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An examination of the major-accident record for explosives manufacturing and storage in the UK

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Abstract

This report examines the historical accident record for explosives manufacture and storage in the UK during the period 1950–1997. Details were found of 79 major explosives events, a major event being defined as one which substantially destroys the building in which it occurs and results in projection of debris and/or blast effects at a distance, so posing a hazard to persons elsewhere on the site or indeed beyond the site. Analysis of the accident record allowed major accident rates to be derived for a number of processes undertaken in the explosives industry. It is suggested that the rates derived in this study might be used in quantitative risk assessments (QRA) of explosives manufacturing and storage plants. It is noted that to date, QRA has been used relatively infrequently in the UK within the civil explosives field. However, with the adoption of the European Union Seveso II Directive, to be implemented in the UK as the Control of Major Accident Hazards (COMAH) Regulations, QRA could now play a more active role in explosives safety in the UK. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Quantity–Distance (QD) principles have for many years formed the basis for the licensing of explosives manufacturing plants and storage areas in the UK. These principles limit the quantities of explosives that can be present in workshops, magazines, etc., according to the proximity of nearby buildings and certain other facilities both on

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and off-site. Explosives limits for these buildings might be further constrained after consideration of such factors as remote vs. nonremote manufacture and minimal quantities for highly sensitive explosives. The aim of QD licensing is to provide an acceptable degree of protection for the workforce and a high level of protection for the public. However, it should be understood that the current QD prescriptions do not guarantee workers and members of the public complete immunity against the effects of accidental explosions—for which aim impracticably large separation distances would be required. Rather, these prescriptions have been formulated on the understanding that the likelihood of a major accident is low and that a limited amount of damage can be tolerated in the unlikely event that an accident shall occur. In short, QD prescriptions limit hazards by ensuring that the consequences of any accidents would be limited to an acceptable level.

A different type of control regime has evolved for other types of major hazard installation, e.g. chemical plants and oil refineries. Such installations are not formerly licensed by the HSE, but rather an onus is placed on the operators to demonstrate that hazards and risks have been identified and are properly controlled. The exact requirements vary depending on the types and quantities of hazardous materials present. In the UK, the operators of the most hazardous installations, where relatively large amounts of dangerous materials are present, are required to submit formal safety reports. A quantitative risk assessment (QRA) often forms an important component of these reports, and the technique is now well-established in the UK for examining and justifying hazardous industrial activities.

In brief, QRA is a process by which the risks from hazardous activities are estimated and then evaluated against the criteria. It normally comprises five distinct phases in which, for the activity being assessed:

1. potential causes of incidents and accidents are identified;
2. incident and accident likelihoods are estimated;
3. incident consequences (in terms of damage, financial cost, etc.) are estimated along with accident consequences (in terms of fatalities and injuries);
4. risk estimates are quantified; and
5. risk estimates are evaluated against the criteria.

Historically, QRA has been used relatively infrequently in the civil explosives field, though significantly, it has in some cases been used successfully to justify the continued operation of facilities that have been unable to comply with QD rules. However, with the adoption by the UK of the European Union Seveso II Directive as the Control of Major Accident Hazards (COMAH) Regulations, QRA could play a more active role in explosives safety in this country. In broad terms, these regulations will require operators of installations which fall within its scope to develop a Major Accident Prevention Policy and to implement management systems to control identified major accident hazards. Explosives establishments will come within the scope of the regulations if the amounts of explosives present exceed certain threshold quantities as specified in Annex 1 of the Directive—which will probably be carried forward into the COMAH. Those plants containing an explosives inventory exceeding an upper threshold value will be classed as ‘top-tier’ sites and will be required to submit safety reports for assessment by the Competent Authority.

QRA could play an important role in the development of safety reports for top-tier explosives establishments. The operators of such sites would certainly need to undertake a QRA were they are unable to comply with the QD rules. The safety report would need to demonstrate to the satisfaction of the HSE that the risks of activities undertaken on-site are not intolerable and have been reduced as low as reasonably practicable (ALARP). The elimination of intolerable risks and the reduction of all others on the ALARP principle is very much the philosophy which lies at the heart of the Health and Safety at Work Act 1974 [1].

