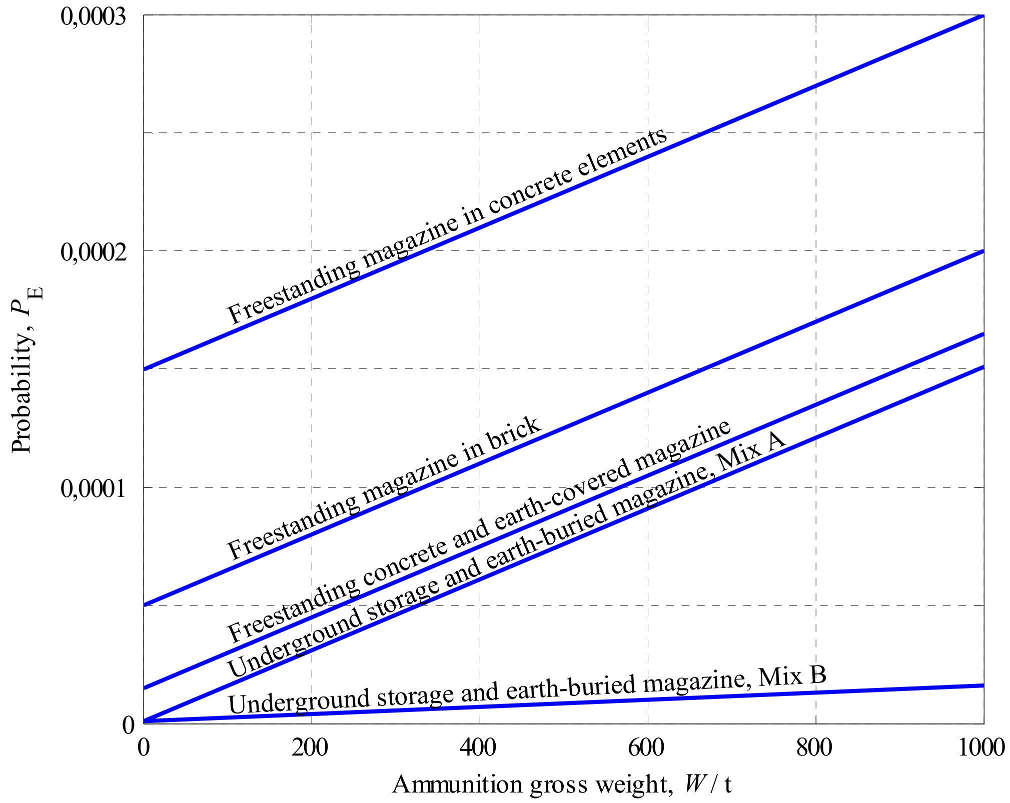


Figure 2.1 *Probability per year of explosion in different storage types as a function of the amount of explosives*

If the gross weight of ammunition is not entered, it is calculated by the formula

$$W = \frac{Q}{0.17} \tag{2.2}$$

where Q is the charge weight.

The event probability may also be entered directly in the program.

3 PHYSICAL EFFECTS

The physical effects created by an explosion in a potential explosion site depend on the type and construction of the explosion site and the amount of explosives stored.

3.1 Aboveground installations

From aboveground installations the considered physical effects are debris throw, air blast and cratering.

3.1.1 Fragment and debris throw

The debris throw from aboveground magazines gives a debris density, which causes lethality according to section 4.3.1.

3.1.1.1 Freestanding installations

The debris from a freestanding ammunition magazine includes crater material, building debris and ammunition components. The total mass is then

$$m_{\mathrm{T}} = m_{\mathrm{B}} + m_{\mathrm{E}} + m_{\mathrm{A}} \tag{3.1}$$

where the indices refer to building, earth and ammunition.

m_{B} is an input parameter. The mass of the earth is estimated to

$$m_{\mathrm{E}} = 100Q \tag{3.2}$$

where Q is the charge weight corresponding to metric tons of TNT. The ammunition debris is

$$m_{\mathrm{A}} = W - Q \tag{3.3}$$

where W is the gross weight of the ammunition.

The debris density is assumed to be exponentially distributed along the distance from the middle of the installation, r:

$$\delta = 0.36\, m_{\mathrm{T}} Q^{-0.58} e^{-0.047 r Q^{-0.29}} \tag{3.4}$$

where δ is debris density (kg/m^2).

3.1.1.2 Earth-covered installations

The debris from an earth-covered installation consists of the same components as from a freestanding magazine. Furthermore, the relation (3.3) applies. The amount of earth thrown out is:

$$m_{\mathrm{E}} = 100Q^{1.1} \tag{3.5}$$

The debris density distribution is

$$\delta = 0.036\, m_{\mathrm{T}} e^{-0.015r} \tag{3.6}$$

3.1.1.3 Earth-buried installations

The debris density from earth-buried installations is estimated as

$$\delta = 8.05 \frac{Q^{1.26}}{V^{0.5}} e^{-r/65} \left(4h + 3\right) \tag{3.7}$$

where h is the depth from the surface down to the middle of the magazine (m) and V is the volume of the magazine (m^3).

3.1.2 Air blast

The lethality from air blast depends on the maximum pressure or the dynamic impulse of the blast wave as described in 4.2. For freestanding and earth-covered magazines the present air blast models were first implemented in AMRISK 2.0 (7). They are based on models described in (8). The air blast model for earth-buried installations was modified for AMRISK 1.2.

3.1.2.1 Freestanding installations

The pressure and the positive phase duration outside a freestanding installation are given by the expression

$$y = k_{\mathrm{u}} \exp\left(A + B \ln r_Q + C\left(\ln r_Q\right)^2 + D\left(\ln r_Q\right)^3 + E\left(\ln r_Q\right)^4 + F\left(\ln r_Q\right)^5\right) \tag{3.8}$$

where

$$r_Q = \frac{r}{10 Q^{1/3}} \tag{3.9}$$

Thus, the scaled distance r_{Q} is denominated $\mathrm{m/kg}^{1/3}$. k_{u} is 0.01 for pressure in bars and 10 for scaled duration in $\mathrm{ms/t}^{1/3}$. The other constants for the pressure are listed below.

Table 3.1 Parameters for determining maximum pressure, p/bar, outside a freestanding magazine

Scaled range, r_Q / $\mathrm{m/kg}^{1/3}$	*A*	*B*	*C*	*D*	*E*	*F*
0.2 – 2.9	7.2106	-2.1069	-0.32290	0.1117	0.06850	0
2.9 – 23.8	7.5938	-3.0523	0.40977	0.0261	-0.01267	0
> 23.8	6.0536	-1.4066	0	0	0	0

Figure 3.1 shows resulting pressure values.

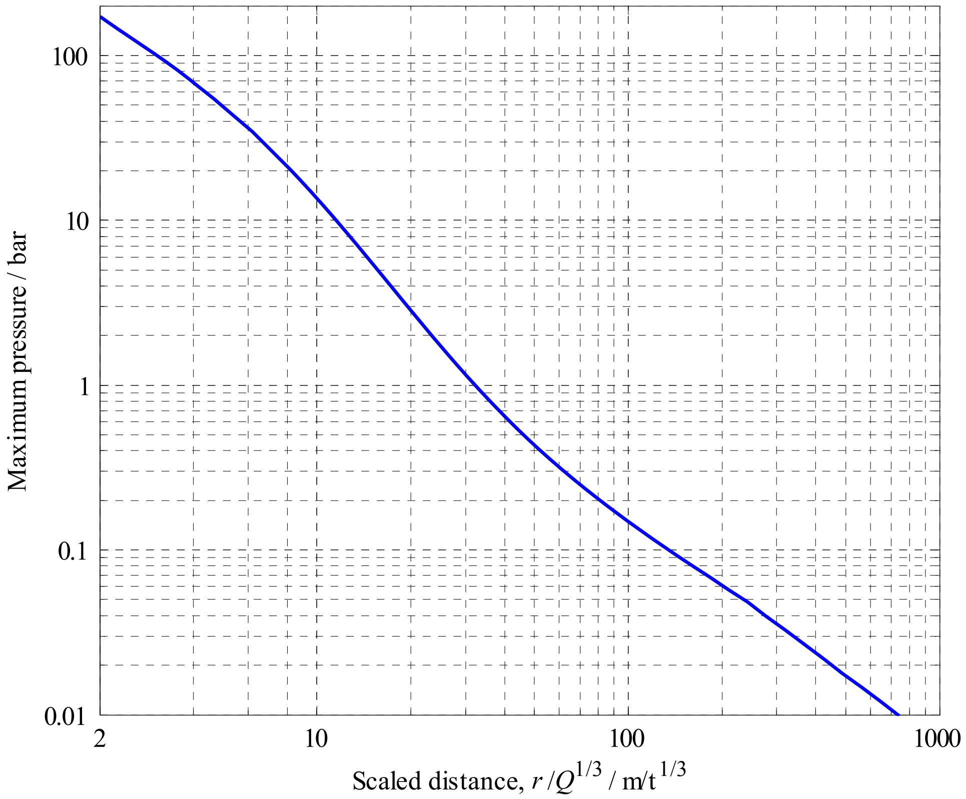


Figure 3.1 Maximum pressure outside a freestanding magazine

The duration is calculated by (3.8) using the parameters specified in Table 3.2.

Table 3.2 Parameters for determining scaled duration, $t_+/Q^{1/3}/\left(ms/t^{1/3}\right)$, outside a free-standing magazine

Scaled range, $\frac{r_Q}{\mathrm{m/kg}^{1/3}}$	*A*	*B*	*C*	*D*	*E*	*F*
0.2 – 1.02	0.5426	3.2299	-1.5931	-5.9667	-4.0815	-0.9149
1.02 – 2.8	0.5440	2.7082	-9.7354	14.3425	-9.7791	2.8535
2.8 – 40	-2.4608	7.1639	-5.6215	2.2711	-0.44994	0.03486
> 40	0.9771	0.2679	0	0	0	0

To find the dynamic impulse $p^{5/3}t_{\mathrm{ip}}$, the effective duration t_{ip} is calculated from the duration by

$$t_{\mathrm{ip}} = \frac{2}{3}t_+ \qquad (3.10)$$

The air blast model for freestanding magazines is valid for scaled distances between 0.2 and 200 m/kg$^{1/3}$. At smaller distances r_Q is set to 0.2 m/kg$^{1/3}$, which gives unreliable values of pressure or dynamic impulse, but the correct lethality of 1. At distances larger than 200 m/kg$^{1/3}$ (2000 m/t$^{1/3}$) neither the pressure and impulse nor the lethality from these effects can be considered correct, but then the lethality is insignificant.

3.1.2.2 Earth-covered installations

Similar to freestanding magazines the calculation of air blast outside earth-covered magazines is based on equation (3.8). The model is reliable for scaled distances between 0.7 and 200 m/kg$^{1/3}$. Outside this range the validity of the results is as explained for freestanding installations.

The pressure in three directions is found by using the parameters in Table 3.3.

Table 3.3 Parameters for determining the maximum pressure, p_{front}, p_{side} and p_{rear} (bar), outside an earth-covered magazine

	A	*B*	*C*	*D*	*E*	*F*
Front	7.6032	-2.28717	-0.34671	0.27438	-0.05391	0.00342
Side	5.65556	-1.164	0.031	-0.0849	0.021	-0.00148
Rear	5.55581	-1.47687	0.14494	-0.08519	0.01745	-0.00118

Front, side and rear correspond to values of the angle from entrance axis, *α,* of 0°, 90° and 180°, see Figure 3.2. At an arbitrary angle the pressure becomes

$$
\begin{aligned}
p &= p_{\mathrm{f/r}} \sqrt{\frac{p_{\mathrm{side}}^{\;2}\left(1+\tan^2\alpha\right)}{p_{\mathrm{side}}^{\;2} + p_{\mathrm{f/r}}^{\;2}\tan^2\alpha}} \\
p_{\mathrm{f/r}} &= \begin{cases} p_{\mathrm{front}} & 270° \le \alpha \le 90° \\ p_{\mathrm{rear}} & 90° < \alpha < 270° \end{cases}
\end{aligned}
\tag{3.11}
$$

Figure 3.2 shows an example of a resulting isobar.

