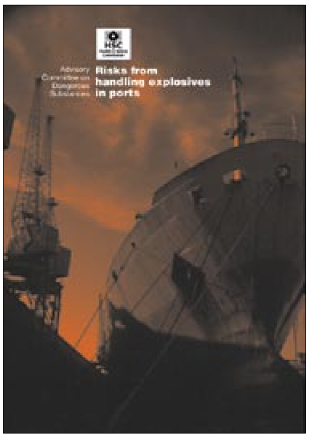
Health and Safety
Executive

Risks from handling explosives in ports

Advisory Committee on Dangerous Substances



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This Advisory Committee on Dangerous Substances (ACDS) report looks at the risk associated with handling explosives in ports. The objective of the study was to obtain best estimate values for the risks of moving explosives through ports by establishing a methodology for the estimation of individual and societal risk from the explosives trade at individual ports and nationally. This report is aimed primarily at managers and specialists in ports and the chemical, petroleum and explosives industries.

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This guidance is issued by the Health and Safety Commission. Following the guidance is not compulsory and you are free to take other action. But if you do follow the guidance you will normally be doing enough to comply with the law. Health and safety inspectors seek to secure compliance with the law and may refer to this guidance as illustrating good practice.

Contents

Technical Annex

Background

1 In 1985, the Health and Safety Commission (HSC) set up a Sub-Committee of its Advisory Committee on Dangerous Substances (ACDS) to consider the recommendation made in the Third Report (1984)[1] of the Advisory Committee on Major Hazards (ACMH) that the major hazard aspects on the transport of dangerous goods was an area requiring further examination.

2 In November 1991 HSC published a report of the ACDS study into 'Major Hazard Aspects of the Transport of Dangerous Substances'[2]. This looked at the hazards and risks of road, rail and marine transport. It developed criteria against which the tolerability of those risks could be measured and made wide-ranging recommendations for reducing the risks.

3 The study did not examine the risks arising from the movement of explosives through ports. At the time of the study the Health and Safety Executive was in the process of licensing ports to handle explosives, as required by the Dangerous Substances in Harbour Area Regulations (DSHAR) of 1987[3]. ACDS felt it was inappropriate to try and assess the risks from handling explosives in ports prior to the completion of the licensing programme. However, ACDS regarded the assessment of these risks to be an outstanding issue and commissioned a study to examine the risks once the new licensing arrangements had been completed in 1992. The ACDS Steering Group began its work in July 1992.

Study of risks from handling explosives in ports

4 The technical assessment was carried out by AEA Technology and the work was supervised by an ACDS Steering Group made up of representatives of the explosives and ports industries, trade unions, local authorities and relevant Government Departments (Appendix 1).

5 The remit of the study was to obtain best estimate values for the risks of moving explosives through ports by establishing a methodology for the estimation of individual and societal risk from the explosives trade at individual ports and nationally.

6 The methodology developed is complex; explosives are not a homogenous group of substances but rather a class of many different substances and articles. The technique of quantified risk assessment (QRA) was used following on from the approach adopted in the previous ACDS study. QRA is a technique for undertaking a systematic analysis of the risks of a hazard situation. It seeks to identify the accidents that might arise from a hazardous activity, to estimate the likelihood that those accidents will occur, to determine the likely consequences of those accidents – in terms of numbers of fatalities and thence to estimate the risk of the activity as expressed by two concepts: individual risk and societal risk.

7 The risks from a hazardous activity are of direct concern to the individual people who might be affected, but they are also of concern to society at large if there is the potential for large-scale disasters. Individual risk, means the risk borne by an individual whilst societal risk refers to the combined risk to a number of people, and expresses the importance of the numbers of people at risk, rather than simply the likelihood of harm to the individual.

8 It was beyond the resources of the study to examine all the 150 ports/berths licensed to handle explosives in detail. Instead the study was approached in two phases which involved, firstly, in depth studies of a few locations which, taken together, covered the range of different types of these licensed ports/berths. Then based on the results of these studies, a rapid risk assessment technique was developed and applied to the remainder of those ports/berths where there is currently an explosives trade.

9 In total five ports and one licensed jetty were selected for detailed study. These locations were chosen to cover the range of different types of explosives handed, the different handling modes as well as other factors associated with the ports themselves including size and infrastructure, geographical location and volume of explosives trade.

10 The detailed studies were undertaken employing the classical form of risk analysis (see para 6 above), that is accident causes, consequences and frequencies were determined and combined to produce estimates of risk. A systematic approach was adopted in which the potential causes of accident initiation of explosives were identified using the Hazard and Operability Study (HAZOP) technique. Potential consequences of explosives events were estimated from explosion effects models. An analysis of the numbers and location of persons in and around the ports at the times explosives cargoes were handled enabled estimates to be obtained for the number of fatalities related to the different explosives events. Estimates for the frequencies with which different types and size of explosives events might occur in ports were computed from rates of dangerous occurrences. Conditional probabilities of initiation, and traffic data for the annual numbers of movements of different types and sizes of explosives cargo moved through ports, were also included.

11 The individual and societal risks associated with the trade at each port were determined from the frequency estimates of different explosives events along with the estimates for the number of fatalities. F-N curves which show the estimated frequency (F) of events resulting in N or more fatalities were produced for each of the ports.

12 A rapid risk analysis methodology was developed, based on the results obtained from the detailed study. Since this study showed that the risk from loading and unloading operations at the berth to be dominant, the rapid risk assessment technique was specifically designed to assess the risks from those handling operations. This enabled a national societal risk estimate to be obtained.

13 The risk analysis procedure provides numerical estimates for the individual and societal risk but does not in itself allow conclusions to be drawn about the tolerability of the risks. To help make those judgements, the estimates for individual and societal risk need to be judged against tolerability criteria.

Risk tolerability and risk reduction and mitigation measures

14 The general principles associated with risk criteria were described in HSE's publication 'The Tolerability of Risk from Nuclear Power Stations'[(6)] which contains a wide discussion of how all risks, nuclear and non-nuclear are controlled in the UK.

15 The judgement of what is tolerable takes its starting point from the general conceptual framework of risk criteria expressed in Figure 1. This sets out which risks are unacceptable, tolerable and broadly acceptable.

16 The framework sets out an upper limit above which a particular risk is regarded as unacceptable to HSE. This upper limit is taken to be an individual risk of death of 1 in 1000 per annum for workers and 1 in 10000 per annum for members of the public; an individual risk that exceeds the appropriate value would be regarded as unacceptable, and actions would need to be taken to reduce it.

17 Below that upper limit is a region where the level of risk is tolerable, but only if it has been reduced as low as is reasonably practicable (the 'ALARP' region). In this region a balance has to be struck between the cost and the demonstrated benefits of any increment to the existing level of safety ie of risk reduction.

18 Below the ALARP region is the region of broadly acceptable risk. That limit, the bottom of the ALARP region, below which it would not be considered necessary to address any risk, would be where the individual risk of death would be one in a million per year.

19 In the ALARP region, the principle of reasonable practicability applies in such a way that the higher or more unacceptable a risk is, the more, proportionately, employers are expected to spend to reduce it. At the point just below the boundary between the unacceptable and tolerable regions they are, in fact, expected to spend up to the point where further expenditure would be grossly disproportionate to the risk.

20 Where the risks are less significant, the less, proportionately, it is worth spending to reduce them and at the lower end of the ALARP region it may not be worth spending anything at all.

Societal risk

21 Some activities could potentially give risk to disastrous accidents in which many people could be killed. Societal risk is usually expressed in the form of an F-N curve showing the cumulative frequency F of accidents involving N or more fatalities.

22 Although the general framework for risk criteria also applies to societal risk, there have been real conceptual difficulties in determining universally relevant levels for unacceptable and broadly acceptable societal risk. Individual risk is fundamentally different from societal risk. Individual risk refers to a particular person; societal risk is a complex concept in which consideration is given not only the many different forms an accident could take, but also to the multiple consequences.

23 Notwithstanding the many necessary qualifications, the ACDS study derived criteria against which to measure the assessed societal risks. The starting point was the second 'Canvey Island' risk assessment [(21)] where, after exhaustive analysis and discussion, including Public Inquiries and Parliamentary Debate, the risks were deemed to be just below the unacceptable borderline. Anything higher would have been judged unacceptable. This allowed a benchmark to be set for the upper limit of societal risk to a local community, using an F-N curve of slope minus 1 through the point N = 500 (fatalities), F = 0.0002 per year. The broadly acceptable limit was set with a frequency three orders of magnitude below this 'Canvey related' line, and with the same slope. (The societal risk and individual risk limits cannot be directly compared because the first relates to the probability of a particular class of event, and the second to the level of risk to a particular individual).

24 The slope of minus 1 of both the unacceptable and broadly acceptable lines was chosen to express the assumption that if a likelihood of 10 or more fatalities is tolerable at a particular level then the risk of 1000 or more fatalities will only be tolerable if it is 100 times less likely. This approach deliberately excluded a factor for aversion to large scale events. This was considered to reflect overall world-wide experience of events involving major installations. The ACDS study concluded that if any additional risk aversion is to be applied then it should be done explicitly.

25 It was suggested that the risks from The Canvey Island complex (risks largely arising from handling toxic and flammable chemicals in bulk) were similar enough in nature to the risks of concern in the ACDS study to allow a limited degree of 'reading across'. Furthermore the ACDS criteria being the best available, have been used as a benchmark in this study.

Comparison of risks with risk criteria

26 Estimates of individual risk are available only for the six locations studied in detail. Not surprisingly those at greatest risk were workers engaged in loading or unloading explosives cargo. However, the individual risks at all the six study locations were found to be in the low ALARP region, and further reduction is only appropriate to the extent that this may be reasonably practicable.

27 Figure 2 shows the estimated F-N curves for the six study locations together with the risk criteria lines derived in the ACDS study; the proposed threshold line for broadly acceptable risk (line B) and the local maximum tolerable risk (line A).

28 When judged against the ACDS criteria, the risks at two of the study locations, B and E, are broadly acceptable. By this measure, these risks are judged so low that no risk reduction measures nor detailed working to demonstrate ALARP will be necessary. The risks at the other four locations are seen to extend into the ALARP region ie these risks are judged tolerable provided that they are reduced to a level as low as reasonably practicable. These risks were found to be in the low ALARP region.

29 Figure 3 shows the national risk faired F-N curve together with the ACDS criteria. It will be seen that the national societal risk, when evaluated against the ACDS criteria, falls either within the low ALARP region ie it is regarded as tolerable provided it has been reduced to a level as low as reasonably practicable or in the broadly acceptable region (ie there is no need to address it).

Risk reduction and mitigation measures

30 Although the risks identified from handling explosives in ports in this study are in the low ALARP region, nevertheless, they should be considered for further reduction so far as is reasonably practicable. Measures to reduce risks include both measures to prevent or mitigate accidents arising from hazards and measures to protect people from their consequences, where necessary.

31 The analysis of risks in this study shows that the risks from operations at the berth and points of loading and unloading to be dominant. In certain circumstances it may be possible to evacuate personnel to a place of safety from the scene of an incident involving an explosives cargo before an explosives event occurs. Successful evacuation will depend to a large extent on both the adequacy of the port emergency plan and its effective implementation. The Dangerous Substances in Harbour Area Regulations 1987 (DSHAR)[3] require Statutory Harbour Authorities to prepare and keep up to date an emergency plan.

32 Some members of the steering group looked at emergency plans produced by a number of ports. They concluded that the plans left scope for improvement and commended the guidance recently published by HSE[17].

33 The study was unable to compare the risks from different modes of handling explosives as, in the cases studied, the different modes were often used with different types of explosives. Methods which keep the number of people exposed to a minimum are preferable but no one method of those in common use (container lift-on-lift off, roll-on-roll-off (RoRo) and break-bulk handling) has any clear advantages over another. Regardless of the handling method employed, since loading and unloading operations were found to account for most of the risks, robust safety management systems, were identified as an essential component in reducing risks in the ALARP region.

34 The risk of an explosives event affecting passenger vessels was found to be sub-ALARP at both the study locations concerned. The introduction of a traffic management system at one of these locations has virtually eliminated the risk by segregating passenger vessels from explosives carrying ships.

Conclusions

35 The analysis of risks, at the six study locations showed that, when judged against the ACDS criteria, two of the study locations are broadly acceptable whilst the other four are found to be tolerable and in the low ALARP region. Further, the national societal risk, when judged against the ACDS criteria, also falls within the low ALARP region.

36 The risks in this study were generally found to be well managed. There was evidence of some scope for improvement in the emergency plans, which recent HSE guidance should help put right. The risks could increase if standards of safety management deteriorate. Effective management of safety is essential.

37 The full explosives licensing arrangements under the Dangerous Substances in Harbour Area Regulations 1987 (DSHAR) had only just been completed at the start of the study. Those regulations together with the requirements in the Management of Health and Safety at Work Regulations 1992 are likely to further result in useful improvements in management of the risks. No further legal controls or guidance are recommended.

38 The results from the study represent a 'snapshot in time'. The risks at the locations studied could change dramatically if patterns of transport were to change; if the volume of explosives traffic was to alter, if different types of explosives were to be handled, or if different methods of loading and unloading were to be employed.

39 The Canvey criteria derived in the ACDS study applied to a locality and not to a specific dangerous substance being handled at a port. Therefore considerable care has to be taken in interpreting the risk figures estimated in this study. It was beyond the scope of this work to determine the overall risks at each of the ports examined. However, the separate contributes to the risk by each trade and their potential for interaction should be borne in mind when evaluating overall port activities.

40 The risk estimates presented in this report are necessarily subject to a number of uncertainties and qualifications. They should be treated with care and not taken out of the context of this study.

41 Finally we would like to acknowledge the considerable help and advice given by so many people in contributing to this study. Special thanks go to the ports and the explosives industries, to the Ministry of Defence and to the members of the Steering Group (Appendix 1).

Figure 1 Levels of risk and ALARP

From 'Tolerability of Risk from Nuclear power Stations' Revised 1992 version.
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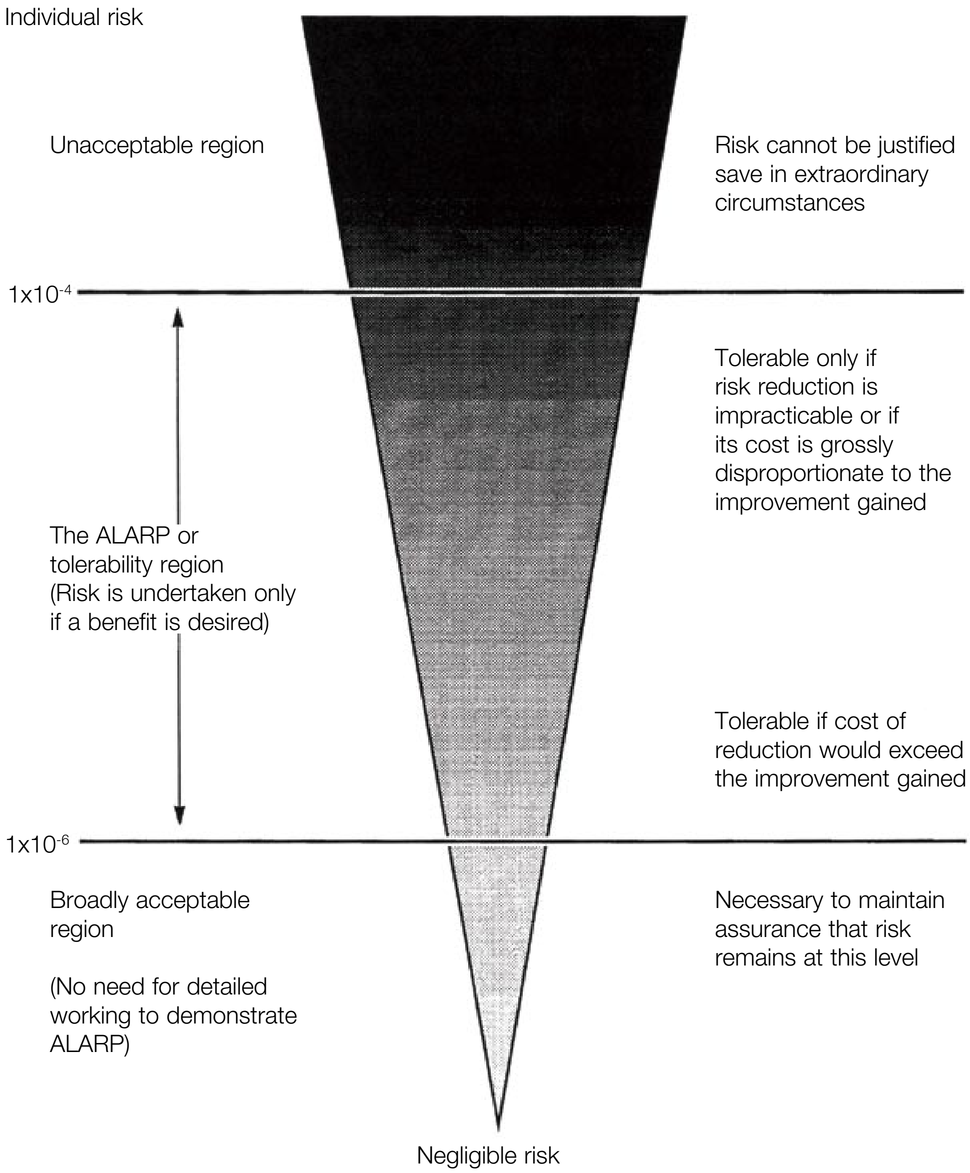


Figure 2 FN curves for study ports

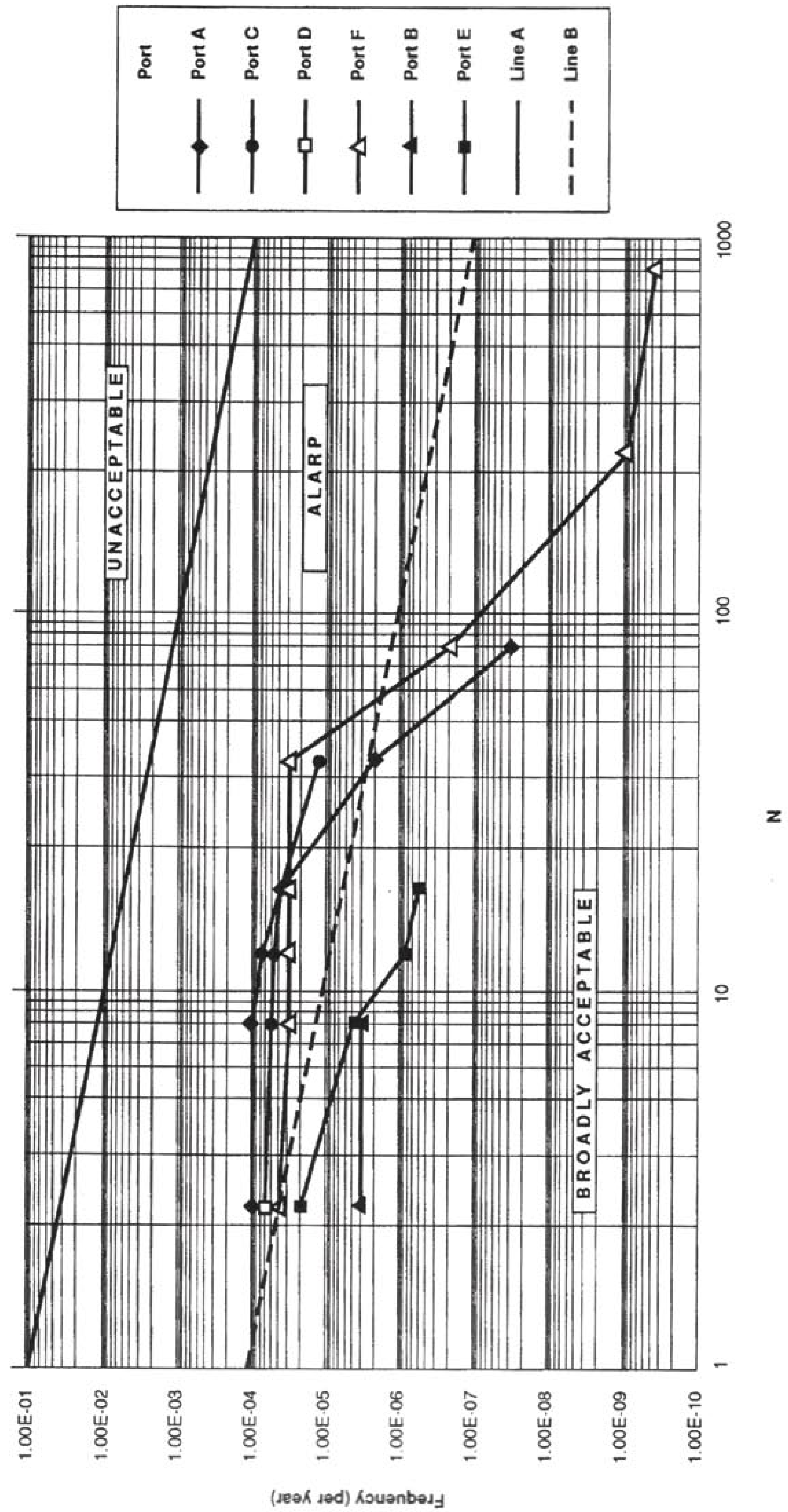
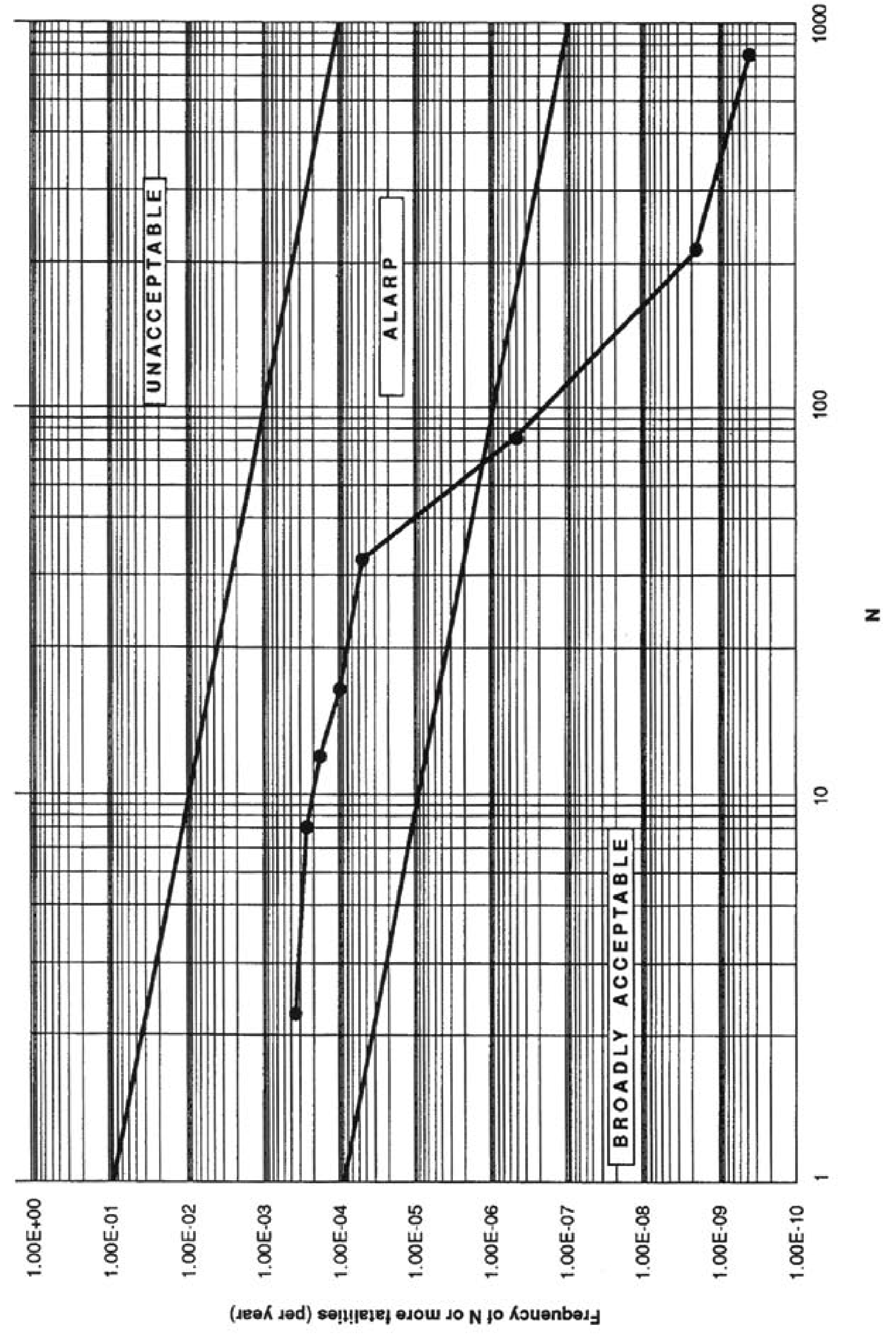


Figure 3 National societal risk comparison with ACDS criteria



1. Introduction

Background to the study

1 In 1974, the Health and Safety Commission (HSC) set up a special committee to examine the dangers to employees and members of the public from non-nuclear hazardous installations. This was in the wake of the Flixborough disaster of that year, when an explosion at a chemical plant caused 28 fatalities and widespread damage. The committee set up by the HSC, known as the Advisory Committee on Major Hazards (ACMH), went on to produce three reports that came to form the basis of a regime for the identification and control of hazards and risks posed by static installations, such as the chemical plant that had exploded at Flixborough. The final report of the ACMH, published in 1984, also briefly discussed major hazard aspects of the transport of dangerous goods and concluded that this was an area that required further examination(1). In the following year, the HSC set up a sub-committee of its Advisory Committee on Dangerous Substances (ACDS) to pursue this recommendation.