To date, little work has been undertaken to assess what risks may be posed to the public from the activities undertaken on licensed civil explosives sites—this is perhaps due to the deterministic nature of current explosives safety legislation. This paper seeks to address this issue in part, by examining the historical frequency of occurrence of major accidents at explosives manufacturing and storage sites to see what inferences can be drawn about accident likelihood under present operating conditions.

2. Assessing the likelihood of accidents

The are many factors which could have some bearing on the likelihood of an explosives event occurring within an explosives manufacturing or storage site. These factors include: (i) the inherent sensitivity and Compatibility Group of the explosives substances and articles manufactured and stored; (ii) the types of manufacturing and handling processes employed (which may include a number of built-in engineered safeguards); as well as (iii) the managerial and procedural safeguards, of which safety culture and training and supervision of staff are important aspects.

The scale of any event would again depend on a number factors, such as the type and quantities of explosives initially involved and equally importantly, the engineered and procedural safeguards in place both to limit the extent of explosives involvement and to contain the effects of explosions and fires. In this respect, there are a number of statutory safeguards which must be observed. As noted in the introduction, these safeguards are built into the terms of the licence and (i) limit the types and quantities of explosives materials that may be present in buildings, and (ii) maintain minimum separation distances between these buildings and other facilities both on and off-site.

Estimates for accident likelihood can be obtained by employing both synthetic and empirical procedures.

Synthetic procedures are deductive in nature and comprise a number of discrete steps. First, techniques such as HAZOP are employed to identify all the potential causes of accidents. In many cases, it is found that a number of faults must occur simultaneously or in a particular sequence for an accident to occur. Thus, the HAZOP stage may be followed by fault tree or event tree analysis in which the various sequences of events identified—including those necessary for a minor incident to escalate into a major accident—are set out in a logical framework. An example fault tree is shown in Fig. 1, which outlines some of the potential causes of fire-induced explosions on trucks carrying commercial explosives [2].