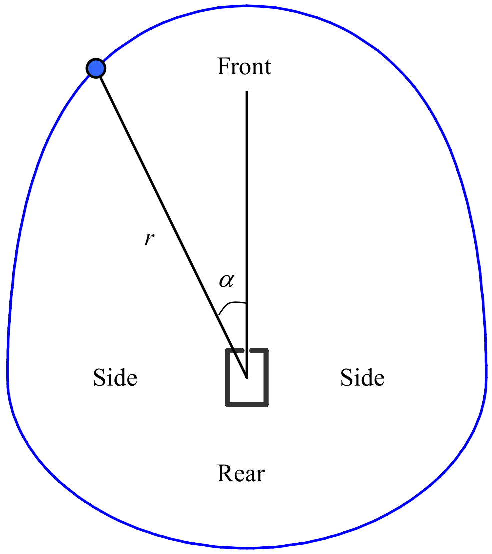


Figure 3.2 Isobar around an earth-covered magazine

The duration is estimated similarly as the pressure with an identical angle distribution, ref. equation (3.11). The parameters for estimating the duration of the blast wave according to equation (3.8) are listed in Table 3.4 below.

Table 3.4 Parameters for determining scaled duration, $t_+/Q^{1/3}/\left(ms/t^{1/3}\right)$, outside an earth-covered magazine

	Scaled range, r_Q / $\mathrm{m/kg^{1/3}}$	*A*	*B*	*C*	*D*	*E*	*F*
Front	0.7 – 2.8	0.386364	0.853478	-0.69357	-2.16149	4.55691	-2.00316
	2.8 – 40	-1.93321	6.16328	-4.9	1.97343	-0.38493	0.029083
	40 – 200	0.460803	0.525296	-0.04567	0	0	0
Side	0.7 – 2.6	0.161349	0.436003	-0.195093	0.657763	0.84928	-1.00476
	2.6 – 40	-0.945587	3.66105	-2.69461	1.09865	-0.225794	0.0183546
	40 – 200	1.00205	0.207429	-0.00055519	0	0	0
Rear	0.7 – 2	0.116706	0.160406	0.600365	1.03725	-0.51708	-0.57615
	2 – 40	-0.37572	2.33924	-1.75688	0.783067	-0.17273	0.014652
	40 – 200	0.334124	0.580877	-0.05944	0	0	0

The dynamic impulse, $p^{5/3}t_{ip}$, is calculated as for freestanding installations.

3.1.2.3 Earth-buried installations

The pressure outside earth-buried magazines is determined by assuming that the isobars are ellipses with a focus at the magazine centre and the major axis coincident with the magazine axis, see Figure 3.3.

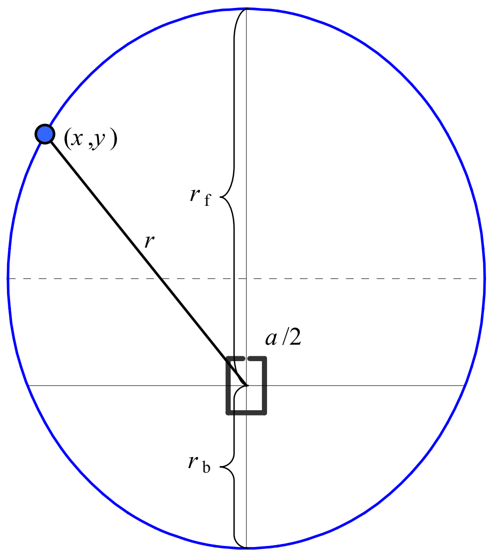


Figure 3.3 Isobar around an earth-buried magazine

When r_f, r_b and $a/2$ are the distances from the focus to the top, bottom and centre of the ellipse, then

$$r_f = r_b + a \tag{3.12}$$

and the ellipse may be described by the relation

$$r_f = \frac{r + a + \sqrt{y^2 + (x-a)^2}}{2} \tag{3.13}$$

with the x-axis pointing upwards.

The pressure in the front of an earth-buried installation is estimated as

$$p_f = e^{13.22 - 4.39\ln\left(\frac{r}{Q^{1/3}}\right) + 2.741\sqrt{\left(\ln\left(\frac{r}{Q^{1/3}}\right) - 3.251\right)^2 + 0.1218}} \tag{3.14}$$

In the opposite direction the pressure is

$$p_b = \frac{13.32}{\left(\frac{h}{Q^{1/3}}\right)^{1.667}\left(\frac{r}{Q^{1/3}}\right)^{1.19}} \tag{3.15}$$

with h as the thickness of the earth cover.

The shape of the isobar crossing (x,y) is found by solving the equation $p_f(r_f) = p_b(r_f\text{-a})$ numerically with respect to a, using (3.13). Then the pressure value of the isobar is given as $p_f(r_f)$ or $p_b(r_f\text{-a})$.

Especially when the cover is thin, the value calculated for $p_b(r)$ may exceed $p_f(r)$ at larger distances. In that case a non-directional pressure function is used,

$$p\left(r \mid p_{\mathrm{b}}(r) > p_{\mathrm{f}}(r)\right) = e^{5.5502-2.0975\ln\left(\frac{r}{Q^{1/3}}\right)+1.4819\sqrt{\left(\ln\left(\frac{r}{Q^{1/3}}\right)-3.6555\right)^2+1.3573}} \tag{3.16}$$

which is the function applied by AMRISK 1.2 for the pressure outside freestanding installations.

The dynamic impulse outside an earth-buried installation is found by defining isocontours similarly as for the pressure. The scaled dynamic impulse at the front and the back of the installation are

$$\left(\frac{p^{5/3}t_{\mathrm{ip}}}{Q^{1/3}}\right)_{\mathrm{f}} = \frac{1.21\cdot 10^{-6}}{\left(\frac{r}{Q^{1/3}}\right)^{3.25}} \tag{3.17}$$

$$\left(\frac{p^{5/3}t_{\mathrm{ip}}}{Q^{1/3}}\right)_{\mathrm{b}} = \frac{1081}{\left(\frac{h}{Q^{1/3}}\frac{r}{Q^{1/3}}\right)^{1.786}} \tag{3.18}$$

If these expressions give larger impulse at the back than at the front, the dynamic impulse is set to the impulse from freestanding magazines (AMRISK 1.2):

$$\frac{p^{5/3}t_{\mathrm{ip}}}{Q^{1/3}} = e^{4.824-0.07626\frac{r}{Q^{1/3}}+0.04984\sqrt{\left(\frac{r}{Q^{1/3}}-35.88\right)^2+167.8}} \tag{3.19}$$

3.1.3 Cratering

The apparent crater at an aboveground installation is assumed to reach 15 m out from each magazine wall, see Figure 3.4.

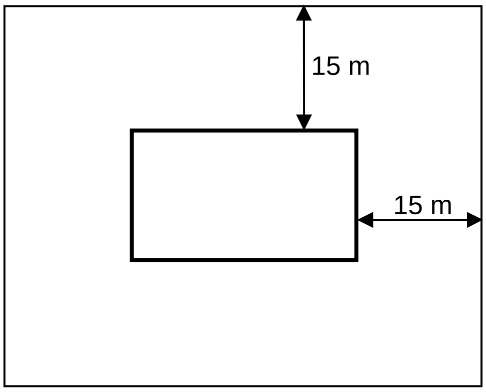


Figure 3.4 Crater zone around an aboveground magazine

In the crater the lethality is 100 %. Compared to the other effects, this will only be significant for small charges.

3.2 Underground installations

The dangerous effects following an explosion in an underground installation are a possible crater in the cover above the chamber and the debris and air blast propagating from the crater. There will also be debris and air blast from the tunnels connected to the installation. Besides, an explosion generates ground shock.

3.2.1 Crater

An explosion in an underground magazine may cause a crater in the cover above the chamber. The maximal charge weight that does not result in a crater is

$$Q_0 = \frac{1}{1000} \max\left(\left(\frac{h}{1.2}\right)^{10/3}, V\left(\left(\frac{2h}{b}+1\right)^2 - 1\right)\right) \tag{3.20}$$

Here h is cover thickness (m), V is chamber volume (m^3), and b is chamber width (m).

The corresponding minimum cover thickness, h_0, is

$$h_0 = \max\left(\min\left(1.2(1000Q)^{3/10}, \frac{b}{2}\left(\sqrt{\frac{1000Q}{V}+1} - 1\right)\right), 1.5b\right) \tag{3.21}$$

If $Q > Q_0$ or equivalently $h < h_0$ there will be a crater. The outer radius of the apparent crater is calculated as

$$r_c = 1.35\sqrt{h_0^2 + 1.42h(h_0 - 1.7h)} \tag{3.22}$$

3.2.1.1 Debris

The lethality of debris from this crater type (chapter 4.3.2.1) implicitly depends on the debris density through a scaled distance defined as

$$\bar{r}_{\mathrm{dc}} = \frac{r}{k_h\, Q^{0.55}\, V^{-0.14}} \tag{3.23}$$

where r is the distance from the crater centre. The parameter k_{h} depends on the scaled cover thickness, $h/Q^{1/3}$, and is approximated by

$$k_{\mathrm{h}} = \begin{cases} 5 & \dfrac{h}{Q^{1/3}} \le 5 \\ 10 - \dfrac{h}{Q^{1/3}} & 5 < \dfrac{h}{Q^{1/3}} \le 10 \\ 0 & \dfrac{h}{Q^{1/3}} > 10 \end{cases} \tag{3.24}$$

The debris flies longer downhill and shorter uphill. The scaled distance changes correspondingly. Therefore the distance downhill is multiplied by a factor g, and the distance uphill is divided by g.

$$g = \frac{4 + |\tan\beta| + \sqrt{\left(4 + |\tan\beta|\right)^2 - 12}}{6} \tag{3.25}$$

where β is the slope angle of the cover.

Only the distance parallel to the slope direction should be increased or decreased. Thus the effective distance is

$$r_{\mathrm{e}} = \begin{cases} r\sqrt{\left(g\cos\alpha\right)^2 + \left(\sin\alpha\right)^2} & , \quad 0° \le \alpha \le 90° \\ r\sqrt{\left(\dfrac{1}{g}\cos\alpha\right)^2 + \left(\sin\alpha\right)^2} & , \quad 90° \le \alpha \le 180° \end{cases} \tag{3.26}$$

where α is the angle between the line from the crater centre to the point considered and the crater direction (uphill), and r is the real distance.

3.2.1.2 Air blast

The air blast from the crater has the following maximum pressure and impulse:

$$p = \left(24 \frac{\left(1 - \dfrac{h}{0.7h_0}\right)^{4/3}}{\dfrac{r}{Q^{1/3}}} \right)^{4/3} \tag{3.27}$$

$$p^{5/3} t_{\mathrm{ip}} = \left(1 - \frac{h}{0.7h_0}\right)^2 \left(190 \frac{Q^{1/2}}{r}\right)^{3/2} \tag{3.28}$$

The resulting lethality is found as described in chapter 4.2.

3.2.2 Tunnel

In AMRISK three types of underground magazines are available: UG1, UG2 and UG3. As there is a block in the chamber in the UG3 magazine, the models for debris from the tunnel and air blast outside the chamber are different. The models for air blast propagation in the tunnel system and outside the tunnel are the same. The UG2 model assumes blast traps at the chamber and tunnel exits and loading density less than 50 kg/m^3. Consequently, the UG2 models for air blast outside the chamber and outside the tunnel differ from the UG1 models. UG1 and UG3 are original AMMORISK models, while UG2 was included later (9).