2 The setting up of the ACDS Sub-committee marked the beginning of a five-year study into the risks arising from the transport of dangerous goods in Great Britain. The scope of the study embraced road, rail and marine transport of commodities that have a potential fire, explosion or toxic hazard, and could affect members of the public in the event of an accident. The risks from five such commodities were examined in detail as part of the road and rail studies: liquefied petroleum gas, liquefied chlorine, liquefied ammonia, motor spirit and explosives. The ACDS(2) concluded that while these risks were not so high as to be intolerable they were also not so low that they could be considered negligible and that efforts should be made to reduce these risks further so as to achieve a level ‘as low as reasonably practicable’ (ALARP). The risks examined in the marine study were those from bulk shipments of crude oil, liquefied gases, liquefied petroleum products, liquid chemicals and ammonium nitrate. Again, the ACDS concluded that these risks were not intolerable but of a level which merited reduction on the ALARP principle: though the ACDS did note that some risks in ports came very close to a level where they might have been regarded as unjustifiable had they been any higher.

3 The ACDS study did not examine the risks arising from movements of explosives through ports. This was because at the time of the study licensing arrangements for ports were in a state of flux following the introduction of the Dangerous Substances in Harbour Area Regulations (DSHAR) in 1987(3). These regulations require those ports where explosives are handled, or brought into the harbour area, to be licensed by the Health and Safety Executive (HSE). The ACDS concluded that an assessment of the risks from the explosives trade at ports would be inappropriate in advance of the completion of the new licensing arrangements. However, the ACDS regarded the assessment of these risks to be an outstanding issue and inaugurated a study to examine the risks once the new licensing arrangements had been completed in 1992. This report presents the results of that study.

The scope of the present study

4 The remit for the study was to obtain best estimate values for the risks of moving explosives through ports and to identify possible risk reduction measures. Decisions concerning the tolerability of the estimated risks and the reasonable practicability of possible risk reduction measures were outside the remit of the study. The specific technical objectives of the study were:

(a) to establish the types and quantities of explosives moved through ports and the populations at risk from such movements;
(b) to establish what types of explosives accidents could occur in ports, what is the likelihood of those accidents and what would be their consequences;
(c) to establish a methodology for the estimation of individual and societal risk from the explosives trade at individual ports and nationally;
(d) to establish a framework for the assessment of possible risk reduction measures.

The nature of explosives

5 As with the earlier ACDS report Major Hazard Aspects of the Transport of Dangerous Substances, the substances and articles studied here are Class 1 explosives in the scheme devised by the UN Committee of Exports on the Transport of Dangerous Goods (UNCOE)[4]. This scheme classifies dangerous goods in the form in which they are to be transported according to the hazard they present during transport, and defines explosives as follows:

(a) Explosive substances: an explosives substance is a solid or liquid substance (or a mixture of substances) which is in itself capable by chemical reaction of producing gas at such a temperature and pressure and at such a speed as could cause damage to surroundings. TNT and dynamite are well-known examples of explosives substances.
(b) Pyrotechnical substances: a pyrotechnic substance is a substance or a mixture of substances designed to produce an effect by heat, light, sound, gas or smoke or a combination of these as a result of non-detonative self-sustaining exothermic chemical reactions. Pyrotechnic substances are commonly found in fireworks.
(c) Explosive articles: an explosives article is an article containing one or more explosives substances. Thus, for example, all natures of ammunition are classified as explosives articles.

6 The UN scheme of classification recognises that many substances and articles classified as explosives do not present the same degree of hazard and subdivides them into four hazard divisions according to their potential for harm:

(a) which give risk to considerable radiant heat, eg bulk packed propellant, or
(b) which burn one after another, producing minor blast or protection effects or both, eg packed cartridge propellant.

HD 1.1 Substances and articles which have a mass explosion hazard (a mass explosion is one that effects the entire load virtually instantaneously) eg dynamite cartridges packed in wooden boxes or high explosives filled aircraft bombs.

HD 1.2 Articles which have a projection hazard eg small mortar but not a mass explosion hazard, eg mortar bombs packed in metal boxes.

HD 1.3 Substances and articles which have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard. This division comprises substances and articles.

HD 1.4 Substances and articles which present no significant hazard. This division comprises substances and articles that present only a small hazard in the event of ignition or initiation during transport. The effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected, eg boxes of small arms ammunition.

The UN has defined two further divisions based on risk rather than hazard:

HD 1.5 Very insensitive substances that have a mass explosion hazard. This division comprises substances which have a mass explosion hazard but are so insensitive that there is very little probability of initiation or of a transition from burning to detonation under conditions of normal transport.

HD 1.6 Extremely insensitive articles which do not have a mass explosion hazard. This division comprises articles which contain only extremely insensitive detonating substances and that demonstrate a negligible probability of accident initiation or propagation.

At the time of the study, no substances of HD 1.5 or articles of HD 1.6 were imported or exported through ports in Great Britain.

Current licensing arrangements for ports

7 As noted in paragraph 3, DSHAR requires ports (and certain other places) where explosives are loaded, unloaded or otherwise handled to be licensed. The form of licence that is issued specifies the maximum quantities of explosives which may be handled at any place and the corresponding distances to give people not involved in the handling operation a high degree of protection even in the unlikely event of an explosion. Those distances also serve for land use planning decisions. The risks to those handling explosives are controlled as a function of the Health and Safety at Work etc Act 1974 and such subordinate legislation as the Management of Health and Safety at Work Regulations 1992 rather than by licensing. The licence provides an added degree of protection to others from any residual risks which then remain.

8 The broad success of these measures is demonstrated by an excellent safety record (there has been only one very minor explosives event, in which no one was killed, in a commercial British port in post-war times). The historical safety performance of British commercial ports suggests that explosives events are unlikely to occur in these locations more often than about once in 40 years, and possibly much less often. However, a better assurance of safety than this is required if there is any possibility that such events might, in certain adverse circumstances, result in large numbers of fatalities and cause widespread damage. This assurance can only come from a detailed study of the risks involved in moving explosives through ports and the knowledge that all reasonably practicable safety measures have been implemented.

9 One technique which can help achieve this goal is quantitative risk assessment. The risks of moving explosives through ports have now been studied using this technique, following on from the approach adopted in the previous road, rail and marine studies mentioned in paragraph 2.

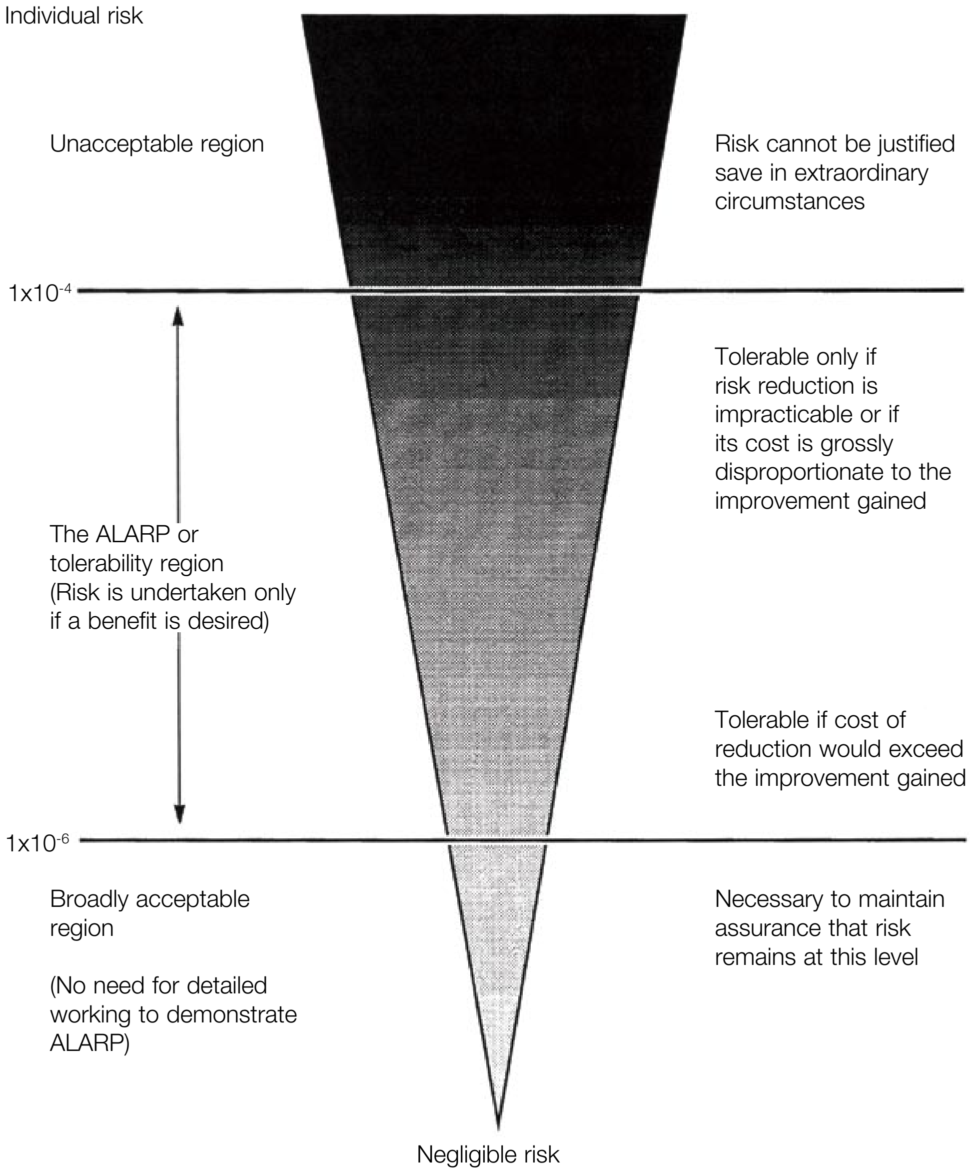
The role of quantitative risk assessment (QRA)

10 In essence, QRA is a technique for undertaking a systematic analysis of the risks of a hazardous situation, evaluating the significance of those risks and providing information for use in decision-making on safety issues. The technique can be conveniently subdivided into two procedures: risk analysis and risk evaluation. Risk analysis is a technical procedure which attempts to estimate the level of risk posed by a hazardous activity, while risk evaluation is essentially an interpretative procedure which attempts to assess the 'tolerability' of the estimated risks.

11 More specifically, risk analysis seeks to identify the accidents that might arise from a hazardous activity, to estimate the likelihood that those accidents will occur, to determine the likely consequences of those accidents – in terms of numbers of fatalities – and thence to estimate the risk of the activity as expressed by two parameters: individual risk and societal risk.

Figure 1 Levels of risk and ALARP

From 'Tolerability of Risk from Nuclear power Stations' Revised 1992 version. ISBN 0-11-886368-1



12 Individual risk, as the name implies, is the risk to a specified individual, for example a dock worker, a member of a ship's crew, a person living or working near a port. It usually expresses the chance per year that the individual will be killed as a result of the occurrence of a particular type of accident. Sometimes, however, it expresses the chance that an individual will be injured or exposed to a dangerous dose of a substance or an effect, and so it is defined in general terms as 'the frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards'[(5)]. In the present study, individual risk is measured as the annual probability that an individual will be killed by an explosives event.

13 Some activities could potentially give rise to disastrous accidents in which many people would be killed. It is well-established that the public view multiple-fatality accidents with particular concern, and expect measures to be in force to ensure that the chance of such accidents is appreciably lower than that for accidents resulting in one or two fatalities. The disaster potential of an activity is measured by so-called societal risk. This usually expresses the chance per year for the occurrence of an accident resulting in not less than a specified number of fatalities. In general terms, societal risk is defined as 'the frequency with which specified numbers of people in a given population may be expected to sustain a specified level of harm from the materialisation of specified hazards'[(5)]. In the present study, societal risk is measured as the annual probability that specified numbers of people will be killed by explosive events.

14 The risk analysis procedure provides numerical estimates for the individual and societal risk of an activity but it does not in itself allow conclusions to be drawn about the tolerability of those risks. Such judgements are essentially political rather than technical and are for appropriate decision-takers to make. Usually, to help make these judgements, estimates for individual and societal risk are judged against criteria to determine tolerability. The criteria applied to the results of the previous road, rail and marine studies divided risks into three bands:

> Unacceptable Region – where the risks are so high that they must be reduced irrespective of cost or the activity giving rise to the risks must cease, except perhaps in extraordinary circumstances such as wartime.
>
> ALARP – where the risks can be considered tolerable provided measures have been taken to reduce them to a level as low as reasonable practicable. If it is possible within a reasonable cost to reduce risks that come within this band then the cost should be incurred to bring about the necessary improvement.
>
> Broadly acceptable region – where the risks are so low that no further measures need to be taken beyond ensuring that the risks remain broadly acceptable and do not rise as a result of negligence.

15 The general conceptual framework of risk criteria is illustrated in Figure 1. An aim of this framework is to make as safe as reasonably practicable all activities that pose risks in the ALARP region. However, risks that are found in the broadly acceptable region may also be examined further to determine whether any measures could be taken to reduce the risk, for example by reducing the chance of an accident or by ameliorating its potential consequences. Possible risk reduction measures are explored in the present study but, as noted in paragraph 4, it is beyond the scope of the study to formulate criteria against which the tolerability of the risks might be judged or indeed to specify criteria against which the reasonable practicability of risk reduction measures may be considered.

The structure of the study

16 There are 150 ports/berths in Great Britain licensed to handle explosives. It was beyond the resources of the project to examine all of these in detail. This necessitated a two-phase approach to the project, in which:

(a) in depth studies were carried out for a few locations which, taken together, covered the range of the different types of ports/berths licensed to handle explosives;
(b) based on the results of these studies, a rapid risk assessment technique was developed and applied to the remainder of those ports/berths where there is currently an explosives trade.

17 A number of factors had to be taken into consideration in selecting ports for detailed study. First of all, the range of ports selected had to cover the different methods by which explosives cargo is transferred between ship and shore. Three such methods are currently in use: container lift-on-lift-off, which, as the name implies, involves use of cranes to transfer freight containers between ship and shore; roll-on-roll-off (RoRo), in which vehicles are driven directly on and off ships; break-bulk handling, in which individual packages or palletised loads are handled manually or by means of fork lift truck (FLT) and either carried on or off ships manually or lifted on and off ship or by means of crane. A fourth type of operation can also be defined, namely, lightering, in which explosives are loaded onto lighters (ie barges) at a berth and transported to a ship at an anchorage where a further transfer operation takes place. Lightering to a suitable licensed anchorage is undertaken when the quantity of explosives to be loaded onto a ship exceeds the licence limit for the berth, and where a higher quantity is permitted at a licensed anchorage nearby. Explosives cargo loaded onto lighters is normally in break-bulk form.

18 In addition to these various modes of loading and unloading, seven other factors formed an important consideration in the selection of ports for detailed study:

(a) Size of port – licensed ports vary considerably in size, from those that extend over a number of square miles and employ many workers to those that cover no more than one or two acres and employ few workers.
(b) Geographical location – some licensed ports are located near to large centres of population while others are located in remote and isolated areas.
(c) Geographical type – licensed ports cover the range from open sea to narrow river.
(d) Infrastructure – licensed ports range from those with modern and extensive infrastructure to those with relatively old and little infrastructure.
(e) Volume of trade – some licensed ports handle explosives often while others handle explosives on only a few occasions per year.
(f) Licence limit – explosives limits for licensed ports range from several hundred tonnes to less than one tonne of HD 1.1.
(g) Types of explosives handled – some ports handle only one or two types of explosives while others handle many different types of explosives.

In total, five ports and one licensed jetty were selected for detailed study. The aim of the selection process was to cover all of the above factors so far as possible. The locations were not in a strict sense standard ports with respect to modes of loading – container lift-on-lift-off, RoRo, break-bulk handling etc – or with respect to any other factory – such as size, geographical type etc. When all of these various factors are considered together with differences in management systems and operating procedures, the variation between ports is such as to preclude an attempt to define a standard port.

19 The five ports and once licensed jetty selected for detailed study are not identified in this report as the aim of these studies was not specifically to assess the safety of operations at these locations, but rather to identify the main components of the risk involved in handling explosives cargo. An alphabetic code is used to refer to the locations:

Port A A major container port

Mode of loading and unloading:
container lift-on-lift off

Geographical type:
wide estuary

Volume of trade: (all types of explosives)
high – in excess of 1000 te NEQ per annum at the time of study

Licence limit:
up to 200 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

This port also has facilities for handling RoRo and break-bulk cargo and an oil jetty for importing and exporting bulk petroleum and chemical products. In addition to the goods trade, the port also has significant passenger ferry services. Virtually all of the explosives cargo handled at the port at the time of the study was containerised. Explosives containers were moved into and out of the port by both road and rail, container gantry cranes being used to load and unload containers at the rail terminal and at the berth. The port handled a wide range of military and commercial explosives at the time of the study.

Port B A small break-bulk port

Mode of loading and unloading:
break-bulk

Geographical type:
narrow river

Volume of trade: (all types of explosives)
low – less than 100 te NEQ per annum at the time of the study

Licence limit:
up to 2 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

This port handles break-bulk cargo exclusively. Cargo is brought into and taken out of the port on road vehicles, fork lift trucks being used to load and unload vehicles at the quay and mobile cranes being used to transfer cargo between ship and shore, though at this particular port the height of lift does not exceed more than a few feet as the deck of the ship is about level with the quay. The port handled a wide range of military and commercial explosives at the time of the study.

Port C A major Ro-Ro port

Mode of loading and unloading:
RoRo

Geographical type:
narrow estuary

Volume of trade: (all types of explosives)
medium - between 100 and 1000 NEQ per annum at the time of the study

Licence limit:
up to 2 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

This port also has facilities for handling conventional and bulk commodities, though most of the freight passing through the port is carried on RoRo vessels. All explosives cargoes imported and exported through the port at the time of the study were carried on RoRo vessels. Both military and commercial explosives loads passed through the port.

Port D A major break-bulk port

Mode of loading and unloading:
break-bulk

Geographical type:
open sea

Volume of trade: (all types of explosives)
high – in excess of 1000 te NEQ per annum at the time of study

Licence limit:
up to 110 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

Military munitions of HD 1.2 were the only types of explosives handled at this port at the time of the study. These munitions were brought into the port on road vehicles. The vehicles were unloaded on the quayside by means of FLT and dockside cranes were used to transfer loads from quay to ship.

Port E A small RoRo port

Mode of loading and unloading:
RoRo

Geographical type:
open sea

Volume of trade: (all types of explosives)
low – less than 100 te NEQ per annum at the time of study

Licence limit:
up to 10 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

This port consists of a single pier with facilities for discharging fishing vessels and for loading and unloading small RoRo ferries. Commercial explosives of Hazard Division 1.1 were the only types of explosives handled at this port at the time of the study.

Port F A licensed jetty

Mode of loading and unloading:
break-bulk

Geographical type:
wide estuary

Volume of trade: (all types of explosives)
high – in excess of 1000 te NEQ per annum at the time of the study

Licence limit:
up to 400 te HD 1.1 or proportionately greater quantities of HD 1.2 or 1.3

This is an isolated jetty within a statutory harbour area. Large consignments of aircraft bombs were exported from this jetty at the time of the study. The bombs were palletised and brought to the jetty on container lorries. The bombs were off-loaded onto the jetty on container lorries. The bombs were off-loaded on the jetty by means of FLT and, depending on overall size of cargo (see paragraph 17), loaded onto either ships or lighters by means of mobile crane. The bombs loaded onto lighters were transported 16 km downstream of the jetty to an anchorage where they were transferred onto ocean-going ships. No other types of explosives were handled at the jetty at the time of the study.

20 The detailed studies were undertaken employing the classical form of risk analysis, ie accident causes, frequencies and consequences were determined and combined to produce estimates of risk. In the present study, this entailed a five-step approach in which:

(a) the potential causes of accidental initiation of explosives were identified in a HAZOP exercise, and those judged by explosives experts to be the most likely sources of explosive events in ports were earmarked for detailed study;
(b) the many different types of explosives cargoes imported and exported through British ports were categorised into a small, manageable number of groups by susceptibility to accidental initiation, type of hazard and size of load;
(c) estimates were obtained for the frequencies with which different types and sizes of explosives events might potentially occur;
(d) estimates were obtained for the consequences (ie the numbers of fatalities) that could be expected should these events occur;
(e) the estimated frequency and consequences of explosives events were combined to produce estimates for two risk parameters: individual and societal risk.

The various steps of the analysis are shown in schematic form in Figure 2. The next section of this report discusses the first stage of the risk analysis procedure: the identification of the potential causes of explosives events in ports.

