What is a "Safety Distance" for a Shell?

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Abstract: *This paper outlines the risk assessment methodologies and calculates the risks affecting the audience from the malfunctioning of shells. Risks may arise from premature functioning of shells, from stars falling on the audience from low bursting shells, and from shells bursting in or near the audience. Two mathematical approaches are taken using* Shellcalc© *derived data to determine the distances from the firing point of a shell that lead to an individual risk to a member of the audience.*

Keywords: *shells, risks, fallout, debris*

Introduction

In developing the European Standards[1] for "professional" fireworks and other pyrotechnics the question of what is the "safety distance" is frequently posed by experts and enforcing authorities. Unfortunately no activity involving pyrotechnics is ever "safe", not for operator and not for audience, and in many cases the nationally prescribed and often fixed "safety distances" may be regarded by others as overly draconian or too lenient. The major problem with fixed "safety" distances is that they do not provide a guarantee of safety – they tend to be arbitrary distances based on local custom and practice, and do not consider any risk control measures that have been adopted by the firer.

But in fact the question (and the answer) is wrong – what we really need to know is what fireworks can be fired at a given site, under the conditions prevailing and the methods and techniques adopted by the firer and hence provide an acceptable level of risk to those exposed to the risks. Any human activity poses some level of risk – it is just that we, both as individuals and as a society, tolerate some levels of risk more than others.

This paper illustrates the risk assessment process for, predominantly, shells at a variety of sites under a variety of conditions which leads to an assessment of the distances required from the point of firing to the audience under the specified conditions.

It does necessarily concentrate on the use of aerial shells at firework displays as these inevitably pose the greatest hazards, but the principles employed would also be suitable for outdoor displays not involving shells, or for events using theatrical or other pyrotechnics.

Safety and risk

Unfortunately, as practitioners of a occupation involving the use of hazardous materials we have to face two basic facts:

- The public are not good at statistics
- The public do not understand the concept of risk

Given these hurdles it is not surprising that the firework industry, and indeed any other industry that presents any form of risk to the public, battles to justify even their normal operation, and faces a barrage of criticism when something goes wrong.

Unfortunately we are not assisted by the law here. Most regulatory regimes require a person creating a risk to identify, assess and manage that risk – this is the basis of the, often abused, Risk Assessment approach to safety management.[2] This approach is the correct approach though – it simply is not realistic to consider only hazard, especially if hazard is considered in isolation to benefit.

Using a non-firework situation, for instance, the

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potential hazards from nuclear power generation are enormous – accidental meltdown after unauthorised experimentation, aerial contamination following a leak, long term mutagenic effects from exposure to radiation, potential terrorist threat at the plant or from its products, massive waste disposal issues, the potential rendering of large areas radioactive and contamination of the food chain – all are realistic potential hazards. What allows the world to even consider using nuclear power is firstly the benefits (electricity generation, lack of acidic or greenhouse gas emissions for such generation, independence of security of supply) but more importantly the control of all the hazards by rigorous application of risk analysis and the resulting extremely low frequency of any of the identified hazards arising.

The difference between risk and hazard

Hazard is the intrinsic harm that may be done by a particular sequence of events – for instance IF a shell bursts in the crowd people will be injured or killed. It does not relate to the likelihood of that event happening – if a shell bursts in the crowd it makes no difference how the shell came to be there!

Risk relates the intrinsic hazard to the likelihood of that event occurring and thus equates the frequency of an event (or series of related events leading to the eventual hazardous outcome) with the hazard of that event to provide a perception of the risk. In essence

$$\text{Risk} = \text{Frequency} \times \text{Hazard}$$

In the case of the shell bursting in the crowd the intrinsic hazard is very high, but the likelihood is normally extremely low – and thus the perceived risk (and the calculated risk – see later) remains acceptable.

Unfortunately when a very rare incident does occur the public and the press react as if that occurrence were actually commonplace, and worse, if the case comes to court, the court will tend to dismiss the frequency and hence the risk arguments and effectively state that in the particular case the frequency was one – it happened – and therefore and measure of the likelihood is now irrelevant and that as a consequence that only the hazard should be considered.

Until the discrepancy between the law makers and the courts is resolved, and until the public appreciate the difference, it is a battle that will continue to have to be fought – not only by the pyrotechnics industry.

Individual and societal risk

In considering risk we need to address the risk of several different classes of people:

- The risks to a single person in the audience or a display firer – usually taken to be the risks to a specified individual
- The risk to a group of people

Assessing the risk to a specified individual is both relatively straightforward and relates to the experience that individual has of risk, whether they are benefiting from the activity causing the risk (e.g. they are a paid display operator), whether they might be aware of the risks being posed to them (again a display operator) and those who neither gain, nor can realistically be expected to understand the potential risks they are being exposed to (in most cases this is the situation of a member of the audience).

Assessing and justifying the risks to a group of people is much more difficult. Society has an understandable aversion to incidents that injure many people – which is not proportionate to the number of people injured. We generally, as an example, are much more averse to a road accident that kills ten people than we would be to ten accidents each killing a single person. This may appear callous, but it is a demonstrable fact borne out, not least, by the media reporting of such incidents.

Many authors have used the F–N curve approach[3] to attempt to quantify the societal risk to members of the public affected by an incident. In this approach N is the number of fatalities and F is the frequency of N or more fatalities, and the resulting plot may typically look like either a step function or a smoothed curve.

It is sometimes appropriate to attempt to superimpose on such a plot the public aversion to the risks identified but there are also more sophisticated[4] ways of determining such aversion.

Societal risk[5] is difficult to quantify in a simple, unambiguous and objective way, and for the remainder of this paper we will concentrate on quantifying individual risk. Where appropriate, however, illustrations of societal risk factors will be made.

Risks and benefits

At firework displays it is important to consider that alongside potential individual and societal risks there are individual and societal benefits associated with the display. For instance for the firers and others involved in the event:

- Income for the firers
- Income generation for other performers

and for those witnessing or benefiting from the event:

- Getting people outdoors
- Income for charities at fund raising events
- Socialising
- General individual "feel good" factor of witnessing a spectacular display
- Enjoyment of a spectacle by a very large number of people, often for no charge, at extended distances

Just because there are associated societal risks doesn't mean that such events should be banned! There are plenty of examples where people, as groups or individuals, are prepared to accept significant risks for their benefit – even when the risks are not directly under their control – for instance:

- Flying away on holiday (risk of plane crash by mechanical or pilot error or by hijacking)
- Taking part in sports (risk of injuries or death)
- Watching a film in a cinema (risk of building fire or collapse)
- Driving (risk of crash caused by mechanical failure, or by driver error or by accident)
- Walking to a bar (risk of accident on the way, or as a result of drinking)

Any meaningful risk assessment process needs to address the costs of identified risk reduction measures, and thus to determine whether such costs are justified. Basing a paper Risk Assessment on unachievable or unaffordable control measures is not helpful or informative to anyone.

Cost–benefit analysis

For instance, in deciding if the risks arising from firing shells can be reduced it is necessary to consider

- How many mortars are used
- How many times they are reused
- How many shows are fired in a year
- How much the control measure would reduce the risk
- How much each control measure would cost
- What cost is placed on a life or on injuries

The last parameter may seem flippant, but without equating benefits and costs a risk assessment approach is almost meaningless. It simply is not practical or sensible to consider that ALL identified control measures are justified. It may be possible to reduce the risk of fatality from, say, one in one million to one in two million – but is such a reduction statistically significant, and is the cost of such a control measure justified? If the cost is, for instance in the case of mortars, comparable to the cost of a mortar the answer is probably "yes" – if the cost is 100 times the cost of a mortar it is almost certainly "no".

In general we believe that any control measure that decreases risk by a factor of less than ten is probably not worth contemplating in isolation.

We will examine this area in more detail later and attempt to equate the risk reduction to the costs of that managing the risk

The simple mathematical treatment of risk

As we have seen, in simple terms, risk is calculated as follows:

$$\text{Risk} = \text{Frequency} \times \text{Hazard}$$

Low risk events may occur if either the frequency or the hazard (or both) is low; the highest risk events

Table 1. *Very simple risk assessment methodology.*

	Low frequency	Medium frequency	High frequency
Low hazard	Very low risk	Low risk	Medium risk
Medium hazard	Low risk	Medium risk	High risk
High hazard	Medium risk	High risk	Very high risk

occur when the hazard and the frequency are high. In the simplest terms it is useful to illustrate the inter-relationship between frequency, hazard and the resulting risk – this is shown in Table 1.