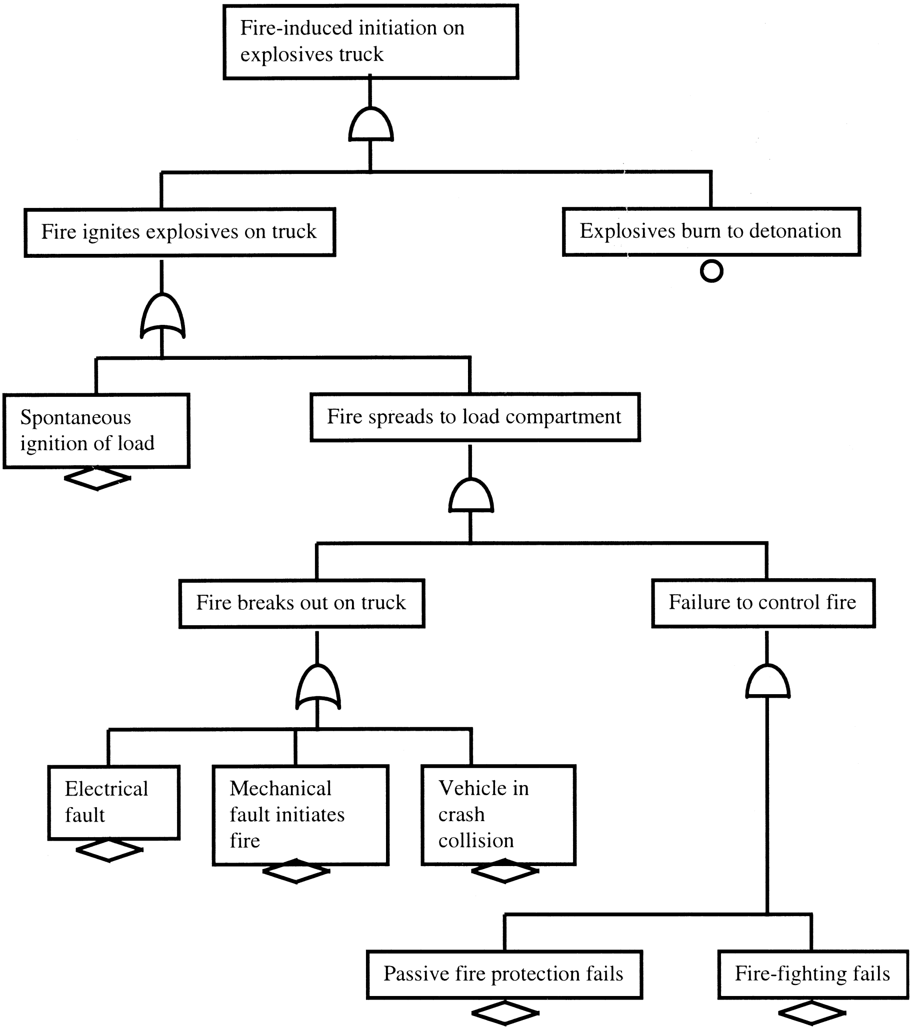

Fig. 1. Some potential causes of fire-induced initiation of explosives on a road vehicle. Key: (half ellipse with a flat side) AND gate—the event above the gate only occurs if all the events immediately below the gate occur; (half ellipse with a concave side) OR gate—the event above the gate occurs if any one of the events immediately below the gate occurs; (circle) Basic fault event; (diamond) Basic fault event which could be developed further.

In the above example, it is postulated that a fire could break out on a truck as a result of an electrical fault (e.g. an electrical short circuit), a mechanical fault (e.g. a binding brake) or the involvement of the truck in a road traffic accident. Fire might then spread to the explosives load if the passive fire protection on the vehicle were breached and fire-fighting action proved ineffective. Should the load ignite, then, depending on the types of explosives present, the load might burn to detonation. In addition to these possibilities, there is also a chance that an explosion could occur as a result of a 'spontaneous' ignition should the load contain explosives that have been badly designed, manufactured or unsafely packaged [3].

A major strength of this synthetic procedure is that it helps the analyst to form a detailed understanding of the risks involved in the process under study. However, experience shows that there are a number of drawbacks to this type of procedure, two of the most important are: (i) it is time-consuming and hence, costly; (ii) data are rarely available to quantify the probabilities of all the base and nodal events in the logic trees and, therefore, full quantification of these trees must rely to some extent on expert judgement.

The empirical procedure is much simpler, being based on a direct analysis of historical accident data. Two sets of data are required:

1. the number of incidents within a specified period of time (N); and
2. the operational experience accrued over the same period (E).

Accident rates are then given by the ratio N/E.

Of course, this approach implicitly assumes the continuance of errors and oversights which give rise to accidents. In general, it might be expected that processes would become safer over time as a better understanding of risk is gained with experience and corresponding safety improvements are made; in particular, it might be expected that lessons learnt from accidents and 'near misses' would result in the necessary corrective action to prevent recurrences. From this point of view, accident rates derived from historical data might be thought to give a pessimistic indication of current accident likelihood. On the other hand, historical records clearly show that certain processes undertaken in the explosives industry have routinely given rise to accidents. An example is the manufacture of gelatine/dynamite explosives, for which there is an accident history stretching from the first commercial production in the latter half of the 19th century to the present day—the last major explosion involving gelatine production in the UK occurred as recently as 1988. It is reasonable to conclude that processes involving sensitive explosives compounds will always carry some significant degree of residual risk.

3. Record of major incidents for explosives manufacture and storage

For the purpose of this study, an examination was made of the major accidents that have occurred during explosives manufacture and storage over the period 1950–1997. A major accident is here defined as: ''an explosion which substantially destroys the building in which it occurs and results in projection of debris and/or blast effects at distance, so posing a hazard to persons elsewhere on the site or indeed beyond the site''.

Such incidents may involve the full explosives licence limit for the building or a substantial proportion of this limit; at any rate, such incidents would have the potential to involve all explosives present in the building and to produce harmful effects at the Inside Quantity Distance or the Outside Quantity Distance as the case may be.

