The Debris Hazard from Fireworks Held in Steel ISO Containers

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Abstract: *A number of serious accidents in European Union countries involving explosions of fireworks stored in steel ISO freight containers has shown that the hazards associated with bulk-stored fireworks might be greater than previously thought. To address this problem an EU research programme was initiated, part of which involved field trials with fireworks packed in ISO freight containers. In a few of these trials a mass explosion effect was observed. This prompted a number of questions, including whether the current quantity-distances applying to fireworks storage under such conditions offer adequate protection to the public. We consider this issue in the current paper by looking at the debris hazard from just one of the mass exploding trials, and show that for that particular firework the inhabited building distance specified in MSER is more than adequate to ensure that members of the public are not exposed to unacceptably high risks.*

Keywords: *Explosives, quantity–safety distances, fireworks, storage, risks*

Introduction

In an earlier paper[1] we presented the results of two propriety explosives steel-magazine trials and discussed how these results could be used to evaluate the adequacy of UK quantity–distance (QD) prescriptions from a risk perspective. The results of these and other small quantities trials on stores built of brick and concrete suggested that the quantity of debris generated in an explosion and the distance to which it would be thrown could be considerably greater than had previously been thought; and that in certain cases, distances set primarily to protect against the effects of blast might not offer sufficient protection against flying debris. The trials were part of a program of work whose aim was to review and revise the QD prescriptions applied to explosives stores.

Following on from this, models were developed to estimate the risks both to an individual living near an explosives store and of an explosion involving multiple fatalities, and to prescribe new QD tables. These tables were subsequently introduced in the UK when the Manufacture and Storage of Explosives Regulations (MSER) came into force in 2005.

More recently some large-scale trials work on fireworks held in steel ISO containers has produced a range of hazardous effects including mass explosions with associated fireball, blast, cratering and fragmentation effects. The purpose of this paper is to test the adequacy of our "new" MSER QD's for fireworks held in steel ISO containers which mass explode. For such situations, QDs are directed by the blast and debris/fragmentation effects.

Hazards associated with bulk stored fireworks

A number of serious accidents[2] in European Union countries involving explosions in the large-scale storage of fireworks have shown that we did not have an adequate understanding of the hazards posed by pyrotechnic articles (especially display fireworks) during transport and bulk storage. To address this problem an EU research programme was initiated entitled 'Quantification and control

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of the hazards associated with the transport and bulk storage of fireworks (CHAF)'. The work was undertaken by three partners: The Health and Safety Laboratory (United Kingdom), TNO Prins Maurits Laboratory (The Netherlands) and Bundesanstalt für Materialforschung und - prüfung (Germany) and coordinated by the former.

To gain a better understanding of the hazards posed by fireworks in transport and storage, part of the CHAF project involved full-scale testing of ignition of fireworks in 20 ft steel ISO containers. Nine such trials were carried out and in three cases a mass explosion effect was observed. The trials producing a mass explosion involved (1) stickless rockets, (2) waterfalls and (3) 150 mm coloured shells. In the latter trial an extra degree of confinement was achieved by placing the ISO container in the ground to a depth of around 1.5 m and covering it with at least 1 m of sand in all directions. Of these three trials, only that involving the stickless rockets have sufficient information for analysis of the associated fragment/debris effects.

Trials on stickless rockets

The trials on stickless rockets involved 720 boxes (86 400 articles) with a net explosives content of 5011 kg, packed inside a 6.1 m (20 ft) ISO container. Almost immediately after ignition a violent explosion of the contents of the container was observed along with the associated ground shockwave, see Figure 1.