3.2.2.1 Debris

Equivalent to debris from the crater above the chamber the lethality from debris thrown out of the tunnel depends on a scaled distance (chapter 4.3.2.2). For UG1 it is given as

$$\bar{r}_{\mathrm{dt}} = \frac{1.26r}{a\left(Q^2/V\right)^{1/9}} \tag{3.29}$$

where V is the chamber volume, and the parameter a depends on the geometry of the tunnel:

$$a = \begin{cases} 1 & d_{\mathrm{T}} \le 5 \text{ m and } \dfrac{L_{\mathrm{T}}}{d_{\mathrm{T}}} \ge 2 \text{ (small angle)} \\[2ex] 0.85 & d_{\mathrm{T}} > 5 \text{ m or } \dfrac{L_{\mathrm{T}}}{d_{\mathrm{T}}} < 2 \text{ (large angle)} \end{cases} \tag{3.30}$$

d_{T} is the tunnel diameter at the adit, and L_{T} is the length of the tunnel section having diameter d_{T}.

For UG3 the scaled distance is

$$\bar{r}_{\mathrm{dt}} = \frac{r}{a\left(p_{\mathrm{s}}^{5/3} t_{\mathrm{ip,a}}\right)^{1/5}} \tag{3.31}$$

$p_e^{5/3}\, t_{ip,a}$ is the dynamic impulse at the tunnel adit, see section 3.2.2.2.

3.2.2.2 Air blast

The calculation of air blast is separated in three parts. First, the blast just behind the chamber exit is determined. Then the propagation of the blast wave through the tunnel is calculated and finally the pressure outside the tunnel is found.

<u>Pressure outside the chamber</u>
If there is no stone block device in the chamber (UG1), the maximum pressure just outside the chamber is

$$p_c = 400\left(\frac{Q}{V}\right)^{2/3}\left(\frac{L_c}{d_0}\right)^{1/3} \tag{3.32}$$

where L_c is the length of the chamber, and d_0 is the tunnel diameter, see Figure 3.5.

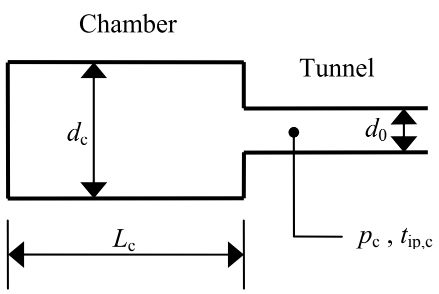


Figure 3.5 Chamber without a block device

The effective duration becomes

$$t_{ip,c} = 20 L_c^{2/3} d_0^{1/3}\left(\frac{d_c}{d_0}\right)^2 \tag{3.33}$$

with d_c as the equivalent chamber diameter which is calculated from the cross section area assuming a circular shape.

For UG2 the pressure outside the chamber is (9)

$$p_c = 479.5\left(\frac{Q}{V}\right)^{0.6}\left(\frac{d_c}{L_c}\right)^{0.44}\left(\frac{d_c}{d_0}\right)^{1.2} \tag{3.34}$$

The duration is estimated by (3.33).

When there is a block closure device in the chamber, see Figure 3.6, the UG3 model is applied.

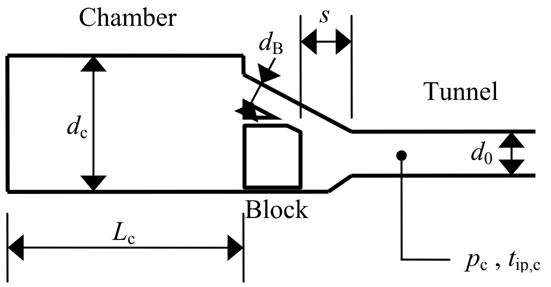


Figure 3.6 Chamber with a block device

The formulas for the air blast properties are then

$$p_c = 240\left(\frac{Q}{V}\right)^{2/3}\left(\frac{L_c}{d_B}\right)^{1/3}\left(\frac{d_B}{d_0}\right) \tag{3.35}$$

$$t_{ip,c} = 1.7\left(\frac{V}{Q}\right)^{0.6}\sqrt{s \cdot l'} \tag{3.36}$$

Here d_B is the equivalent diameter at the side of the block, s is the distance the block has to move to close the exit, and l' is the ratio of the volume and the backside area of the block.

<u>Air blast in tunnel</u>
The geometry of the tunnel system outside the chamber is modelled by tunnel elements of various shapes. The elements affect the pressure wave in different ways.

In an ordinary straight tunnel element (TE) the blast pressure is reduced because of friction in the tunnel walls. The reduction depends on the propagated distance and the wall roughness put together in a distance coefficient, χ, which is

$$\chi = k_\varepsilon\left(L_T - 5d\right) \tag{3.37}$$

L_T is the length of the tunnel element, and d is the equivalent tunnel diameter. The factor k_ε is

$$k_\varepsilon = \varepsilon\left(\frac{2.8}{d}\right)^{4/3} \tag{3.38}$$

where ε describes the wall roughness, see Table 3.5.

Table 3.5 Values for wall roughness

Wall type	Roughness coefficient, ε
Concrete	1
Shotcrete	4
Rock	6

The wall roughness is significant from five tunnel diameters into the element.

In addition to the distance coefficient the pressure reduction depends on a corresponding duration coefficient,

$$\tau = k_\varepsilon t_1 \tag{3.39}$$

where t_1 is the duration at the beginning of the tunnel element.

The pressure reduction in a straight tunnel element is given as the ratio of the pressures at the end and at the beginning of the element, p_2 / p_1.

$$\frac{p_2}{p_1} = \begin{cases} 1 & C < 1 \\ 1.7929 - 1.9977C + 1.8570C^2 - 0.7498C^3 + 0.097987C^4 & 1 \le C \le 3.254 \\ \dfrac{0.3254}{C} & C > 3.254 \end{cases} \tag{3.40}$$

where

$$\begin{aligned} C &= \frac{(\log \chi) + 6.35B}{1+B} \\ B &= 0.01818A^2 + 0.16387A - 0.08809 \\ A &= \log\left(\frac{1000}{\tau} + 1\right) \end{aligned} \tag{3.41}$$

Figure 3.7 shows the pressure reduction as a function of χ and τ.

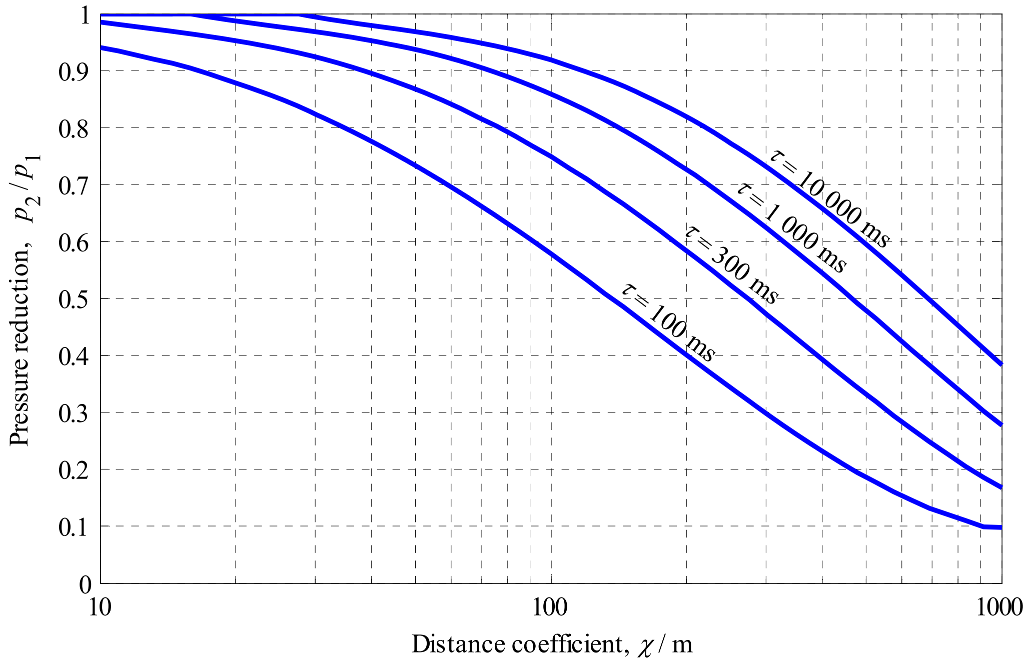


Figure 3.7 Pressure decrease caused by wall roughness

For the duration the increase is estimated to

$$\frac{t_2}{t_1} = \begin{cases} \dfrac{p_1}{p_2} & \tau < 1000 \text{ ms} \\ 1 + 10^{-4}\left(\chi(E+8) + \chi^2 \dfrac{E}{1000}\right) & \tau \geq 1000 \text{ ms} \end{cases} \tag{3.42}$$

Here,

$$E = -3.1192 + 1.1953D + 2.6238D^2 - 0.6415D^3$$
$$D = \sqrt{\frac{p_1}{40}} \tag{3.43}$$

where p_1 is the initial pressure in bars.

When $\tau \geq 1000$ ms, the duration increase becomes as Figure 3.8 shows.

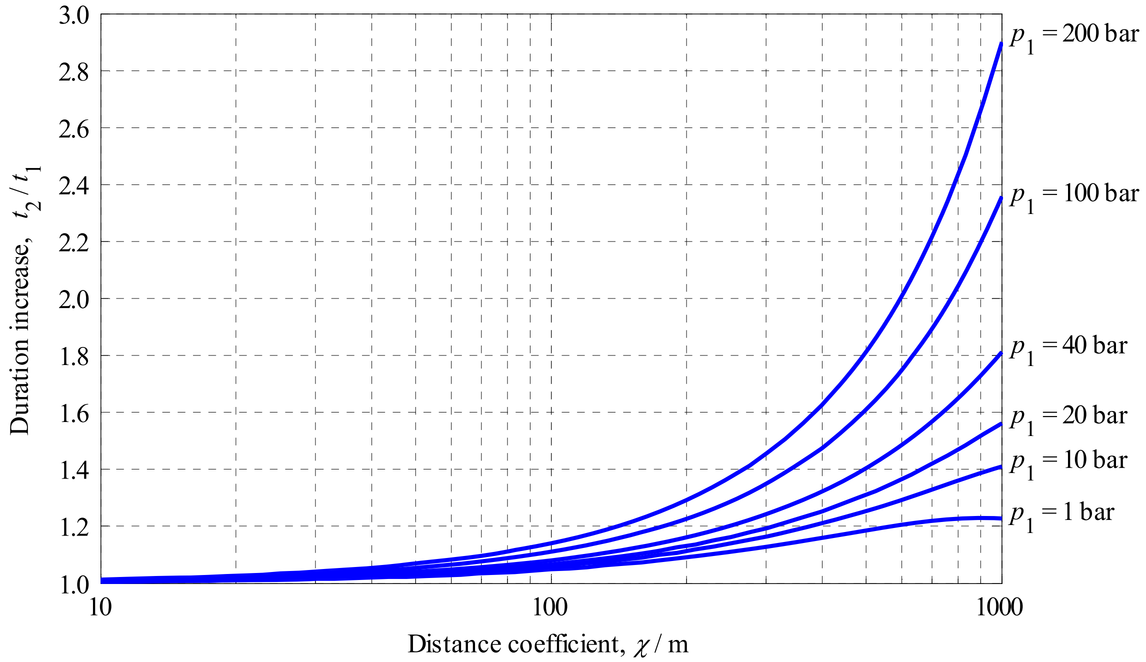


Figure 3.8 Increase in blast wave duration caused by wall roughness, τ ≥ 1000 ms

After passing an orifice or an expansion chamber (OR) the pressure is reduced according to

$$\frac{p_2}{p_1} = 0.001\left(-6.69 + 1038.20\,G_o + 496.26\,G_o^{\,2} - 529.37\,G_o^{\,3}\right) \tag{3.44}$$

$$G_o = \sqrt{\min\left(\frac{F_1}{F_2}, \frac{F_2}{F_1}\right)} \tag{3.45}$$

where F_1 is the cross-sectional area in front of and behind the element, and F_2 is the cross section of the element, see Figure 3.9.