Details of accidents were obtained from the EIDAS database [4], which in turn has been compiled from various reports and data sources. The following sources are the most relevant to the present study.

The annual reports of Her Majesty's Inspectorate of Explosives. These reports give details of all accidents at commercial explosives sites (Royal Ordinance and government sites are excluded) reported to the Explosives Inspectorate over the period 1875–1974. The Explosives Inspectorate was incorporated into the Health and Safety Executive at the latter date when publication of the annual reports ceased [5].

ESTC leaflet 5, which details a number of incidents of major explosions and fires at commercial sites, Royal Ordinance factories and military sites during the period 1945–1967 [6].

An unpublished AEA / Royal Ordinance report concerning: ''An examination of the historical record with regard to the frequency of occurrence of fire and explosions involving explosives materials at UK explosives storage sites operated by the Ministry of Defence, Royal Ordinance plc and other commercial organisations during the post-1946 period''.

Biasutti's book on the history of accidents in the explosives industry. This covers the period up to 1984 [7].

Records held by the Health and Safety Executive. These records cover the period 1974 to the present date.

The results of the search are presented in Table 1. A total of 79 major incidents were identified, 40 of which resulted in fatalities on-site. It is significant that none of these 79 accidents resulted in fatalities off-site, a fact which clearly demonstrates the benefit of QD licensing.

Table 1 shows a breakdown of the incidents according to the type of explosives and the process type; brief notes on the causes of the accidents are also included where these were determined.

Enquiries were then made of explosives manufacturers to obtain building population data so that the raw accident statistics presented in the above table could be converted, so far as possible, into accident rates. Building data were kindly supplied by a number of explosives manufacturers. The rates derived are shown in Table 2.

It will be seen that the calculated rates range from 1 to about 10^{-4} per building-year. Some of these rates can be regarded as reasonably robust, being based on several accidents and several hundred building-years of experience (manufacture of nitroglycerine and black powder, are examples); other rates (filling of stab detonators, for example) are based on very small data sets, i.e. only one accident in less than 10 years of operational experience. These latter rates reflect actual historic safety performance, but it would be dangerous to infer much from them concerning accident likelihood for similar types of processes. In fact, the reading across of these rates to other processes may give quite misleading estimates of risk—it may be that similar types of processes have been carried out over a number of years without incident. Of course, the corollary of this is that any operation for which there is a zero-incident record stretching over a number of years is no guarantee in itself that the accident likelihood for a similar type of operation will be low. Once again, there is the argument that if the above processes were to be undertaken over a greater period of time, safety improvements would be made and accident rates would fall.

The process for which the most extensive data were available is that of cartridging gelatine/dynamite explosives. Data were obtained from three sites and accident rates

Table 1
List of major explosives accidents at licensed UK sites for the period 1950–1997