The container was fragmented into small pieces, typically 5–70 cm wide and 5–200 cm long. The mass of the fragments varied between 0.1 and 30 kg. The largest distance where a fragment was recovered was 462 m. In total about 560 kg of fragments were recovered, representing about 25% of the total mass of the container. The blast data at 400 m distance corresponded to a detonation of 3367 kg TNT; i.e. an equivalence of 0.67 (based

Figure 1. *Full-scale ISO container testing of stickless rockets.*

on peak pressure). Full details of the large scale ISO container fireworks trial and results are given in the CHAF 'Work Package 9' report.[3]

Debris-throw distribution

The debris-throw data were analyzed[4] by dividing the debris field into 20 m deep sectors and counting the number of pieces of potentially lethal debris found in each. For example, five fragments were found between 20 and 40 m of the container (mid range 30 m) and 16 fragments were found between 40 and 60 m of the container (mid range 50 m). The complete results are summarized in Table 1 below.

Basis of current QD prescriptions

The UK QD prescriptions do not guarantee members of the public complete immunity against the effects of an accident on a licensed explosives site, for which aim impractically large distances would be required. Rather the prescriptions are designed to offer members of the public a high level of protection should an accident occur and to limit property damage to an acceptable level (typically broken windows and other easily repairable damage). This qualification notwithstanding, the QD prescriptions can be said to have stood the test of time: in the last 60 years there have been almost 100 incidents of major accidental explosion on licensed explosives sites in the UK, not one of which has caused fatal injury off site.

In 2005 the Health & Safety Executive (HSE) introduced MSER.[5] These regulations (through an associated Approved Code of Practice[6]) included, amongst many other things, revised and increased QDs for relatively small quantities of mass exploding explosives held in steel and brick magazines. The revised QD prescriptions

Table 1. *Fragment data for stickless rockets trial*

Radius/m	Annulus/m	No. of fragments	No. of fragments per m^2
30	20–40	5	1.326×10^{-3}
50	40–60	16	2.546×10^{-3}
70	60–80	24	2.728×10^{-3}
90	80–100	15	1.326×10^{-3}
110	100–120	46	3.328×10^{-3}
130	120–140	70	4.285×10^{-3}
150	140–160	102	5.411×10^{-3}
170	160–180	83	3.885×10^{-3}
190	180–200	90	3.769×10^{-3}
210	200–220	145	5.495×10^{-3}
230	220–240	54	1.868×10^{-3}
250	240–260	76	2.419×10^{-3}
270	260–280	38	1.120×10^{-3}
290	280–300	13	3.567×10^{-4}
310	300–320	11	2.824×10^{-4}
330	320–340	8	1.929×10^{-4}
350	340–360	9	2.046×10^{-4}
370	360–380	2	4.301×10^{-5}
390	380–400	4	8.162×10^{-5}
410	400–420	4	7.764×10^{-5}
430	420–440	0	0
450	440–460	3	5.305×10^{-5}
470	460–480	2	3.386×10^{-5}
490	480–500	0	0
510	500–520	0	0

were designed to ensure that the individual risk to members of the public would be kept to a level judged to be broadly acceptable (i.e. a risk of fatal injury no greater than 10^{-6}, or 1 in one million per year). In cases where licensed facilities are located near to areas of high population density (‘urban’), more restrictive distances apply; these are designed to ensure that the chance of an accident causing 10 or more fatalities would be less than 10^{-5} per year, in addition to ensuring that no one person would be exposed to an individual risk greater than 10^{-6}.

Adequacy of quantity distances against trials results

The CHAF large scale ISO container trial on 5011 kg of stickless rockets produced debris out to 462 m. The TNT equivalence for this configuration of fireworks was measured as 3367 kg, and the MSER inhabited building distance (IBD) for this mass of TNT is 362 m. The question then is whether the MSER prescriptions are adequate, given that debris was thrown beyond the currently prescribed IBD. This is now examined first in regard to individual risk.

The individual risk (IR) for a person living at the IBD from an explosives facility is given by:

$$\mathrm{IR} = \mathrm{PE} \times \mathrm{FE} \times (T_O \times L_O + T_I \times L_I)$$

where

> PE is the likelihood of accidental explosion, expressed as an annual probability;
>
> FE is the individual’s fractional exposure, i.e. the fraction of time per year that the individual is present at the IBD;
>
> T_O is the fraction of time the individual spends outdoors at the location;
>
> L_O is the conditional probability that the individual would be killed in the event of an explosion, given that the person is outdoors;
>
> T_I is the fraction of time the individual spends indoors at the location;
>
> L_I is the conditional probability that the individual would be killed in the event of an explosion, given that the person is located indoors.