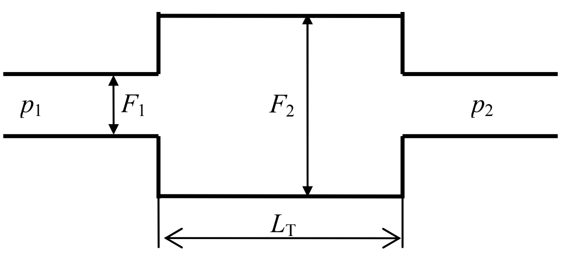


Figure 3.9 Expansion chamber

Hence G_o is always less than or equal to 1. The blast wave duration is unchanged.

In the case of a relatively short expansion chamber the effective cross-sectional area is reduced according to the condition

$$F_2 = \min(F_2, \pi L_T^{\ 2}) \tag{3.46}$$

If there is just an expansion (EP) the pressure reduction is

$$\frac{p_2}{p_1} = 0.001\left(-4.43 + 641.78\,G_e + 2625.67\,G_e^{\ 2} - 4127.46\,G_e^{\ 3} + 1866.65\,G_e^{\ 4}\right) \tag{3.47}$$

when the expansion is continuous and

$$\frac{p_2}{p_1} = 0.001\left(-1.23 - 52.61\,G_e + 4149.94\,G_e^{\ 2} - 5285.35\,G_e^{\ 3} + 2186\,G_e^{\ 4}\right) \tag{3.48}$$

when the expansion is sudden. Here,

$$G_e = \sqrt{\frac{F_1}{F_2}} \tag{3.49}$$

is used with F_2 as the cross sectional area after the expansion and F_1 as the area before, see Figure 3.10.

The duration is also reduced,

$$\frac{t_2}{t_1} = G_e \tag{3.50}$$

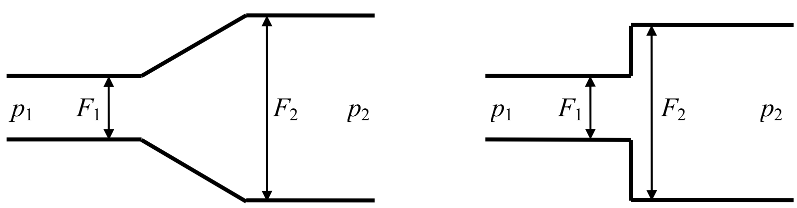


Figure 3.10 Continuous and sudden expansion

Figure 3.11 shows the pressure reduction after an orifice or an expansion chamber and after a continuous and sudden expansion.

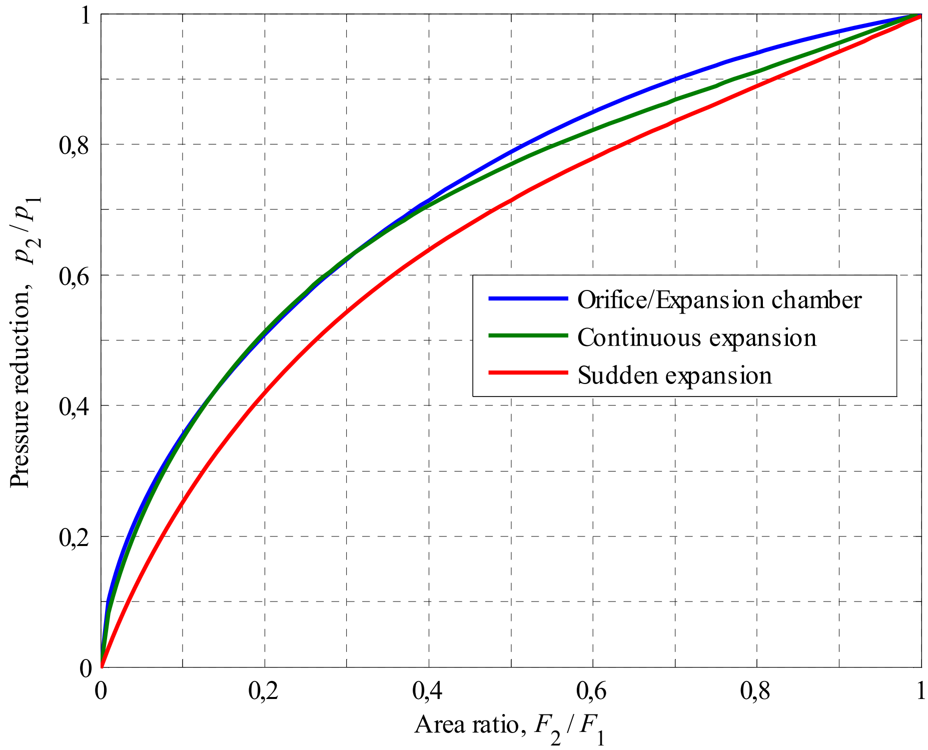


Figure 3.11 Pressure decrease caused by orifices, expansion chambers or expansions

The relations for constrictions (CS) are correspondingly:

$$\frac{p_2}{p_1} = 0.001\left(3425.46 - 4059.30\,G_c + 3565.65\,G_c^{\,2} - 2049.44 G_c^{\,3}\right) \tag{3.51}$$

with

$$G_c = \sqrt{\frac{F_2}{F_1} - 0.08} \tag{3.52}$$

for a continuous change and

$$\frac{p_2}{p_1} = \begin{cases} 1.66 & \dfrac{F_2}{F_1} < 0.08 \\ 0.001\left(1754.41 - 1087.69\dfrac{F_2}{F_1} + 345.81\left(\dfrac{F_2}{F_1}\right)^2\right) & \dfrac{F_2}{F_1} \geq 0.08 \end{cases} \tag{3.53}$$

for a sudden change. Figure 3.12 shows the resulting pressure increase.

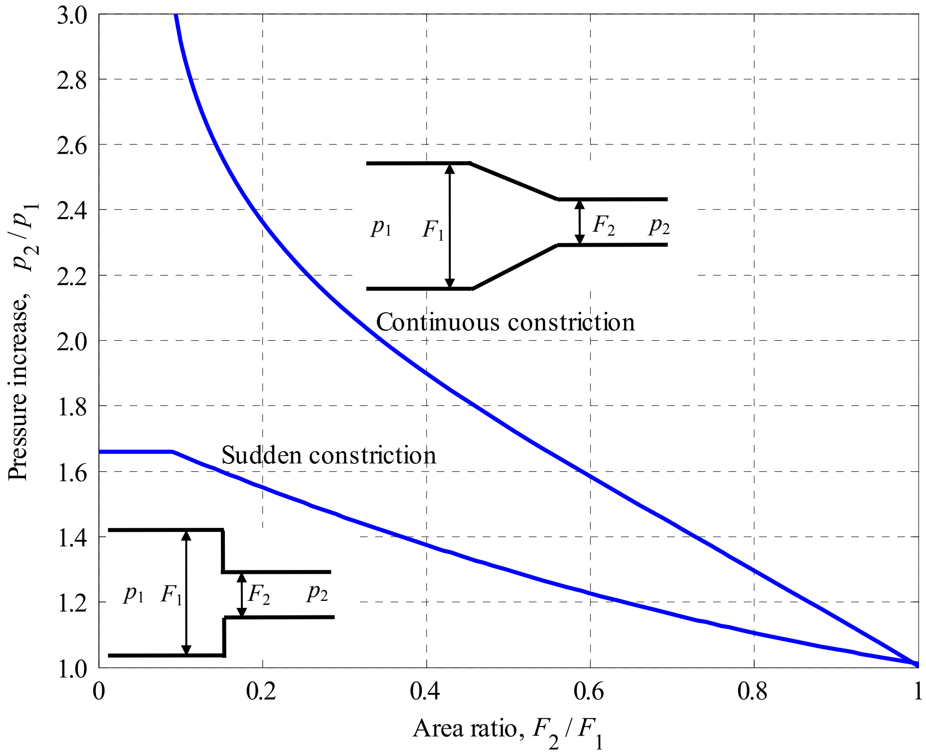
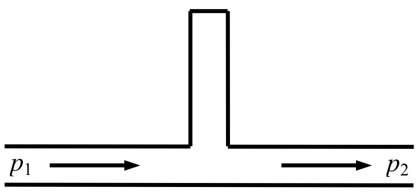
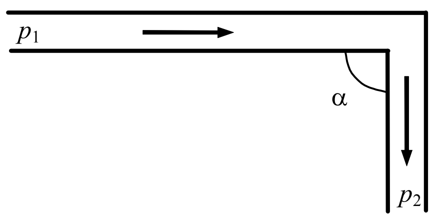


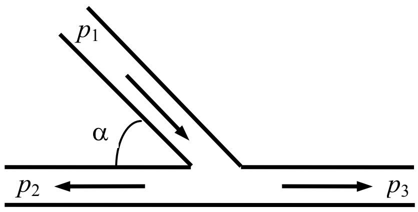
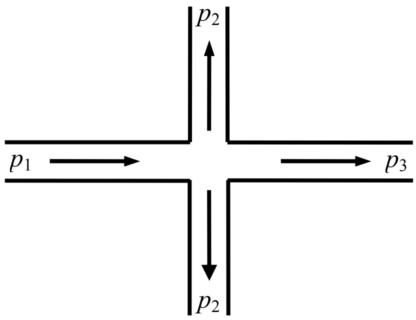
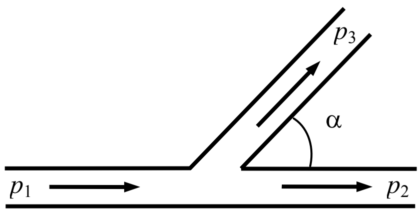
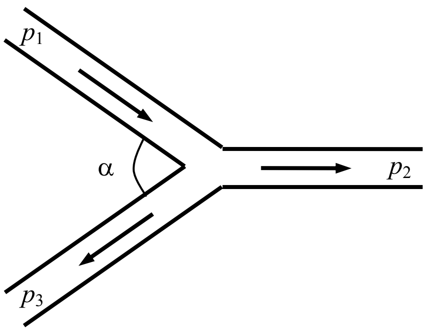
Figure 3.12 Pressure increase caused by tunnel constrictions

The duration is not affected by a constriction.

Junctions or branch points are described by a series of tunnel elements. Table 3.6 shows how the pressure and duration are influenced by the different junction types.

Table 3.6 Changes in pressure and duration after tunnel junctions

Blind tunnel (BT)	 	$\dfrac{p_2}{p_1} = 0.9$ $\dfrac{t_2}{t_1} = 1$
Turn (TR)	 	$\dfrac{p_2}{p_1} = \begin{cases} 0.9 & \alpha = 90^\circ \\ 1 & \alpha \neq 90^\circ \end{cases}$ $\dfrac{t_2}{t_1} = 1$

Joining tunnel (J1)		$\frac{p_2}{p_1} = \sqrt{\frac{\alpha}{180°}}$ $\frac{p_3}{p_1} = \sqrt{1 - \frac{\alpha}{180°}}$ $\frac{t_2}{t_1} = \frac{t_3}{t_1} = 0.7$
Crossing tunnels (J2)		$\frac{p_2}{p_1} = 0.8$ $\frac{p_3}{p_1} = 0.25$ $\frac{t_2}{t_1} = \frac{t_3}{t_1} = 0.7$
Separating tunnel (J3)		$\frac{p_2}{p_1} = 0.8$ $\frac{p_3}{p_1} = 0.8\left(1 - \frac{\alpha}{180°}\right)$ $\frac{t_2}{t_1} = \frac{t_3}{t_1} = 0.7$
Y-type junction (J4)		$\frac{p_2}{p_1} = 0.9 - 0.6\left(\frac{\alpha}{180°}\right)^2$ $\frac{p_3}{p_1} = 0.2 + 0.6\frac{\alpha}{180°}$ $\frac{t_2}{t_1} = \frac{t_3}{t_1} = 0.7$

Air blast outside the tunnel

Outside the tunnel the relation between the pressure and the distance along the tunnel axis, r_p, is found to be

$$\frac{p}{p_\mathrm{a}} = \left(\frac{0.7 d_\mathrm{t}}{r_p}\right)^{10/9} \tag{3.54}$$

where the index a denotes the pressure at the tunnel adit, and d_t is the equivalent tunnel diameter. The isobars are approximated as circles with radius 0.57 r_p and the centre 0.43 r_p

from the tunnel adit. When the line from the tunnel adit to the point considered has length r and an angle α to the tunnel axis, this corresponds to

$$\frac{r_p}{r} = \frac{\sqrt{0.57^2 - \left(0.43\sin\alpha\right)^2} - 0.43\cos\alpha}{0.57^2 - 0.43^2} \tag{3.55}$$

The parameters are shown in Figure 3.13.