In most cases we simply do not engage with high risk events at firework displays – it would be morally wrong, and commercially suicidal, to do so. However, as a consequence of only dealing with relatively low risks and especially with very low likelihood events there is a danger of complacency on the part of the operator, an assumption that "low risk" equates to "safe" and often a reluctance to comprehend the actual risks posed.

Somewhat more complex approaches to risk assessment include ranking of both likelihood and hazard on a suitable scale and treating the product of the two numbers as the risk.[6] We generally use the approach where hazard and likelihood are both rated on a 0–10 biased scale – because the resulting product has a maximum value of 100, and because there are situations where either the likelihood or frequency is truly zero and zero times anything is still zero! Biasing the scale puts greater emphasis on the highest frequency or highest hazard events and means, for instance, where a number of related events are considered together these high frequency or high hazard occurrences are not ignored.

There are occasions, however, where the simplistic approach is not appropriate and a simple quantified risk assessment (QRA) leads to better understanding (and therefore potentially better mitigation) of the risks.

This is the approach we will take in this paper.

The risks at firework displays

The risks at firework displays can be broadly separated into two areas

- Risks from the normal functioning of the fireworks (e.g. expected debris)
- Risks from the abnormal functioning of the fireworks (by product failure or operator error)

Both are important in determining the choice of fireworks and the suitability of site and the inter-relationship between the two. If the site has inbuilt flexibility (e.g. a barge that can be moved to maximise the fallout area under any wind conditions) then the choice of fireworks for the display may be much more extensive than if the site is fixed (e.g. a rooftop). Furthermore on the rooftop there may have to be various contingency plans to curtail or cancel the display in adverse conditions which may not need to be mirrored for the display on a barge.

If we take a typical firework display mix of products we can determine which are likely to pose the greatest risks as shown in Table 2.

The potential risks from "normal" debris from shells are relatively low (although the frequency of "normal" debris falling on the audience is surprisingly high, the hazard is low and hence the risk is low) and most firework companies have developed tables equating shell burst height and wind strength with fallout distance.

The SHELLCALC© programme, developed by Harradine and revised by Smith,[7] calculates the trajectories of shells and comets depending on a variety of user-inputs including:

- calibre
- firing angle
- wind direction and strength
- "barrelling" or "tumbling" effects (which add a realistic variation in shell dispersion)
- muzzle velocity (if known)
- mass of the shell or comet if known (and calculates comets having a decreasing mass during flight)
- shell delay (for determining if the shell

Table 2. *Potential risks from various firework types.*

Firework type	Subtypes	Potential risks
Shells	Colour shells	Normal debris (especially long burning stars) Risks from subcomponents Abnormal firing angles (from mortar disruptions) "Blinds" Blast/fragments from bursts
	Maroons	As above plus Increased blast/fragments from bursts
	Aqua shells	Unpredictable range
Roman candles	All types	Projectile effects
Rockets	Flight rockets	Random flights
	Display rockets	Blast/fragments from bursts Debris (sticks)
Mines	All types	Minor projectile effects Risks from subcomponents
Fountains	All types	Sparks Failure of casing – unintended explosion
Set pieces	Lancework	Relatively minor
	Wheels and set pieces	"Throwing" driver from wheel Failure of support

reaches the ground or bursts in the air)

In general SHELLCALC© is not particularly useful in determining "normal" debris from the functioning of shells. For this, analysis of wind speed and direction from the burst point (which of course may itself be estimated by using SHELLCALC©) and the time for fallout to reach the ground (or other areas) are more useful.

In the case of shells, in general it is the largest calibre shells, fired from displaced mortars, that pose the greatest risks. However lower hazard, higher frequency, events may actually pose the same or at least significant risks to both operators and the audience. For instance the main "normal" debris from rockets (their sticks) can travel significant distances downwind of the firing site and has the potential to cause significant harm.

For a display with several different calibres of shells, which is the norm, the high hazard/low frequency failure of the largest calibre shells may be outweighed by less hazardous but more frequent failures of lower calibre shells. This arises for four main reasons:

- In general large calibre shells are manufactured to a higher quality than small calibre shells (for instance they may contain dual or multiple internal delay fuses)
- There is usually a higher number of smaller calibre shells than large calibre shells in a display – indeed the numbers of shells fired are usually inversely related to their calibre (because of cost and aesthetic features)
- Smaller shells are more usually fired at greater deliberate angles than large calibre shells
- Smaller shells are more usually fired from "racks" than larger calibre shells

However, as will be seen, the risks from the largest calibre shells are usually the ones considered in risk assessments. This is because

- Larger shells generally rise to a greater height – therefore "normal" debris is likely to travel further downwind than debris from smaller calibre shells

- If the mortar is disrupted the range of the shells is greater
- The burst charges of larger calibre shells are greater and hence likely to cause greater injury if a larger calibre shell bursts in/near the audience

Mathematical evaluation of risk

The remainder of this paper will address a more complex mathematical evaluation of the risks posed from shells to the audience at firework displays – a so-called "Quantified Risk Assessment" (QRA). The principles applied are also valid for other firework types, and for use of other pyrotechnic devices (for instance indoors).

To evaluate the risks to individuals in the audience from shells, we first need to consider what are considered the benchmarks for the acceptability of risk.

In general the following are the UK accepted guidelines for risk of fatality

- 1×10^{-6} – broadly acceptable
- 1×10^{-5} to 1×10^{-4} – the so called "ALARP" region (1×10^{-5} to 1×10^{-3} for workers)
- $>1 \times 10^{-4}$ – unacceptable ($>1 \times 10^{-3}$ for workers)

This means that a member of the public should consider broadly acceptable the chance of being killed at a firework display as one in a million – about ten times the chance the same individual has of winning the UK lottery on any one week. This seems at least reasonable – no one expects to win the lottery, no one should expect to be killed at a firework display!

In general we will use the 1×10^{-6} "broadly acceptable" criterion for determining the risk to an individual.

The so called "ALARP" region (discussed below) is where the level of risk is still permissible, but that measures should (if at all possible and practical – especially when related to cost) be implemented to reduce the risk still further.

It is accepted that people who directly benefit from an activity involving risk (i.e. firers) may be subject to a greater range of ALARP than would the audience and this is reflected in the figures given above. However neither should ever be exposed to risks in the "unacceptable" region.

ALARP
"As Low As is Reasonably Practical"

The UK Health and Safety Website[9] includes the following observations (our emphasis) on ALARP:

> *Thus, determining that risks have been reduced ALARP involves an assessment of the risk to be avoided, of the sacrifice (in money, time and trouble) involved in taking measures to avoid that risk, and a comparison of the two.*
>
> *This process can involve varying degrees of rigour which will depend on the nature of the hazard, the extent of the risk and the control measures to be adopted. The more systematic the approach, the more rigorous and more transparent it is to the regulator and other interested parties. However, duty-holders (and the regulator) should not be overburdened if such rigour is not warranted. The greater the initial level of risk under consideration, the greater the degree of rigour HSE requires of the arguments purporting to show that those risks have been reduced ALARP.*

It is clear that the costs are critical in determining the proportionality of any risk control measures. Demonstration, by means of analyses such as presented in this paper, should be enough to satisfy that the the risks have been reduced to ALARP and hence that they should be accepted by operators, the audience and, if necessary, the courts provided, of course, that they truly represent the risks involved and that operator error or disproportionate ratios of product failure have not been a contributing factor.

Risk to the operator vs risk to the audience

In all assessment of risks it is essential to consider all consequences of the identified hazard. For instance in firing shells it is important to consider:

- The effects on the audience AND
- The effect on the operators

Some things that reduce risk for operators MAY increase risk to audience (and *vice versa*). For instance, it is often (correctly) stated that electric firing of shells is safer for the operator – but it possible that electric firing of shells actually poses a greater risk to the audience than manual firing. It could conceivably be that the firing of one shell (as discussed below) displaces an adjacent mortar so that it is directed at the audience – if the firer is "merely" pushing a button 100 m away along a piece of wire they will fire the second shell unaware that it is lying in a displaced mortar. A person manually firing would simply not fire the second shell! This is NOT to say electric firing is bad – just that the consequences of one risk reduction method might actually increase the risks to another party and therefore appropriate measures to control the additional risk should be taken.