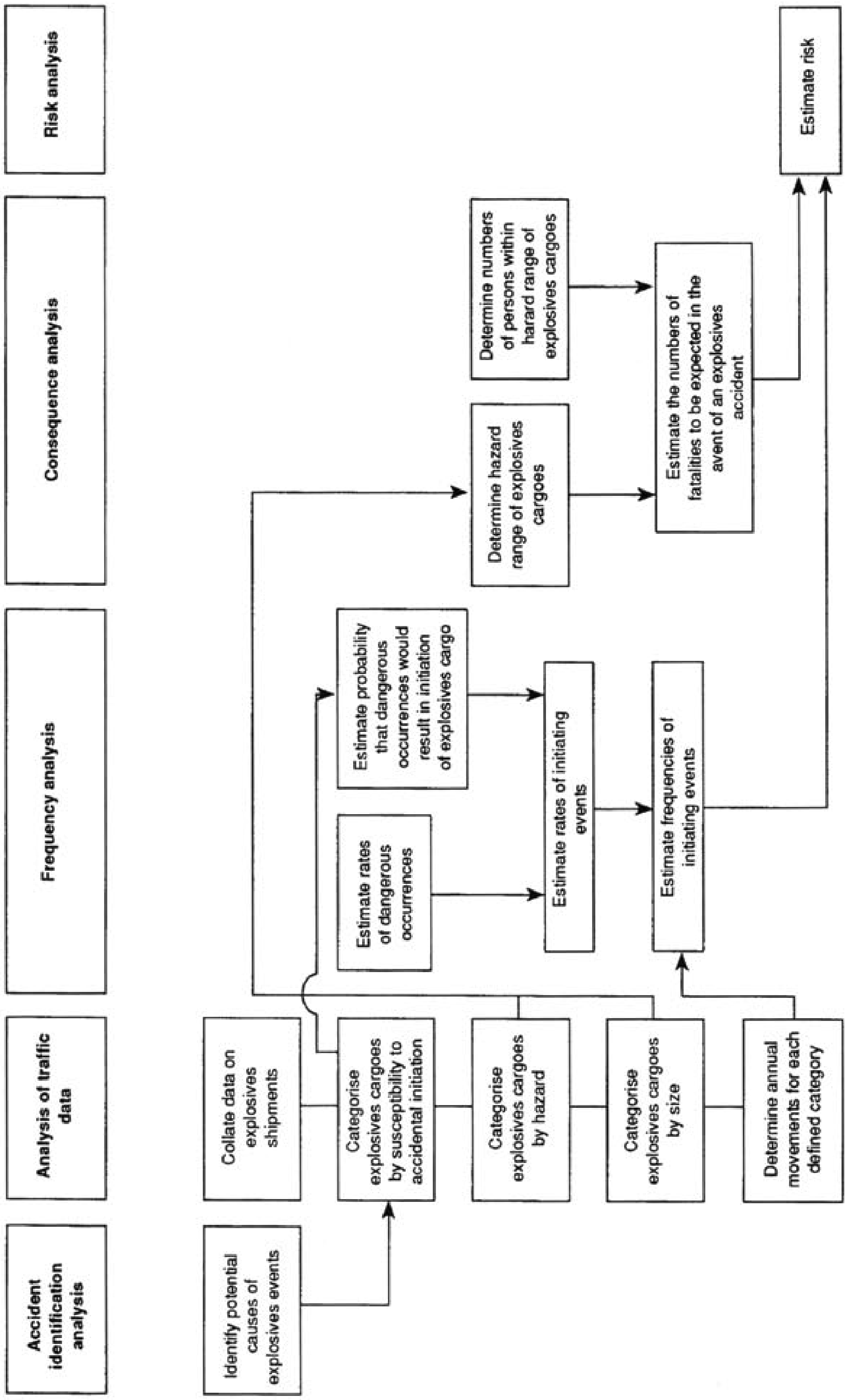


Figure 2 Steps in the analysis to estimate the risks of moving explosives through ports

2. The potential causes of explosives events in ports

21 All explosives are thermodynamically unstable and will react exothermically to a more stable form given the necessary activation energy. In an intentional initiation of explosives, the activation energy would normally be supplied by an initiating device, such as a detonator or a fuse. However, in accident conditions, the activation energy could be supplied by a number of different types of energetic stimuli. These stimuli include:

impact/friction
thermal energy
fragment attack/overpressure
electrostatic discharge
electromagnetic radiation (in the case of electro explosives devices)
chemical reaction

22 All explosives transported in the UK must by law be classified in the form in which they are to be transported. An essential prerequisite to classification is an assessment against UNCOE criteria that the explosives will be safe under normal conditions of transport. Military explosives generally are subjected to additional tests designed to demonstrate the safety in handling and use of the explosives during their entire manufacture to disposal life cycle.

23 However, there is a possibility that failures in safety management might result in the despatch of explosives that do not conform to the required standards and that are in an unsafe condition. Such explosives are referred to in this study as 'unsafe explosives' (see Appendix 3) and may have been badly designed, manufactured, packaged or have deteriorated prior to despatch. Certain types of unsafe explosives could be initiated by the knocks and jolts cargoes typically receive while in transit.

24 In addition to this possibility, explosives cargoes could also initiate in various types of energetic accidents, for example lorry crashes and falls of loads from cranes, even if the cargoes do not contain explosives in an unsafe condition. The outcome of these types of accidents would depend on a number of factors, including the types of explosives present, the type and standard of packaging employed and the types and levels of energetic stimuli imported to the cargo. In general, it could be expected that explosives cargoes would remain safe in impact accidents, provided all explosives in the cargo conformed to required standards. However, an accident that resulted in a fire could pose a greater danger; it could be expected that most explosives cargoes would initiate within several minutes of being engulfed in fire. For both impact and fire accidents, but more especially in the former case, the chance of initiation would be higher should the cargo contain explosives in an unsafe condition.

25 From these arguments it follows that two broad categories of unintentional initiation can be defined:

(a) Errors or breaches of regulations that result in unsafe explosives entering the transport chain, with the result that initiation occurs during conditions of normal transport, ie without the involvement of explosives cargoes in external accidents, such as lorry crashes or falls of loads from cranes.
(b) Accidents that result in the exposure of explosives cargo to levels of energetic stimuli of a sufficiently high intensity for initiation to occur.

26 The significance of the threat posed by unsafe explosives is clearly demonstrated by the historical record for accidents that have occurred during transport of explosives in the UK. This historical record is reproduced in Appendix 2 in three parts. Section 1 lists explosives events that have occurred within ports, Section 2 lists explosives events that have occurred during rail transport while Section 3 lists explosives events that have occurred during road transport. The period examined, 1950 to the present date, has been chosen to exclude a number of incidents that occurred in the late 1940s and which involved initiations of unsafe ammunition manufactured under wartime conditions when quality assurance procedures were less rigorous than those applied in modern practice. In total, eleven transport incidents involving ignition of explosives occurred in the UK within this period and five of these incidents were caused by unsafe explosives material of one type or another.

27 A number of categories of unsafe explosives may be defined. Some of these categories are unique to particular types of explosives substances or articles. Furthermore, some of these categories pose more of a threat than others; some types of explosives are more susceptible to initiation than other types when in a deteriorated condition. It follows that some types of explosives are inherently less safe than others, though good quality control procedures should help to ensure that no types of explosives are despatched in an unsafe condition. The various categories of unsafe explosives are defined in Appendix 3, Section 1, where examples are also given of a number of past transport and storage incidents caused by unsafe explosives of one type or another. Of course, lessons have been learnt from these incidents and steps taken to prevent, or at least reduce, their chance of recurrence. But there is always a possibility that such incidents will occur in the future as a result of failures in safety management. There is also a possibility that unsafe explosives could enter the transport chain inadvertently: safety flaws in the design, manufacture, processing, keeping, packaging and conveyance of explosives sometimes only become apparent with the occurrence of explosives events. Again, there is no guarantee that such incidents will not occur in the future; indeed it is notable that the last explosives event in the UK caused by transport of unsafely packaged explosives occurred as recently as 1989.

28 Explosives cargoes which contain unsafe items of one type or another may initiate spontaneously, ie without the involvement of the cargoes in external accidents, such as lorry crashes or falls of loads from cranes. Explosives cargoes that do not contain unsafe items may initiate in the event that they become involved in accidents, such that sufficient energy is imparted to explosives material in the cargo to bring about an explosion or fire. There are a number of different types of accidents that could occur in ports and which in theory could result in an initiation of explosives cargo. These accidents were identified by undertaking a hazard and operability (HAZOP) study of the various methods used for moving explosives through ports, with particular reference to operations at the six locations selected for detailed study. The details of this study and the results obtained are discussed in Appendix 3, Section 1.

29 The HAZOP study identified a number of different types of accidents which could occur in ports and which could potentially result in initiations of explosives cargoes. The study also highlighted various statutory regulations, codes of practice and safe working procedures that have been implemented to guard against such events. It was generally recognised, however, that these measures could not be guaranteed to prevent explosives accidents, only to reduce their likelihood and consequences: a residual risk would remain at all ports that had an explosives trade.

30 The list of accident scenarios identified in the HAZOP study was examined by a small group of explosives experts drawn from the HSE, the MoD and the commercial explosives industry. The aim was to identify those scenarios that could be expected to pose the dominant threat of an explosives event. An element of judgement was necessarily involved in this exercise, but this was informed judgement based on a knowledge of accidents that have occurred in the past as well as an understanding of the susceptibility of explosives items to various types of energetic stimuli. It was clear that some of the accident scenarios identified in the HAZOP study were so improbable that they could be judged *'a priori'* not to warrant consideration in the further stages of the risk analysis. These scenarios fell into two categories:

(a) accidents that are likely to occur (and indeed are known to occur) in ports from time to time but which would be most unlikely to result in explosives events, for example falls of packages during unloading of vehicles (providing, of course, that the packages do not contain explosives in an unsafe condition);
(b) accidents that could be expected to result in explosives events but which have an extremely low probability of occurrence, for example aircraft crashes onto vessels loading or discharging explosives cargo.

31 In total, nine scenarios, involving fire or impact, were selected for further study:

Fire accidents
road vehicle fires
train fires
ship fires

Impact accidents
road vehicle crashes and collisions
train derailments and collisions
crushing or penetration of packages by fork lift trucks
falls of loads from cranes
ships striking vessels loading explosives
ship collisions

32 The involvement of explosives cargo in any of the above types of accidents would not necessarily result in an explosives event. These accidents can be regarded as 'dangerous occurrences' that would pose a threat to the safety of explosives cargo but would not inevitably result in the initiation of an explosion or a fire within an explosives load. In fact, much would depend on the types of explosives present in the load, explosives not all being equally susceptible to initiation by fire and impact. This issue is explored further in the following section, where the categorisation of explosives loads by susceptibility to accidental initiation is discussed, together with categorisation of explosives loads by hazard and size.

3. Analysis of traffic data: categorisation of explosives cargoes

33 Many different types of explosives cargoes are imported and exported through ports in Great Britain. Some of these cargoes comprise only one explosives substance or article while others comprise mixed loads of different substances, articles or both. Explosives cargoes are also of many different sizes. It is not practicable to analyse separately the risks posed by each of these many different types and sizes of explosives cargoes. Accordingly, the approach adopted in this study has been to categorise the cargoes into a small number of groups with respect to the important risk factors. The important risk factors are:

(a) susceptibility of the cargo to accidental initiation by impact;
(b) susceptibility of the cargo to accidental initiation by fire;
(c) hazard, ie types of harmful effects that would be produced by the cargo on initiating;
(d) size of cargo, ie net explosives quantity (NEQ).

34 Separate categorisation schemes have been developed for each of these factors following consultations with explosives experts in the MoD, HSE and the commercial explosives industry. The objective of each scheme is to categorise explosives into a small number of groups, such that all explosives belonging to a particular group may be considered either to produce similar effects on initiating or to be roughly equally susceptible to energetic stimuli. In devising suitable categorisation schemes, a compromise inevitably has to be struck between accuracy of analysis, which would increase with the number of categories chosen, and convenience of analysis which is greater with fewer categories. The schemes are discussed under the appropriate headings in the following paragraphs.

Categorisation of explosives by hazard

35 The hazard categorisation scheme used in this study is based on the well-established system of hazard divisions developed by the United Nations Committee of Experts on the Transport of Dangerous Goods[4]. This system subdivides explosives into six hazard divisions as described at paragraph 6 above. The scheme employed in the present study differs from the system in that it subdivides Divisions 1 and 3 into substances and articles. To explain the rationale behind this decision it is necessary to consider in more detail the effects that would be produced by initiations of substances and articles of HD 1.1 and HD 1.3.

36 Explosives of HD 1.1 pose a mass explosion hazard, ie should part of a load consisting of these explosives (whether substances or articles) be initiated, the explosion could communicate near-instantaneously to the remainder of the load. The harmful effects that would be produced by such an event include:

(a) A blast wave, ie a pressure wave generated in the surrounding air by the energy released in the explosion.
(b) Initiations of loads containing articles of HD 1.1 may produce a hazardous effect in the form of primary fragments, ie pieces of the casing of the article projected at high velocity by the explosion.
(c) Secondary fragments, missiles produced by the shattering of objects in the vicinity of the explosion and whole objects picked up and projected by the blast wave. The secondary fragments produced by an explosion on board a ship could vary considerably in size and include both small land large pieces of debris produced by the break-up of the ship or quay.

37 Explosives of HD 1.3, by definition, present primarily a fire hazard rather than a significant blast or fragment hazard. The extent of this hazard could be expected to vary between substances and articles of this division, as substances are more likely to produce what are termed 'idealised fires'. An idealised fire is one in which the whole mass of explosive burns virtually simultaneously and is over in a few seconds, giving rise to a pulse of radiation rather than a steady state flux; a non-idealised fire is one in which flame propagation is hindered by the thermal inertia of packaging and the spacing between packages, giving rise in the extreme, to a number of sequential fires involving one package or article at a time. The thermal radiation effects from a non-idealised fire could be minimal although the duration of the fire could extend to several hours depending on the size of the load. Fires involving bulk packed propellant are likely to be of the idealised type, but packaged cartridge propellant is more likely to give rise to non-idealised fires.

38 The last two divisions of Class 1 goods defined by the United Nations Committee of Experts on the Transport of Dangerous Goods, HD 1.5 and HD 1.6, are based on risk rather than hazard – explosives of these divisions demonstrate an almost negligible probability of accidental initiation. At the time of the study, no explosives belonging to these divisions were imported or exported through British ports, and accordingly they do not feature in the categorisation schemes reported here.

39 Thus the hazard categorisation scheme employed in the present study partitioned explosives cargoes into six groups:

- articles of HD 1.1
- substances of HD 1.1
- articles of HD 1.2
- articles of HD 1.3
- substances of HD 1.3
- articles of HD 1.4

Explosives cargoes made up solely from articles of HD 1.4 were excluded from the further stages of the study as these cargoes, by definition, do not pose a major hazard. The effects that could be expected from initiations of these cargoes would depend on the particular items present: in some cases the effects of the initiation would be confined to the package, while in other cases thermal effects could be produced a few metres beyond packaging material.

Categorisation of explosives by susceptibility to impact-induced initiation

40 It is foreseeable that explosives cargoes will be involved in traffic accidents and port accidents – such as falls from cranes – from time to time. Explosives are therefore designed and packaged to standards that ensure they would be unlikely to initiate in such accidents. Most types of explosives imported and exported through commercial ports in Great Britain will have passed a 12 meter drop test (which involves a free fall of explosives packages from a height of 12 metres onto a hard, unyielding surface). This test was originally instituted to provide some confidence that explosives items would survive the worst credible drop that could occur during ship to shore transfer. To pass the test, items must show no explosives reaction on impact and be safe for collection and disposal afterwards. Success in these tests may be taken as confirmation of theoretical predictions that an explosive reaction would be unlikely to occur in the event that an explosives item were to fall from a height of 12 metres. However, only two or three tests are normally carried out for each type of item (this is for economic reasons) and successful outcomes in such a small number of tests do not provide results which

are in themselves statistically significant; three successful tests do not indicate whether the true probability of initiation is one-in-ten, one-in-a-thousand, one-in-a-million or indeed truly negligible.

41 Although the 12 metre drop test provides a severe examination of the capacity of explosives items to remain safe on sustaining considerable impact forces, it is recognised that this test does not in fact simulate the worst possible drop accident that could occur in a port, and this is for two reasons:

(a) At some commercial ports explosives loads are lifted to heights in excess of 12 metres (though these loads tend to be in freight containers).

(b) At some ports there is a potential for explosives cargo to be dropped into sharp objects, such as deck fittings, or for sharp objects to be dropped onto explosives cargo stowed within a ship's hold or awaiting transfer on the quay. This type of accident poses a greater threat of initiation than the planar impact simulated in the standard 12 metre drop test, because:

    (i) the rupturing of explosives packages by sharp objects might result in nipping or crushing of explosives substances between two surfaces;

    (ii) in the case of accidents involving explosives articles, failure of the casing of an article by the mechanisms of distributive flow or thermoplastic shear could result in a hot disc of metal being pushed into the explosives filling. This type of event is often referred to as 'spigot intrusion'.

42 Nonetheless, there is a certain amount of empirical evidence to suggest that correctly packaged explosives articles would be unlikely to initiate in the event of their involvement in typical port accidents. For example, there have been a number of dropped-load crane accidents in British military ports during the last 40 years and not one of these has resulted in an explosives event; during the same period there have been several impact accidents involving road and rail cargoes of explosives, and, again, none of these resulted in an explosives event[(2)]. Further evidence for the capacity of explosives articles to withstand large impact forces is provided by trials data, for example missile impact tests (in which explosives-filled cartridges are projected at various velocities into steel plates) have shown that an impact velocity appreciably in excess of that generated in a 12 metre free fall is necessary to bring about an initiation of cartridges filled with some of the more sensitive types of blasting explosives[(7)].

43 At the same time, trials have shown that explosives articles are not all equally insensitive to impact. It is clear that a few types of munitions would be more likely to initiate in accident conditions than the majority of explosive items, though this risk may still be low in absolute terms. Of particular interest here is a series of trials carried out by the MoD involving the dropping of weighted spigots onto munitions (these trials were devised in recognition of the fact that the standard 12 metre drop test does not simulate the worst drop accident that could occur in a port). The results of these trials suggest that a few types of explosives articles might initiate if they were to be involved in particularly severe impact accidents, in which spigot-type objects were to rupture the casing of the articles. The chance of such an accident occurring is difficult to assess. The spigot intrusion trails carried out by the MoD were performed with **unpackaged** munitions, and unpackaged munitions are not moved through commercial ports. In fact robust methods of packaging are employed for explosives cargoes moved through commercial ports and it could be expected that this packaging would provide some protection against spigot-type objects in accident conditions. Furthermore, containers may provide an additional level of protection against impact above that provided by normal packaging material. It is judged that there is only small chance that these cargoes would initiate were they to be involved in the types of impact accidents that typically occur in ports.

44 It is also apparent that some types of munitions are particularly insensitive to impact. For example, certain types of aircraft bomb are capable of penetrating several feet of concrete before exploding. Moreover, wartime experience suggest that bombs may be dropped from typical aircraft flying heights without detonating on impact if the fuse fails to function. It follows that unfused bombs would be most unlikely to be initiated in the types impact accidents that could be anticipated to occur in ports – such as falls of loads from cranes.

45 In summary, all correctly packaged explosives cargoes would be unlikely to initiate were they to be found involved in the types of impact accidents that could be anticipated to occur in ports, though a few types of explosives items would be more likely than others to initiate in such circumstances – albeit that the chance of this outcome may be low in absolute terms. A few types of munitions, such as unfused general purpose aircraft bombs, can be regarded as being highly insensitive to impact and would be extremely unlikely to initiate in any credible impact accident. These considerations suggest that explosives can be partitioned into three impact risk groups:

Impact Risk Group 1
(abbreviated to I1 in the further sections of this report)

> This is the highest risk group and comprises items that have been shown in trials to be more susceptible to impact-induced initiation than the majority of explosive items. Rocket motors and munitions incorporating rocket motors were the only types of munitions in this group moved through commercial ports at the time of the study.

Impact Risk Group 2
(abbreviated to I2 in the further sections of this report)

> Items in this group are generally considered to be insensitive to the levels of impact forces generated in accident conditions, though the possibility of impact induced initiation cannot be entirely dismissed. This group comprises the vast majority of explosives items moved through commercial ports.

Impact Risk Group 3
(abbreviated to I3 in the further sections of this report)

> Items in this group are specifically designed to withstand considerable impact forces. There is only a remote chance that these items would be initiated by impact forces generated in typical port accidents.

Categorisation of explosives by susceptibility to fire-induced initiation

46 Arguments were presented in the previous section to suggest that it would be unlikely for explosives cargoes to be initiated by the level of impact forces typically generated in transport accidents. However, it is recognised that fire would generally pose a much greater threat to the safety of explosive loads. Most explosive substances and articles in Hazard Division 1.1 could be expected to initiate on exposure to fire, though burn to explosion times would depend on rates of heating and could vary between items.

47 Liquid Fuel Fire Tests conducted on a variety of UK in-service munitions indicate that, for the majority of such munitions, the time between exposure to the fire and initiation is likely to exceed ten minutes; on the other hand however, some types of commercial explosives in flammable packaging may initiate within a shorter time.

48 Trials have shown that a few types of substances of HD 1.1 would be more likely to burn rather than explode following ignition. Based on this evidence, a decision was made to partition explosives into two groups with respect to their reaction to a thermal input:

Fire Risk Group 1
(abbreviated to F1 in the further sections of this report)

This group comprises articles and substances that would most probably burn to explosion following ignition. Most explosives substances of HD 1.1 together with most articles of HD 1.1 and HD 1.2 come within this group.

Fire Risk Group 2
(abbreviated to F2 in the further sections of this report)

This group comprises substances of HD 1.1 that would be unlikely to burn to explosion. The group includes both certain types of military explosives – such as Plastic Explosives 4 (PE4) – and commercial explosives – such as slurries and emulsions. The latter have become more widely used in recent times in preference to older and inherently less safer types of blasting explosives, such as dynamite.

49 In practice, the combination of the three UN hazard divisions of relevance in this study with the three impact risk groups and two fire risk groups defined above, produces only ten out of a possible 30 categories of explosives. These are shown in Table 1.

Cargoes containing different types of explosions are categorised in the following manner: the hazard division of the cargo is assigned by the substance/article in the cargo that comes highest in the following list – HD 1.1 (highest), HD 1.2, HD 1.3 -; similarly the impact risk group of the cargo is assigned by the substance/article in the cargo that comes highest in the following list – I1 (highest), I2, I3 -; and finally the fire risk group is determined by the substance/article in the cargo that comes highest in the following list – F1 (highest, F2).

50 It is again noted that the choice of a categorisation scheme necessarily involves a compromise between accuracy of analysis and convenience of analysis. The uncertainties that may have been introduced into the analysis by adoption of the scheme described here are discussed in Appendix 7.

Table 1 Summary of Categorisation Scheme

Hazard Division 1.1					Hazard Division 1.2		Hazard Division 1.3		
Articles			Substances		Articles		Articles		Substances
I1, F 1	I2, F1	I3, F1	I2, F1	I2, F2	I1, F1	I2, F1	I1, F1	I2, F1	I2, F1

Typical load size selection

51 Explosives are moved through ports in many different sizes of load, each of which has its own hazard range (the greater the size of the explosives load, the greater the distance over which harmful effects could occur). It is not practicable to calculate fatality estimates for all sizes of explosives loads; in order to keep the analysis within manageable proportions it is necessary to group the loads into a small number of notional sizes of cargo. There are a number of ways in which this might be done, but the method adopted in this study has been to determine, for each of the ten categories of explosives cargo defined in Table 1, the mean net explosives quantity (NEQ) of loads within the following logarithmic bands:

1–99 kg
100–999 kg
10000–9999 kg
10,000–99,999 kg
100,000–1,000,000 kg

Analysis of port traffic data

52 The various operators of the five ports and one licensed jetty selected for detailed study kindly supplied data on explosives shipments over a period that allowed reasonably accurate scaling to a year's traffic. The data were analysed to produce a breakdown of explosives cargoes by hazard division, impact risk group, fire risk group and size of load. Some example results from this analysis are shown in Table 2. This table lists the different types and sizes of explosives cargoes moved into and out of Port C on road vehicles.

So, for example, it is seen that lorry cargoes made up of articles of HD 1.1 are partitioned into three notional sizes: the lightest loads have an average NEQ of only 4 kg, the medium-size loads have an average NEQ of 400 kg while the largest size loads have an average NEQ of 1800 kg; these loads account for 2%, 4% and 6% of road cargoes respectively.

53 Similar analyses were carried out to partition road, rail (where appropriate) and ship cargoes handled at the five ports and one licensed jetty selected for detailed study. The following section of this report describes the methods used to obtain estimates of the frequencies with which different types and sizes of explosives events might potentially occur in ports, while Section 5 describes the analysis carried out to estimate the consequences of these events.

Table 2 Example results from traffic data analysis – breakdown of explosives cargoes moved into and out of Port C on road vehicles

Category of Load	Size of Load (kg)	Percentage of Total Movements
Articles of HD 1.1 Impact Risk Group: I2 Fire Risk Group: F1	4 400 1800	2% 4% 6%
Substances of HD 1.1 Impact Risk Group: I2 Fire Risk Group: F1	20 200	11% 5%
Substances of HD 1.1 Impact Risk Group: I1 Fire Risk Group: F2	20	2%
Articles of HD 1.2 Impact Risk Group: I1 Fire Risk Group: F1	600	2%
Articles of HD 1.2 Impact Risk Group: I1 Fire Risk Group: F1	20 300	6% 8%
Articles of HD 1.3 Impact Risk Group: I1 Fire Risk Group: F1	30 300	2% 6%
Articles of HD 1.3 Impact Risk Group: I1 Fire Risk Group: F1	10 500 2500	11% 10% 12%
Substances of HD 1.3 Impact Risk Group: I2 Fire Risk Group: F1	30 3600 13,000	2% 8% 4%

4. The likelihood of explosives events occuring in ports

54 The potential causes of explosives events in ports were discussed in Section 2. It was noted that these events might occur as a result of explosives cargoes becoming involved in certain types of fire or impact accidents or as a result of unsafe items initiating spontaneously without the involvement of cargo in any external accident. The fire and impact accidents considered to pose the dominant threat of an explosives event are:

Fire Accidents

- road vehicle fires
- train fires
- ship fires

Impact Accidents

- road vehicle crashes and collisions
- train derailments and collisions
- crushing or penetration of packages by fork lift trucks
- falls of loads from cranes
- ship strikings
- ship collisions

It was noted that these types of accidents could be regarded as dangerous occurrences whose outcome would depend on the types of explosives present in the accident affected load. This point was taken up in Section 3, where categorisation schemes were discussed for the partitioning of explosives cargoes by susceptibility to impact – and fire-induced initiation. This section of the report discusses the analysis of historical data to determine rates for dangerous occurrences and use of accident data, trials data and expert judgement to deduce the conditional probability that a specified category of explosives load would initiate in the event of its involvement in a particular type of dangerous occurrence. The final part of the section discusses the use of the historical accident record to deduce frequencies of initiations of unsafe explosives.