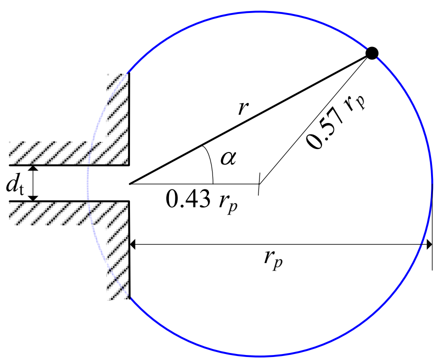


Figure 3.13 Isocontour for pressure and impulse outside a tunnel adit

The isocontours of the impulse are defined similarly as the isobars, and the impulse values are found from

$$\frac{p^{5/3} t_{\mathrm{ip}}}{p_{\mathrm{e}}{}^{5/3} t_{\mathrm{ip,a}}} = \left(0.36 \frac{d_{\mathrm{t}}}{r_p}\right)^2 \tag{3.56}$$

This procedure for determining pressure and impulse applies when the UG1 or UG3 model is used. With UG2 the directional effects outside the tunnel are addressed by the factor k_{n}:

$$k_{\mathrm{n}} = \begin{cases} 1 & |\alpha| \le 30° \\ 0.89 & 30° < |\alpha| \le 60° \\ 0.67 & 60° < |\alpha| \le 90° \\ 0.5 & 90° < |\alpha| \le 120° \\ 0.25 & |\alpha| > 120° \end{cases} \tag{3.57}$$

where α is the angle to the tunnel direction. The pressure and dynamic impulse becomes

$$p = \left(\frac{0.89 k_{\mathrm{n}} d_{\mathrm{t}} p_{\mathrm{a}}{}^{0.7} d_0{}^{0.003}}{\left(p_{\mathrm{a}}/p_{\mathrm{c}}\right)^{0.33} V^{0.003} r} \right)^{1.42} \tag{3.58}$$

$$p^{5/3}t_{\mathrm{ip}} = p_{\mathrm{e}}{}^{5/3}t_{\mathrm{ip,a}}\left(\frac{0.36d_{\mathrm{t}}}{rk_{\mathrm{n}}}\right)^{2}\frac{p}{p_{\mathrm{e}}\left(\frac{0.7d_{\mathrm{t}}}{r}\right)^{10/9}} \tag{3.59}$$

The resulting lethality is determined according to chapter 4.2.

3.2.3 Ground shock

The ground shock effects from an underground installation are described by the scaled distance, $\overline{r}_{\mathrm{g}}$,

$$\overline{r}_{\mathrm{g}} = \frac{r - d_{\mathrm{c}}/2}{Q^{1/3}V^{1/9}} \tag{3.60}$$

where r is the shortest distance from the exposed object to the centre line from the entrance to the back side of the chamber. The lethality is given by (4.13).

3.2.4 Propagation of explosion

The explosion in a chamber may propagate through the chamber walls to another chamber or a neighbouring tunnel. The maximum charge that does not cause propagation of the explosion, is

$$Q_{\mathrm{c}} = \frac{1}{1000}\left(\frac{d}{k}\right)^{10/3} \tag{3.61}$$

where d is the distance to the nearest chamber or tunnel, and

$$k = \begin{cases} 2.0 & \text{for chambers in different tunnel systems} \\ 0.6 & \text{for chambers without innerbuildings in one tunnel system} \\ 0.3 & \text{for chambers with concrete innerbuildings in one tunnel system} \\ 0.2 & \text{for chamber and tunnel} \end{cases} \tag{3.62}$$

If $Q > Q_{\mathrm{c}}$, AMRISK displays a warning.

4 LETHALITY

4.1 General

Lethality (λ) is the probability of fatal damage. The damage is caused by one or more physical effects. The effect quantity that a person can survive is a stochastic value. The lethality may then be considered the probability that the tolerance level is less than the physical effect value,

v. The probability is found by applying a function $z(v)$ whose values are assumed standard normally distributed. In its simplest form, the function is

$$z = A \ln v + B \tag{4.1}$$

with constants A and B. The lethality as a function of z becomes the cumulative standard normal distribution. For $\lambda_2 = (1 - \lambda)$ AMRISK uses the approximate function

$$\lambda_2 = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} \left(b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5 \right) \tag{4.2}$$

where

$$t = \frac{1}{1 + p|z|} \tag{4.3}$$

$p = 0.2316419$
$b_1 = 0.31938153$
$b_2 = -0.356563782$
$b_3 = 1.781477937$
$b_4 = -1.821255978$
$b_5 = 1.330274429$

If $z < 0$, $\lambda_2 = 1 - \lambda_2(z)$. λ is found from $\lambda(z) = \lambda_2(-z)$. When the physical effect parameter is some scaled distance, the corresponding z-function directly gives $-z$ as output, hence $\lambda = \lambda_2(z)$.

(4.1) applies for air blast and scaled distance from tunnel debris. For debris density from aboveground installations and scaled distance from ground shock and crater debris, the function contains additional terms, cf. the respective sections.

The lethalities from different effects (λ_i) are assumed independent, giving a total lethality of

$$\lambda_{\text{tot}} = 1 - \prod_i 1 - \lambda_i \tag{4.4}$$

4.2 Lethality from air blast

The lethality from air blast is in AMRISK generally dependent on the peak pressure, p, or the dynamic impulse, i_q. The dynamic impulse of the blast wave, i_q, is given as

$$i_q = 0.12 p^{5/3} t_{\text{ip}} \tag{4.5}$$

where t_{ip} is the impulsively effective duration, which can be estimated from the duration t_+ by (3.10). In the lethality calculations the parameter $p^{5/3}t_{ip}$ is used, without the factor 0.12.

The lethality at free-field objects is set to the largest of the lethality values from pressure and impulse. For other object types, only one of the parameters applies. The model for air blast lethality is valid for charges larger than 1 t.

The pressure gives values of the variable z according to

$$z = A \ln p + B \tag{4.6}$$

where the parameters A and B depend on the object type, see Table 4.1.

Table 4.1 Parameters for determining the lethality variable z for pressure

Object type		A	B
Free-field		3.4425	-3.0205
Building light	$p < 0.0594$ bar	0.7441	-1.5790
	$p \geq 0.0594$ bar	2.1622	2.4244
Building normal	$p < 0.101$ bar	0.7441	-1.5790
	$p \geq 0.101$ bar	2.1622	1.6721
Building strong	$p < 0.192$ bar	0.7441	-1.5790
	$p \geq 0.192$ bar	2.1622	0.7612

The lethality is then calculated from z as described above assuming a standard normal distribution. Figure 4.1 shows the relation between lethality and pressure using a graph with a normally distributed ordinate scale and a logarithmic abscissa scale.

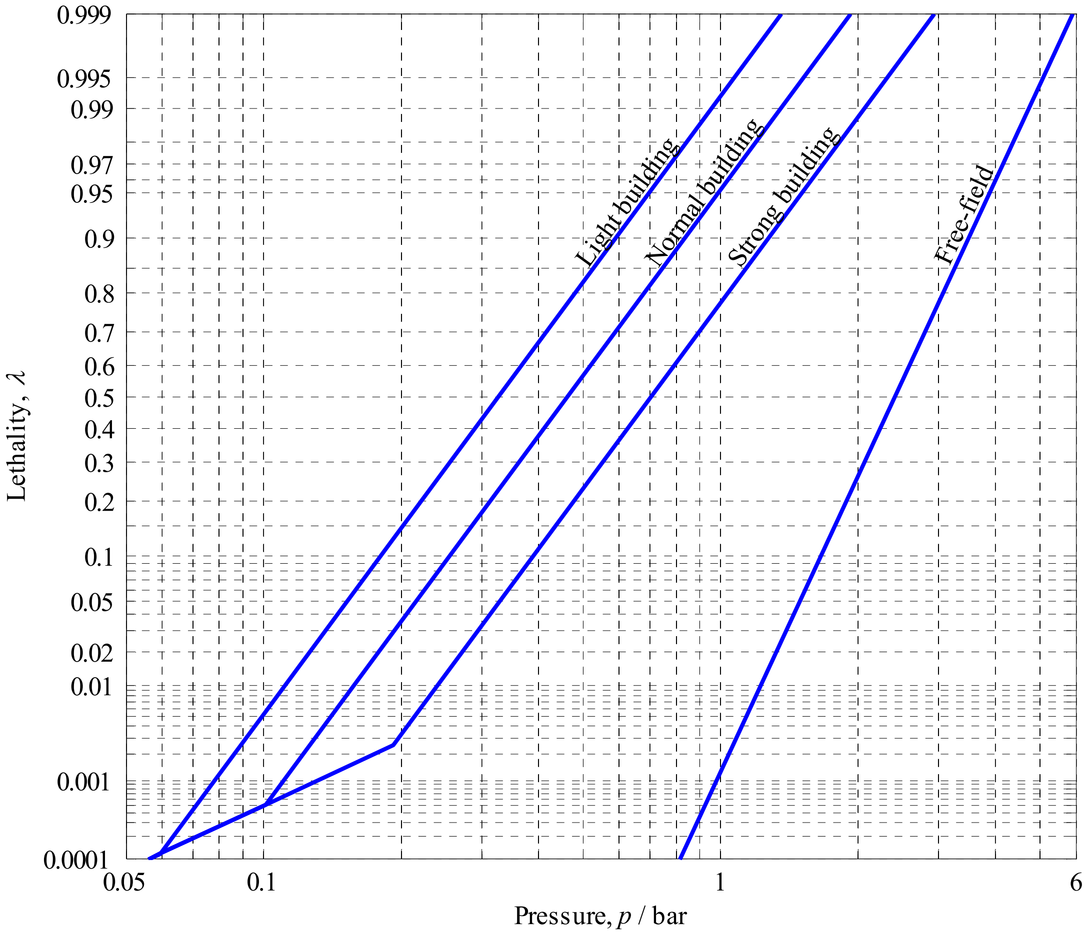


Figure 4.1 Lethality from air blast pressure

The same relation is used for impulse as for pressure,

$$z = A\ln\left(p^{5/3}t_{\mathrm{ip}}\right) + B \tag{4.7}$$

with the parameter values shown in Table 4.2.