For simplicity, for the remainder of this investigation we will concentrate on the effects to the audience only.

Hazards from shells

There are several major hazards from the firing of shells as shown in Table 3. Of course, the risks arising from these hazards depend on the frequency of each event occurring. In the remainder of this paper we will concentrate on fatality hazards, and risks to the audience.

It is important to identify the critical events to consider, and where possible to separate key events leading to various scenarios.

For example

- What is the overall rate of shell failures (of any type)
- What proportion of general failures could affect the correct functioning of an adjacent mortar
- If a mortar is fired at an undesirable (and unplanned) angle – what proportion of those could affect the audience (i.e. are "shot" towards the audience
- What proportion of shells fired from disrupted mortars could actually impact on the audience, and which will function "normally" without affecting the audience – for instance by bursting at sufficient height that the stars do not reach the audience
- What proportion will function "abnormally" (e.g. fail to burst in the air) and thus present a different hazard to the audience
- How many people may be affected by each failure mode

Table 3. *Potential hazards from shells.*

Type	Hazards	Comments
"Normal" functioning of a shell	Lit debris drifting downwind, especially from long burning stars	General unlikely to cause fatalities by direct action – although may impact on structures leading to fire
"Abnormal" functioning of a shell when fired in designed orientation	"Blind" shells	Obviously worst if the mortar is angled
Premature functioning of a shell	Flowerpot, muzzle breaks or in mortar explosion – especially if it leads to disruption of adjacent mortars	See below
Disruption of the mortar from external event and subsequent "normal" functioning	Low bursting shells at unplanned firing angles – risk if stars reach the audience	If mortar is fired near vertical then the risk of stars impacting the audience is very low
Disruption of the mortar from external event and subsequent "abnormal" functioning (e.g. "blind")	Shells at unplanned firing angles – risk if shell lands in or adjacent to the audience	Impact or close-proximity effects from fragments and blast

Table 4. *UK shell accidents from EIDAS database.*

Date	Location	Injuries	Fatalities	Cause/Comments
5/11/2005	Kettering, UK	1 major, 10 minor		Rack collapse, shell burst near crowd
1/11/2004	Middleton, UK	1		Shell or stars fired into leg
3/11/1996	Wilmington, UK		1	Incorrectly fired (Cat 3)
2/11/1996	Hazelmere, UK		1	Head over mortar (Cat 3)
1927	Unknown		1	Head over mortar
25/6/1910	Leeds, UK	7	3	Shell detonated in steel tube
19/9/1898	Folkestone, UK	1		Mortar burst
2/6/1896	Doncaster, UK	3	1	Mortar lands in audience
5/8/1895	Brighton, UK	25	1	Mortar burst
24/12/1886	Bately, UK	5	1	Mortar tipped over prior to firing
25/9/1882	Hull, UK	3	2	Mortar burst
19/7/1882	London, UK		1	Mortar burst

- What is the frequency of injuries/fatalities from the postulated shell failure mode

We have made some very general assumptions on the basis of data regarding shell failures collated from informal and formal surveys of the UK firework industry.

For injury and fatality data we have examined the UK Explosives Incidents (EIDAS)[10] database for reported accidents involving shells and the results are shown in Table 4.

Note that in several cases identified in EIDAS it appears that fragments of the mortar were the cause of the injuries/fatalities – rather than the shell itself. This is obviously an important factor, particularly when using metal mortars, but we have not considered it further here for 3 main reasons:

- The use of metallic mortars (particularly steel) is decreasing
- The injuries are most likely to occur to operators not the audience
- There has been a general trend to move fireworks further from the audience for aesthetic and practical reasons, as well as for general perceived safety reasons.

It is also relevant to note that the number of accidents is actually very low – the data spans 1882 to 2005 and includes the period (up to 1996) when shells were available for the general public to purchase and use.

Where a shell lands in the crowd, the apparent outcome is most likely to be a single fatality (if a fatality occurs) – so we have set the likelihood of such a fatality to be 1. For shells that do not burst in the crowd we have set the fatality likelihood as 0.1 (see Table 5).

All the above information is collated in Table 6.

The nature of the display site and the scale of the display also affect the likelihood of a particular shell reaching the audience.

Most significant is the angle that the audience subtend, that is they occupy, at the perimeter of a circle drawn around the display site and examples are given in Table 7. It is often the case that smaller professionally fired displays subtend relatively small angles to the audience – a private function for example is likely to have a relatively

Table 5. *The failure modes of shells involving fatalities.*

Failure mode	No and likelihood of fatalities	Comments
Shell bursts above the audience so that stars reach the audience	Multiple injuries Single fatality (hazard = 0.1)	
Shell busts in or near the audience so that people are affected by impact or by bursting of the shell, or by fragments of the shell	Multiple injuries Single fatality (hazard = 1)	It is possible for multiple fatalities to occur in this situation – a brief examination of the societal risk aspects will be made below

small audience in a relatively small area – and the display itself to be fired some distance away.

Larger displays often are fired from positions where the audience may subtend significant angles – up to situations where the audience, in effect, surrounds the display site. However, in general, as the display gets larger the proportion of shells that can reach the audience decreases as the audience is beyond the design range of the smaller calibre shells, and hence the risks from the smaller

Table 6. *Individual components of frequencies and hazards of shell failures.*

Failure	Estimated frequency	Comments
Frequency of failure of a shell in any manner	0.01	This is pessimistic – and improvements in manufacture are reducing this. However we have considered ANY failure of a shell
Frequency of above shell failure leading to mortar failure	0.01	
Frequency of disruption of adjacent mortars	1	We have assumed ANY failure of a mortar will cause disruption of adjacent mortars in a rack or trench. This is overestimating significantly.
Frequency of adjacent mortar containing a shell being ignited	0.5	The adjacent tube may be empty or non-existent (failure of last shell in a rack) – and the evidence from accidents (e.g. Kettering) is that some shells remain unfired in mortars even after having been disrupted.
Angle factor – adjacent shell fires towards audience	0.1	This is variable – see text.
Frequency of fatalities occurring from shell bursting above audience	0.1	Measure of hazard to a person standing within the star burst radius of a shell
Frequency of fatalities from blast occurring from shell bursting in/near audience	1	Measure of hazard to a person standing within the immediate burst radius of a shell where they will be affected by blast
Frequency of fatalities from fragments of a shell bursting in/near audience	1	Measure of hazard to a person standing within the immediate burst radius of a shell where they will be affected by fragments
Frequency of shell bursting adjacent to mortar	0.01	For instance muzzle break or flowerpot. In most cases this affects the operator only.
Frequency of fatalities occurring from shell bursting in/near operator	0.1	

Table 7. *Effect of the nature of the display site.*

Type	Description	Typical angle subtended
Where the audience only subtend a small fraction of a circle around the firing site	Typically an event where the number of people are small and are well controlled – e.g. a wedding where the audience are assembled on the steps of a hotel	36° 0.1 of a circle
Where the audience are on one side of the display site	Typical of many shows	180° 0.5 of a circle
Where the audience are all around the display site	Large displays, or displays from rooftops	360° A complete circle

shells bursting in the crowd are reduced to near zero. This can be used to calculate the likely risks in one of two ways:

- By only performing calculations on the largest shell calibres and counting only those largest calibre shells
- By applying a "show factor" for the show – but counting all shells fired – for instance as shown in Table 8

We have used both methods and find they yield similar results. However where the normal pattern of distribution of shell sizes is inappropriate then calculations may have to be made across a variety of shell calibres/numbers and the results combined to give a value of the total risk.

Proportionality factors

HSE in the UK recognise that any work required to mitigate a particular risk must be proportionate to the reduction in risks achieved. The higher the original (unmitigated) risk, and the greater the risk reduction, the more affordable are the mitigation measures.

For instance, taking the "cost" of a life as £1 million a reduction in risks from the "broadly acceptable" (1×10^{-6}) risk to lower would be justified if the benefits exceeded £1 million (i.e. there is a proportionality factor of 1 in this case). For a risk of ca. 1×10^{-5} the proportionality factor would be arbitrarily set at about 4, i.e. measures would be justified if the benefits exceeded £250 000 or in essence one-quarter of a life, or significant numbers of major injuries.