Rates of dangerous occurrences

55 Rates for dangerous occurrences ideally would have been derived from historical experience of accidents involving explosives cargoes at the five ports and one licensed jetty selected for detailed study. However, the operators of these locations reported that they had no records for the involvement of explosives cargoes in any of the dangerous occurrences of interest. This is considered most likely to be due to the non-occurrence of accidents rather than non-reporting or recording of accidents. Accordingly, rates for dangerous occurrences have had to be derived from accident databases covering a broader range of ports, types of cargo and types of operation than those that are the subject of the present study. It could be expected that the use of such databases will in general lead to conservative results as more care tends to be exercised when explosives cargoes (as opposed to non-hazardous cargoes) are handled.

Road vehicle fires

56 A search of various sources of accident data failed to uncover any records for incidents (post-war) involving fire on explosives vehicles in UK ports. There have been a number of incidents involving fire on explosives vehicles travelling on the public highway, and these suggest that there is a potential for such incidents in ports. This is further reinforced by reports from a number of port operators of minor fires on vehicles carrying goods other than explosives. These fires were ignited by various mechanical and electrical faults, such as overheating brake drums, defective heaters and defective wiring in engine compartments and cabs. Most of these fires were extinguished soon after ignition and none resulted in cargo damage.

57 In the absence of any data for cargo-damaging vehicle fires in ports, rates for the potential occurrence of such incidents have had to be derived from an analysis of generic lorry fire data supply by the Home Office. The data were ‘factored down by expert judgement’ to take account of statutory fire precaution measures required by the Carriage of Explosives Regulations(8), though the analysis also made some allowance for non-compliance with these regulations. The rate derived from this analysis was previously used in the first phase of the ACDS study(2) (which included a consideration of the risks from the road transport of explosives). The details of the analysis have been reported elsewhere(9). Two rates were derived: one for special goods vehicles (SGVs)* and freight container lorries and one for ordinary heavy goods vehicles (HGVs):

Cargo-damaging lorry fire rates

SGVs and Freight Container Lorries	Ordinary HGVs
2.10^{-9} per vehicle-km	5.10^{-9} per vehicle-km

Train fires

58 Train fires are of interest in this study as containerised explosives loads are moved into and out of one of the study ports by rail. There are no records of containers having been damaged by fire either in port rail terminals or freightliner terminals. However, the potential for such incidents is suggested by the occurrence of a number of fires on British Rail running lines and in marshalling yards. In the absence of any data for incidents in rail terminals, the cargo-damaging train fire rate used in this analysis has been based on a previously derived rate for cargo-damaging fire incidents in marshalling yards (this rate was derived in the first phase of the ACDS study, which included a consideration of risks from the rail transport of explosives). This rate was in turn based on an analytical approach which considered the various sequences of events leading to fires on rail vehicles from all potential sources of ignition, such as overheated axle boxes and crashes involving tank containers carrying flammable liquids. Quantification of the rate involved the use of both historical data to determine rates for precursor incidents, such as hot axle boxes, and expert engineering judgement to estimate the probability that such incidents would result in cargo damage.

* A special goods vehicle is defined in the Carriage of Explosives Regulations(8) as a goods vehicle specially designed or adapted for carrying a type or a quantity of explosives for which an ordinary heavy goods vehicle is unsuitable. The additional features are described in paragraph 4 of the Approved Code of Practice for regulation 6.

Cargo-damaging train fire rate

4.10^{-9} per container arrival in terminal

This is the best figure that could be obtained under the circumstances, but it is based on engineering judgement to a large extent and as such it is inevitably subject to a large measure of uncertainty. The figure is all in all probability conservative in the context of the present study as trains carrying explosives into a port's rail terminal are inspected immediately on arrival; it could be expected that faults, such as hot axle boxes, would be detected at this stage and appropriate remedial action taken.

Ship fires

59 Rates of fire outbreak on ships were determined from records kept by the Marine Accident Investigation Branch (MAIB) of the Department of Transport and the Fire Statistics Unit of the Home Office. The records were analysed to determine the potential sources of ignition of such fires and the frequencies with which they occur. It was found that all cargo-damaging fires that have occurred on ships in UK ports over the period examined (1975–1991) were initially ignited in cargo sections of the ships. No records have been found of fire spreading from a ship's engine room or accommodation to cargo. The possibility of such an occurrence has not been dismissed in this study, but its probability necessarily had to be estimated by an analytical approach that examined the circumstances under which fire could spread through a ship. This analysis was based on work undertaken in a previous study that examined possible routes leading to fire spread through a cargo vessel used to carry explosives. The derivation of cargo-damaging fire rates from the various sources of data is described in detail in Appendix 4. Rates were determined for three types of vessels:

Cargo-damaging ship fire rates

General Cargo Ships

1.10^{-6} per ship arrival in port

RoRo ships

1.10^{-6} per ship arrival in port

Container ships

2.10^{-8} per ship arrival in port

Road vehicle crashes and collisions

60 Only Port A had records for cargo-damaging container-lorry traffic accidents. One such accident (not involving explosives) occurred in a period in which 2,240,000 container lorries passed through the port. These statistics, when combined with the average length of lorry route through the port (2 km), produce a mean cargo-damaging crash/collision rate of $1/(2,240,000 \times 2) – 2.10^{-7}$ per vehicle-km. The operators of the other locations selected for detailed study reported no cargo-damaging vehicle incidents in the period for which records were available. An accident rate based on just one incident is subject to considerable uncertainty and it is therefore desirable to compare the derived rate with a more robust generic accident rate. This was achieved by using data provided by the commercial explosives industry for a larger number of cargo-damaging traffic accidents on the public highway. The derivation of this rate has been described elsewhere[(9)]. The value obtained is 8.10^{-8} per vehicle-km and this agrees within a factor of 2.5 with the rate derived from the one port incident. Use of the rate in the present study would assume that traffic accidents are as likely to occur in ports as on the public highway. This assumption may be conservative in view of speed restrictions applying to ports, though the greater density of junctions in ports may militate against this view. The average of the two rates, rounded to one significant figure, has been used in the present study.

Cargo-damaging road vehicle crash/collision rate
1.10^{-7} per vehicle-km

Train derailments and collisions

61 So far as is known, there have been no container-damaging derailment or collision incidents within rail terminals in British ports; a search of various sources of accident data failed to uncover any records for such incidents. The rate used in this study has been based on experience of accidents in freightliner terminals, which operate in a very similar manner to port rail terminals. British Rail supplied accident statistics covering a recent five-year period of operations in freightliner terminals. These statistics show the occurrence of only one relevant incident. The amount of traffic that passed through freightliner terminals in this period amounted to 3,250,000 containers. Therefore:

Cargo-damaging train derailment/collision rate
3.10^{-7} per container arrived in terminal

As noted in the previous paragraph, accident rates based on small numbers of incidents are subject to a large measure of uncertainty. However, this is the best estimate which could be obtained in the circumstances.

Crushing or penetration of packages by fork lift trucks

Did you want **'(FLTs)'** inserted here?

62 It is known that there have been a number of incidents in ports, manufacturing sites and storage depots in which explosives packages have been damaged by fork lift trucks. The danger which such events pose is illustrated by a number of minor explosives events that have occurred at manufacturing sites as a result of FLTs running over spills of explosives substances or as a result of loose explosives articles being caught up and crushed in the moving parts of FLTs. However, so far as is known, there have been no explosives events triggered by FLT accidents involving finished and packaged explosive items.

63 It has not been possible to convert FLT accident statistics collated from various sources into accident rates (expressed in terms of chance of cargo-damage per FLT operation) because of the lack of any data on the relevant numbers of FLT operations performed. This difficulty has meant that accidents rates have had to be derived by methods other than those based on direct historical experience. The rates used in the present study were taken from the results of a 'human factors' study of FLT operations at an MoD Central Ammunition Depot (CAD). This work was undertaken in the 1980s as part of a wider risk assessment study of the CAD. The analysis took account of the strength of various packaging details.

Cargo-damaging FLT accident rates

wooden packages	7.10^{-7} per FLT operation
metal packages	7.10^{-9} per FLT operation

Falls of loads from cranes

64 Data for cargo-damaging crane accidents were available from a number of sources.

(a) The operators of Port A had records of five cargo-damaging accidents involving uncontrolled descent of loads from container gantry cranes. These accidents occurred over a period in which approximately 4,699,000 crane lifts were performed. These statistics produce a mean accident rate of 5/4,690,000 = 1.10^{-6} per crane lift.
(b) Data for cargo-damaging accidents involving container gantry cranes were provided by the operators of two commercial ports not involved in the present study. The operators of one of these ports reported one accident in a period in which approximately 149,000 crane lifts were performed (mean accident rate = 7.10^{-6} per crane lift), while the operators of the other port reported three accidents, involving four containers in total, in a period in which approximately 1,000,000 container lifts were performed (mean accident rate = 4.10^{-6} per crane lift).
(c) The MoD provided information on five accidents involving jetty cranes in military ports. Two of these incidents had been officially classified as 'serious', ie munitions had sustained damage in the accidents and the investigating body considered that there had been a threat (though possibly remote) of an explosives event. These accidents occurred in a period in which 700,000 cranes lifts had been performed (ie mean accident rate = 3.10^{-6} per crane lift).

The rate used in this study has been derived by combining the crane accident data collated from the various sources discussed above: 12 accidents in approximately 6,500,000 crane lifts. Therefore:

Cargo-damaging crane accident rate
2.10^{-6} per crane lift

Ship strikings and collisions

65 The ship striking and collision rates used in this analysis were originally derived in the first phase of the ACDS study (which considered the risks from the marine transport of dangerous substances in bulk). Rates were derived separately for four types of ports: open sea, wide estuary, wide river and narrow river. In the present study, striking and collision are only considered realistic scenarios in the case of Port A and Port F, both of which are located on wide estuaries.

Wide estuary striking rate:
4.10^{-6} per ship passing

Wide estuary collision rate:
4.10^{-5} per ship encounter

Conditional probabilities of initiation

66 It is stressed once again that the involvement of explosives cargoes in any of the above accidents would not inevitably result in an explosives event. The rates quoted above are for dangerous occurrences and not initiating events. The next step in the analysis requires estimates to be derived for the conditional probability that explosives cargoes would initiate in fire or impact accidents.

Response of explosives cargoes to heat

67 All explosives could be expected to react on exposure to fire, though depending on the type of explosives involved, the reaction could vary from slow burning to deflagration to detonation*. Burn to initiation times could also vary considerably between different types of explosives. Most articles and substances classified as HD 1.1 could be expected to explode following ignition, though some substances of this division have been shown to be insensitive to heat and could be expected to burn rather than explode in accident conditions. These issues were explored in paragraphs 46–48 where it was suggested that explosives could be categorised very broadly into two fire risk groups:

Fire Risk Group 1 (F1)

Articles and substances that would most probably react explosively following ignition. Most explosives substances and articles of HD 1.1 together with most articles of HD 1.2 come within this group.

Fire Risk Group 2 (F2)

Substances of HD 1.1 that would be unlikely to burn to explosion. The group includes certain types of military explosives – such as Plastic Explosives 4 (PE4) – and certain types of commercial explosives – such as slurries and emulsions.

68 Experience shows that while some cargoes categorised as belonging to F1 are more likely than not to react explosively in the event of ignition, such an outcome is not inevitable+. For the purpose of this study, however, the conservative assumption has been made that all cargoes assigned to this fire risk group would react explosively following ignition in accident conditions, ie the conditional probability of initiation is taken to be unity.

69 Only a small number of substances have been assigned to F2. These substances have been shown in trials carried out by the MoD or other organisations to be unlikely to burn to explosion. In general, however, only a small number of trials have been carried for each substance in this group, and while an explosive reaction has not been observed in any of these trials, the small amount of data collated does not allow any firm conclusions to be drawn about whether there is still a small chance that these substances could explode in accident conditions. The available evidence indicates that such an outcome would be unlikely, but a cautious view has been taken in this study and a burn-to-explosion probability of 0.1 has been applied to these substances. Further work in this area may well justify the use lower conditional probabilities of initiation.

* The terms detonation and deflagration refer to the speed at which explosives react. In a detonation, the reaction progresses at supersonic speed (ie faster than the speed of sound in the material which is detonating). This is typically in the range of 1000 to 6500 meters per second. This is in contrast to deflagration where the explosives burn at subsonic velocities. Both types of reaction are capable of causing damage; detonations providing a shattering effect whilst deflagrations give a bursting effect. Both phenomena are commonly referred to as ‘explosions’.

\+ A search of the HSE/MoD/AEA Explosives Incident Database, EIDAS, uncovered records for a small number of incidents in which cargoes of dynamite burned but did not explode following accidental ignition.

Response of explosives cargoes to impact

70 Arguments were put forward in paragraphs 42 to 45 to suggest that explosives would be unlikely to initiate in the event of their involvement in the types of impact accidents that typically occur in ports. These arguments were based on results obtained from various types of impact tests and accident experience. It was noted that a number of transport accidents have occurred in the UK in post war times in which explosives cargoes sustained severe impact forces without initiating. The capacity of correctly packaged explosives items to remain safe in transport accidents is also demonstrated by experience abroad: reports have been obtained of numerous transport accidents in which packaged explosives have been badly damaged but have not initiated. However, there is a need for caution here, as suggested by reports of a few incidents in which explosives cargoes apparently were initiated by the impact forces generated in crane accidents, though the details contained in these reports are sketchy and it is not clear whether unsafe explosives items were primarily responsible for these events. Taken at face value, these reports suggest that the possibility of impact-induced initiation cannot be entirely dismissed (ref A2.4).

71 These arguments were developed in paragraph 45, where a three-group scheme was proposed for the categorisation of explosives by susceptibility to accidental impact-induced initiation. The groups were denoted, in decreasing order of risk, Impact Risk Group 1 (I1), Impact Risk Group 2 (I2) and Impact Risk Group 3 (I3). The highest risk group, I1, comprises only a small number of munitions that have been shown to be less robust than most explosives items and to be more susceptible to initiation by impact forces in accident conditions, though these munitions would most likely remain safe were they to be involved in most types of typical impact accidents that occur in ports. The second group, I2, comprises explosives items that have been shown to be largely insensitive to the levels of impact forces typically generated in port accidents, though the possibility that these items might initiate in such accidents cannot be entirely dismissed (the vast majority of explosives items moved through commercial ports fall into this group). Finally, I3, comprises a few munitions specifically designed to withstand considerable impact forces and which would be extremely unlikely to initiate in the event of any foreseeable impact accident within a port.

72 An attempt has been made to derive values for the conditional probability that explosives in these various groups would initiate following their involvement in the types of impact accidents considered in this study. It will be seen from the discussion presented in the following paragraphs that these values have had to be derived from small amounts of data, modified in some cases by expert judgement. This is one of the major areas of uncertainty in the study and further work in this area would clearly be desirable. Consideration is first given to quantification of the conditional probability that explosives classified as I2 (the majority of explosives moved through ports) would initiate given their involvement in the impact accidents considered in this study.

Impact Risk Group 2 (I2)

73 Most of the explosive cargoes that pass through commercial ports can be classified I2 by the scheme devised for use in this study. There are insufficient data available to allow objective values to be derived for the conditional probability that these cargoes would be initiated by impact forces generated in typical port accidents. Nobel's Explosive Company (NEC) confronted this problem some years ago and carried out an extensive series of drop-hammer trials to try to generate appropriate data to solve the problem[7]. The trials were undertaken with cartridges filled with nitroglycerine-based blasting explosives – which are more sensitive to impact than many types of blasting explosives now commonly in use – and were designed to mimic the impact forces that cased cartridges would sustain on falling

through a height in excess of 12 meters onto a hard, unyielding surface. The cartridges typically sustained indentations but no initiations were observed in a total of 1150 trials. A statistical analysis of these results indicates an initiation probability with a value below 1.30^{-3} (70% confidence level).

74 In the absence of any more extensive data, the results of the NEC trials have been used in this study to provide an upper estimate of the conditional probability that explosives loads classified as I2 would initiate given their involvement in accidents in which items in the loads sustained planar impact forces – such as might happen, for example, if explosives loads were to be dropped from cranes onto flat surfaces. However, since the probability is based on an upper statistical limit obtained from zero events in a number of trials carried out with a comparatively sensitive type of blasting explosive, it is likely to be conservative to a considerable degree with regard to the more robust items assigned to I2.

Impact Risk Group 3 (I3)

75 It has been noted that certain types of aircraft bombs are capable of penetrating several feet of concrete without immediately exploding; these bombs are initiated by an internal fuse that can be set so as to become fully alarmed only after the bomb has impacted the ground. These bombs are transported without fuses and this precludes the possibility of an explosion occurring as the result of the functioning of a defective fuse in accident conditions. It is most unlikely that these bombs would initiate in any foreseeable impact accident that might occur in a port. However, there are insufficient empirical data to allow this possibility to be dismissed completely and a cautious approach has accordingly been taken: the above value of conditional probability has been reduced by an order of magnitude for these types of munitions ie the conditional probability of these munitions initiating following an impact accident is taken to be 1.10^{-4}.

Impact Risk Group 1 (I1)

76 Trials carried out by the MoD and certain other organisations have shown that a very small number of munitions are comparatively sensitive to impact, though the chances are that these munitions would not initiate were they to be involved in most of the typical impact accidents that occur in ports. In fact, very few of these types of munitions are moved through commercial ports; most of these munitions are moved through military ports and are handled in particular ways that minimise the risk. The only types of munitions moved through commercial ports that might be considered ‘impact sensitive’ are those which contain rocket motors filled with solid propellant. In one particular series of trials, 45 rockets in fibreglass shipping containers were drop tested individually from a height of 12 metres onto a concrete pad; two of the rockets ignited, giving an ignition probability of 0.04[10]. In practice, munitions containing rocket motors moved through ports subject of this study are either not lifted by crane, being imported or exported on RoRo vessels, or are packed inside ISO freight containers. These latter types of containers could be expected to offer a greater degree of protection against impact that the fibreglass shipping containers that featured in the drop trials. This extra degree of protection cannot be precisely quantified without undertaking further trials, but expert opinion within the MoD suggests that a factor of four improvement could at least be expected. Thus, a value of (0.04/4) = 0.01 has been used in this study for the conditional probability that a containerised rocket motor filled with solid propellant would ignite in the event of being dropped by a crane onto a flat surface.

77 Consideration has also been given to the possibility that particularly severe impact accidents might result in spigot-type objects breaching explosives articles. Such an accident might occur, for example, if an explosives load were to be dropped onto a sharp fitting on the deck of a ship. In such an event the sharp object might rupture packaging material and then puncture the casing of the article, causing a hot disc of metal to be pushed into the explosives filling. Trials carried out by the MoD have shown that certain items assigned to Impact Risk Group 1 would most likely initiate in such circumstances (see paragraph 43). The chance of such an accident occurring with correctly packaged explosives items cannot be reliably assessed without carrying out appropriate trials. Expert opinion within the MoD conservatively estimates this probability to be no greater than 0.01 in the case of crane accidents – ie one chance in one hundred per dropped load. This value has been used in the present study.

78 In summary, values have been estimated for the conditional probability that explosives loads belonging to different risk groups would initiate in the event of an accident. The values are summarised in Table 3 below:

Table 3 Values used in this study for the conditional probability of initiation of different types of explosive loads

Type of Accident	Risk Group	Conditional Probability of Initiation
Engulfing Fire	F1 F2	1 0.1
Impact Accident – cargo sustains planar impact forces	I1 I2 I3	10^{-2} 10^{-3} 10^{-4}
Impact Accident – cargo reutured by spigot type objects	I1	1 (but multiplied by 10^{-2} to represent the chance of rupture given a spigot impact)

79 It must be stressed once again that the values presented in Table 3 are largely based on expert judgement and as such are subject to uncertainty. The small amount of accident and trials data available suggests that most of these values are likely to err on the side of caution. While the use of such values is in keeping with the 'conservative best estimate approach' to the risk analysis (see Appendix 7), further research to establish objective values of conditional probability would clearly be desirable.

Calculation of event frequencies

80 Estimates for the frequencies (annual probabilities) with which different types and sizes of explosives events might potentially occur in ports have been computed from rates for dangerous occurrences, conditional probabilities of initiation and traffic data for the annual numbers of movements of the different types and sizes of explosives cargoes moved through ports. An example of this computation is set out in Table 4. This illustrates the calculation of frequency estimates for the potential occurrence of different types and sizes of explosives events in Port C resulting from the ignition of fire on heavy goods vehicles carrying explosives cargo through the port. The different types and sizes of explosives loads that are moved through this port on heavy goods vehicles have previously been specified in Table 2 on page 21; a value for the rate of ignition of cargo-damaging fires on heavy goods vehicles was discussed in paragraph 57, while traffic levels have been calculated by multiplying the number of vehicles carrying specific types and sizes of explosives loads by the length of the route through the port.

Table 4 Calculation of Frequency Estimates for the Potential Occurrence of Explosives Events Initiated by Fire on Heavy Goods Vehicles travelling through Port C

Type of Explosives Load	Size of Load (kg)	Fire Risk Group	Cargo-damaging Fire Rate, R (per vehicle-km)	Cond. Prob. of Initiation P	Annual Level of Traffic, T (vehicle-km)	Frequency of Event = RxPxT (per year)
33Articles of HD 1.1	4 400 1800	F1 F1 F1	5.10^{-9} 5.10^{-9} 5.10^{-9}	1 1 1	1.86 3.72 5.58	9.10^{-9} 2.10^{-8} 3.10^{-8}
Substances of HD 1.1	20 200	F1 F1	5.10^{-9} 5.10^{-9}	1 1	11.16 3.72	6.10^{-8} 2.10^{-8}
Substances of HD 1.1	20	F2	5.10^{-9}	0.1	1.86	9.10^{-10}
Articles of HD 1.2	600	F1	5.10^{-9}	1	1.86	9.10^{-9}
Articles of HD 1.2	20 300	F1 F1	5.10^{-9} 5.10^{-9}	1 1	5.58 7.44	3.10^{-8} 4.10^{-8}
Articles of HD 1.3	30 300	F1 F1	5.10^{-9} 5.10^{-9}	1 1	1.86 5.58	9.10^{-9} 3.10^{-8}
Articles of HD 1.3	10 500 2500	F1 F1 F1	5.10^{-9} 5.10^{-9} 5.10^{-9}	1 1 1	11.16 9.3 11.16	6.10^{-8} 5.10^{-8} 6.10^{-8}
Substances of HD 1.3	30 3600 13,000	F1 F1 F1	5.10^{-9} 5.10^{-9} 5.10^{-9}	1 1 1	1.86 7.44 3.72	9.10^{-9} 4.10^{-8} 2.10^{-8}

Similar calculations have been performed to estimate the frequency (annual probability) with which different types and sizes of explosives events might occur as a result of vehicle crashes and collisions in the port. The procedure has been extended to obtain frequency estimates for the potential occurrence of explosives events initiated by the various types of dangerous occurrences listed in paragraph 54. In mathematical terms, the procedure can be summarised by the following equation:

$$F \quad \sum_{i=l}^{i=n} A_i * L * P(I \setminus A_i)$$

Where:

F is the frequency (annual probability) of an explosives event involving a particular type and size of explosives load

A_i is the rate at which the explosives load is affected by accident type i

L is a measure of the annual volume of traffic for loads of the specific type and size

$P(IA_i)$ is the conditional probability that the load would initiate given its involvement in accident type i

Likelihood of events caused by unsafe explosives

82 In addition to the possibility of explosives events arising from fire and impact accidents, experience shows that these events can also occur spontaneously should unsafe items be present in explosives loads. The historical accident record for the transport of explosives in the UK (see Appendix 2) shows that about 50% of all initiating events that have occurred since 1950 have been caused by unsafe explosives items of one type or another (none of these accidents occurred within

commercial ports). Unsafe conditions cannot always be foreseen and unsafe explosives may enter the transport chain inadvertently* or as a result of a failure in safety management. In either case, when accidents have occurred, lessons have been learnt and steps taken to try to prevent any recurrence; but nonetheless, the potential remains for similar types of accidents to occur in the future. In considering the likelihood of such accidents, the approach adopted in this study has been the pragmatic one of noting past failures and assuming a similar rate of further failures in the future. The assumptions are based on proper compliance with statutory legislation.