Table 4.2 Parameters for determining the lethality variable z for impulse

Object type			A	B
Free-field			2.0950	-11.2814
Free-field, forest		$p^{5/3}t_{\mathrm{ip}} < 67$ bar$^{5/3}$ms	2.0194	-9.0244
		67 bar$^{5/3}$ms $\le p^{5/3}t_{\mathrm{ip}} < 298$ bar$^{5/3}$ms	0.7956	-3.8788
		$p^{5/3}t_{\mathrm{ip}} \ge 298$ bar$^{5/3}$ms	2.0950	-11.2814
Car	Normal conditions		1.6979	-7.6197
	Unfavourable conditions	$p^{5/3}t_{\mathrm{ip}} < 34.3$ bar$^{5/3}$ms	1.6979	-7.6197
		$p^{5/3}t_{\mathrm{ip}} \ge 34.3$ bar$^{5/3}$ms	2.5643	-10.6826

Train	Normal conditions	$p^{5/3}t_{ip} < 66.2$ bar$^{5/3}$ms	1.3530	-7.3237
		$p^{5/3}t_{ip} \geq 66.2$ bar$^{5/3}$ms	2.5063	-12.1590
	Unfavourable conditions	$p^{5/3}t_{ip} < 66.2$ bar$^{5/3}$ms	1.3530	-7.3237
		$p^{5/3}t_{ip} \geq 66.2$ bar$^{5/3}$ms	3.9723	-18.3055

The resulting lethality is shown in Figure 4.2.

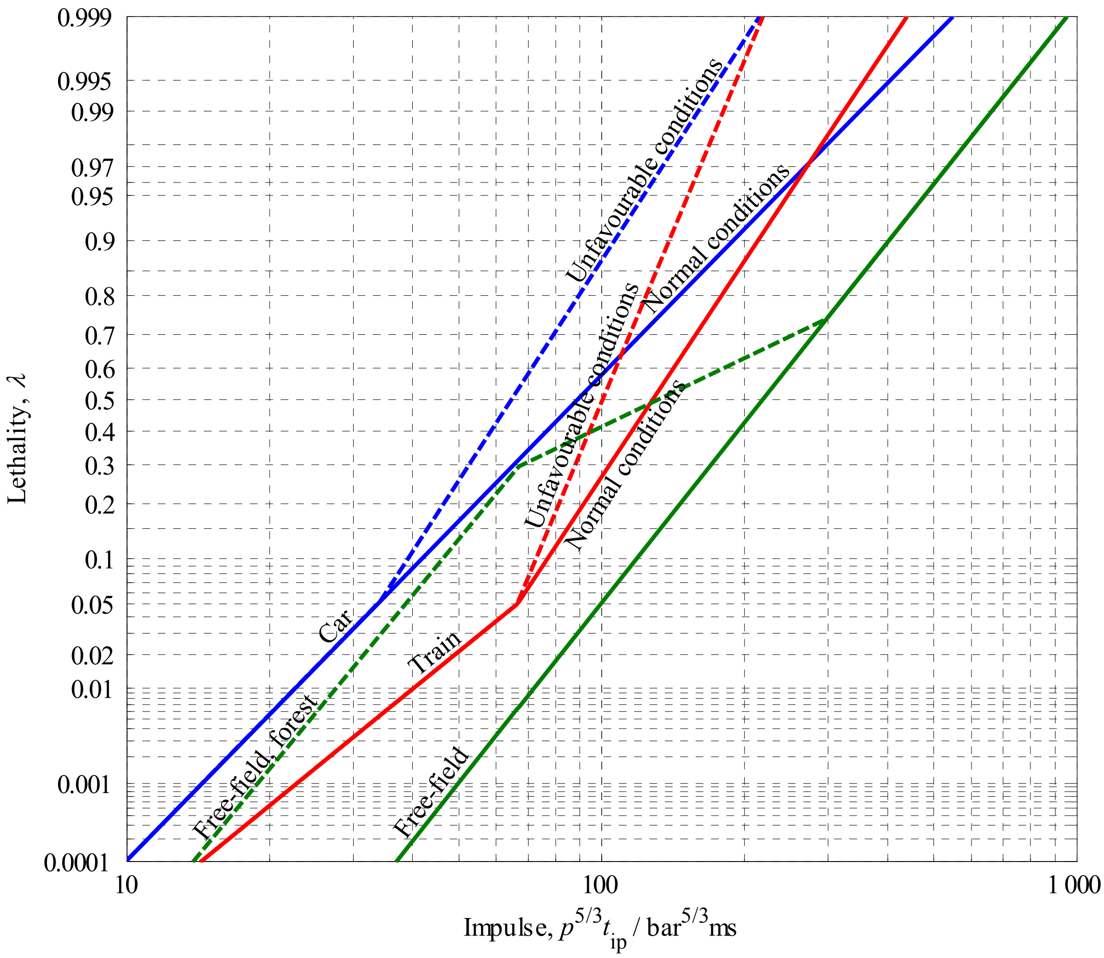


Figure 4.2 Lethality from dynamic impulse from air blast

4.3 Lethality from debris

4.3.1 Aboveground magazines

For magazines, the debris effect is given as debris density, δ, which is estimated according to chapter 3.1.1. The formula employed to calculate the lethality parameter z, is

$$z = A + B\ln\delta + C\sqrt{(\ln\delta - D)^2 + E} \tag{4.8}$$

where the parameters A, B, C, D and E depend on the exposed object, see Table 4.3.

Table 4.3 Parameters for determining the lethality variable z for magazine debris throw

<table>
<tr><td colspan="2">Object type</td><td>A</td><td>B</td><td>C</td><td>D</td><td>E</td></tr>
<tr><td colspan="2">Free-field</td><td>-2.85</td><td>0.948</td><td>0.6731</td><td>1.427</td><td>5.72</td></tr>
<tr><td colspan="2">Free-field, forest</td><td>-3.188</td><td>0.7399</td><td>0.4967</td><td>1.593</td><td>14.43</td></tr>
<tr><td rowspan="2">Car</td><td>Normal conditions</td><td>-3.525</td><td>0.6779</td><td>0.3749</td><td>3.419</td><td>22.11</td></tr>
<tr><td>Unfavourable conditions</td><td>-2.85</td><td>0.948</td><td>0.6731</td><td>1.427</td><td>5.72</td></tr>
<tr><td colspan="2">Train</td><td>-3.882</td><td>0.4893</td><td>0.2955</td><td>1.944</td><td>46.34</td></tr>
<tr><td colspan="2">Building</td><td>-4.103</td><td>0.4631</td><td>0.2524</td><td>3.285</td><td>39.95</td></tr>
<tr><td colspan="2">Building, forest</td><td>-4.566</td><td>0.4006</td><td>0.2557</td><td>2.346</td><td>59.13</td></tr>
</table>

Figure 4.3 shows the relation between lethality and debris density.

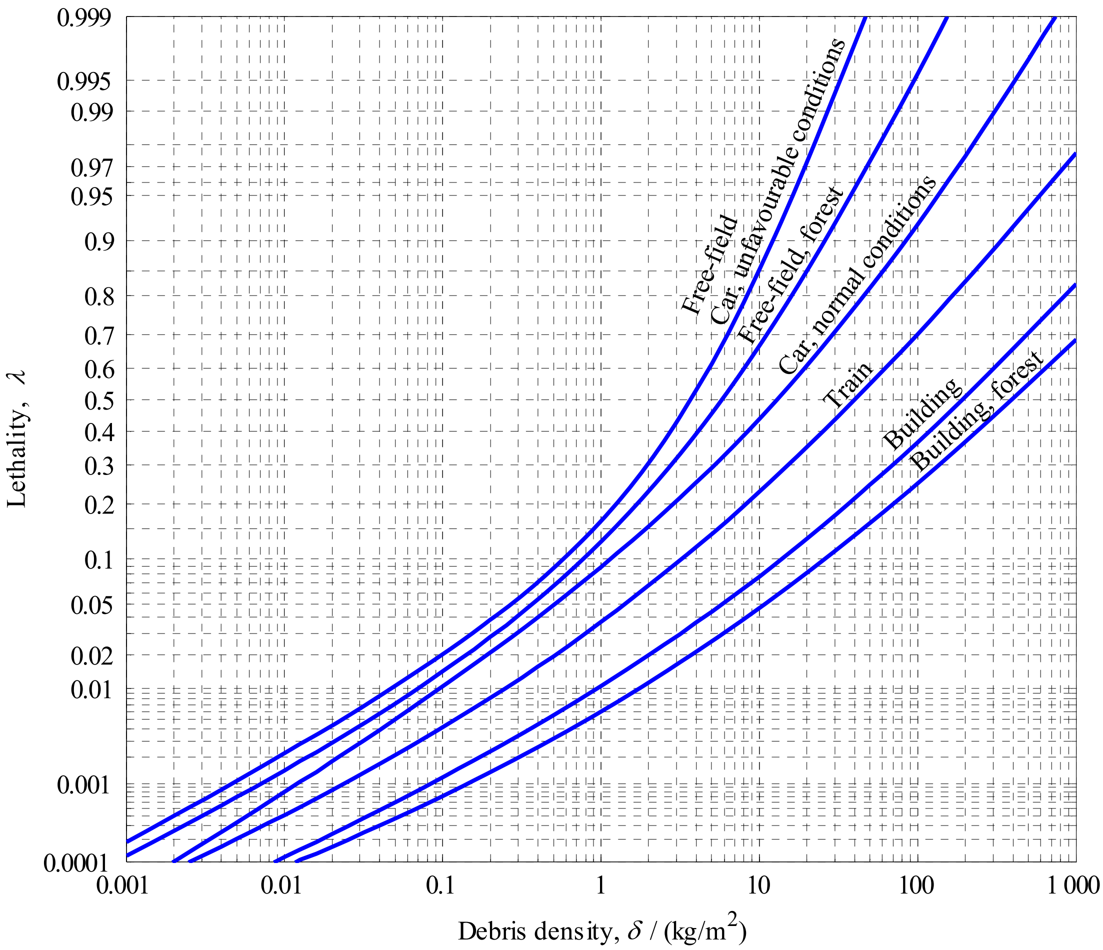


Figure 4.3 Lethality from debris from aboveground installations

4.3.2 Underground installations

4.3.2.1 Crater

The lethality from debris from crater above an underground installation is found from the relation

$$z = A\left(\ln \overline{r}_{\mathrm{dc}}\right)^2 + B \ln \overline{r}_{\mathrm{dc}} + C \tag{4.9}$$

where $\overline{r}_{\mathrm{dc}}$ is estimated as described in 3.2.1.1. Table 4.4 shows values of the parameters *A*, *B* and *C* for different object types.

Table 4.4 Parameters for determining the lethality variable z for debris throw from crater over a chamber

Object type		*A*	*B*	*C*
Free-field	$\overline{r}_{\mathrm{c}} < 47$	-0.2652	2.5976	-2.5706
	$\overline{r}_{\mathrm{c}} \geq 47$	0	0.5943	1.2125
Car/Train		0	1.142	-0.384
Building (light/normal/ strong)		0.0644	0.7934	0.3325

The lethality then becomes as shown in Figure 4.4.