The costs associated with such benefits can be

Table 8. *Show factors applied to the total number of shells fired in a display.*

Type of show	Shells used	Typical value for show factor
Small – e.g. private wedding	Several 75 mm Several 100 mm 1 × 150 mm	0.2
Medium – e.g. public concert	Many 75 mm Many 100 mm Many 125 mm Many 150 mm A few 200 mm	0.1
Large show – e.g. national event	Very many 75 mm Very many 100 mm Very many 125 mm Many 150 mm Many 200 mm	0.05

spread over many mortars and many uses of the mortars and effectively amortised over the lifetime of the mortar. For instance for a medium sized company

- Doing 100 displays each year
- Holding 2000 mortars in stock
- An average number of shells fired per show is 125
- With a total number of shells fired over a 4 year period of 50 000
- Where each mortar is reused 6.25 times a year and 25 times in a 4 year lifetime
- Assuming shows have an audience of 1000, of which 100 are at risk and that the audience subtend 1/10 of a circle

and then examining four possible risk reduction measures:-

- Tinfoil over mortars to prevent ignition from stray sparks – if the mortar is, for instance, disrupted by an adjacent mortar explosion
- Waterproofing mortars to boost structural integrity (e.g. for fibreboard or GRP mortars to prevent freeze-cracking)
- Replacing each mortar each year
- Redesigning and implementing new mortar racks

illustrates the measures that are sufficient r necessary.

For a large display company firing multiple displays on the same site (or a very large display for a single event) the calculations are somewhat different. Assuming that the display

- is repeated 10 times each year
- 2000 shells are used per display (or 20 000 per year)
- and assuming multiple shows have 100 000 audience, of which 1000 are at risk and that the audience subtend at least 1/2 of a circle, or a single very large display has a 1 million audience subtending a full circle.

leads to a differnt set of conclusions.

Where there are many displays each year (for instance at theme parks) more elaborate control measures may be justified, but in general some measures are justified for all shows and relatively simple "housekeeping" is essential for all. Mortars and racks should be checked regularly to ensure the integrity of both.

The results are shown in Tables 9 and 10.

The risks from firing shells range from "broadly acceptable" to lower risks – they DO NOT pose unacceptable risks. Larger displays merit greater "in depth" analysis than smaller shows and can justify additional expenditure on risk reduction measures.

Individual risk model

The remainder of this paper looks at the use of SHELLCALC© data to investigate the individual risk to persons in the audience of a firework display. This approach could be applied generally, but for the purposes of this paper we have made the following assumptions for inputting data into SHELLCALC©.

- Ignore wind
- Factor in "typical" tumbling and/or

Table 9. *Risk reduction for medium shows.*

Risk reduction method	Cost per mortar	Total cost over 4 year period	Estimate of risk reduction	Cost benefit analysis indicates control method worth doing
Tinfoil to protect shells from sparks	£0.10	£5000	5×10^{-6} to 1×10^{-6}	Yes
Waterproof mortars (renew each year)	£1.00	£8000	5×10^{-6} to5×10^{-7}	Yes
All new mortars each year	£10.00	£80 000	5×10^{-6} to 2.5×10^{-7}	No
Redesigned mortar racks (each with 5 mortars)	£20 (i.e. £100 per rack)	£40 000	5×10^{-6} to 1×10^{-7}	No

Table 10. *Risk reduction for multiple large displays (or single very large display).*

Risk reduction method	Total cost for 10 shows (or single very large display)	Risk reduction	Cost benefit analysis indicates control method worth doing
Tinfoil to protect from sparks	£2000	5×10^{-5} to 1×10^{-5}	Yes
Waterproof fibreboard mortars	£20 000	5×10^{-5} to 5×10^{-6}	Yes
Additional sand barriers, new racks etc	£200 000	5×10^{-5} to 2×10^{-6}	Marginal – may be justified for large budget productions
“Catchers”[a]	£500 000	5×10^{-5} to 1×10^{-6}	Generally no

[a] Disney style “catchers” are barriers erected to stop low trajectory shells reaching the audience.

barrelling

- Assume standard mortars, shell weights etc
- Run the Shellcalc©model using 150 mm shells.

We have also made the assumption that if a mortar falls over there is an equal likelihood of the shell firing at any time, and therefore at any angle, as it falls to the ground.

We have then calculated the range and likely effect of firing a shell towards the crowd at 5° increments and investigated whether a shell

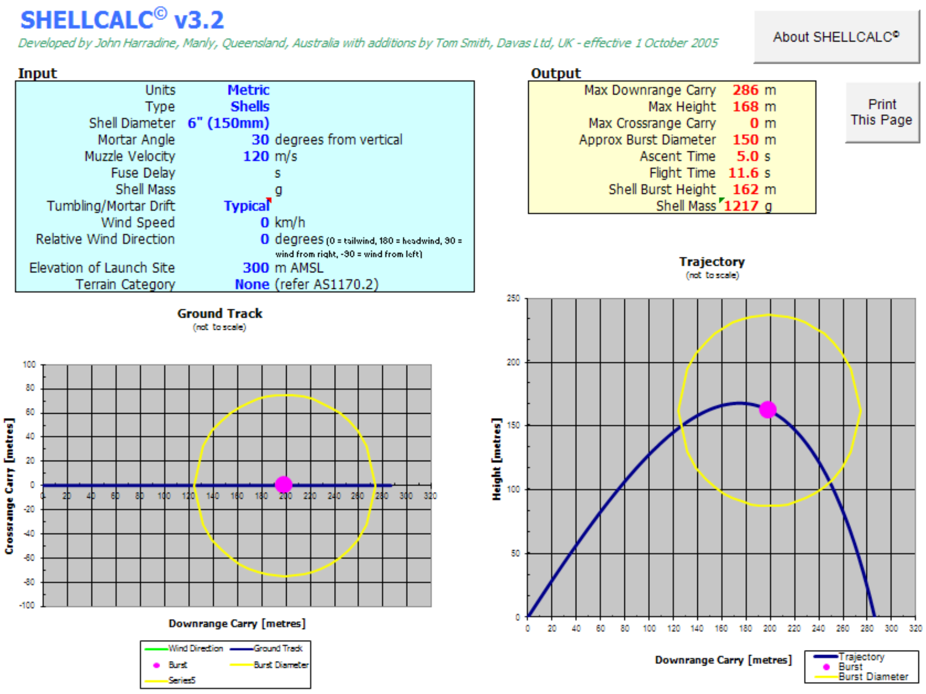
- Bursts over the audience at such a height that the stars impact on the audience
- Bursts at or near ground level so that persons may be affected by blast or fragments

The raw data derived from from Shellcalc© are given in Table 11 and illustrated in Figures 1 to 3.

Table 11. *Data for 150 mm shell derived from Shellcalc©.*

Angle of firing	BLIND Burst range	NORMAL Burst range	NORMAL burst height	Stars reach the ground between distances[b]	
0					
15	188	118	207		
20	226	147	195		
25	259	173	180		
30	286	199	162		
35	309	222	143		
40	325	243	121		
45	334	262	98		
50	339	278	74	270	290
55	336	292	49	240	350
60	327	303	22	230	370
65	310	310	0[a]	230	390
70	282	282	0	210	360
75	236	236	0	180	310
80	169	169	0	90	250
85	33	33	0	−40	110
90	11	11	0	−80	80

[a] Star functions on the ground even if burst time is “normal”. [b] See Figure 2 and Figure 3 for examples.