83 A detailed investigation of the potential threat posed by unsafe explosives would include an examination of the possible causes of breakdown in quality control procedures that would allow unsafe explosives items to enter the transport chain. This in turn would require detailed analysis of manufacturing, maintenance and checking procedures for many different types of explosives substances and articles, many of which have changed as new types of explosives have been brought into service. Such an investigation was beyond the scope of the present project. In this study it has been possible to do no more than examine the historical accident record for the transport of explosives in the UK in order to draw some broad conclusions about the relative threat posed by unsafe explosives. As previously noted, this record shows that unsafe explosives are as likely a source of transport events as fire and impact accidents. Based on this observation, an allowance for the risks of unsafe explosives has been made by simply doubling the explosives event frequencies derived for the various fire and impact accidents considered in the study. This is a major source of uncertainty and further work in this area would clearly be desirable.

* In this case, explosives items that conform to current safety standards contain unrecognised safety flaws that only come to light with the occurrence of accidents. An accident of this type occurred in Germany in 1985. Albeit not in the transport chain this involved the accidental ignition of the rocket motor of a Pershing I1 missile. The ignition was caused by an electrostatic discharge (ESD). The type of propellant used in the motor had been tested for sensitivity to ESD and had been found to meet the required criteria. However, these tests had been carried out on samples of propellant of small grain size, rather than the large grain size used in the rocket motor. It was subsequently found that the sensitivity of the propellant to ESD increased with grain size.

5. The consequences of explosive events occuring in ports

84 An explosives event in a port could have a number of adverse consequences, including: death, injury, loss of assets and property damage. It is the risk of such accidents causing fatalities that is of concern in this study. There are a number of factors that would determine the extent of any fatalities that would result from such an incident. These factors include the types and quantities of explosives initiated as well as the numbers and locations of people in and around the port at the time of the incident. The types and quantities of explosives initiated will determine the range over which the explosives event will produce lethal effects while the locations of people in and around the port will determine the numbers of persons exposed to these effects. The lethal effects could include blast, fragments and thermal radiation, depending on the types of explosives present in the cargo.

85 Estimates for the numbers of fatalities that could be expected from explosives events in ports have been calculated employing a three-step procedure in which:

(a) Explosion effects models were used to determine the distances from an explosion at which lethal effects could occur. In fact, ranges to various levels of lethality were determined together with the areas, or 'hazard zones', bounded by these ranges. This process is illustrated in Figure 3: this shows the ranges to 100%, 90%, 50%, 10% and 1% fatalities, denoted as L_{100}, L_{90}, L_{50}, L_{10} and L_{01} respectively, and the hazard zones bounded by these 'hazard ranges'. So, for example, a person located at the L_{10} hazard range would stand a 10% chance of being killed in the event of an initiating accident, while a person located further away from the accident at the L_{01} hazard range would stand only a 1% chance of being killed. The average fatality probability for persons located between these two hazard ranges is taken to be 5%, hence the outermost hazard zone shown in Figure 3 is denoted Z_{05}.

(b) Estimates were obtained for the numbers of persons who would be likely to be within the various hazard zones at the time of an incident. This stage of the analysis took account of the possibility that some accidents would not result in an explosives event immediately but only after a period of gradual escalation. An example of such an accident would be the ignition of fire in the engine room of a ship laden with explosives; persons in the vicinity of the accident might have time to reach a place of safety before any explosion occurred.

(c) Fatality estimates for each hazard zone were obtained as the product of the number of persons within the zone and the average fatality probability for the zone. The sum of these products provided an estimate for the overall number of fatalities that could be expected from an explosives event. This computational procedure can be summarised by the following equation:

$$N_F = \sum_{i=l}^{i=n} P_i * N_i$$

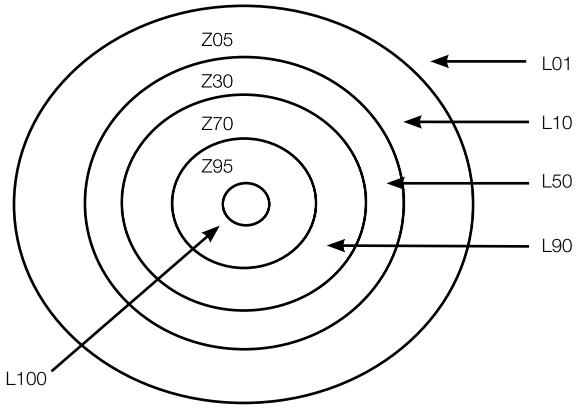
Where:

N_F is the total number of fatalities expected from the event

P_i is the average fatality probability for persons in hazard zone i

N_i is the number of persons in hazard zone i

n is the number of hazard zones considered (four in the case of the example shown in Figure 3)



L100:	Range to 100% fatalities	Z95:	95% fatality hazard zone
L90:	Range to 90% fatalities	Z70:	70% fatalities hazard zone
L50:	Range to 50% fatalities	Z30:	30% fatality hazard zone
L10:	Range to 10% fatalities	Z05:	5% fatality hazard zone
L01:	Range to 1% fatalities		

Figure 3 Hazard Ranges and Explosives Cargo

86 The hazard zones associated with explosives cargoes will vary with both the types and quantities of explosives present (except in the case of cargoes made up solely of articles of HD 1.2 where the various hazard ranges – such as those shown in Figure 3 – will be essentially independent of the overall size of load – see paragraph 93). The fact that different types of explosives produce different effects was previously considered in paragraphs 35–39, where a scheme was proposed for categorising explosives according to hazard, ie according to the types and the extent of the harmful effects explosives would produce on initiating. The scheme was based on the well-established system of hazard divisions devised by the UN Committee of Experts on the Transport of Dangerous Goods*. The UN system was modified slightly for the purposes of this study in that two of the divisions, HD 1.1 and HD 1.3, were further subdivided into articles and substances making six hazard groups in total:

HD 1.1 (Substances) – blast effect plus secondary fragment effect

HD 1.1 (Articles) – blast effect plus primary and secondary fragment effects

HD 1.2 – small blast plus primary fragment effects

HD 1.3 (Substances) – fire and thermal radiation effects

HD 1.3 (Articles) – fire and thermal radiation effects

* See footnote on page 43.

HD 1.4 – no significant effect: effect largely confined to package and no projection of fragments of appreciable size or range to be expected. Explosives belonging to this division are not considered further in the present study.

87 The hazard group to which an explosives cargo belongs will thus determine the types of effects that the cargo will produce on initiating. Explosion effects models are then required to estimate the distances over which the effects produced by an explosives event could prove lethal. A number of explosion effects models have been developed by various groups to provide such estimates. These models were reviewed by a team of experts drawn from the HSE and the MoD and those considered to be the best available (within the constraints of being reasonably quick and simple to apply) were selected for use in this study. Explosion effects modelling continues to remain an active field of research; indeed some of the models selected for use in the present study were improved versions of models used in the first phase of the ACDS work – which considered risks from the road and rail transport of explosives. It is anticipated that research work will lead to further improvements in these models. Most of the models chosen have been designed to produce some slight overestimate of the effects of explosions. The use of these models is in keeping with the conservative best estimate to approach to the risk analysis (see Appendix 7). The models selected for each of the hazard groups are described below under the appropriate headings after the dominant mechanisms of harm associated with each hazard group have been reviewed.

Hazard Division 1.1 (mass explosion hazard)

88 An initiation of an item within a cargo comprising explosives of HD 1.1 could trigger a mass explosion, ie the explosion could communicate near-instantaneously to the rest of the explosives in the cargo. Such an event could cause damage and injury from the effects of blast, fragments, ground shock and heat. However, experience shows that blast and fragments are the dominant mechanisms of harm for this type of explosion. Three types of blast injury can be distinguished:

(a) Primary blast injuries. These are produced by the direct effects of a blast wave on the body. However, humans are very resilient to blast, and considerable overpressures are required before fatalities are produced by direct blast effects (whereas considerably lower overpressure can give rise to fatalities from secondary blast effects). The available evidence indicates that lung haemorrhage is the most likely cause of death in these cases.

(b) Secondary blast injuries. These are caused by the structural collapse of buildings following the impingement of a blast wave. Experience shows that structural collapse is the dominant mode of injury and death from explosions in built-up areas.

(c) Tertiary blast injuries. These are caused by body movement and two modes may be distinguished:

    injuries caused by differential displacement of internal body organs following high acceleration;

    injuries caused by impact, ie when the body is blown over or picked up by the blast wave and thrown against an object.

89 Fatal primary and tertiary blast injuries usually only occur with relatively high levels of overpressure and thus generally only occur among people in very close proximity to an explosion. However, structural collapse, leading to fatal secondary blast injuries, can occur at much lower levels of overpressure. It follows that if a mass explosion were to occur in a built-up area, blast effects would most likely cause greater numbers of fatalities among people indoors and outdoors.

90 However, people in the open are likely to be at greater risk from the fragments generated in an explosion; people inside buildings would be afforded a degree of protection against fragments by structural features, such as walls and roofs. Two types of fragments can be distinguished:

(a) Primary fragments. These are fragments produced from the casing material of articles containing high explosives.
(b) Secondary fragments. These are missiles produced as a result of the blast wave picking up and projecting whole objects or as a result of the blast wave shattering objects in the vicinity of the explosion. The secondary fragments produced by an explosion on board a ship could vary considerably in size and include both small and large pieces of debris produced by the break-up of the ship or quay.

Thus explosives articles, which produce both primary and secondary fragments, could be expected to cause greater fragment damage than explosives substances packaged in soft materials, such as fibreboard and cardboard.

91 It follows from all this that a comprehensive set of fatality models for HD 1.1 would need to take account of both blast and fragment effects and differentiate between people indoors and outdoors. This has necessitated the use of three separate models in the present study:

(a) The MoD Explosives Storage and Transport Committee Indoor Blast Model(11). This is an empirical model based on an analysis of casualty data collated from records of a number of major incidents of accidental explosion (including some incidents that occurred in ports). The data on which the model is constructed do not distinguish between those people killed by blast and those killed by fragments. It is assumed that blast effects were the cause of most of the fatalities recorded in these incidents but the model implicitly makes some allowance for fragment effects. The model gives a single estimate of fatality probability (P) as a function of scaled distance (S)*:

   $\log(P) = 1.827 - (3.433 * \log S) - (0.853 * (\log S)^2) + (0.356 * \log S)^3)$ within the limits $3 < S < 200$

(b) The MoD (ESTC) Outdoor Blast Model. This is a theoretical model based on a review of the literature on the direct effects of blast on the human body. The model gives a single estimate of fatality probability as a function of scaled distance:

$$P = \frac{e^{(-5.785 * S) + 19.047}}{100}$$

(c) The MoD (ESTC) Primary Fragment Model. This model is based on an analysis of the fragment pattern recorded from detonations of stacks of various types of fragmenting munitions. The model can be used to estimate fatality probabilities for persons located indoors and outdoors.

* Scaled distance is defined as the actual distance from an explosion divided by the cube root of the mass of explosive detonated. The parameter derives from Hopkinson's 'cube root' Law which states that when two charges of the same explosive and geometry but of different size are detonated in the same atmosphere, self-similar shock waves are produced at the same scaled distance.

92 The choice of model to estimate the lethal effects of initiations of explosives cargoes containing HD 1.1 material was dictated by the make up of the cargo (substances or articles) and the location of the exposed population (indoors and outdoors). The choice was as follows:

Hazard Group	***Location of Population***	***Models Used***
HD 1.1 (Substances)	Indoors	ESTC Indoor Blast Model
HD 1.1 (Substances)	Outdoors	ESTC Outdoors Blast Model
HD 1.1 (Articles)	Indoors	ESTC Indoor Blast Model and ESTC Primary Fragment Model
HD 1.1 (Articles)	Outdoors	ESTC Outdoor Blast Model and ESTC Primary Fragment Model

Thus the blast/secondary fragment and primary fragment effects that could be expected from initiations of articles of HD 1.1 were analysed by separate models. In order to avoid 'double counting' of fatalities, standard probability mathematics were used to determine combined fatality probabilities from the two effects, viz:

$$P_T = P_B + P_F - P_B.P_F$$

Where:

P_T is the combined fatality probability for the two effects

P_B is the fatality probability due to blast/secondary fragment effects

P_F is the fatality probability due to primary fragment effects

Hazard Division 1.2 (MoD (ESTC) fragment hazard model)

93 Explosives loads consisting solely of articles of HD 1.2 would not be expected to detonate *en masse*. An accidental initiation of an item in such a load could be expected to ignite a fire which in turn would cause further articles in the load to explode in ones and twos over a period of time: in general, the larger the size of the load the greater the duration of the event. These loads thus pose essentially a fragment hazard rather than a mass explosion or significant blast hazard. The fragment densities produced by such an event would depend on the type of articles present in the load: some articles belonging to HD 1.2 contain detonating explosives which produce high energy fragments by shattering the casing of the article, while other articles of this division contain deflagrating explosives which do not shatter the casing of the article but project it more or less intact. Data generated by the ESTC model show that even the most hazardous HD 1.2 articles would be unlikely to produce any significant lethal effects beyond a range of 25 metres, provided the articles functioned in the designed mode. In accident conditions, these articles might produce fewer but larger fragments that might prove lethal at distances significantly greater than 25 metres. In any event, it is not expected that more than a few fatalities would result from an accidental initiation of an HD 1.2 load. Most of these fatalities would probably be caused by the initial explosion; it can be assumed that the survivors of the initial event would have time in the intervening minutes before any subsequent explosion to take shelter behind structural features or reach a position of reasonable safety. In the present study, it has been assumed that an accidental initiation of an HD 1.2 load might cause up to four fatalities. The development of definitive models for HD 1.2 explosives must await further research.

Hazard Division 1.3 (MoD (ESTC) fire hazard model)

94 Substances and articles belonging to HD 1.3 pose primarily a fire hazard. An ignition of these substances and articles could give rise to one of two types of fire: idealised and non-idealised. An idealised fire (which produces more serious effects) is one in which the whole mass of explosive burns simultaneously and is over in a few seconds, producing a fireball and an associated pulse of thermal radiation. A non-idealised fire is one in which flame propagation is hindered by the thermal inertia of packaging and the spaces between packages, giving rise, in the extreme, to a number of sequential fires involving one article at a time. The thermal radiation effects from a non-idealised fire would be minimal although the duration of the fire could be very long.

95 Substances of HD 1.3 packaged in soft material, for example propellant in fibreboard boxes, are likely to produce fires of the idealised kind, given the flammable nature of the packaging and the close packing of the load. On the other hand, fires involving articles of HD 1.3 for example cartridges packed in metal boxes, are unlikely to be completely idealised, given the thermal inertia of both the casing of the article and the packaging material (although over the duration of such a fire, one or more periods of idealised behaviour could be expected from the simultaneous burning of a number of cartridges). All HD 1.3 fires may also be expected to give rise to minor blast and fragment effects. For the purpose of this study, it has been assumed that cargoes of HD 1.3 substances in soft packaging material would invariably burn in an idealised manner, while cargoes consisting of articles of HD 1.3 would invariably produce non-idealised fires.

96 The lethal effects of idealised and non-idealised fires have been estimated from models developed by the MoD (ESTC). These models calculate the thermal radiation dose that people might be expected to receive at various distances from a fire involving a specified mass of propellant. Thermal radiation dose is related to fatality probability (P) by the Eisenberg probit:

$$P = 2.561*\ln(\text{dose}) - 14.9$$

The models assume that people are outdoors and are not shielded by buildings and other structures. These assumptions add an element of conservatism into the analysis though this turns out not to be of any great significance as the dominant explosives risks at most ports are associated with cargoes of HD 1.1 explosives.

Use of explosion effect models to calculate hazard ranges

97 In the next step of the analysis, appropriate explosion effects models were used to estimate the hazard ranges associated with the various types and sizes of explosives loads moved through the five ports and one licensed jetty selected for study. Specifically, the models were used to estimate the ranges at which the following levels of lethality could be expected: 100%, 90%, 50%, 10% and 1% fatalities (denoted as L_{100}, L_{90}, L_{50}, L_{10} and L_{01} respectively – see Figure 3). These ranges were crucially dependent on load size for all types of explosives with the exception of those belonging to HD 1.2. For this class of explosives it was judged that no more than a few kilograms NEQ would initiate any one time (see paragraph 93). The following example illustrates the use of explosion effects models to calculate hazard ranges. This illustrates the calculation of hazard ranges for the largest notional cargo of HD 1.1 substances carried on heavy goods vehicles though Port C – 200 kg (see Table 2). The ESTC Indoor Blast model is used to estimate hazard ranges for persons inside buildings (see paragraph 91a) while the ESTC Outdoor Blast Model is used to calculate hazard ranges for persons in the open (see paragraph 91b):

Persons indoors

Hazard range	Scaled distances (kg.m$^{-1/3}$)	Actual distance for 200 kg load (meters)
L_{100}	3.07	18
L_{90}	3.16	19
L_{50}	3.68	22
L_{10}	5.39	32
L_{01}	9.49	56

Persons outdoors

Hazard range	Scaled distances (kg.m-1/3)	Actual distance for 200 kg load (meters)
L_{100}	2.47	14
L_{90}	2.48	14.5
L_{50}	2.58	15
L_{10}	2.86	17
L_{01}	3.25	19

98 It is seen that the lethal effects of blast for people in the open fall off very quickly with increasing distance from the explosion. In general, the lethal effects from a mass explosion will extend over greater distances for persons indoors than outdoors. The analysis considers the lethal effects of an explosives event out to the 1% lethality range. This takes account of most of the fatalities that would result from such an event, but there could always be occasional deaths and more probably casualties at greater distances. It follows that evacuation distances should be significantly greater than the 1% lethality range. In fact the recommended evacuation distance for a 200 kg quantity of high explosives is 400 metres.

Exposed population

99 The next step was to establish the numbers and locations of persons in and around the ports at the times when explosives cargoes were handled. This in turn allowed estimates to be obtained for the numbers of persons that came within the hazard ranges of the various types and sizes of explosives cargoes that passed through the ports. Population data were very kindly supplied by the operators of such of the five ports and one licensed jetty selected for detailed study. At some ports the numbers of persons that would be encompassed by the hazard ranges varied with both time of day and day of week in line with shift changes at these times. This was a particularly important consideration in the case of Port A, where explosives brought in by rail were handled between the hours of 24:00 – 06:00, when the population in the port was at the lowest level.

Escape and evacuation

100 In certain circumstances it may be possible for people to escape from the scene of an accident involving explosives cargo before the occurrence of an explosives event. This is particularly true in the case of fire accidents, for example fires in ships' engine rooms, in which explosives cargo is not initially involved but is only affected after a period of gradual escalation. Successful evacuation in these circumstances will depend to a large extent on both the adequacy of the port's emergency plan and the effective implementation of that plan. These issues are discussed in some detail in Appendix 4. For the purposes of this study the view has been taken that a port's emergency plan might not guarantee effective evacuation in all cases. In particular, if a fire were to ignite and spread out of control on an explosives-laden ship, the chance that all personnel would be evacuated to a place of safety before an explosion occurred was judged to be around 50% (as a conservative best estimate).
101 Certain types of accidents could be expected to offer much less of an

opportunity for successful evacuation. For example, events induced by impact or initiations of unsafe items could be expected to occur simultaneously with or very shortly after the initial incident. For the purposes of this study it has been assumed that evacuation would not be achieved in such circumstances. In fact, this assumption may well introduce an element of conservatism into the analysis, as drop trials have shown that impact accidents may initially induce a smouldering reaction in an explosives item rather than an immediate detonation. Similarly, an initiation of an unsafe item may initially ignite a fire within an explosives load rather than induce an immediate explosion: indeed this was the sequence of events that occurred in two of the incidents initiated by unsafe explosives in the UK in the post-war period – the Bedenham and the Peterborough incidents (see Appendix 2).

Calculation of fatality estimates

102 Estimates were obtained for the numbers of fatalities that could be expected from each of the many different types and sizes of explosives events that could potentially occur in the study ports. These estimates were obtained by the procedure described in paragraph 85. In each case, the L_{100}, L_{90}, L_{50}, L_{10} and L_{01} hazard ranges (see Figure 3) were calculated from the appropriate explosion effects models; the numbers of persons within the areas bounded by those hazard ranges were then determined and the fatality estimates calculated viz:

$$N_T = N_{100} + 0.95.(N^{90} - N_{100}) + 0.7\ (N_{50} - N_{90}) + 0.3\ (N_{10} - N_{50}) + 0.05\ (N_{01} - N_{10})$$

Where:

N_T is the total number of fatalities expected,

N_{100} is the number of persons within L_{100},

N_{90} is the number of persons within L_{90},

N_{50} is the number of persons within L_{50},

N_{10} is the number of persons within L_{10},

N_{01} is the number of persons within L_{01},

It will be seen from this formula that an average fatality probability of 0.95 has been assumed for those persons within the area bounded by L_{100} and L_{90} and, similarly, average fatality probabilities of 0.7, 0.3 and 0.05 have been assumed for those persons within the areas bounded by L_{90} - L_{50}, L_{50} - L_{10} and L_{10} -L_{01} respectively. These assumptions are conservative with respect to initiations of explosives of HD 1.1, as blast overpressure decays exponentially and not linearly with distance – so, for example, L_{70} is closer to L_{90} than L_{50}.

103 Finally, it is noted once again that explosion effects modelling continues to remain an active field of research. The explosion effects models used in this study were the best available at the time the work was undertaken but it can be expected that better models will become available in the future. The models used in this study will generally overestimate the effects of explosives events and give results that err on the side of conservatism. This, of course, provides some assurance that the risks of moving explosives through ports will not be underestimated. The various sources of uncertainty inherent in the results produced by these models are reviewed in Appendix 6. It is to be hoped that further research will allow definitive explosion effect models to be developed.

6. The risks of moving explosives through ports

104 The analysis presented thus far has considered the potential causes of explosives events in ports, the likelihood of those events occurring and their consequences. The next step in the analysis involved the calculation of the societal and individual risk associated with the explosives trade at each of the five ports and one licensed jetty selected for detailed study. This process required frequency estimates to be determined for all of the different types and sizes of explosives events that could potentially occur in these locations along with estimates for the numbers of fatalities that could be expected from these events. Frequency estimates were calculated by the procedure described in Section 4 while fatality estimates were calculated by the method described in Section 5. These estimates were then combined to provide two measures of societal risk: FN curves, which show the estimated frequency (F) of events resulting in N or more fatalities; and 'expectation values' which express the long term average number of fatalities per year that could be expected from the explosives trade at the study locations. In the present case a cut-off has been applied to the FN plot at $F = 1.10^{-9}$.

105 FN data for each of the five ports and one licensed jetty selected for detailed study were derived employing a five-step procedure in which:

(a) Points within the port were identified where explosives events could be initiated by the various types of accidents discussed in Section 2. This involved establishing the routes through the port and harbour along which explosive cargo was transported together with the points of loading and unloading.
(b) Explosives cargoes were partitioned into hazard groups and notional sizes of load to determine the different types and sizes of explosives events that could potentially occur at the points identified in (a). This stage of the analysis was accomplished by the procedure described in Section 3.
(c) Frequency estimates, f, were calculated for each type and size of event that could potentially occur at the points identified in (a). This step in the analysis was accomplished by the procedure described in Section 5.
(d) Estimates were calculated for the number of fatalities, N, that could be expected from each potential explosives event. This step in the analysis was accomplished by the procedure described in Section 5.
(e) From the individual fN pairs, calculations were made for the overall frequency, F, of events resulting in more than the following numbers of fatalities: 1, 5, 10, 15, 20, 50, 100, 500, 1000.