Operation	Date	Comments
Assembling fireworks	19/06/57	Incorrect use of drill
Assembling fireworks	10/04/68	Failure to wear overshoes
Assembling fireworks	06/07/89	Operative assembling turning pieces
Assembling fireworks	06/09/90	Filling gerb with gunpowder/titanium mixture
Burning of waste ammonium nitrate	19/09/89	Ammonium nitrate prill confined in heavy-gauge polythene
Burning of waste blasting explosives	17/09/59	
Burning of waste explosives	01/10/57	
Centrifuging of ball powder	07/09/59	Shock or friction in machine
Cutting cambric	19/04/56	
Drying black powder	12/03/70	Explosion in stove of fuse dept
Drying nitrocotton	03/07/56	Handling immediately after drying
Drying of cordite	30/08/61	
Drying of dinitro toluamide	27/06/76	Product left in dryer for excessive length of time
Drying of nitrocellulose	05/12/85	Excessive drying
Drying of propellant	04/10/74	Failure to wear over shoes
Drying of pyrotechnic comp	1967	
Drying of tetryl	06/01/53	
Extruding propellant	28/08/91	
Filling ammunition with primary comp	13/10/90	
Filling dynamite/gelatine cartridges	04/04/50	
Filling dynamite/gelatine cartridges	18/10/54	Attempt to clear blockage in extruder machine
Filling dynamite/gelatine cartridges	28/08/57	Explosion during filling by Miller–Dann extrusion machine
Filling dynamite/gelatine cartridges	20/05/65	Explosion in du Pont cartridging machine
Filling dynamite/gelatine cartridges	20/02/67	Explosion in Niepmann cartridging house
Filling dynamite/gelatine cartridges	07/05/68	Friction on nozzle
Filling dynamite/gelatine cartridges	23/03/71	Bad maintenance of extruder
Filling shotgun cartridges	14/11/73	
Handling firework comp	11/01/74	Use of steel pen knife
Machining propellant	23/01/68	Incorrect setting of lathe
Melting pentolite	02/02/71	Incorrect use of steam line + sulphur contamination
Corning black powder	29/07/63	
Milling black powder	01/09/67	Explosion in edge runner
Milling black powder	14/02/74	Scraping tray of edge runner
Milling of black powder	19/12/60	Fire spread from oily rag in motor room
Corning black powder	12/03/62	Spread of gorse/grass fire
Milling of blasting powder	23/06/63	Explosion in edge runner
Mixing gelatine/dynamite	07/11/50	Werner Pfleiderer machine inappropriate for operation
Mixing gelatine/dynamite	06/10/55	Explosion during unloading of MacRoberts mixer
Mixing gelatine/dynamite	27/03/63	Transport of NG from bogie to mixer
Mixing gelatine/dynamite	14/06/88	Explosion in mixing building
Mixing propellant	06/07/88	
Mixing propellant	05/06/91	Steel nut in mixer
Mixing pyrotechnic composition	12/12/55	

Table 1 (continued)

Operation	Date	Comments
Mixing pyrotechnic composition	28/11/58	Explosion in Planetary mixer
Nitrating dinitroresorcinol	29/08/56	Insufficient nitric acid caused blockage of discharge line
Nitrating glycerine	25/08/54	Failure of glycerine valve on Schmid–Meissner plant
Nitrating glycerine	09/12/67	Leak of mixed acid from pipeline
Nitrating glycerine	17/12/70	Operative dropped NG sample jar
Nitrating glycerine	Sep/72	Explosion in separator
Nitrating glycerine	15/09/85	Explosion in waste acid inspection house
Nitrating: manufacture of TATB	05/01/89	
Pressing of black powder	18/02/72	
Processing of incendiary bombs	Jul/56	
Processing of torpedoes	Aug/63	Battery fire
RDX manufacture	29/06/51	
Storage of ammunition	30/06/52	Copper azide in det of shell
Storage of black powder	04/05/52	Explosion elsewhere on site communicated to magazine
Storage of black powder	12/03/62	Spread of gorse/grass fire
Storage of black powder	14/09/70	Vandalism resulted in explosion of factory magazine
Storage of blasting explosives	1954	
Storage of blasting explosives	1964	Malicious activity
Storage of cap compositions	11/06/63	Handling of cap comp in expense magazine
Storage of dets	05/02/70	Corroded dets
Storage of fireworks	04/06/63	
Storage of fireworks	05/10/95	Attempted robbery
Storage of nitrocotton	29/08/58	Spontaneous combustion
Storage of propellant	09/07/59	Spontaneous ignition
Storage of propellant	06/01/72	Handling of dried-out propellant in magazine at burning ground
Storage of propellant	29/07/92	Traces of NG on hinge of tank
Storage of pyrotechnic comp	09/07/58	Operative handling chlorate comp in expense magazine
Storage of pyrotechnic comp	23/04/68	Overheating of damp residues of star comp
Transport of HMX	26/02/59	HMX charge dropped
Transport of propellant	03/09/51	Propellant grains spilled onto bogie track
Transport of waste NG	06/06/51	NG leaked onto bogie wheels
Transport of waste propellant	04/03/80	Truck toppled
Washing of nitroglycerine	25/11/53	
Washing of nitroglycerine	08/02/56	
Washing of nitroglycerine	22/06/60	Explosion in washing house of Meissner continuous NG plant
Washing propellant	11/12/67	Contact of propellant with hot surface