SHELLCALC© v3.2

Developed by John Harradine, Manly, Queensland, Australia with additions by Tom Smith, Davas Ltd, UK - effective 1 October 2005

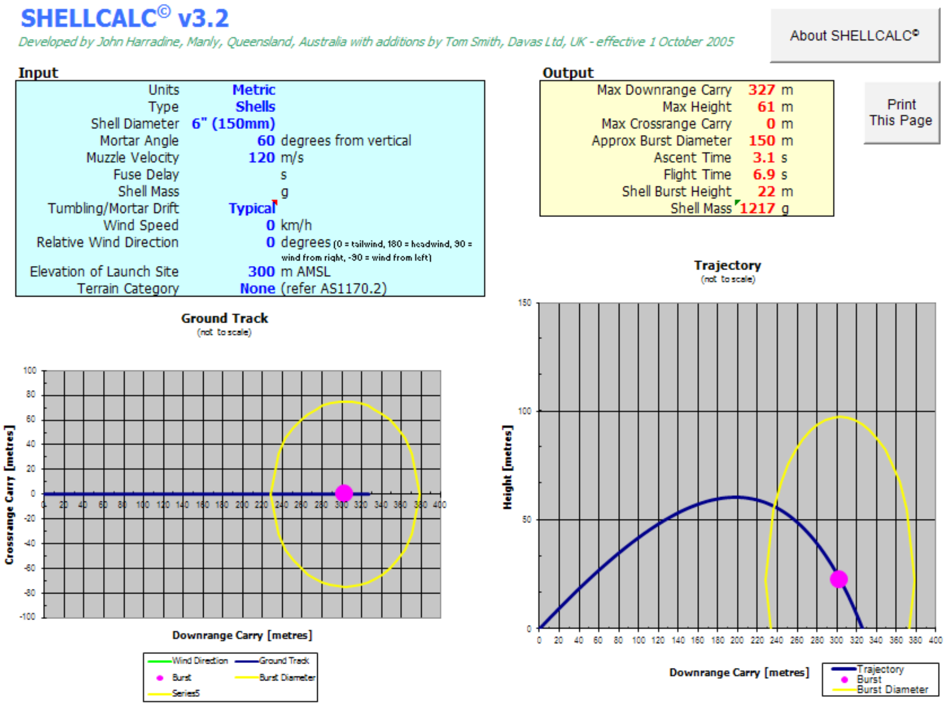
Input

Units **Metric**
Type **Shells**
Shell Diameter **6" (150mm)**
Mortar Angle **30** degrees from vertical
Muzzle Velocity **120** m/s
Fuse Delay s
Shell Mass g
Tumbling/Mortar Drift **Typical**
Wind Speed **0** km/h
Relative Wind Direction **0** degrees (0 = tailwind, 180 = headwind, 90 = wind from right, -90 = wind from left)
Elevation of Launch Site **300** m AMSL
Terrain Category **None** (refer AS1170.2)

Output

Max Downrange Carry **286** m
Max Height **168** m
Max Crossrange Carry **0** m
Approx Burst Diameter **150** m
Ascent Time **5.0** s
Flight Time **11.6** s
Shell Burst Height **162** m
Shell Mass **1217** g

Figure 1. *SHELLCALC output for 150 mm shell fired at 30 degrees – note that the stars from a "normal" burst do not affect the audience.*



SHELLCALC© v3.2

Developed by John Harradine, Manly, Queensland, Australia with additions by Tom Smith, Davas Ltd, UK - effective 1 October 2005

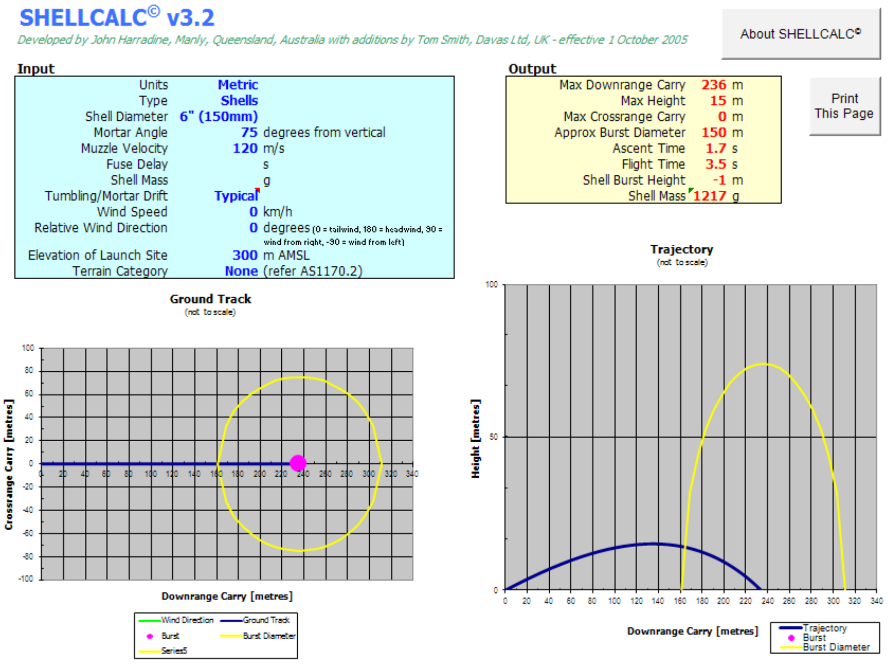
Input

Units **Metric**
Type **Shells**
Shell Diameter **6" (150mm)**
Mortar Angle **60** degrees from vertical
Muzzle Velocity **120** m/s
Fuse Delay s
Shell Mass g
Tumbling/Mortar Drift **Typical**
Wind Speed **0** km/h
Relative Wind Direction **0** degrees (0 = tailwind, 180 = headwind, 90 = wind from right, -90 = wind from left)
Elevation of Launch Site **300** m AMSL
Terrain Category **None** (refer AS1170.2)

Output

Max Downrange Carry **327** m
Max Height **61** m
Max Crossrange Carry **0** m
Approx Burst Diameter **150** m
Ascent Time **3.1** s
Flight Time **6.9** s
Shell Burst Height **22** m
Shell Mass **1217** g

Figure 2. *SHELLCALC output for 150 mm shell fired at 60 degrees. Note that the stars from the "normal" burst affect the audience. Note that the elongation of the shell "burst" is a function of automatic axis fitting in Excel and is not intended to indicate aspherical bursts.*



SHELLCALC© v3.2

Developed by John Harradine, Manly, Queensland, Australia with additions by Tom Smith, Davas Ltd, UK - effective 1 October 2005

Input

Units Metric
Type Shells
Shell Diameter 6" (150mm)
Mortar Angle 75 degrees from vertical
Muzzle Velocity 120 m/s
Fuse Delay s
Shell Mass g
Tumbling/Mortar Drift Typical
Wind Speed 0 km/h
Relative Wind Direction 0 degrees (0 = tailwind, 180 = headwind, 90 = wind from right, -90 = wind from left)
Elevation of Launch Site 300 m AMSL
Terrain Category None (refer AS1170.2)

Output

Max Downrange Carry 236 m
Max Height 15 m
Max Crossrange Carry 0 m
Approx Burst Diameter 150 m
Ascent Time 1.7 s
Flight Time 3.5 s
Shell Burst Height -1 m
Shell Mass 1217 g

Figure 3. *SHELLCALC output for 150 mm shell fired at 75 degrees. Note that the shell bursts at ground level.*

From these data we have applied the risk calculations outlined above to calculate the individual risk for persons standing at distances of 0 to 500 m from the firing point relating to

- Very early bursts (e.g. muzzle breaks)
- Displaced mortars firing shells that burst "normally"
- Displaced mortars firing shells that function abnormally

In each case we also examine hazards from

- The effects of burst at very close distances (2 m – taken as fatal at this distance)
- The effects of fragments of shells at extended distances (10 m – taken as fatal at this distance) – this, in general, combines with the burst hazard so that we have calculated anyone within 10 m has a fatality frequency of 1
- The effects of stars (taken to the burst radius of the shell – taken as 80 m – with a fatality of 0.1)

The risk calculations relate to the number of shells fired according to the formula

$$\text{Risk}_n = 1 - (1 - \text{Risk}_1)^n)$$

and not simply

$$\text{Risk}_n = n \times \text{Risk}_1$$

where Risk_n is the risk from n shells and Risk_1 is the calculated risk from a single shell. Tossing a coin 10 times does not mean you will get 5 "heads" (10 × 0.5 = 5) – it doesn't even mean you will get any "heads". The likelihood you will get at least one head in this case is 1-(1/1-024) or approximately 0.99. For very small probabilities the two formulae tend to coalesce.