PE for UK commercial explosives magazines has been estimated[7] to be 10^{-4} per magazine-year.

FE is conservatively assumed to be unity, i.e. the person is constantly exposed to risk.

T_O and T_I, the fraction of time each individual resident is assumed to spend both outdoors and indoors at the location, are 0.11 and 0.89 respectively (these figures are typically used by HSE in studies of the risks arising from industrial activities).

L_O and L_I express lethality from the combined effects of both debris and blast. The overall level of lethality for population outdoors (L_O) and indoors (L_I) is then given by:

$$L_O = F_{Do} + F_{Bo} - F_{Do} \times F_{Bo}$$

and

$$L_I = F_{Di} + F_{Bi} - F_{Di} \times F_{Bi}$$

where

> F_{Do} is the outdoor probability of fatal injury due to debris effects,
>
> F_{Di} is the indoor probability of fatal injury due to debris effects,
>
> F_{Bo} is the outdoor probability of fatal injury due to blast effects,
>
> F_{Bi} is the indoor probability of fatal injury due to blast effects,
>
> and the products $F_{Do} \times F_{Bo}$ and $F_{Di} \times F_{Bi}$ prevent double counting.

Thus:

$$\mathrm{IR} = 0.0001 \times 1 \times [0.11 \times (F_{Do} + F_{Bo} - F_{Do} \times F_{Bo}) + 0.89 \times (F_{Di} + F_{Bi} - F_{Di} \times F_{Bi})]$$

Lethality due to debris effects

Outdoor lethality, L_O, is effectively determined by debris effects (blast effects to people outdoors are negligible except at very close range) and is dependent on both the density of lethal debris at the given range and the target area presented by the exposed person, viz.

$$L_O = 1 - e^{-D \times A}$$

where

> D is the lethal debris density, and
>
> A is the effective target area of the exposed person

This Poisson distribution equation gives the probability that a given person at the range will be struck by at least one piece of potentially lethal debris. If a value can be assumed for the target area presented by an average person to incoming debris, then values of L_O can be computed using the debris density measurements derived from the analysis of the magazine trial data.

Target areas will, of course, be dependent on the size and shape of the exposed person and the angle of descent of the incoming debris. Ballistic calculations suggest that debris landing in the mid to far field, where the IBD will be located, will mostly impact the ground at angles between 49° and 76°, giving an average target area of 0.22 m^2. For debris projected out horizontally and passing the range below head height an average target area of 0.56 m^2 is appropriate.

Determination of lethal debris densities

In the next stage of analysis values were computed for the density of lethal debris produced at various distances from the explosion. Two possible procedures were considered, the first producing "pseudo trajectory normal" (PTN) debris densities and the second producing "modified pseudo trajectory normal" (MPTN) debris densities[4].

The PTN method assumes that a person at a particular range is at risk of being struck not only by debris landing at that range but also by all the debris that travels beyond the range. This implies that fragments which pass over the range do so at head height or below. In practice many of these fragments are likely to pass at heights significantly greater than head height.

The MPTN method provides an alternative, less conservative procedure for analyzing the data. This assumes that only one-third of the debris passing beyond a given range poses a risk to anyone located at that range; in other words two-thirds of the debris passes above head height.

As with the previous analysis for the MSER QDs, the less conservative MPTN method has been adopted in this study. This is largely in consideration of the fact that steel ISO containers can be expected to balloon somewhat before fragmenting, resulting in a more even distribution of debris launch angles than would be the case with brick stores holding a small NEQ – where the roof of the buildings lifts off vertically and where the walls move out more or less horizontally towards any exposed sites.

Applying this methodology to the data presented in Table 1 allows the data in Table 2 to be constructed.