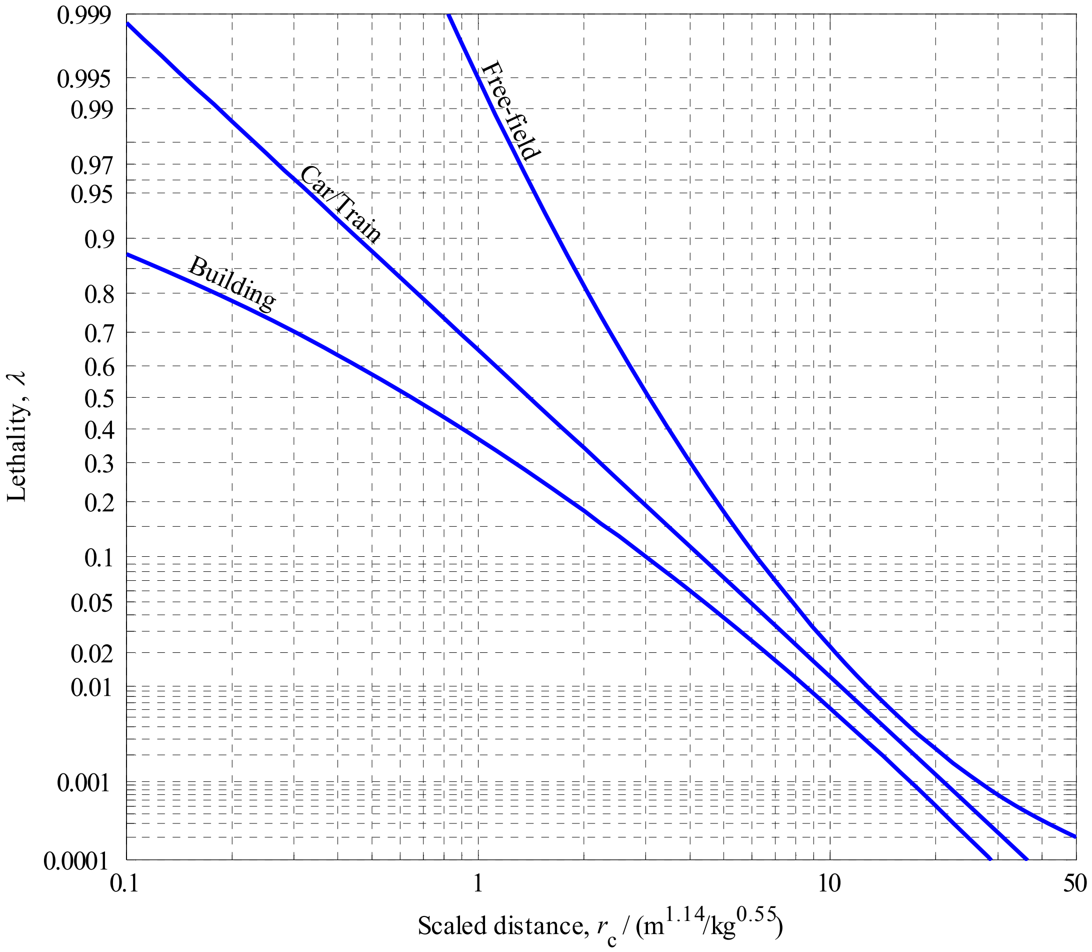


Figure 4.4 Lethality from debris from crater above underground installations

4.3.2.2 Tunnel

For the debris thrown out from the tunnel (cf. section 3.2.2.1) the lethality parameter *z* is calculated as

$$z = A \ln \overline{r}_{dt} + B \tag{4.10}$$

Different object types have the parameter values given in Table 4.5.

Table 4.5 Parameters for determining the lethality variable z for debris throw from tunnel

Object type	Block		*A*	*B*
Free-field/Car		$\overline{r}_{dt} \leq 670$	3.296	-18.886
		$\overline{r}_{dt} > 670$	1.196	-5.221
	X		4.353	-13.711

Object type	Block		*A*	*B*
Train/Building light		$\overline{r}_{dt} \leq 530$	3.296	-18.132
		$\overline{r}_{dt} > 530$	1.196	-4.942
	X		4.353	-12.740
Building normal/ strong		$\overline{r}_{dt} \leq 400$	3.296	-17.160
		$\overline{r}_{dt} > 400$	1.196	-4.600
	X		4.353	-11.486

Figure 4.5 shows the resulting lethality values.

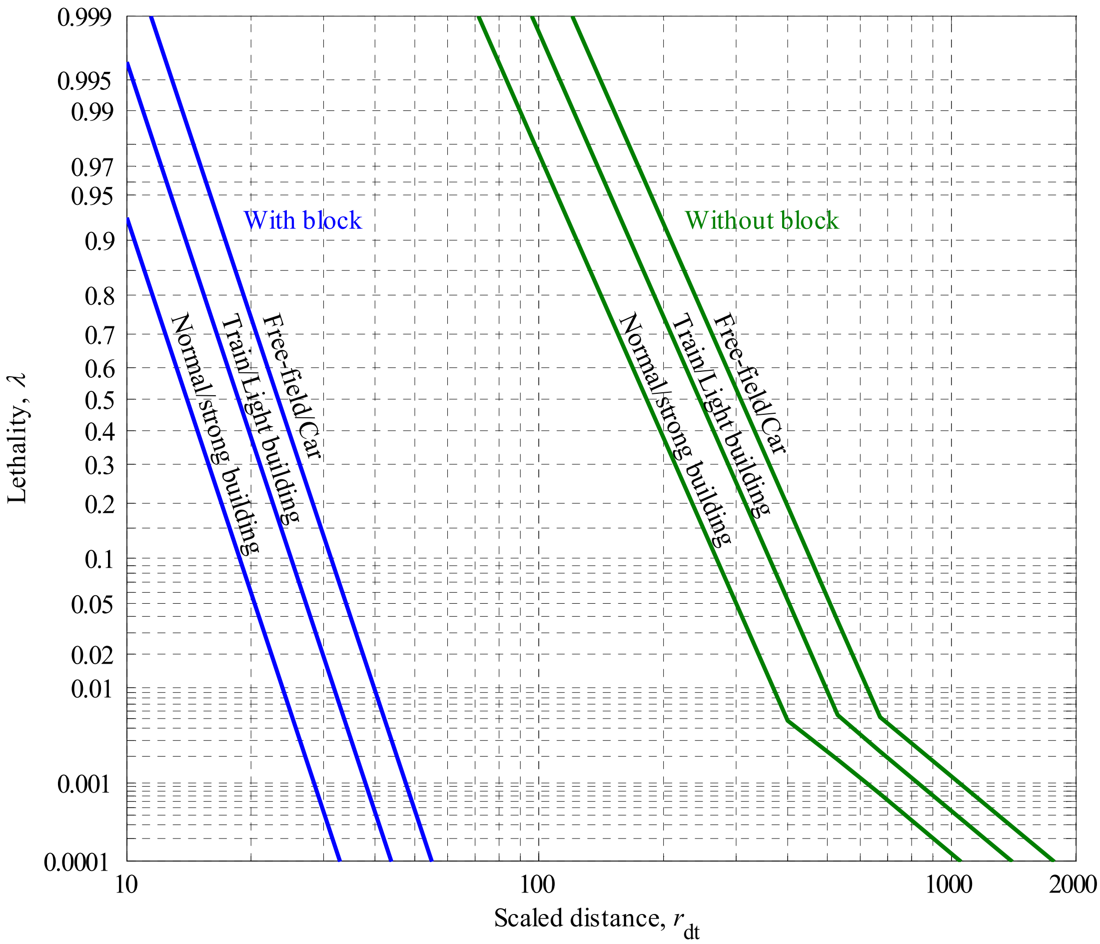


Figure 4.5 Lethality from debris from tunnels at underground installations

Note that the scaled distance has different definitions with and without a block; see equations (3.29) and (3.31).

If there are barricades or terrain limitations in front of the tunnel exit, some additional considerations are made. The area outside the tunnel is divided in 12 sectors, see Figure 4.6.

On each side of the tunnel axis, there are three 2.5° sectors and then three 7.5° sectors. Outside these 12 sectors, the lethality is 0.

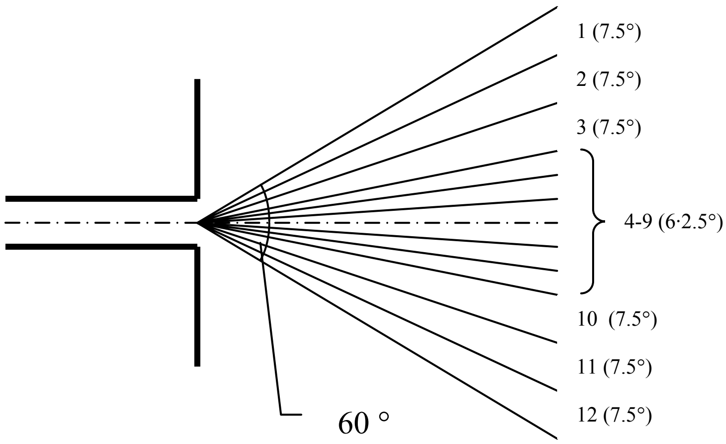


Figure 4.6 Sectors for determining debris lethality outside tunnels

If there are no terrain limitations or barricades, the lethality in the 60° sector is the values shown in Figure 4.5. Otherwise the lethality in the different sectors depend on the height of the limitations given as the height angle seen from the tunnel opening. The height angle can take the values 5°, 7.5°, 15°, 22.5° and 30°.

When the lethality of an object in a sector is determined, three of the height angels are relevant, depending on the tunnel opening shape (cf. equation (3.30)) and if there is a block. Table 4.6 shows the angles.

Table 4.6 Applicable height angles for determining lethality from tunnel debris

With block	φ_1	φ_2	φ_3	
Small angle	5°	7.5°	15°	
Large angle	7.5°	15°	22.5°	Small angle
	15°	22.5°	30°	Large angle
	φ_1	φ_2	φ_3	Without block

The lethality depends on the distance to the exposed object compared to the distance to the barricades with the height angles shown above.

$$\lambda = \begin{cases} \lambda_0 & r \le r_1 \\ \max\left(0.3, \lambda_0\right) & r_1 < r \le r_2 \\ \max\left(0.05, \lambda_0\right) & r_2 < r \le r_3 \\ 0 & r > r_3 \end{cases} \tag{4.11}$$

where λ_0 is the basic lethality shown in Figure 4.5, r_i is the distance to the barricades with the height angles according to Table 4.6 and r is the distance to the exposed object. When there are only one or two barricades in a sector, only the corresponding relations in (4.11) apply. For instance, with a small angle opening without block and a barricade with height angle 15° placed 10 m from the tunnel mouth the expression simplifies to

$$\lambda = \begin{cases} \lambda_0 & r \le 10 \text{ m} \\ \max\left(0.05, \lambda_0\right) & r > 10 \text{ m} \end{cases} \tag{4.12}$$

4.4 Lethality from ground shock

Ground shock from underground installations may cause damage to buildings and subsequent lethality to people inside. From the scaled distance, $\overline{r}_g$, estimated as described in 3.2.3, the lethality parameter z is calculated as

$$z = 0.3783\left(\ln \overline{r}_g\right)^2 - 0.7088 \ln \overline{r}_g - 0.5778 \tag{4.13}$$

Figure 4.7 shows the resulting lethality.

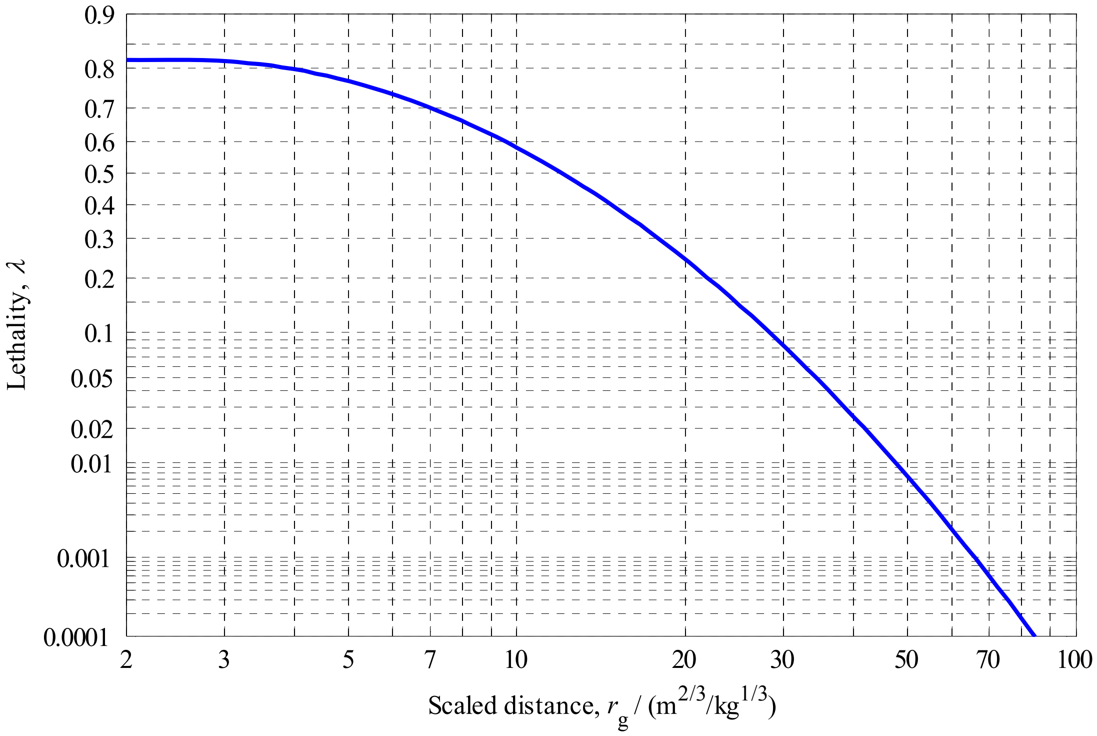


Figure 4.7 Lethality in buildings from ground shock

4.5 Lethality at objects

The lethality of a person at a given point is determined by the methods described above. This is also the lethality at a point-fixed object. The lethality values from different effects are added up according to (4.4).