Figure 4 shows the distribution of distances where either a "blind" shell may fall or the stars from a "normally" functioning shell might reach the ground. The distribution was calculated by analysing the SHELLCALC© derived data in an Excel spreadsheet and analysed according to the following criteria:

- That if a mortar is displaced there is equal probability of it firing at any angle of displacement
- That a "blind" shell is considered to affect an area of its impact point on the ground and 10 m either side of it

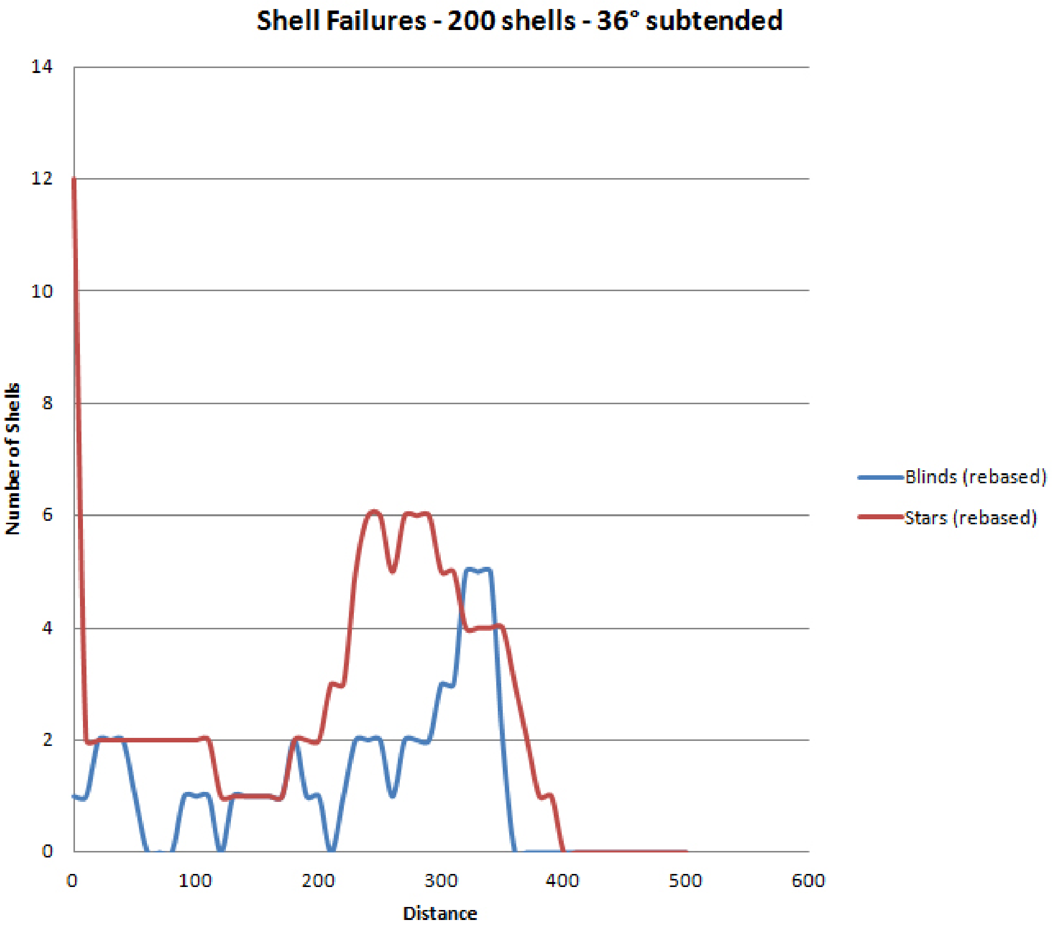


Figure 4. *Ranges where shells may fall "blind" and where stars from shells fired from displaced mortars may reach the ground.*

- That the analysis is carried out using 10 m increments of distance – up to 500 m from the firing point
- The likelihood of a shell failing in either mode is then applied to the range distribution, and the overall risk calculated
- The risk is then rebased because the Excel analysis overcounts shells – it effectively counts all possible times a shell affects the audience whereas the audience will only be affected once per single shell.

Figure 4 does not imply that, for instance 5 shells reach the ground at approximately 250 m, rather that if stars from a "normally" functioning shell reach the ground they are 5 times more likely to reach the ground at 250 m than they are at 150 m. This is entirely in concordance with real life observations and the SHELLCALC plots. If a shell is fired at a small deviation from the vertical and functions normally then the stars do not reach the ground.

The "jagged" nature of the plot reflects the mathematical analysis used and does not mean that there are particular distances where the likelihood of a "blind" shell falling or the stars reaching the ground is particularly high or low. We have chosen to ignore this "jagged" anomaly

The plot for a show containing 200 150 mm shells and subtending an angle of 36° (i.e. 1/10 of a circle) is shown in Figure 5.

Excel also allows an estimated regression to be made, which is also shown in Figure 5, and which is a more realistic evaluation of the risk at any particular point.

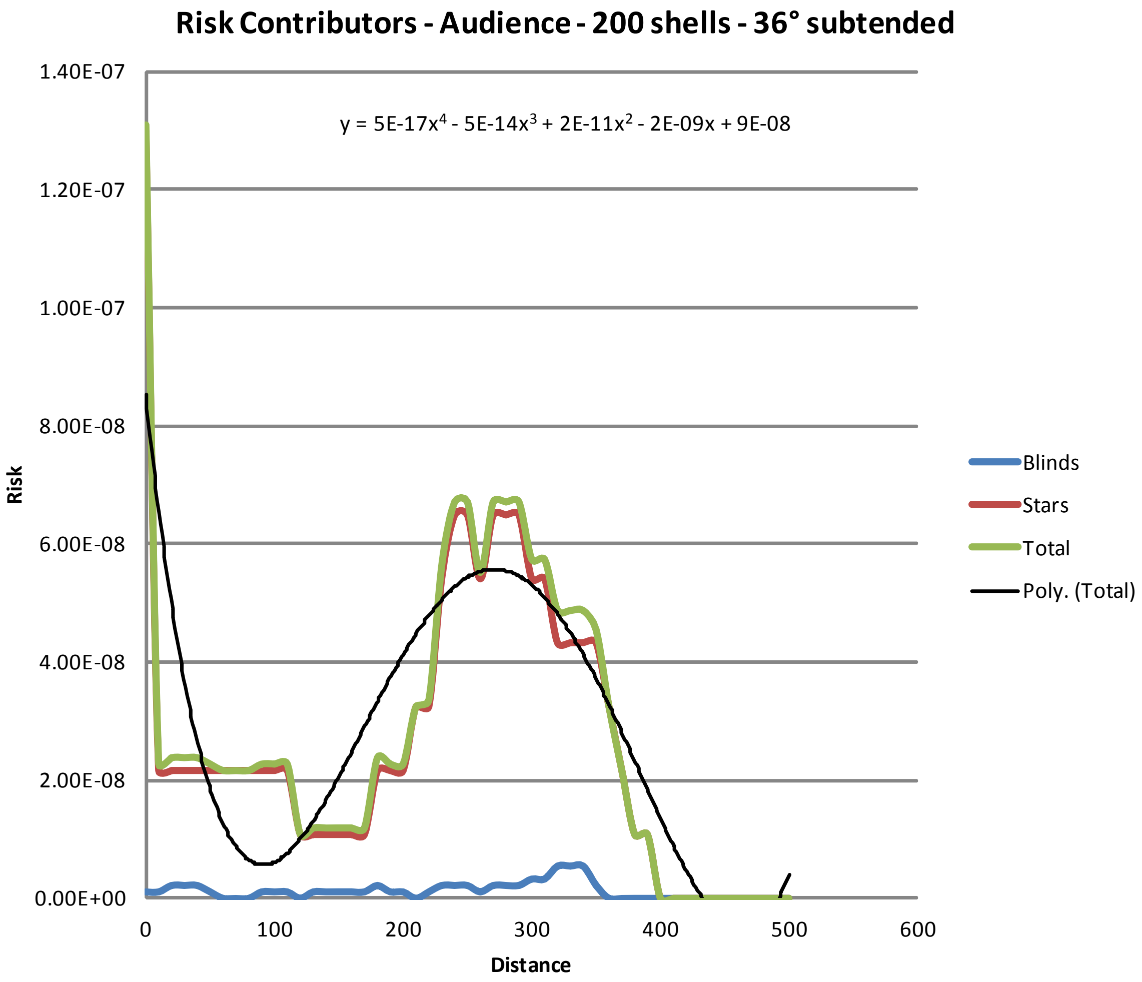


Figure 5. *Individual risk from 200 shells – audience 36°.*

A similar plot for a show containing 500 shells where the audience subtend 360° is shown in Figure 6.

From these plots it is possible to calculate

- The distance at which an individual is subject to more than a "broadly acceptable" – i.e. 1×10^{-6} risk.
- The total risk for persons at all distances

In the case of 50 shells subtending 36° there is no position away from immediately adjacent to the firing point at which the individual risk is greater than 1×10^{-6}.