An example of this procedure is set out in Table 5. This table lists frequency and fatality estimates for the different types and sizes of explosives events that could potentially occur on ships docked at Port C. This is a RoRo port for which the only potential causes of explosives events on board ships are taken to be ignition of fire on board ship and spontaneous initiation of unsafe items.

106 Table 5 shows that the various explosives cargoes carried on ships into and out of Port C have been partitioned into five hazard groups (column 1) and that each hazard group has been partitioned into a number of notional sizes of load (column 2). In total, this gave twelve representative types and sizes of loads for which frequency estimates (column 3) and fatality estimates (column 4) had to be determined. The expectation values shown in column 5 were calculated as the product of the values shown in columns 3 and 4, ie as the product of the estimated frequency of events and the estimated numbers of fatalities that would be caused by the events.

Table 5 fN data for explosives events on ships docked at Port C

Type of Explosives Cargo initiated	Size of Load (kg)	Frequency of Initiation, f, (year $^{-1}$)	No of Fatalities N	Expectation Value (year $^{-1}$)
Articles of HD 1.1	4	1e-6	4	4e-6
	400	2e-6	48	1e-4
	2,000	4e-6	51	2e-4
Substances of HD 1.1	20	6e-6	4	2e-5
	200	2e-6	17	4e-5
Articles of HD 1.2	All sizes	9e-6	4	4e-4
Articles of HD 1.3	10	6e-6	0	-
	500	6e-6	7	4e-5
	3,0000	6e-6	19	1e-4
Substances of HD 1.3	30	1e-6	1	1e-6
	4,000	4e-6	21	9e-5
	13,000	2e-6	33	8e-5

107 FN data can now be constructed from the fN data shown in columns 3 and 4. It will be seen that the frequency of events (F) resulting in N or more fatalities is as follows:

Frequency (F) of N or more fatalities (per year)					
N>=1	N>=5	N>=10	N>=15	N>=20	N>=50
$4.3.10^{-5}$	$2.6.10^{-5}$	$2.0.10^{-5}$	$2.0.10^{-5}$	$1.2.10^{-5}$	4.10^{-6}

The overall expectation value for explosives events on ships docked at the port is calculated as the sum of the values listed in column 5 of the above table, ie 1.10^{-3} fatalities per year.

108 Similar calculations were performed for all the other points in Port C where explosives events could potentially occur. Likewise, FN data were calculated for the other four ports and one licensed jetty selected for detailed analysis. The results obtained and the conclusions that could be drawn from these results are discussed in the following section of this report.

7. The results obtained from the detailed studies of the five ports and one licensed jetty

Port A

109 Port A is a major container port that also has facilities for handling RoRo and break-bulk cargo and an oil jetty for importing and exporting bulk petroleum and chemical products. Significant passenger ferry services also operate out of this port. There are a number of terminals within the port, all of which are licensed to handle explosives. In practice, however, most of the explosives trade is handled at the most isolated terminal, which is licensed to handle comparatively large quantities of explosives – up to 200 tonnes of HD 1.1.

110 The port handled a wide range of military and commercial explosives at the time of the study. All of the commercial loads were moved into or out of the port on container lorries while most of the military loads were brought into the port by rail. Lorries carrying explosives for export were driven straight to the quay after entering the port. On arriving at the quay, the lorries were immediately unloaded by container gantry cranes which transferred the loads directly onto a waiting ship. The ship departed from the berth as soon as the lost explosives container had been loaded, explosives cargo always being the last to be loaded onto ships. Explosives were imported by the reverse procedure and explosives cargoes were always the first to be off-loaded from the ship. This last-on first-off policy ensured that explosives cargoes did not remain in the port for more than the minimum period of time. Most of these operations were performed during normal working hours.

111 Military explosives brought into the port by rail were carried on specifically chartered trains (these train carried no other types of goods). The trains were unloaded at the port's rail terminal by means of container gantry cranes, which transferred containers directly from rail vehicles onto road trails. The trailers were then driven about 2 kilometres through the port to the quay where container gantry cranes immediately transferred the containers from the trailers onto a waiting ship. These operations were performed at night when only small numbers of people were present in the vicinity of the rail terminal.

112 Virtually all of military and commercial explosives cargoes moved through the port at the time of the study were containerised. At no point were the containers opened and palletised loads of explosives removed. The containers remained sealed during passage through the port.

Potential causes of explosive events

113 Explosives events might occur at any of the following points in the port: (i) the rail terminal, (ii) all points along lorry routes between the port entrance or rail terminal and the quay, (iii) the quay, (iv) all points along the shipping channel through the harbour. The types of accidents that might give rise to explosives events in these locations are as follows:

Rail terminal:
- Train fires
- Train collisions/derailments
- Crane accidents

Lorry routes between the port entrance/rail terminal and the quay:
- Vehicle fires
- Vehicle crashes/collisions

Quay:
- Ship fires
- Ship strikings
- Cranes accidents

Shipping channel between the quay and the harbour entrance:
- Ship fires
- Ship collisions

In addition to these possibilities, explosives events could occur at any of the above locations as a result of a spontaneous initiation of an unsafe item.

Societal risk

114 Following the procedure described in Section 6, frequency (f) and fatality (N) estimates were calculated for the different types and sizes of explosives events that could result from these accidents. The fN data pairs obtained were processed to produce a table of fN values as shown in Table 6.

115 FN curves of these results are shown in ‘faired’ form in Figure 4. The faired curves have been obtained by plotting the geometric means of the adjacent Fs and Ns in the above table. This process results in the loss of a data point from each FN set and it follows that the faired FN curves are more compressed than the graphs that would be obtained by simply plotting the results presented in Table 6. ‘Fairing’, as noted in the report on the first phase of the ACDS work[(2)], is a process for producing a smooth FN curve rather than a step-wise FN graph.

116 It is estimated that fatal explosives events might occur in the port with a frequency of 10^{-4} yr^{-1}, ie one chance in 10,000 per year. This result is, of course, based on the types and quantities of explosives moved through the port at the time of the study; it can be expected that risks will change in line with patterns of traffic. Most of the risk is associated with loading and unloading operations at the quay and rail terminal. The transport of explosives along lorry routes through the port and along the shipping channel of the harbour does not contribute significantly to the overall risk. This is shown in Figure 4 but also most clearly by a comparison of the expectation derived for the different locations in the port where explosives are handled:

Location	*Expectation Value (No. of fatalities per year)*	*Percentage of total*
Quay	1.10^{-3}	62%
Rail terminal	6.10^{-4}	29%
Shipping channel	1.10^{-4}	7%
Lorry routes	3.10^{-5}	2%

By this measure, the risk of carrying explosives through the port on lorries and ships accounts for less than 10% of the overall risk of the explosives trade at the port.

Table 6 FN values for the explosives trade at Port A

N	Estimated frequency of events (per year)				
	Accidents at the rail terminal	Accidents between the port entrance/ rail terminal and the quay	Accidents at the quay	Accidents between the quay and harbour entrance	Total
1	4e-5	64-6	6e-6	7e-6	1e-4
5	4w-5	1e-6	6e-5	6e-6	1e-4
10	4e-5	7e-7	6e-5	5e-6	1e-4
15	2e-5	2e-7	3e-5	5e-6	5e-5
20		2e-7	3e-5	5e-6	3e-5
50		4e-8	2e-7		2e-7
100		5e-9			5e-9

117 However, it will be seen from Table 6 that an explosives event on a lorry *en route* between the port entrance/rail terminal and the quay could cause the highest number of fatalities of any of the explosives events that could potentially occur in the port. This result is explained by the presence of a number of office blocks adjacent to the lorry routes. An explosion involving the maximum quantity of explosives of HD 1.1 permitted on a container lorry (16 tonnes) might result in over 100 fatalities were the explosion to occur along the section of route closest to these buildings. The frequency of such an event, however, is estimated to be remotely low -5.10^{-9}.

118 Figure 4 shows that events are most likely to occur during the loading and unloading of explosive cargoes on the quay. An explosion during these operations could cause up to about 50 fatalities were the largest and most hazardous types of cargoes to be involved. About 30 of these fatalities would occur among the ship's crew and workers at the berth while around a further 20 fatalities could occur among persons on board a passing ship. The frequency with which these events might occur is estimated as 2.10^{-7}. It is more likely that only the ship loading or discharging explosives cargo would be affected by an explosion at the quay: an analysis of shipping movements shows it is unlikely that a vessel would be in the shipping channel within the hazard range of explosives cargo at the time of any accident. In these circumstances an explosion at the quay might cause about 30 fatalities among quay workers and the crew of the ship alongside and the frequency of such events is estimated as 3.10^{-5} yr^{-1}. It is unlikely that such an event would cause any fatalities among port office workers as the nearest

building to the quay (some 630 metres away) lies beyond the 1% fatality range (400 metres) for the largest notional sizes of cargoes handled. The nearest off-site buildings and public highway are located some 1.25 kilometres from the quay and at this distance the fatality probability for a person located indoors is conservatively estimated to be 0.1%.

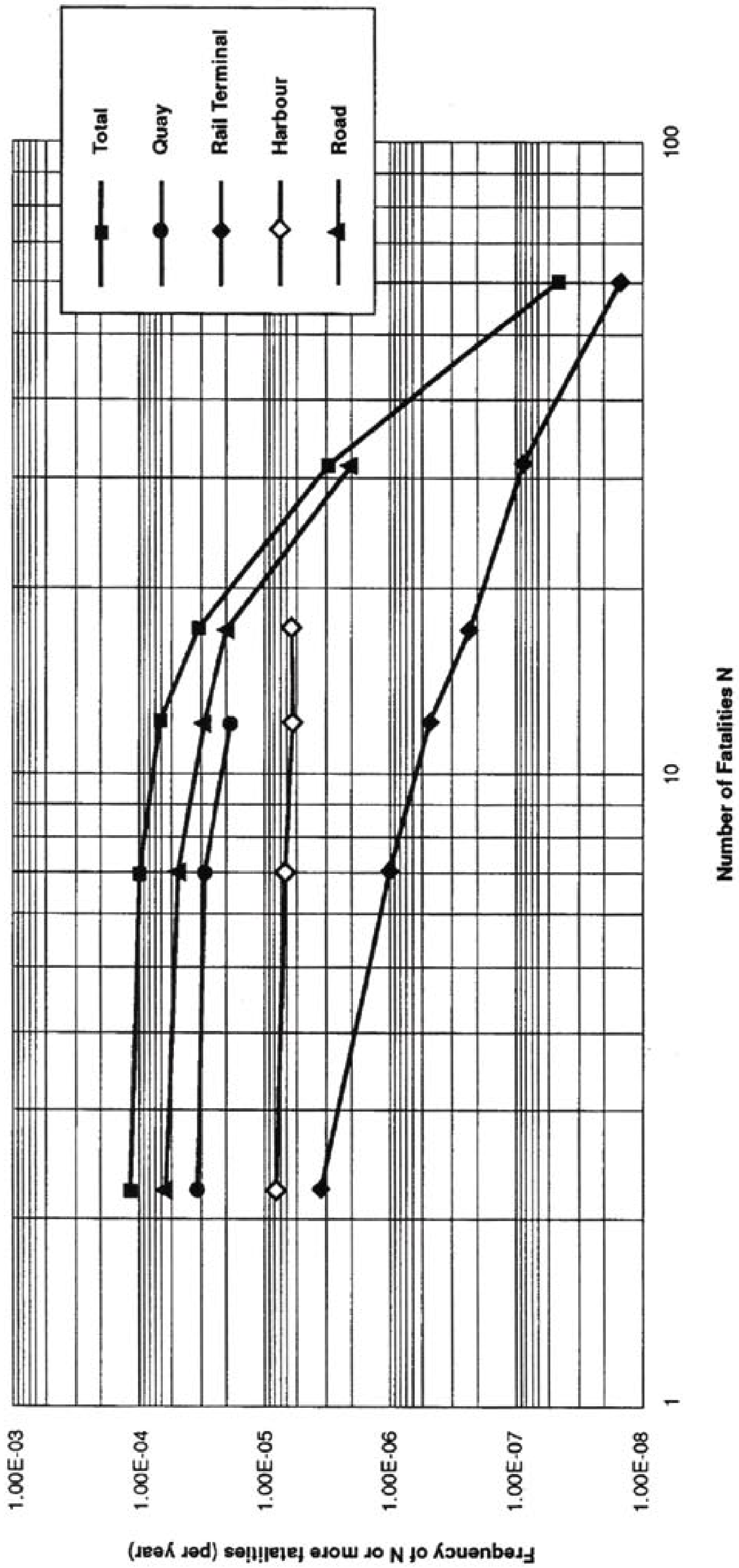
Individual risk

119 Those at greatest risk from the explosives trade at the port are the workers engaged in the loading or unloading of explosives cargo at the quay or the rail terminal. It is not possible to derive precise values of individual risk for these workers as they do not remain in fixed positions during loading and unloading operations and, as discussed previously (see paragraph 98), the lethal effects of explosives events can fall off quite markedly with only small increases in distance from the event. Conservative estimates for individual risk have been calculated as the annual probability of a fatal explosives event at the various points of loading and unloading:

Location	*Annual probability of a fatal explosives accident (taken as a conservative measure of individual risk)*
Quay (silent hours)	5.10^{-5}
Quay (normal working hours)	8.16^{-6}
Rail terminal, south point	2.10^{-5}
Rail terminal, mid point	1.10^{-5}
Rail terminal, north point	8.10^{-6}

These estimates of individual risk are conservative as they assume that a particular worker is always present at the quay or at a certain point in the rail terminal whenever explosives are present in the event of the accidental initiation of HD 1.1 explosives.

Figure 4 Risk estimates for Port A by location of accident



Circumstances in which passenger vessels could be affected by explosive events

120 It was noted in the introduction to this section that significant passenger ferry service operate out of Port A. This raises the question whether there are any circumstances in which these ferries could be affected by an explosion in the port. This issue is explored in some detail in Appendix 6, but it may be noted that the ferries that operate out of Port A dock at a berth that is over 2 kilometres downstream of the quay where explosives are handled. At this distance, the ferries are beyond the hazard range of the largest sizes of explosives cargoes handled at the quay. Ferry services also operate out of the port on the opposite bank of the estuary. These ferries do in fact pass the quay where explosives are handled but at a distance that is beyond the hazard range of the largest size of load handled. The distance at which these ferries pass the quay is also greater than the stopping distance for the ferries, and this should ensure that vessels loading or unloading explosives at the quay would not be struck in the event of these ferries loosing steerage. This leaves the possibility of a passenger ferry being affected by an explosives event on a ship underway in the navigation channel of the harbour. Such an event might occur as a result of a fire igniting on a ship carrying explosives (but in this case there should be time for the harbour authorities to isolate the area of danger), as a result of a spontaneous initiation of an unsafe explosives item on the ship, or as a result of a collision between the explosives carrying ship and the passenger ferry. The chance of such an accident was very remote even before the institution of the traffic management system mentioned in paragraph 122, but it was theoretically possible that over 1000 fatalities could result from an event involving the largest of HD 1.1 cargoes and the largest of passenger ferries.

121 In fact, the chance of such an accident at the time of the study was very remote, though it was theoretically possible. Large quantities of HD 1.1 explosives were only loaded onto ships at night, and these ships fortuitously left the berth at times when passenger vessels were not scheduled to arrive in or depart from the port. There was a possibility that an explosives carrying ship underway in the harbour might have passed a passenger ferry running late due to bad weather or operational problems, but the chance of this event was considered to be very low and since it could not be reliably determined from the available data it has not been considered here.

122 Since the completion of the study, the operators of Port A have instituted a traffic management system that effectively prevents explosives carrying ships from passing passenger vessels in the harbour’s navigation channel. The details of this system are discussed in Appendix 5, which also looks at risks to passenger vessels in more detail.

Port B

123 Port B is located on a narrow river about 11 kilometres upstream of the open sea. At the time of the study, a range of commercial and military explosives were imported and exported through the port on a frequent basis. Export cargoes were brought into the port on heavy goods vehicles and off-loaded on the quay by means of fork lift truck. The palletised loads of explosives were picked up on the quay by fork lift trucks and placed into freight containers. The freight containers were then lifted onto ships by mobile crane; however, the height of lift did not exceed more than a few feet as the deck of the ship was about level with the quay. Accordingly, crane accidents are not considered a credible source of explosives events at this port. Explosives were imported by the reverse procedure. The port operated a last-on first-off policy for explosives to ensure that these cargoes were not present in the port for more than the minimum period of time if necessary.

Potential causes of explosives events

124 Explosives events might occur at any of the following places in the port: (i) all points along the lorry route from the port entrance to the quay, (ii) the quay, (iii) all points downstream of the quay and the open sea. The potential causes of explosives events in these locations are as follows:

Lorry route from public highway to the quay:
  Vehicle fires
  Vehicle crashes/collisions

Quay:
  Fork lift truck accidents
  Ship fires
River channel between the quay and the open sea:
  Ship fires

In addition to these possibilities, explosives events could occur at any of the above locations as a result of a spontaneous initiation of an unsafe term.

Societal risk

125 FN values, calculated as described in Section 6, are presented in Table 7.

Table 7 FN values for the explosives trade at Port B

N	Estimated Frequency of Events (per year)			
	Accidents between the public highway and the quay	Accidents at the quay	Accidents between the quay and the open sea	Total
1	5e-7	1e-5	2e-5	3e-5
5	2e-8	7e-6	2e-6	9e-6
10	2e-9	2e-6	2e-8	2e-6
15		5e-7	6e-9	5e-7
20		5e-7	1e-9	5e-7

FN curves of these results are shown in 'faired' form (see paragraph 115) in Figure 5. Based on the types and quantities of explosives handled at the time of the study, it is estimated that fatal explosives events could occur in the port with a frequency of 3.10^{-5} yr^{-1}. The results presented in Table 7 suggest that these accidents are most likely to occur during loading and unloading operations at the quay and transport of explosives along the river, the dominant sources of such events being ignition of fires on ships and spontaneous initiations of unsafe items. It will be seen that the carriage of explosives along the lorry route through the port does not contribute significantly to the overall risk, this is clearly shown in Figure 5. When the frequency and fatality estimates are combined to produce expectation values (ie the estimated long term average number of fatalities per year) it is seen that most of the risk is centred on the quay:

Location	*Expectation value (No. of fatalities per year)*	*Percentage of total*
Quay	8.10^{-5}	66%
River	4.10^{-5}	33%
Lorry route	1.10^{-6}	1%

126 An explosion involving the largest and most hazardous type of explosives cargo handled at the quay could be expected to cause around 20 fatalities. It is likely that any fatalities caused by such an event would be confined to the ship' crew and those working on or near the quay at the time of the explosion. The nearest inhabited building to the port is located some 350 metres from that part of the quay where explosives are loaded and unloaded onto ships; this is beyond the 1% lethality range (200 metres) of the largest and most hazardous type of explosives cargo handled. The frequency of events resulting in around 20 fatalities is estimated to be 5.10^{-7} yr^{-1}.

127 On leaving the port, ships pass a village on the opposite bank of the river about 500 metres downstream of the quay. An explosion in this section of the river could have fatal consequences in the village; it is estimated that the largest and most hazardous cargo might cause around five fatalities in the village. However, the frequency of this type of event is remotely low (5.10^{-8} yr^{-1}). It is noteworthy that this is the only port studied where residential population came within the hazard range of explosives loads transported along water courses.

Individual risk

128 Estimates for individual risk have been calculated from estimates for the frequency of fatal accidents occurring in various locations in the port and off-site:

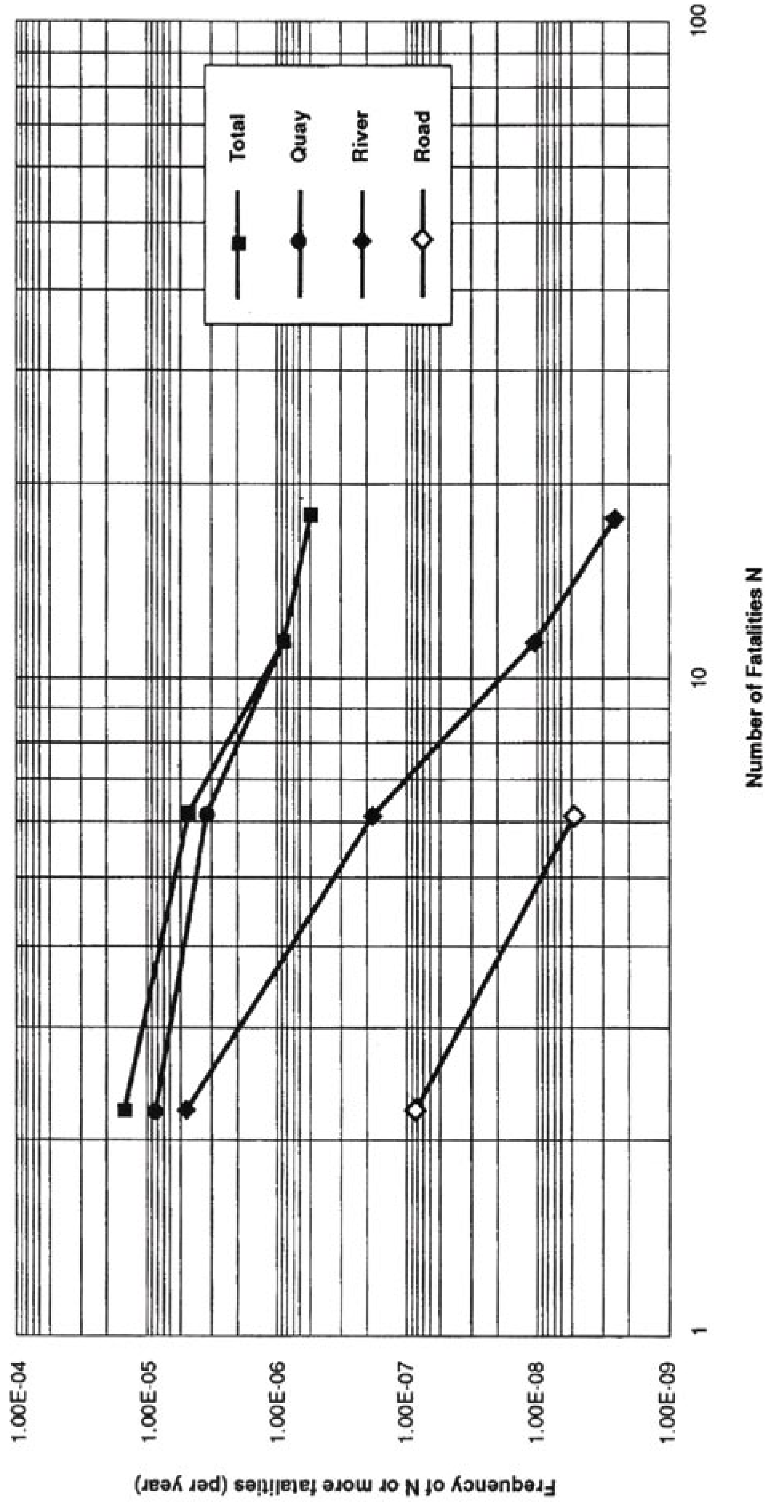
Location	*Frequency of fatal accident (per year)*
River	2.10^{-5}
Quay	1.10^{-5}
Lorry route	5.10^{-7}
Village	1.10^{-8}

These results suggest that the ship's crew are exposed to the highest level of individual risk. In fact nearly all explosives loads imported and exported through this port were carried on one particular ship that operated a regular service between the port and the continent. Assuming that the ship was crewed by the same personnel on each occasion explosives were carried, and that the crew remained on board during loading and unloading operations at the quay, and, furthermore, that one particular member of crew would have been killed in the event of any fatal accident, then the maximum level of individual risk to the crew can be taken as 3.10^{-5}.

Port C

129 Port C is a major RoRo port that also has facilities for handling conventional and bulk commodities. At the time of the study, the port handled a range of commercial and military explosives, all of which were imported or exported on RoRo vessels. These loads were carried on heavy goods vehicles that were driven directly on and off vessels and no cargo was removed from these vehicles at any point of the operation. Like the other ports included in this study, Port C operated a last-on first-off policy for explosives cargoes, ensuring that these cargoes did not remain in the port for more than the minimum practical period of time. Two important restrictions were applied to the times when explosives cargoes could be moved: these cargoes were not allowed into the port when passenger ferries were present or when tankers were loading or unloading at the oil jetty.