A regression analysis of these data produces the following lethality function:

$$L_{Do} = -6.780171583533 \times 10^{-16} R^6$$
$$- 1.423336053601 \times 10^{-12} \times R^5$$
$$+ 2.540655404929 \times 10^{-9} \times R^4$$
$$- 1.275797107962 \times 10^{-6} \times R^3$$
$$+ 2.568501531817 \times 10^{-4} \times R^2$$
$$- 2.687365853920 \times 10^{-2} \times R$$
$$- 7.830518274706 \times 10^{-1}$$

where R is the range (m) within the limits 30–490 m.

There is, of course, no underlying physical reason why lethality for people located in the open should be related to the 6th power of the range; the regression analysis is simply a convenient way of providing a continuous function.

In general, people indoors would be afforded a certain amount of protection from flying debris by the walls and roof of the building. Clearly the degree of protection will increase the smaller the area of glazing and the greater the thickness and strength of the walls and roof. The approach adopted in this study is to assume that occupants will only be at risk from those pieces of debris that strike an area of glazing (this assumption was also applied in the derivation of the MSER QD tables). Taking account of typical debris descent angles and dimensions for modern housing, indoor lethality probabilities are assumed to be one-twelfth of those derived for outdoor population.

Lethality due to blast effects

Two well-established blast models were available to the study: the ESTC Outdoor Blast Model[8] (for population located in the open) and the ESTC Indoor Blast Model[9] (for population located inside buildings of conventional construction). These models are described briefly below.

The ESTC Outdoor Blast Model

Table 2. *Lethality for persons outdoors (L_{Do}) as a function of range from ISO container*

Range/m	Area/m^2	No. of fragments	MPTN Density	L_{Do}
30	3770	5	7.3447×10^{-2}	3.9863×10^{-2}
50	6283	16	4.4970×10^{-2}	2.4024×10^{-2}
70	87976	24	3.2122×10^{-2}	1.6916×10^{-2}
90	11310	15	2.3746×10^{-2}	1.2764×10^{-2}
110	13823	46	2.0562×10^{-2}	1.0329×10^{-2}
130	16336	70	1.7439×10^{-2}	8.2745×10^{-3}
150	18850	102	1.5008×10^{-2}	6.5430×10^{-3}
170	21363	83	1.1058×10^{-2}	4.8594×10^{-3}
190	23876	90	8.9304×10^{-3}	3.7125×10^{-3}
210	26389	145	8.3493×10^{-3}	2.7949×10^{-3}
230	28903	54	3.8289×10^{-3}	1.5078×10^{-3}
250	31416	76	3.4165×10^{-3}	1.0915×10^{-3}
270	33929	38	1.6701×10^{-3}	5.5433×10^{-4}
290	36442	13	7.5004×10^{-4}	2.9870×10^{-4}
310	38956	11	5.5619×10^{-4}	2.1543×10^{-4}
330	41469	8	3.8583×10^{-4}	1.5046×10^{-4}
350	43982	9	3.1831×10^{-4}	1.0867×10^{-4}
370	46496	2	1.3621×10^{-4}	6.1653×10^{-5}
390	49009	4	1.4283×10^{-4}	5.2234×10^{-5}
410	51522	4	1.0999×10^{-4}	3.5195×10^{-5}
430	54035	0	3.0844×10^{-5}	1.7273×10^{-5}
450	56549	3	6.4841×10^{-5}	1.8273×10^{-5}
470	59062	2	3.3863×10^{-5}	7.4498×10^{-6}
490	61575	0	0	0

The ESTC Outdoor Blast Model is designed to estimate the likelihood of blast-induced fatality for persons in the open following an explosion of Hazard Type 1 (mass exploding) material. It is based on a review of the available literature on primary and tertiary blast effects, and gives a single prediction of fatality probability as a function of scaled distance. Fatality probability, range and NEQ are related by equation (1):

$$F_{Bo} = \frac{e^{\left(-5.785\times\left(R/Q^{1/3}\right)+19.047\right)}}{100} \tag{1}$$

where F_{Bo} is the fatality probability, R is the range (m) and Q is the NEQ (kg).

The model is applicable to population in the open between a scaled distance (actual distance/$Q^{1/3}$) of 2.5 and 5.3 m kg$^{-1/3}$.