In the case of 500 shells fired at 360° then the distance at which an individual is subject to the same risk is approximately 360 m. There is a area nearer the firing point at which the risk is the same – but this is discounted for obvious reasons.

Overall the risks remain extremely low – even in the second case the risks do not approach twice the

Table 12. *Total risk to the audience for a number of display scenarios.*

	Angle subtended/degrees		
No of shells	36	180	360
50	3.5×10^{-7}	1.8×10^{-6}	3.5×10^{-6}
100	7.1×10^{-7}	3.5×10^{-6}	7.1×10^{-6}
200	1.4×10^{-6}	7.1×10^{-6}	1.4×10^{-5}
500	3.5×10^{-6}	1.8×10^{-6}	3.5×10^{-5}
1000	7.1×10^{-6}	3.5×10^{-6}	7.1×10^{-5}

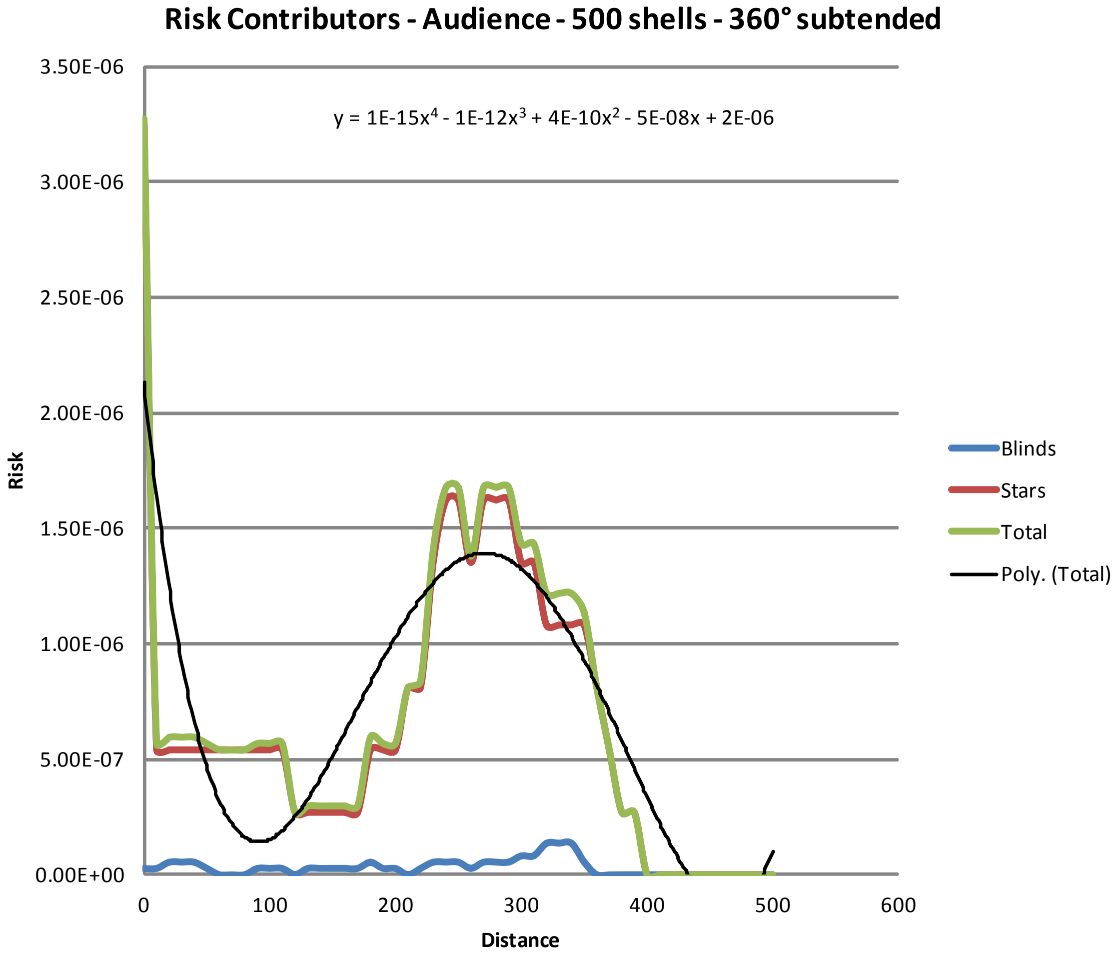


Figure 6. *Individual risk from 500 shells – audience 360°.*

"broadly acceptable" risk at any point.

Table 12 shows the total risk for a variety of numbers of shells fired and angle the audience subtends. Even for the most extreme case (1000 shells, audience at 360°) the risks are still within the ALARP region and therefore merit additional control measures – they do not pose unacceptable risks.

Table 12 also gives an indication of the societal risk, albeit not precisely. An alternative approach would be to sum the total risks to individuals between two specified distances and relate this to the number of people occupying such a range of distances given a specific angle that they subtend.

A second approach to risk assessment

We have also interrogated the SHELLCALC© derived data in a different manner. In this case we have examined the likelihood of fatality at each distance (again from 0–500 m in 10 m increments) and calculated that if a "blind" shell falls to the ground or the stars from a "normally" functioning shell reach the ground at any distance greater than the specified distance then a potential fatality will occur.

The results for the same situations as outlined above are shown in Figures 7, 8, 9 and 10.

Distances calculated for an individual risk of less than 1×10^{-6} from this method for the two given scenarios are approximately 80 m and 320 m respectively.

These differ from, but are consistent with, the first method. The appropriateness of each method

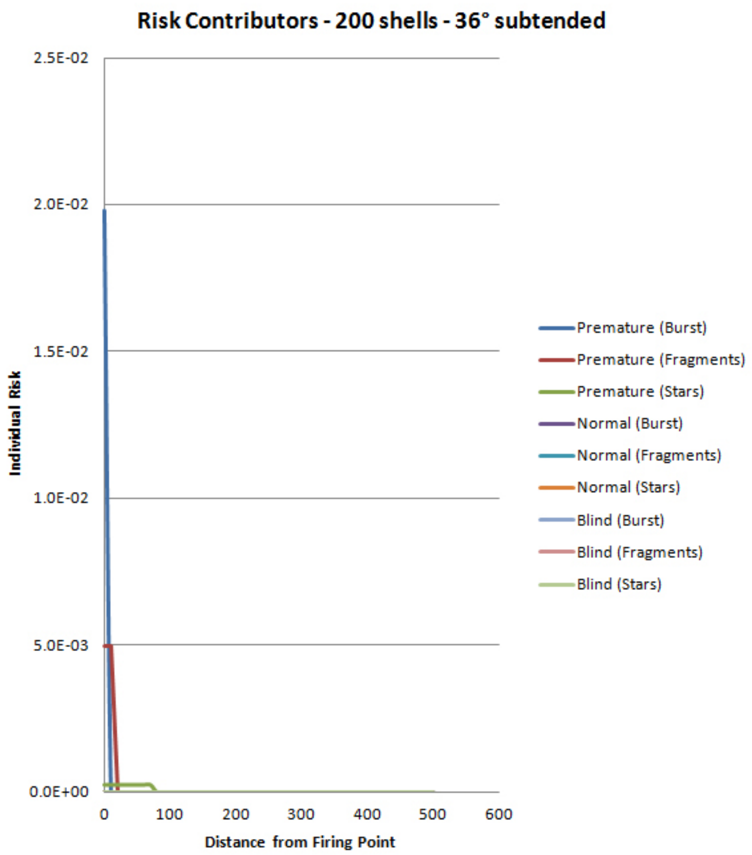


Figure 7. *Calculation of individual risk by method 2 for 200 shells subtending 36°.*

should be chosen on its merits for a particular display at a particular venue on the basis of the likely distribution of the audience.

Further work

The methods illustrated in this paper relate to a relatively narrow range of hazards to the audience. Although "normal" debris is unlikely to produce a fatality hazard, none the less it is an important factor to be considered when siting a fireworks display – especially because "normal" debris (card or composite fragments of the shell case, unburnt stars or long burning stars reaching the ground) is significantly affected by the wind strength and direction after the shell (or other firework) bursts.

This will be the study of further papers in due course dealing with societal risks of both fatality and injury to audience members and to operators at both firework displays and where other pyrotechnic items are used in proximity to the audience.