Accidents are grouped by type of operation and explosives involved.

were found to range from 1×10^{-2} per building-year (three accidents in 240 building-years) to 2×10^{-3} per building-year (one accident in 575 building-years). The differences in these rates may possibly reflect different types of equipment, operating

Table 2
Accident rates for various explosives manufacturing processes

Process	No. of major incidents	Operational experience (building-years)	Accident rate (per building-year)
Milling black powder	3	99	3×10^{-2}
Corning black powder	2	342	6×10^{-3}
Pressing black powder	1	208	5×10^{-3}
Drying safety fuse	1	60	2×10^{-2}
Drying propellant	1	240	4×10^{-3}
Nitrating glycerine (batch process)	1	84	1×10^{-2}
Nitrating glycerine (continuous process)	1	88	5×10^{-3}
Separating nitroglycerine from spent acid[a]	2	180	1×10^{-2}
Hand-filling NG cartridges	1	3	3×10^{-1}
Machine-filling NG cartridges[b]	6	1082	6×10^{-3}
Melting pentolite	1	18	6×10^{-2}
Filling munitions (A5 Comp)	1	9	1×10^{-1}
Filling stab detonators	1	1	1
Centrifuging ball powder	1	5	2×10^{-1}
Extruding propellant	1	6	2×10^{-1}
Mixing pyrotechnic composition (SR580)	1	10	1×10^{-1}
Manufacture of water-based explosives[c]	1	300	3×10^{-3}
Drying nitrocotton	1	84	1×10^{-2}
Manufacture of RDX	1	22	5×10^{-2}
Burning waste explosive	1	45	2×10^{-2}
Mixing gelatine[d]	3	256	1×10^{-2}
Storage of explosives	9	27	3×10^{-4}

[a] This figure has been calculated from data obtained from two sites (one accident in 52 building-years and another in 128 building-years).
[b] This figure has been calculated from data obtained from three sites (two accidents in 267 building-years; three accidents in 240 building-years; one accident in 575 building-years).
[c] This figure has been calculated from international data which shows the occurrence of one accident in approximately 300 plant-years.
[d] This figure has been calculated from data obtained from three sites (one accident in 42 building-years; one accident in 52 building-years; one accident in 162 building-years).

conditions, procedures, and levels of production. This result suggests that accident rates of at least an order of magnitude difference could be expected across sites carrying out the same or similar types of processes.

3.1. Accident rates for explosives storage

The rate derived for explosives storage is generic and is worthy of further consideration. A total of nine incidents were recorded for the period 1950–1986 (the data set excludes incidents in factory expense magazines and also all incidents at Royal Ordinance factories and MoD ammunition depots). Three of these incidents were caused by malicious action, i.e. vandalism and attempted robbery, a fact which suggests malicious action to be a significant threat at sites at which there are little or no security measures.

It is notable that there have not been any incidents involving finished and packaged high explosives stored on secured premises. Further enquiries of commercial explosives manufactures indicated that the corresponding storehouse years accrued since 1950 amounts, in rough terms, from 10 000 to 20 000. Based on these zero-incident data, a statistical upper limit for the major accident rate can be calculated from the binomial probability distribution, taking a 90% confidence interval:

$$R = 1 - (1 - 0.9)^{1/20{,}000} = 1.10^{-4} \text{ per storehouse-year,}$$

where R is the accident rate.

It is recognised that the above value is a statistical upper limit and that the true rate may be considerably lower.

Explosives storage often dominates the off-site risk at explosives manufacturing plants. This is because storage buildings tend to be located towards the perimeter of such sites, while process buildings tend to be located towards the centre. The upshot of this is that magazines, rather than process buildings, often determine the yellow line [1] at such sites.