Linear objects are divided in segments where the average lethality is calculated and multiplied with the segment length. Summing up these values gives a lethality length, L_λ

$$L_\lambda = \sum_m \tfrac{1}{2}\left(\lambda(r_m) + \lambda(r_{m+1})\right)\left(r_{m+1} - r_m\right) \tag{4.14}$$

which may be considered the lethality averaged over the object and multiplied by the length of the object.

For trains first a value of L_λ is calculated for the railway by (4.14). Then a corresponding lethality length, $L_{\lambda\text{train}}$, is calculated for the train at each of the positions where the front or the end of the train is at a segment limit. The dimensioning length, L^*, is the distance along the railway between the positions where $L_{\lambda\text{train}}$ is 20 % of its maximum value. The resulting lethality length for trains becomes

$$L_{\lambda \mathrm{t}} = \begin{cases} L_{\lambda} \dfrac{l_{\mathrm{z}}}{L^{*}} & L_{\lambda} \dfrac{l_{\mathrm{z}}}{L^{*}} \le \max\left(L_{\lambda \mathrm{train}}\right) \\ \max\left(L_{\lambda \mathrm{train}}\right) & L_{\lambda} \dfrac{l_{\mathrm{z}}}{L^{*}} > \max\left(L_{\lambda \mathrm{train}}\right) \end{cases} \tag{4.15}$$

where l_{z} is the train length. Hence, the lethality length used for trains is limited by the maximum value of $L_{\lambda \mathrm{train}}$.

For a limited area object a lethality area, $A_{\lambda \mathrm{l}}$, is calculated as

$$A_{\lambda \mathrm{l}} = \sum_{m} \sum_{n} \tfrac{1}{2} \left(\lambda(r_{m+\frac{1}{2},n}) + \lambda(r_{m+\frac{1}{2},n+1}) \right) \left(r_{m+1} - r_{m} \right) \left(r_{m+\frac{1}{2},n+1} - r_{m+\frac{1}{2},n} \right) \tag{4.16}$$

where

$$r_{m+\frac{1}{2},n} = \tfrac{1}{2} \left(r_{m,n} + r_{m+1,n} \right) \tag{4.17}$$

m and n refer to the orthogonal axes parallel to the sides of the object.

Dividing the lethality area by the object area, A, gives the average object lethality, λ_A:

$$\lambda_A = \frac{A_{\lambda \mathrm{l}}}{A} \tag{4.18}$$

For an unlimited area, the area elements are not rectangular, but circle segments. The area of an element reaching from $r_n - \Delta r/2$ to $r_n + \Delta r/2$ and having width $\Delta\theta$, is

$$A_n = r_n \Delta r \Delta \theta \tag{4.19}$$

when θ is given in radians. The lethality integrated over the area becomes

$$A_{\lambda \mathrm{u}} = \sum_{m} \sum_{n} \lambda(r_{n,} \theta_{m}) A_n \tag{4.20}$$

AMRISK shows lethality values for different object shapes according to Table 4.7.

Table 4.7 Lethality values presented by AMRISK

Object type	Value
Point fixed	λ
Linear free-field	L_{λ}
Linear road	L_{λ}/v
Linear train	$L_{\lambda\mathrm{t}}$
Limited area	λ_{A}
Unlimited area	$A_{\lambda\mathrm{u}}$

The lethality value of linear roads is a lethality duration found by dividing the lethality length by the car velocity, v.

5 EXPOSURE ANALYSIS

By the exposure analysis the number of people at exposed objects at different times is found. To an exposed object, a representative number of persons, *PKZ*, is assigned. This is the number of persons at point fixed objects, the number of persons per km at linear free-field objects, the number of persons per meter train, the number of persons per km^2 for area objects or average daily traffic for roads.

In different situations, normally different periods of the day, the number of people may vary. To allow for this, a presence factor, *PF*, is used. It specifies the ratio of the number of people present at an object in a given situation and the representative number of persons.

The duration of a situation relative to the total time period considered is denoted *SD*.

Analogous to other object shapes the presence factor for roads is the ratio of the number of people passing the road per hour and the representative number of persons. When the representative number is given as average daily traffic, the presence factor of situation j is calculated as

$$PF_{\mathrm{car}\,j} = \gamma \frac{fr_{\mathrm{c}\,j}}{24} N_{\mathrm{c}\,j} \tag{5.1}$$

Here $N_{\mathrm{c}j}$ is the average number of persons in a car. $fr_{\mathrm{c}j}$ is the ratio of the situation's car frequency and the average frequency, hence $fr_{\mathrm{c}\,j}/24$ represents the situation's hourly portion of the daily traffic. The factor γ takes the fluctuations of the traffic density within a situation into account, a recommended value for normal roads is 1.5 (4).

The train object is also a situation, and a presence factor different from 1 is not meaningful. The relative situation duration is calculated from the travel time of the distance L^* or the corresponding distance when the lethality length is max ($L_{\lambda\,\mathrm{train}}$), as described in section 4.5:

$$t^* = \begin{cases} \dfrac{L^*}{v} & L_\lambda \dfrac{l_z}{L^*} \leq \max\left(L_{\lambda\,\mathrm{train}}\right) \\ \dfrac{L_\lambda l_z}{v \cdot \max\left(L_{\lambda\,\mathrm{train}}\right)} & L_\lambda \dfrac{l_z}{L^*} > \max\left(L_{\lambda\,\mathrm{train}}\right) \end{cases} \tag{5.2}$$

v is the train velocity. The relative situation duration becomes

$$SD_{\mathrm{train}} = k_f f_{\mathrm{train}} t^* \tag{5.3}$$

where f_{train} is the train frequency and $k_f = 1/604800$ converts the frequency from trains per week to trains per second.

6 RISK MEASURES

6.1 Individual risk

The individual risk is the probability that a person is lethally damaged, normally considering the person most present at an object. For object i it is calculated as

$$r_i = \sum_k r_{ik} = \sum_k PF_{\max i} P_{\mathrm{E}k} \sum_{j=a}^{n} \lambda_{ijk} SD_j \tag{6.1}$$

where r_{ik} is the risk portion from storage k. $PF_{\max i}$ is the average presence of the person most connected to the exposed object and $P_{\mathrm{E}k}$ is the probability of an accident at the potential explosion site. The second summation goes over the situations {a . . n} in which there are persons at the object ($PF_j > 0$). Individual risk is applicable to point fixed and limited area objects where λ_{ijk} is the lethality at the point or averaged over the area (λ_A). The lethality depends on the situation if the UG3 model is used with separate situations for an open and a closed chamber block.

The probability ri_i of lethal damage given that an explosion has taken place, is found by setting $P_{\mathrm{E}k} = 1$ for all k in the expression above.

6.2 Collective risk

Combining the lethality from an explosion in magazine k and the representative object number of object i, PKZ_i, gives the characteristic object value, OKZ_{ik}:

$$OKZ_{ik} = PKZ_i \sum_j \lambda_{ijk}' SD_j \tag{6.2}$$

λ_{ijk}' is the lethality value of the object according to Table 4.7, except for limited areas where λ' = $A_{\lambda 1}$. Usually, the lethality is the same in all situations, and the summation can be replaced by λ_{ik} since the sum of the relative durations is 1. However, this does not apply to trains where the relative duration of the single train situation represents the fraction of the time the train is exposed to explosion effects.

OKZ_{ik} denotes the expected maximum number of fatalities at the object, except for roads. When *PKZ* for roads is given as average daily traffic, OKZ_{ik} is the expected number of cars hit by a lethal effect, multiplied by 24.

When the variations in presence during the day is considered, the expected number of fatalities at an object becomes

$$OO_{ik} = \sum_j OKZ_{ik}\, PF_{ij}\, SD_j \tag{6.3}$$

This is the object's portion of the total expected number of fatalities after an explosion in magazine *k*:

$$RO_k = \sum_i OO_{ik} \tag{6.4}$$

The collective risk of a magazine is the product of *RO* and the probability of an explosion, $P_{\mathrm{E}k}$.

$$R_k = RO_k\, P_{\mathrm{E}k} = \sum_i OO_{ik}\, P_{\mathrm{E}k} \tag{6.5}$$

giving the expected number of fatalities in a year caused by a possible explosion in magazine *k*. The summation terms are the contributions from each object.

The collective risk from several potential explosion sites is also found by summation,

$$R = \sum_k R_k \tag{6.6}$$

6.3 Perceived collective risk

To account for the aversion against events with a high number of fatalities, an aversion factor is applied. This factor Φ is evaluated for each situation and for each magazine or charge according to

$$\Phi_{jk} = \begin{cases} 2^{N_{jk}/5} & N_{jk} \le 20 \\ 16 & N_{jk} > 20 \end{cases} \tag{6.7}$$

where N_{jk} is the expected number of fatalities caused by an explosion in situation j,

$$N_{jk} = \sum_i OKZ_{ik} PF_{ij} \tag{6.8}$$

The expected number of fatalities of an object when the aversion factor is included, becomes

$$OE_{ik} = \sum_j OKZ_{ik} PF_{ij} SD_j \Phi_{jk} \tag{6.9}$$

Summing OE_{ik} over the objects gives the expected perceived consequence of an explosion in a magazine:

$$RE_k = \sum_i OE_{ik} \tag{6.10}$$

Similar to the real collective risk the perceived collective risk becomes

$$R_{\mathrm{p}} = \sum_k R_{\mathrm{p}k} = \sum_k RE_k P_{\mathrm{E}k} = \sum_k \sum_i OE_{ik} P_{\mathrm{E}k} \tag{6.11}$$

APPENDIX

A RANGE OF APPLICABILITY OF AMRISK MODELS

A.1 Volume and inventory

Table 6.1 Applicable ranges of volumes, inventories and loading densities

Type of magazine	Volume / m^3	Inventory / t TNT	Loading density / (kg TNT/m^3
Underground	2 000 – 10 000	1 – 200	0.1 – 100
Earth-buried	1 000 – 5 000	5 – 100	1.0 – 100
Earth-covered	500 – 600	1 – 50	2.0 – 100
Freestanding	600 – 3 000	1 – 100	0.3 - 100

A.2 Shape

Table 6.2 Applicable shapes and proportions

Type of magazine	Shape	Proportions Length : Width	Location of entrance
Underground	Square to rectangular	Max. 15 : 1	Narrow side
Earth-buried	Rectangular	Max. 10 : 1	Any
Earth-covered	Rectangular	Max. 10 : 1	Any
Freestanding	Rectangular	Max. 10 : 1	Any

A.3 Earth cover

Table 6.3 Applicable earth cover

Type of magazine	Earth cover / m
Earth-buried	1 – 2
Earth-covered	0.5 – 1

A.4 Construction type

Freestanding magazine: Construction of brick or normal reinforced concrete

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