Conclusions

Modelling of individual risk by knowledge of the likely failure rates and likely hazards and applying this over the possible failure modes for shells allows distances to be estimated where the individual risk is approximately 1×10^{-6}. The procedures demonstrate that it is essential to recognise the angle subtended by the audience, the number of shells fired and the possible mechanisms by which such shells could cause injury or fatality to members of the audience.

Although we propose that, in general, the estimates of frequency and hazard have been quite pessimistic, the overall risks to audience members remain extremely low – which concurs with the observed accident statistics. Form other studies[11] we estimate that in the UK some 12 million people attend an organised firework display annually and the number of fatalities remains extremely low.

Finally, it is apparent from the analyses carried out that it is not appropriate, for professionals, to apply set "safety distances" for shells of a

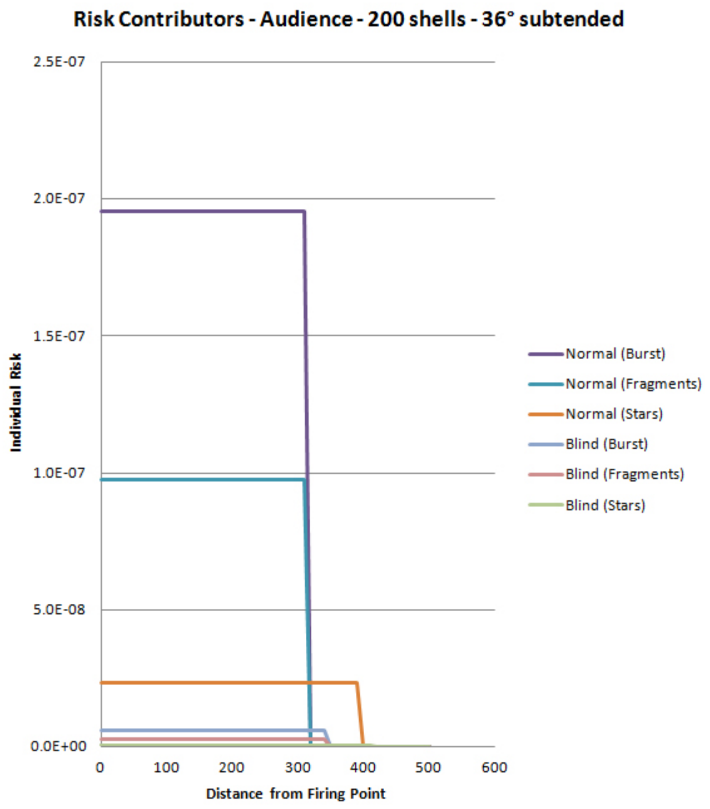


Figure 8. *Individual risk (zoomed in) area from Figure 7.*

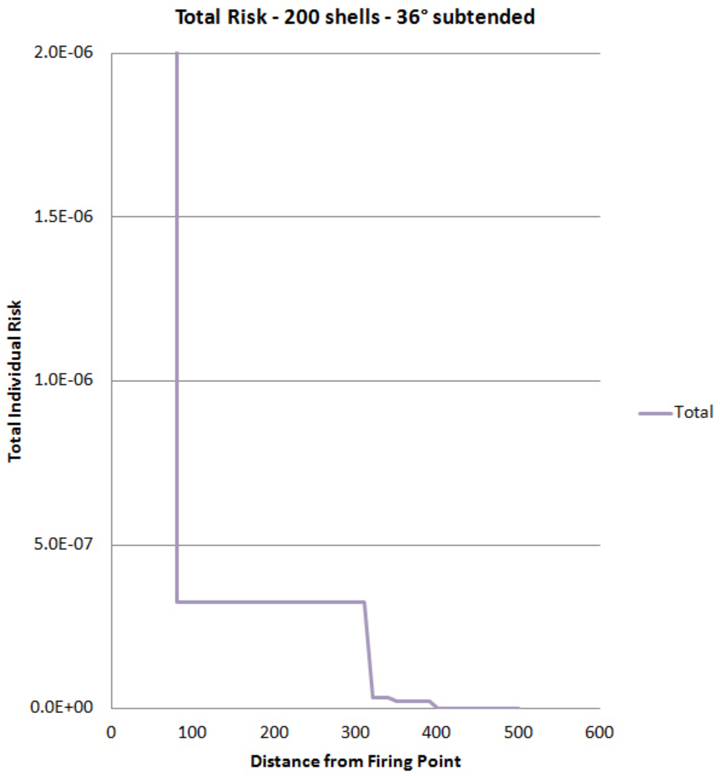


Figure 9. *Individual risk (zoomed in) from Figure 8.*

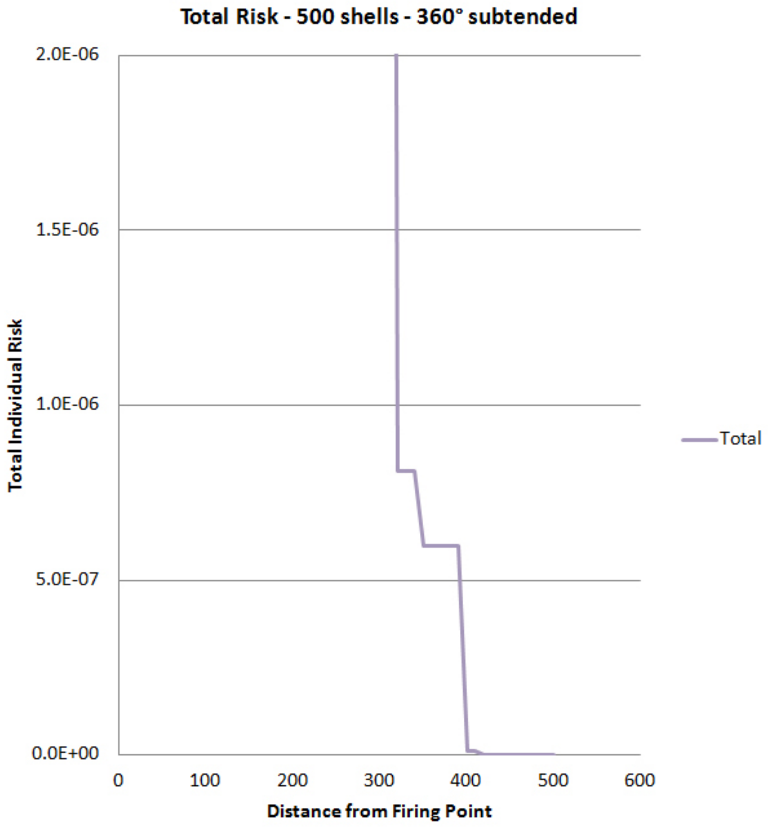


Figure 10. *Individual risk from 500 shells subtending 360° .*

particular calibre – even if the shells are always fired in the same manner. The nature of the site and the display has a critical role in determining appropriate distances where the risks are reduced to an acceptable level.

References

1 For details of the CN Standardisation work see http://www.cen.eu/cen/Sectors/TechnicalCommitteesWorkshops/CENTechnicalCommittees/Pages/default.aspx?param=6193&title=CEN/TC%20212

2 For a definitions of terms see http://www.iacs.org.uk/document/public/Publications/Other_technical/PDF/FSA_Glossary_pdf437.pdf

3 See for example http://home.att.net/~d.c.hendershot/papers/pdfs/riskland.pdf

4 Societal Risk: Initial briefing to Societal Risk Technical Advisory Group, http://www.hse.gov.uk/research/rrpdf/rr703.pdf

5 Societal risk – Estimating the chances of people being harmed from an industrial incident, http://www.hse.gov.uk/societalrisk/ and links to papers therein.

6 T. Smith, *Journal of Pyrotechnics*, Issue 18, 2003, pp. 32–42 (http://archives.jpyro.com/?p=158).

7 J. Harradine and T. Smith, *Journal of Pyrotechnics*, Issue 22, 2005, pp. 9–15 (http://archives.jpyro.com/?p=23).

8 Principles and guidelines to assist HSE in its judgements that duty-holders have reduced risk as low as reasonably practicable, http://www.hse.gov.uk/risk/theory/alarp1.htm

10 The Explosives Incidents (EIDAS) database is available at http://www.hse.gov.uk/explosives/eidas.htm. Although this is the HSE official database of incidents, the data appear not to be complete and concerns have been expressed about the validity of some of the data provided.

11 Explosive Industry Group survey, results to be published.