A fatality probability of unity is assumed for scaled distances less than 2.5 m kg$^{-1/3}$ while a zero fatality probability is assumed for scaled distances greater than 5.3 m kg$^{-1/3}$.

The ESTC Indoor Blast Model

The ESTC Indoor Blast Model is designed to estimate likelihood of blast-induced fatality for persons within a conventional UK brick building following an explosion of Hazard Type 1 material external to the structure. This model is based on an analysis of casualty data collated from records of a number of major incidents of accidental explosion. It is worth noting that the fatality data on which the model is based do not differentiate between those killed by blast and those killed by fragments; it is assumed that blast effects were responsible for most of the fatalities recorded, but the model implicitly makes some allowance for fragment/debris effects. Fatality probability, range and NEQ are related by equation (2):

$$Log(F_B) = 1.827 - 3.433.Log\left(\frac{R}{Q^{1/3}}\right) - 0.853.\left(Log\left(\frac{R}{Q^{1/3}}\right)\right)^2 + 0.356.\left(Log\left(\frac{R}{Q^{1/3}}\right)\right)^3 \quad (2)$$

where

F_{Bi} is the fatality probability, R is the range (m), Q is the NEQ (kg)

The model is applicable to population inside buildings of conventional construction and for scaled distances in the range 3.06 to 55 m kg^{-3} and has been applied within these limits. A fatality probability of unity is assumed for scaled distances less than 3.06 m kg^{-3} while a zero fatality probability is assumed for scaled distances greater than 55 m kg^{-3}.

Possible IBD based on individual risk criterion

The individual risks at distance from the large scale stickless rockets trial can now be calculated using the earlier formula:

$IR = 0.0001 \times 1 \times [0.11 \times (F_{Do} + F_{Bo} - F_{Do} \times F_{Bo}) + 0.89 \times (F_{Di} + F_{Bi} - F_{Di} \times F_{Bi})]$

The results of these calculations are shown in Table 3.

This shows that at a distance around 142 m the individual risk of fatality is 1×10^{-6}.

Table 3. *Individual risks at distance from the large scale stickless rockets trial.*

Radius/ m	No. of fragments	Outdoor blast lethality	Outdoor fragment lethality	Indoor blast lethality	Indoor fragment lethality	Overall individual risk of fatality (per year)
30	5	1.00×10^{0}	4.07×10^{-2}	1.00×10^{0}	3.39×10^{-3}	1.00×10^{-4}
50	16	7.78×10^{-3}	2.35×10^{-2}	7.05×10^{-1}	1.96×10^{-3}	6.31×10^{-5}
70	24	3.45×10^{-6}	1.64×10^{-2}	1.79×10^{-1}	1.37×10^{-3}	1.62×10^{-5}
90	15	0	1.28×10^{-2}	6.39×10^{-2}	1.07×10^{-3}	5.92×10^{-5}
110	46	0	1.04×10^{-2}	2.80×10^{-2}	8.70×10^{-4}	2.68×10^{-6}
130	70	0	8.53×10^{-3}	1.41×10^{-2}	7.10×10^{-4}	1.41×10^{-6}
150	102	0	6.75×10^{-3}	7.86×10^{-3}	5.63×10^{-4}	8.24×10^{-7}
170	83	0	5.09×10^{-3}	4.73×10^{-3}	4.24×10^{-4}	5.15×10^{-7}
190	90	0	3.62×10^{-3}	3.02×10^{-3}	3.02×10^{-4}	3.36×10^{-7}
210	145	0	2.44×10^{-3}	2.03×10^{-3}	2.03×10^{-4}	2.25×10^{-7}
230	54	0	1.56×10^{-3}	1.41×10^{-3}	1.30×10^{-4}	1.54×10^{-7}
250	76	0	9.69×10^{-4}	1.02×10^{-3}	8.07×10^{-5}	1.08×10^{-7}
270	38	0	5.90×10^{-4}	7.52×10^{-4}	4.93×10^{-5}	7.78×10^{-8}
290	13	0	3.60×10^{-4}	5.70×10^{-4}	3.00×10^{-5}	5.74×10^{-8}
310	11	0	2.23×10^{-4}	4.41×10^{-4}	1.86×10^{-5}	4.34×10^{-8}
330	8	0	1.43×10^{-4}	3.48×10^{-4}	1.19×10^{-5}	3.36×10^{-8}
350	9	0	9.53×10^{-4}	2.78×10^{-4}	7.94×10^{-6}	2.65×10^{-8}
370	2	0	6.61×10^{-4}	2.26×10^{-4}	5.50×10^{-6}	2.13×10^{-8}
390	4	0	4.71×10^{-4}	1.86×10^{-4}	3.92×10^{-6}	1.74×10^{-8}
410	4	0	3.37×10^{-5}	1.54×10^{-4}	2.81×10^{-6}	1.44×10^{-8}
430	0	0	2.33×10^{-5}	1.30×10^{-4}	1.94×10^{-6}	1.20×10^{-8}
450	3	0	1.47×10^{-5}	1.10×10^{-4}	1.22×10^{-6}	1.01×10^{-8}
470	2	0	7.79×10^{-6}	9.39×10^{-5}	6.49×10^{-7}	8.50×10^{-9}