Figure 5 Risk estimates for Port B by location of accident



Potential causes of explosives events

130 Explosives events might occur at any of the following places in the port: (i) all points along the lorry route from the port entrance to the berth, (ii) the berth and (iii) all points along the navigation channel through the harbour waters. The potential causes of explosives events in these locations are:

Lorry route between the port entrance and the berth:
- Lorry fires
- Lorry crashes/collisions

Berth:
- Ship fires

Navigation channel between the berth and the harbour entrance:
- Ship fires

In addition to these possibilities, explosives events could occur at any of these locations as a result of a spontaneous initiation of an unsafe item.

Societal risk

131 FN values, calculated as described in Section 6, are presented in Table 8.

FN curves of these results are shown in faired form (see paragraph 115) in Figure 6. Based on the types and quantities of explosives handled at the time of the study, it is estimated that fatal explosives events could occur in the port with a frequency of 9.10^{-5} yr^{-1}. The results presented in Table 8 suggest that these accidents are most likely to occur during loading and unloading operations at our berth and transport of explosives through harbour waters, ignition of fires on ships and spontaneous initiations of unsafe items being the most likely causes of such accidents. In common with most of the other ports studied, the carriage of explosives on lorries does not contribute significantly to the overall risk from the explosives trade in the port. This can be seen from the results presented in Table 8 and the FN curves drawn on Figure 6.

132 An explosion involving the most hazardous explosives cargo handled at this port (2 tonnes of HD 1.1) might cause up to about 50 fatalities (see Appendix 7). This relatively high number of fatalities is explained by the large numbers of persons present on the RoRo vessels that operate out of the port – typically 25 crew and 45 lorry drivers. However, the comparatively small quantities of explosives carried on these vessels (2 tonnes is the maximum quantity of HD 1.1 explosives permitted under the terms of the port’s licence) means that any explosives event would not produce a lethal effect much beyond the vessel itself. Calculations show that nearly all of the fatalities that could be expected from these events would be confined to persons on board, regardless of whether the vessels were docked at the berth or underway in harbour in harbour waters. The nearest occupied building in the port is located some 170 metres from the berth, just beyond the 1% lethality range (165 metres) of the most hazardous explosives load handled at the berth. The nearest public amenity off-site is the road leading to the entrance to the port.

Figure 6 Risk estimates for Port C by location of accident

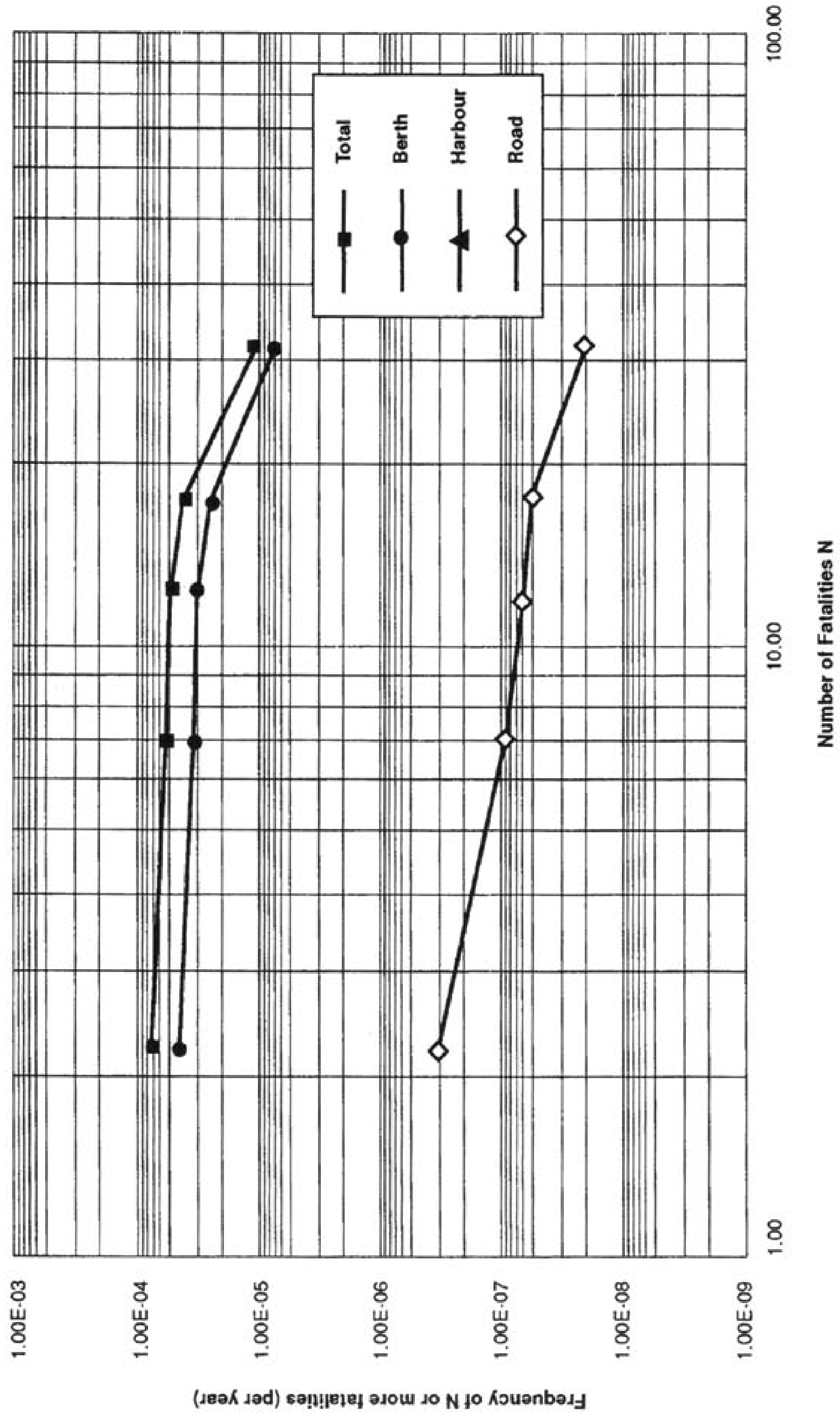


Table 8 FN values for the explosives trade at Port C

N	Estimated Frequency of Events (per year)			
	Accidents between the port entrance and the berth	Accidents at the berth	Accidents between the berth and the harbour entrance	Total
1	8e-7	4e-5	4e-5	9e-5
5	1e-7	3e-5	3e-5	5e-5
10	7e-8	2e-5	2e-5	4e-5
15	6e-8	2e-5	2e-5	4e-5
20	5e-8	1e-5	1e-5	3e-5
50	8e-9	4e-6		5e-6

133 The expectation values (the estimated long term average number of fatalities per year) calculated for various locations in the port show that the risk is almost equally divided between the berth and the harbour waters:

Location	*Expectation Value (No. of fatalities per year)*	*Percentage of total*
Berth	1.10^{-3}	52%
Harbour	9.10^{-4}	48%
Lorry route	3.10^{-6}	-

Individual risk

134 The persons most exposed to risk from the movement of explosives cargoes through this port are those workers that supervise the loading and discharging of vehicles at the berth. A conservative estimate for the individual risk to which these workers are exposed can be taken as the frequency (per year) of fatal explosives accidents at the berth. This is calculated as 5.10^{-5}. This estimate assumes that one particular worker is always present at the berth whenever explosives are loaded or unloaded and would inevitably be killed in the event of a fatal explosives accident. Both of these assumptions are known to be conservative; but if the level of individual risk so derived is found not to be intolerable, then it can be claimed to pass a very strict test of tolerability.

Port D

135 Port D is a dock that is entered by vessels via a lock to the open sea. Military munitions of HD 1.2 were the only types of explosives handled at this port at the time of the study. These munitions were brought into the port as palletised cargoes on heavy goods vehicles. The vehicles were unloaded on the quay by means of fork lift truck and the palletised loads transferred to ships by means of dockside cranes. No other types of cargoes besides military munitions were carried on these ships. The quantities of munitions loaded were typically very large (in excess of 1000 tonnes gross weight) and the loading operations proceeded over several days.

Potential causes of explosives events

136 Explosives events might occur at the quay or along any section of the lorry route from the port entrance and the quay. The potential causes of explosives events in these locations are:

Lorry route from the port entrance to the quay:
- Vehicles fires
- Vehicle crashes and collisions

Quay:
- Fork lift truck accidents
- Crane accidents
- Ship fires

In addition to these possibilities, explosives events could occur in these locations as a result of a spontaneous initiation of an unsafe munition.

Societal risk

137 As explained in paragraph 91, an initiation of an HD 1.2 load would have a very limited effect. It is judged that such an accident might cause between one and four fatalities. Frequency estimates for these events have been calculated by the procedure described in Section 4. The results are presented in Table 9.

Based on the types and quantities of explosives handled at the time of the study, it is estimated that fatal explosives accidents might occur in the port with a frequency of 7.10^{-5} yr^{-1}. The results presented in Table 9 indicate that these accidents would most likely occur at the quay during the loading of cargo on to ships. The risks from the carriage of explosives through the port on lorries is not insignificant; explosives events on lorries are estimated to contribute almost 30% of the total event frequency. Port D was alone among the ports studied in producing this result. It is explained by the relatively few but very large sizes of loads handled at the port at the time of the study. The pattern of traffic was characterised by a very high number of lorry movements and very few shipping movements.

Table 9 FN values for the explosives trade at Port D

N	Estimated frequency of events (per year)		
	Accidents between the port entrance and the quay	Accidents at the quay	Total
1	2e-5	5e-5	7e-5

Combining the frequency and fatality estimates produced the following expectation values (ie the estimated long term average number of fatalities per year):

Location	*Expectation Value (No. of fatalities per year)*	*Percentage of total*
Quay	$1.4.10^{-4}$	64%
Lorry route	8.10^{-5}	36%

Individual risk

138 The chance of a fatal accident occurring at the quay is estimated as 5.10^{-5} per year. The individual risk at the quay can be taken as one-third of this value as loading operations proceeded over three shifts, ie individual risk = 2.10^{-5} (to one significant figure).

Port E

139 Port E is a small open sea port consisting of a single pier with facilities for discharging fishing vessels and for loading and unloading small RoRo ferries. The port had a small trade in commercial explosives at the time of the study. All explosives cargoes brought into the port were packed in special goods vehicles* and carried on chartered ferries. Each ferry typically carried one special goods vehicle with no other cargoes or vehicles being present. As a safety precaution, the pier was evacuated of non-essential personnel prior to the arrival of an explosives carrying vessel. The special goods vehicle was driven off the vessel as soon as it had docked.

Potential causes of explosives events

140 Explosives events might occur at the point of disembarkation on the pier or along any section of the route between the pier and the public highway. The potential causes of explosives events in these locations are:

Point of disembarkation on the pier:
Ship fires

Lorry route along pier to public highway:
Vehicle fires
Vehicle crashes and collisions

Societal risk

141 FN values, calculated as described in Section 6, are presented in Table 10.

Table 10 FN values for the explosives trade at Port E

N	Estimated frequency of events (per year)		
	Accidents at the point of disembarkation on the pier	Accidents along the lorry route from the pier to the public highway	Total
1	4e-6	4e-9	4e-6
5	4e-6	1e-9	4e-6
10	4e-6	7e-10	4e-6

Based on the types and quantities of explosives moved at the time of the study, it is estimated that fatal explosives accidents might occur in the port with a frequency of 4.10^{-6} yr^{-1}. The results presented in Table 10 suggest that such an accident is most likely to occur at the mooring on the pier. The most likely causes of such an event are ignition of fire on board the ferry and spontaneous initiation of an unsafe item. The nearest inhabited building to the pier is located 225 metres from the mooring. The chance that a person inside this building would be killed in the event of an explosion is of the order of 0.1%, ie it is unlikely that anyone inside the building would be killed. However, eleven people are normally present on the pier when explosives loads are moved. It could be expected that all of these people would be killed in the event of an explosion (assuming the pier is not evacuated prior to the event). This result leads to the production of a flat FN curve, as shown in Figure 7. It will also be seen from Figure 7 that lorry movements do not contribute significantly to the overall risk from the explosives trade. The expectation values derived for the mooring and the lorry route further illustrate this point.

* A special goods vehicle is defined in the Carriage of Explosives Regulations[8] as a goods vehicle specially designed or adapted for carrying a type or a quantity of explosives for which an ordinary heavy goods vehicle is unsuitable. The additional features are described in paragraph 4 of the Approved Code of Practice for regulation 6.

Location	*Expectation Value (No. of fatalities per year)*	*Percentage of total*
Mooring on pier	4.10^{-5}	100%
Lorry route	3.10^{-8}	-

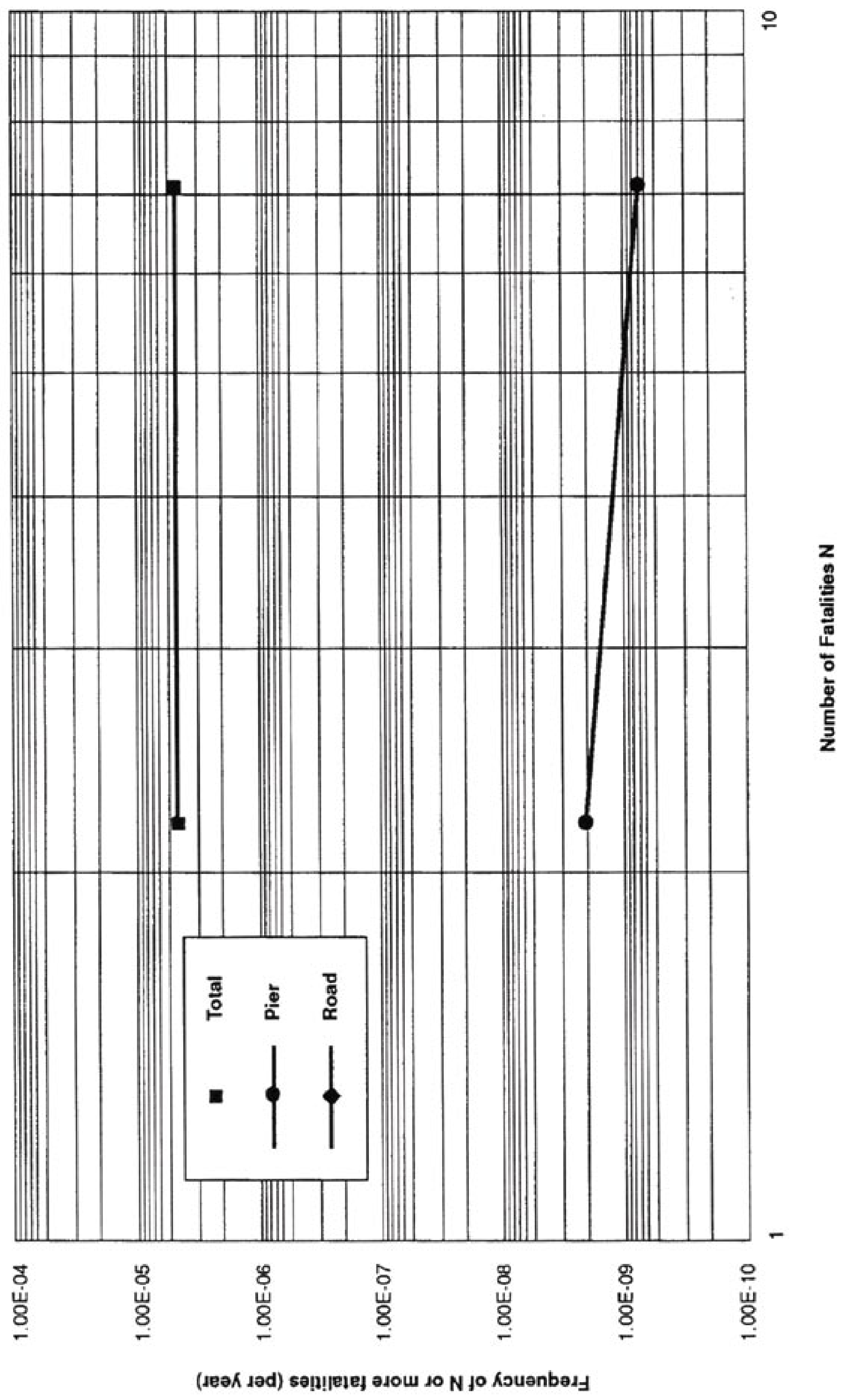
Individual risk

142 Several hundreds are always present on the pier whenever explosives are brought into the port. It can be expected that these people would be killed in the event of an explosion occurring at the mooring without prior evacuation of the pier. Thus the individual risk to which these people are exposed from the explosives trade can be taken simply as the frequency of explosives events without prior evacuation of the pier, ie 4.10^{-6}.

Port F

143 Port F is not a port in the true sense of the word but an isolated jetty within a statutory harbour area. The jetty juts into an estuary that carries a mixture of passenger and freight traffic. The jetty is approached on the shore side by a narrow track that runs for approximately 2 kilometres from the public highway. Because of its isolated position, the jetty has been licensed to handle comparatively large quantities of explosives (up to 400 tonnes of HD 1.1). A number of large consignments of aircraft bombs were exported from this location at the time of the study, but these were the only types of explosives handled in this period. The bombs were brought to the jetty as palletised cargo on container lorries. The lorries were unloaded at the end of the jetty by fork lift trucks which also transported the bombs the short distance along the jetty to the mooring. The bombs were loaded by mobile cranes onto either ships or lighters (barges) depending on the overall size of the consignment. When this exceeded the licence limit for the jetty, part of the consignment was loaded onto a lighter and transported approximately 16 kilometres downstream to an anchorage where a further transfer operation took place onto an ocean-going ship, the transfer being effected by means of ships crane. Several lighters were used in this operation and these performed round-robin trips until all of the consignment had been transferred to the ship at the anchorage. Fork lift trucks were used to move the palletised bombs into stowage positions on board the ship. Bombs were loaded directly onto ocean-going ships on those occasions when the overall size of the consignment did not exceed the licence limit for the jetty.

Figure 7 Risk estimates for Port G by location of accident



Potential causes of explosives events

144 Explosives events might occur at any of the following locations within the environs of the jetty and the statutory harbour area: (i) all points along the lorry route from the public highway to the jetty, (ii) the jetty, (iii) all points downstream of the jetty to the anchorage, (iv) the anchorage. The potential causes of explosives events in these locations are as follows:

Lorry route from public highway to jetty:
- Vehicle fires
- Vehicle crashes/collisions

Jetty:
- Fork lift truck accidents
- Crane accidents
- Ship fires
- Ship strikings

Navigation channel from jetty to anchorage:
- Ship fires
- Ship collisions

Anchorage:
- Fork lift truck accidents
- Crane accidents
- Ship fires
- Ship strikings

In addition to these possibilities, explosives events could occur at any of the above locations as a result of a spontaneous initiation of an unsafe item.

Societal risk

145 FN values, calculated by the procedure described in Section 6, are presented in Table 11. Based on the types and quantities of explosives moved at the time of the study, it is estimated that fatal explosives accidents might occur in the port with a frequency of 4.10^{-5} yr^{-1}. The data presented in Table 11 suggests that such an accident, albeit remote, is most likely to occur at the jetty during the loading of explosives onto ships or lighters. The most likely causes of such an event are ignition of fire on board the vessel and spontaneous initiation of an unsafe item.

146 The number of fatalities that could be expected in the event of an explosion on the jetty would vary considerably depending on the quantity of explosives initiated and the location of vessels, including passenger ships, in the estuary. The quantity of explosives initiated would be dependent on the stage reached in the loading operation at the time of the accident; if the accident occurred at the beginning of the operation then only small quantities of explosives would be present on the jetty whereas up to 400 tonnes of explosives could be present at the end of the operation. In the latter case, it could be expected that all those involved in the operation on and around the jetty (about 50 persons in total) would be killed. The frequency of accidents resulting in 50 or more fatalities is assessed to be 2.10^{-5} yr^{-1}.

147 Higher numbers of fatalities could be expected were vessels to be present in the estuary within the hazard range of the explosives at the time of the accident. Passenger vessels occasionally pass the jetty and accidents resulting in excess of 500 fatalities are theoretically possible, though the chance of these accidents is assessed to be remotely low -3.10^{-10} yr^{-1}. Passenger vessels could also be affected by explosives events in the navigation channel of the estuary and at the anchorage. Again the frequency of such accidents is estimated to be remotely low – 4.10^{-10}

yr^{-1} for events resulting in 500 or more fatalities. The risks to passenger ships are considered in more detail in Appendix 6.

148 The nearest inhabited building to the jetty is located some 1.2 kilometres away. This is appreciably beyond the 1% lethality range (700 metres) for the largest notional size of load handled. It can be concluded that it would be unlikely that people in the building would be killed in the event of an accident at the jetty.

149 A plot of the results presented in Table 11 is shown in faired form in Figure 8. It will be seen that the overall risk of the explosives trade is largely dominated by the risk of accidents occurring during loading operations at the jetty. The risk of transporting explosives along the estuary and loading explosives at the anchorage becomes more significant at high N. As previously noted, high consequence accidents at these locations, while theoretically possible, are extremely unlikely. That the risk from the explosives trade appears to be largely centred on the jetty is shown by a comparison of the expectation values (ie the estimated long term average number of fatalities per year) derived for the various stages of the export operation:

Location	*Expectation Value (No of fatalities per year)*	*Percentage of total*
Jetty	$1.4.10^{-3}$	86%
Anchorage	8.10^{-5}	9%
Lorry route	5.10^{-5}	4%
Estuary	1.10^{-5}	1%

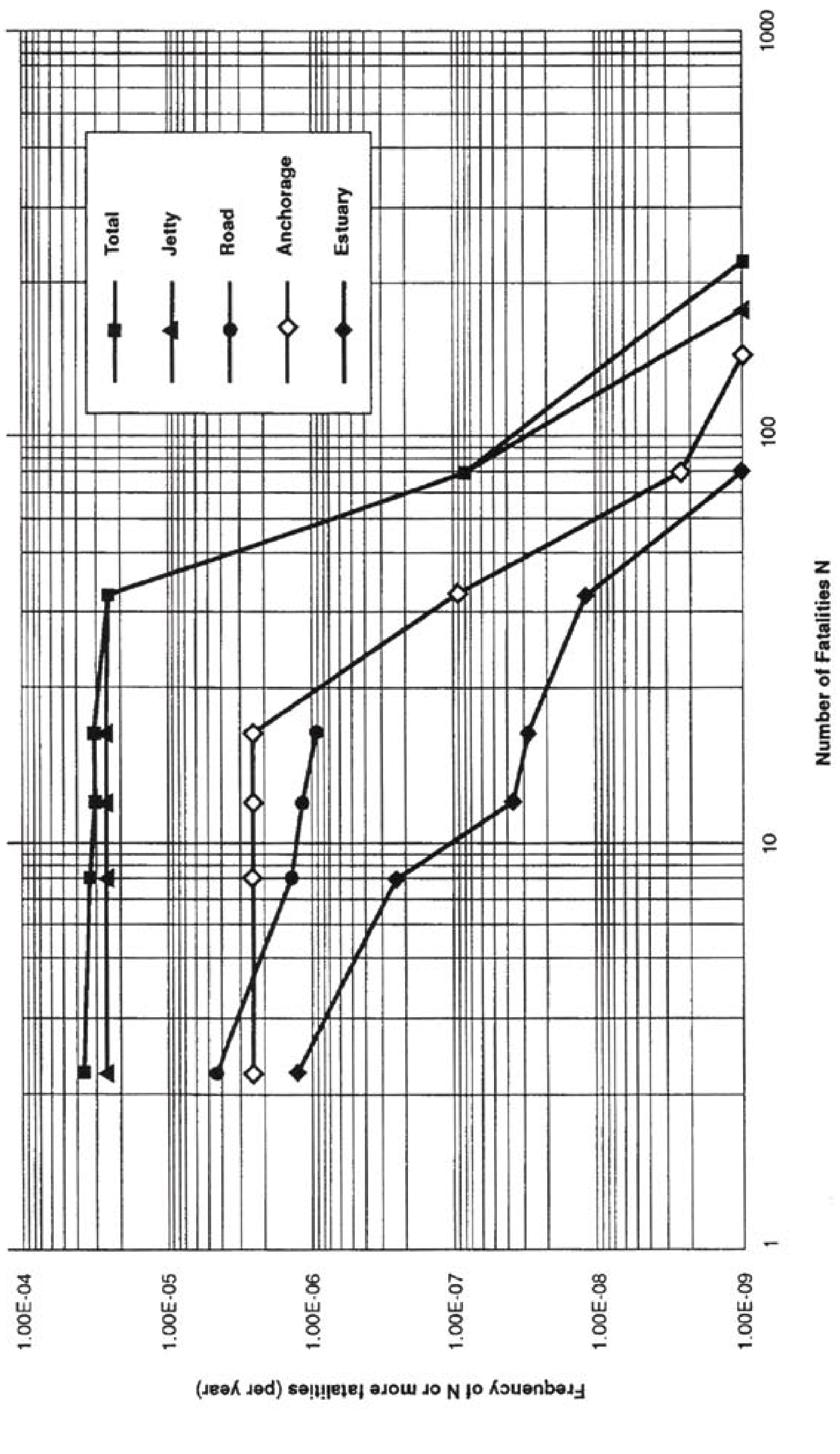
Individual risk

150 Those at greater risk from the explosives trade are the personnel on the jetty during the loading of ammunition on to ships and lighters. It is understood that certain persons are always present at the jetty when explosives are handled. It can be conservatively assumed that these persons would always be killed in the event of a fatal explosives accident occurring at the jetty, hence the individual risk to which these persons are exposed can be taken as the estimated frequency of fatal accidents occurring at the jetty. This is calculated to be 4.10^{-5}.