3.2. Accident rates for production of modern blasting agents

It is notable that some of the processes listed in Table 2 are no longer undertaken in the UK or are undertaken on a much reduced scale. For example, black powder is no longer manufactured and production of nitroglycerine-based explosives, such as gelatines and dynamites, has declined as ammonium nitrate and water-based explosives, i.e., ANFOs, slurries, and emulsions, have become more popular. These latter types of explosives are generally regarded as being safer, from the point of view of accidental initiation, certainly by impact and friction, than the former—as evidence in support of this view, there can be cited the very high Figure of Insensitiveness (typically > 200) for water-based explosives. It is noteworthy that to date, there have been no major accidents in the UK involving production of these newer types of explosives.

There have, however, been a number of major accidents abroad involving manufacture of water-based explosives. Details are known of a number of accidents which have occurred since 1990 [8]. The following are the brief details of some of these accidents.

18/04/90, Mt. Wright, Canada. This incident occurred during the transfer of emulsion explosives from one truck to another. Investigations indicated that emulsion had ingressed into the hollow rotor of the pump that had been used in the transfer operation. The explosion occurred after the pump had been left running dry for about 10 min while the operatives took a tea break—this led to a thermally-induced initiation.

23/08/90, South Africa. This incident occurred during the packaging of emulsion by means of cavity pump. The explosion occurred after the operatives had over-ridden a cut-out switch connected to a pressure sensor.

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[1] Inhabited building distances around licensed sites were originally denoted by yellow lines on Ordinance Survey maps. The Inhabited Building Distance constrains the quantity of explosives that can be held in the magazine.

11/12/90, South Africa. This incident occurred after smoke had been seen coming from the feed hopper above the pump. The building was evacuated and the explosion occurred 10 min later. Subsequent investigations revealed that emulsion had ingressed into cavities in three similar pumps, and it was thought that excessive heat may have been produced at the gland assembly, the universal joints, the rotor/stator or the heating tape.

01/11/90, Asbest, Russia. This was a particularly catastrophic accident which resulted in the loss of 16 lives. The explosion occurred during the transfer of emulsion from a storage tank to a truck. Investigations suggested that the cause of the explosion may have been the presence of foreign bodies in the gear pump or a thermal decomposition in the holding tank—analysis of the emulsion matrix showed that it was abnormally sensitive.

02/08/94, Porgera, Papua New Guinea. Eleven lives were lost in this particular incident. Again it is believed that the accident occurred during a transfer operation involving a pump.

Unfortunately, it is not possible to derive accident rates from the available worldwide data as (i) it is not known whether the data set is complete, and (ii) the corresponding operational experience is unknown. It is known that most accidents involving production of emulsion explosives have arisen as a result of problems involving pumps. It follows that manufacturers employing pumps of an intrinsically safe design or which have added safety features might obtain a safety performance significantly better than the indicative rate of 3×10^{-3} per plant-year reported in Table 2.

4. Use of accident rates in QRA

The accident probabilities used in QRA studies of hazardous industrial plants are normally subject to some measure of uncertainty. It is important that this uncertainty be dealt with in a systematic manner. HSE policy [9] in this regard is to adopt a ‘cautious best estimate’ approach, i.e. to use realistic best-estimate assumptions wherever possible and to use some over-estimate for the value of a parameter when its exact value is not known; in this way, confidence is gained that risks will not be underestimated. Having due regard for this, it is suggested that the following major accident rates, derived from the historical analysis presented in this report (Table 2), might reasonably be used in QRA studies of explosives manufacturing and storage sites in the UK.

Manufacture or processing operations, except those involving modern blasting agents	10^{-2} per process-building-year
Manufacture or processing of modern blasting agents	10^{-3} per process-building-year
Storage on nonalarmed civil sites	10^{-3} per storage-building-year
Storage on alarmed civil sites [2]	10^{-4} per storage-building-year

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[2] Of recent years, all security attractive explosives have been held in secured stores which are alarmed and linked to an effective response force.

It is recognised that the above values are course estimates and are subject to uncertainty. An operator might be able to justify the use of lower rates by undertaking a structured analysis as outlined at the beginning of Section 2. This would involve identification of all potential causes of accidents and assessment of the relevant engineered and procedural safeguards, followed by quantification of probabilities for component failure and human error. Finally, it is stressed that the above values assume levels of safety management at least as good as the average and would no longer be valid if safety standards were to decline.

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