Possible IBD based on group risk criterion

The criteria against which the revised and current QD prescriptions were fixed, were (1) to limit the level of individual risk of fatality to any identifiable person to 10^{-6} per year, and (2) to ensure that the chance of an accident causing 10 or more fatalities would be less than 10^{-5} per year. This latter criterion is somewhat stricter than that advocated in the first report of the Advisory Committee on Major Hazards (ACMH), which recommended that the chance of a serious accident (involving the death of 10 or more people) at any one major non-nuclear plant should be less than 10^{-4} per year.[10] In practice the group risk criterion only takes effect in the case of stores located near to areas of urban population density (4210 persons per km^2).[11] Given that the generic rate of accidental explosion has been assessed as 10^{-4} per storehouse-year,[7] it can be shown[11] that the group risk criterion is met when the average number of fatalities expected in the event of an accident does not exceed 6.225[12]. From this it follows that the minimum IBD conforming to the group risk criterion can be obtained from the following equation:

$$6.225 = A \times d \times (L_O \times T_O + L_I \times T_I)$$

where

A is the area of the danger zone

d is the population density in the danger zone,

L_O, T_O, L_I and T_I are defined as before.

The danger zone is defined as that area between the inhabited building distance (IBD) already determined by the individual risk criterion, and the range where the effects of any potential explosion would decay to a level that could be considered, for all practical purposes, sub lethal. The latter range is defined as the distance at which lethality falls to 10^{-4}, as predicted by the explosion consequence models. This range corresponds to an individual risk of 10^{-8}, a value generally regarded as negligible. The model involves iterative calculations in which the IBD is extended by 1 m at a time until the group risk criterion is met. In this instance whilst the outer radius of the danger area is 450 m, the group risk criterion is met at a distance of 198 m.

Conclusions

The furthest distance of debris travel from the large-scale stickless-rocket fireworks ISO container trial was just over 450 m. The TNT equivalent of the associated explosion was measured to be 3367 kg, which if stored inside an unmounded metal magazine, would be required under MSER to have an IBD of 362 m. From an analysis of the debris distribution data from the fireworks trial and, based on the individual risk criteria of 1×10^{-6} outlined above, an IBD prescription of 142 m would be appropriate. If a person were permanently located at the MSER IBD of 362 m the individual risk to that person would be 3×10^{-8}. This is an exceptionally low level of risk and is very much below the overall background level of risk to which people are exposed in their daily lives. A further analysis of the trials debris data based on the group risk criteria outlined above, indicates that an IBD prescription of 198 m would be appropriate. Clearly this distance is well within the current IBD. Thus based both on the individual and group risk criteria, the existing MSER IBD prescription is more than adequate to ensure a high level of safety for persons living, working or travelling near an area where an ISO container packed with mass-exploding fireworks of the type described in this paper is located.

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