Table 11 FN Values for the explosives trade at Port F

N	Estimated frequency of events (per year)				
	Accidents between the public highway and the jetty	Accidents at the jetty	Accidents between the jetty and the anchorage	Accidents at the anchorage	Total
1	1e-5	4e-5	2e-6	2e-6	4e-5
5	2e-6	3e-5	1e-6	2e-6	3e-5
10	1e-6	3e-5	4e-8	2e-6	3e-5
15	1e-6	3e-5	3e-8	2e-6	3e-5
20	8e-7	3e-5	3e-8	3e-6	3e-5
50		2e-5	5e-9	4e-9	2e-5
100		3e-10	2e-10	1e-9	2e-9
500		3e-10	2e010	2e-10	8e-10
1000		8e-11	6r-11	6e-11	2e-10

Figure 8 Risk estimates for Port F by location of accident



Main findings of the detailed studies

151 Most of the risk of moving explosives through ports appears to be concentrated at berths and points of loading and unloading. This is shown most clearly by a comparison of the expectation values (the long term average number of fatalities per year) derived for the various locations in the study ports where explosives are handled or moved. This comparison is made in Table 12.

Table 12 Comparison of expectation values derived for the various locations in the study ports where explosives are handled or moved

Port	Location	Percentage of total expectation value
Port A	Quay	62%
	Rail terminal	29%
	Navigation channel	7%
	Lorry routes	2%
Port B	Quay	66%
	River	33%
	Lorry route	1%
Port C	Berth	52%
	Harbour	48%
	Lorry route	Negligible
Port D	Quay	78%
	Lorry route	22%
	Harbour waters	N/A
Port E	Pier	100%
	Lorry route	Negligible
Port F	Jetty	91%
	Anchorage	5%
	Lorry route	3%
	Navigation channel	1%

152 Loading and unloading operations were found to account for most of the risk of the explosives trade at nearly all of the ports studied. Only Port C were the risks of transporting explosives through harbour waters found to account for nearly as much as 50% of overall risks. Port C is a RoRo port, for which the major potential source of explosives events is the ignition of fire on ships. To establish the risk of fire ignition in the harbour's navigation channel, an arbitrary division of risks is assumed reflecting the time spent by the ship in the channel and at the berth. At this particular port, the length of time explosives are present at the berth is approximately equal to the length of time the ship takes to clear the harbour, and so it is assumed that there is an equal chance of fire affecting explosives cargo while the ship is docked at the berth as underway in the harbour. In either case the fatalities produced by a fire-induced explosion would mostly be confined to the ship (see paragraph 129) – hence the equal risk for operations at the berth and transport through harbour waters. At all of the other ports studied, the risks of operations at the berth were found to be dominant.

153 The quantities of explosives that can be present at any berth are controlled by the statutory licensing procedure. This does not in itself give any further degree of protection to those handling the explosives than is afforded by the safe systems of work required by relevant health and safety legislation. But it serves that purpose for other people in the port and the public beyond, by specifying zones which must be kept clear before any explosives may be handled and until handling has been completed.

154 At all of the ports studied it was found that explosives events in harbour waters would be unlikely to produce lethal effects in inhabited areas. Only at Port B, which is a narrow river port located 11 kilometres upstream of the open sea, was it found that an explosion on a ship underway could be expected to produce a lethal effect in a residential area. However, the frequency of such accidents was assessed to be extremely low -5.10^{-8} yr^{-1}.

155 At two of the ports studied, Port A and Port F, it was found that there was a possibility of explosives events affecting passenger vessels. The risk at Port A was found to be extremely low (less than 10^{-10} yr^{-1}) and could not be reliably assessed. However, since the completion of the study, the operators of this port have taken measures to eliminate this risk entirely by instituting a traffic management system which effectively segregates passenger vessels from explosives carrying ships (see Appendix 6). The risk of passenger vessel involvement was also found to be extremely low at Port F: the frequency of accidents resulting in 500 or more fatalities on these vessels was assessed to be 7.10^{-10} yr^{-1}. Two important factors ensured that this risk was remote: at the time of the study the volume of both passenger and explosives traffic was very low and only comparatively insensitive types of explosives were handled at the jetty.

156 The risk results presented in this report represent a ‘snapshot in time’. The risks at the locations studied could change dramatically if patterns of traffic were to increase or decrease, if different types of explosives were to be handled, or if different methods of loading and unloading were to be employed. Finally, it must be remembered that the risk results presented here are necessarily subject to a number of uncertainties and qualifications and should not be taken out of the context of this study.

8. Rapid risk analysis and methodology

157 There are 150 ports/berths in Great Britain licensed to handle explosives. It was beyond the resources of the project to analyse all of these locations in the manner described in the previous section. Instead a simplified risk analysis technique was developed, based on the results obtained from the detailed studies of the five ports and one licensed jetty, and applied to all those licensed ports/berths that had a trade in explosives at the time of the study.

158 The detailed studies had shown that most of the risk involved in moving explosives through ports is concentrated on the berths where explosives are loaded onto and off-loaded from ships. The rapid risk assessment technique was designed specifically to assess the risk of handling explosives at berths. The technique took account of the following parameters:

(a) the hazard group of the explosives handled;
(b) the quantities of explosives handled;
(c) the number of cargoes handled in a representative period;
(d) the types of loading and unloading procedures employed – RoRo, lift-on-lift-off (containerised cargo), lift-on-lift-off (break-bulk cargo);
(e) the number of persons on board ships and around the berth at the time when explosives are handled;
(f) the distances of these persons from the explosives cargo.

159 Data for these various parameters were obtained from specially designed questionnaires. These were sent out to the operators of those licensed ports/berths that had not been included in the first, detailed phase of study. The operators were asked to complete the questionnaires in respect of explosives moments over a representative two-month period. It transpired that most of the licensed ports/berths did not handle explosives in the period for which data were requested. In fact on further investigation it was found that many of these places had not handled explosives for some years, while others typically handled only two or three shipments of explosives in any year. In total, data were obtained for just 60 locations, of which 20 handled explosives. It was not possible to determine whether the 20 locations that had handled explosives, together with those studied in detail, were indeed the only ports/berths to have handled explosives at the time of the study. However, an examination of records kept by the Health and Safety Executive clearly indicated that those locations for which data had been obtained would account for the vast majority of explosives cargoes imported and exported through British ports. Thus it could be confidently predicted that the combined risks from these locations would give a reasonably accurate picture of the overall national risk arising from the movement of explosives through ports.

National risk

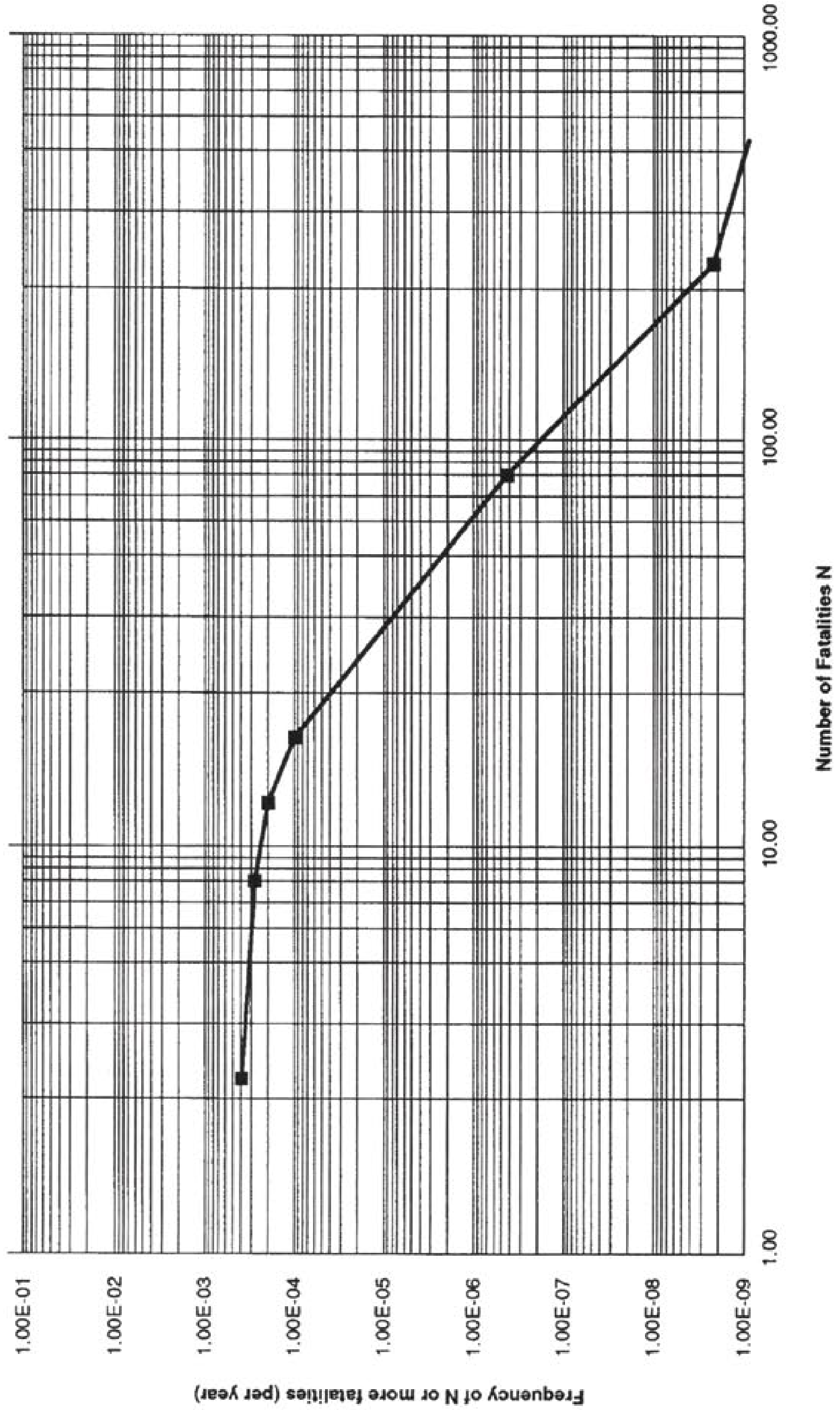
160 The results obtained from the application of the rapid risk analysis technique are presented in Table 13, together with the results obtained from the earlier detailed study. It is seen that fatal explosives events are estimated to occur in ports nationally with a frequency of 6.10^{-4} yr^{-1}. At most of these ports, no more than about 10 fatalities would be expected in the event of an explosion. Higher numbers of fatalities could be expected at ports where explosives are loaded onto ships which carry relatively large numbers of people, or where relatively large numbers are employed at berths where explosives are loaded and unloaded, and also at ports where there is a potential for passenger vessels to be involved in explosive events. Events resulting in about 15 to 20 fatalities are estimated to occur nationally with a frequency of 1.10^{-4} yr^{-1}, while catastrophic accidents resulting in 100 or more

fatalities are estimated to occur with a frequency of 1.10-4 yr^{-1}, while catastrophic accidents resulting in 100 or more fatalities are estimated to occur with a frequency of 7.10^{-9} yr^{-1}. A plot of the results is presented in Table 13 is shown in faired form in Figure 9.

Table 13 National Risk Estimates

Location	Frequency (per year) of Events Resulting in Fatalities > = N								
	N = 1	N = 5	N = 10	N = 15	N = 20	N = 50	N = 100	N = 500	N = 1000
	Results obtained from detailed risk studies								
Port A	1.E-04	1.E-04	1.E-04	5.E-05	3.E-05	2.E-07	5.E-09		
Port B	3.E-05	9.E-06	2.E-C6	5.E-07	5.E-07				
Port C	9.E-05	5.E-05	4.E-05	4.E-05	3.E-05	5.E-06			
Port D	7.E-05								
Port E	4.E-06	4.E-06	4.E-06						
Port F	4.E-05	3.E-05	3.E-05	3.E-05	3.E-05	2.E-05	2.E-09	8.E-10	2.E-10
	Results obtained from rapid risk analysis studies								
Port G	8.E-06	7.E-07							
Port H	1.E-05	5.E-06							
Port I	9.E-06	4.E-06							
Port J	3.E-06	4.E-07	2.E-07						
Port K	2.E-05								
Port L	5.E-06	1.E-07	1.E-07						
Port M	0.E+100								
Port N	1.E-04	5.E-05	5.E-05						
Port O	0.E+100								
Port P	1.E-07								
Port Q	1.E-06	1.E-07	1.E07	1.E-07					
Port R	1.E-06	7.E-07	5.E-07	1.E-07					
Port S	3.E-05								
Port T	3.E-05	1.E-05	9.E-06						
Port U	1.E-06								
Port V	9.E-06	4.E0-06							
Port W	4.E-06	4.E-06	4.E-06						
Port X	4.E-07								
Port Y	2.E-05	1.E-06	9.E-06						
Port Z	3.E-07								
Grand Total	6.E-04	3.E-04	3.E-04	1.E-04	9.E-05	3.E-05	7.E-09	8.E-10	2.E-10

Figure 9 National Societal Risk Estimate



9. Conclusions – technical

161 In this technical study a methodology has been developed to provide an estimation of both individual and societal risk from the explosives trade at individual ports and nationally. This study has used quantified risk assessment (QRA) techniques to estimate the risks of moving explosives through ports. Whilst QRA attempts to express the risk of a hazardous activity in quantitative terms, the procedure is not an exact science and its results are subject to uncertainty. Notwithstanding these qualifications, the technical study has obtained best estimate values for the risks from the explosives trade through ports.

162 Decisions concerning the tolerability of the estimated risks and the reasonable practicability of possible risk reduction measures were outside the remit of the technical study. However, the study has produced some sign posts for future improvements.

163 The risks in this study were found to be well managed. However, the estimates of risk are conditional upon one major premise: that the existing standards of management are maintained or enhanced further. The risks could increase if standards of safety management deteriorate. The full explosives licensing arrangements under the Dangerous Substances in Harbour Area Regulations 1987 (DSHAR) had only just been completed at the start of the technical study. It is likely that as these bed down and the requirements in the Management of Health and Safety at Work Regulations 1992 take effect further useful improvements in management of the risks can be anticipated.

164 The analysis of risk in this study shows that most of the risk involved in moving explosives through ports is concentrated on the berths where explosives are loaded onto and unloaded from ships. In certain circumstances it may be possible to evacuate personnel to a place of safety from the scene of an incident involving an explosives cargo before an explosives event occurs. Successful evacuation will depend to a large extent on both the adequacy of the port emergency plan and its effective implementation. The Dangerous Substances in Harbour Area Regulations 1987 (DSHAR) requires the Statutory Harbour Authorities to prepare and keep up to date an emergency plan.

165 Some members of the steering group looked at emergency plans produced by a number of ports. They concluded that the plans left scope for improvement and commend the recently published HSE guidance on explosives aspects of ports emergency plans as a basis for further development of existing plans.

166 This study did not compare the risks from different modes of handling explosives in ports as the different modes were often used for handling different types of explosives. However, methods which keep the number of people exposed to a minimum are preferable. Regardless of the method employed, loading and unloading operations account for most of the risks. Robust safety management systems are identified as essential components in minimising risks.

167 Traffic management systems within the port/jetty were also considered. At two of the study locations there was the possibility of an explosives event affecting passenger vessels. During the study one of the study locations introduced a traffic management system. This virtually eliminated the risk by segregating passenger vessels from explosives carrying ships.

168 Historical accident data suggests ‘unsafe explosives’ to be one of the main causes of explosives accidents. The term in this study is taken to mean explosives which may have been badly designed, manufactured, packaged or deteriorated prior to despatch. It was beyond the scope of this study to investigate the data or to analyse the casual factors. For the purposes of this study, historical accident records were taken to draw some broad conclusions about the relative threat posed by such explosives. The fact that many of these accidents predate modern controls legal controls and operational practice leads to uncertainty in the risk figures and further work in refining accident frequency estimate data for ‘unsafe explosives’ would be desirable.

169 The results from this study represent a ‘snapshot in time’. Risks at the locations studied are based the volume and type of explosives trade at the time of the study and may change in the future. The estimates are necessarily subject to a number of uncertainties *and* qualifications, as discussed in Appendix 7.

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Glossary

This glossary draws heavily on a booklet on nomenclature published by the Institution of Chemical Engineers. Other sources include the Royal Society Study Group on risk assessment, and the reports of the Advisory Committee on Major Hazards. We do not wish to attempt to impose a single definition but it is necessary to make it clear how certain terms are used in the particular context of this report.

Expectation value Average number of predicted deaths per year (derived from the calculated societal risks).

Exponential notation (eg 1E-6) Used on the graphic ordinates. The letter E represents 10 and the number that follows it is an exponent, eg 1E-3 instead of 10^{-3}.

1E-6(=10^{-6} per year) Denotes one in a million per year.

Fault tree analysis A method of representing the logical combinations of various systems states which lead to a particular outcome (top event).

FN curve A plot showing, for a specified hazard, the frequency of all events causing a stated degree of harm to N or more people, against N.

Faired Fairing is, in effect, a process for smoothing a curve which is established from relatively few points. For FN curves it means taking the results of the models, obtaining the logarithmic mean of adjacent Fs and Ns to obtain logarithmic mid points, and then drawing a curve between the faired points.

Flash fire The burning of a flammable vapour cloud at very low propagation speed. Combustion products are generated at a rate low enough for expansion to take place easily without significant overpressure ahead or behind the flame front. The hazard is therefore only due to thermal effects.

Flash point The temperature above which the vapour pressure of a fuel is great enough for combustion to occur.

Fireball The burning of a flammable gas cloud, the bulk of which is initially over-rich (ie above the upper flammable limit). The whole cloud appears to be on fire as combustion is taking place at eddy boundaries where air is entrained (ie a propagating diffusion flame). The buoyancy of the hot combustion products may lift the cloud from the ground, subsequently forming a mushroom shaped cloud. Combustion rates are high and the hazard is primarily thermal.

Great Britain England, Scotland and Wales excluding the Channel Islands and the Isle of Man.

Hazard A physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these.

HD 1.1 Substances and articles which have a mass explosion hazard.

HD 1.2 Substances and articles which have a projection hazard but not a mass explosion hazard.

HD 1.3 Substances and articles which have a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosive hazard.

HD 1.4 Substances and articles which present no significant hazard.

Notifiable installations Installations which contain a specified minimum quantity of defined hazardous substances and must give to the Health and Safety Executive prescribed details of the activities under the Notification of Installations Handling Hazardous Substances Regulations 1982 (NIHHS).

Overpressure Maximum pressure above atmospheric pressure experienced during the passage of a blast wave from an explosion.

Pool fire A pool of flammable liquid burning with a stationary diffusion flame.

Risk The likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either a frequency (the number of specified events occurring in unit time) or a probability (the probability of a specified event following a prior event), depending on the circumstances.

> **Individual risk** The frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards.
>
> **Residual risk** The remaining risk after all proposed improvements to the facility under study have been made.
>
> **Societal risk** The relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards.

'Unsafe explosives' This term is used throughout the report to mean the breakdown in quality control procedures that would allow unsafe explosives items to enter the transport chain.

Abbreviations

ACC	Association of County Councils
ACHM	Advisory Committee on Major Hazards
ALARP	As low as reasonably practicable
CAD	Central ammunition depot
CBI	Confederation of British Industry
CIMAH	Control of Industrial Major Accident Hazards Regulations
DTp(MSA)	Department of Transport (Marine Safety Agency)
DSHAR	Dangerous Substances in Harbour Areas Regulations
ESTC	Explosives, Storage and Transport Committee
FLT	Fork lift truck
GB	Great Britain
HAZOP	Hazard and operability study
HSC	Health and Safety Commission
HSE	Health and Safety Executive
LPG	Liquefied petroleum gas
MoD	Ministry of Defence
NEQ	Net explosive quantity
QRA	Quantitative risk assessment
RoRo	Roll-on Roll-off
Te	Metric tonne, ie 1000 kg
TUC	Trades Union Congress
UNCOE	UN Committee of experts on the transport of dangerous goods

Appendix 1

Membership of the ACDS Steering Group for the study of risks from handling explosives in ports

Members		From	To
Chairman	A J Williams, HSE	7/92	10/92
	A V Jones, HSE	10/92	9/94
CBI	Dr G Jeacocke, EXCHEM Plc	7/92	9/94
	Dr J M McLaughlin, ICI NOBELS	7/92	9/94
	Dr D Pittam, ICI NOBELS	2/93	9/94
TUC	T Mellish	7/92	9/94
ACC	E L Clark, North Yorkshire CC	7/92	9/94
Ports Safety Organisation	M Compton	7/92	9/94
	R Barnes	7/92	9/94
MoD	Col P Sextone (retired)	7/92	9/94
	J Henderson	7/92	9/94
DTp(MSA)	Capt D Jaswal	7/92	2/94
	Capt P Wilkins	2/94	9/94
AEA Technology	Dr P Moreton	7/92	9/94
HSE	Dr N Riley	7/92	9/94
HSE	J Alexander	7/92	9/94
HSE	D Goodhew	7/92	9/94
HSE	Dr R Merrifield	7/92	9/94
HSE	L Beaumont	7/92	9/94
Secretary	Dr R M Turner, HSE	7/92	8/92
	N Morton, HSE	8/92	1/94
	J C Bugler, HSE	1/94	9/94

Appendix 2

Historical Accident Record for Transport of Explosives in Great Britain, 1950 – 1994

The historical record is presented in three parts. Section 1 lists the explosives events that have occurred in ports; Section 2 lists the explosives events that have occurred during rail transport, while Section 3 lists the explosives events that have occurred during road transport.

The 45-year period, 1950 – 1994, has been specifically chosen to avoid including into the record a number of incidents which occurred in the late 1940s and which involved initiations of unsafe ammunition manufactured under wartime conditions when quality assurance procedures were less rigorous than those applied in modern practice.

Details of incidents were obtained from the HSE/MoD/AEA explosives accident database, EIDAS. It is believed that the list of incidents is comprehensive, having been compiled initially from records kept by the MoD and the HSE.

1. Explosives events in UK ports, 1950 - 1994

(i) Date: 14/07/1950
Location: Bedenham, Hampshire (military port)
Type of Explosives: Ammunition (depth charge)
Cause of accident: Unsafe explosives

A major explosion occurred following the loading of depth charges into a lighter moored alongside a jetty. A fire ignited in one of the depth charges and this in turn initiated two small explosions followed by two major explosions. There were no fatalities although considerable damage was caused in and around the port. Numerous minor casualties were caused by the blasts but only six people were detailed in hospital. The fire is believed to have been caused by defects and impurities in the filling of the depth charge. A similar accident occurred in Gibraltar in the following year.

(ii) Date: 16/06/1955
Location: Portland, Dorset (military port)
Type of Explosives: Ammunition (experimental torpedo)
Cause of accident: Unsafe explosives

An experimental torpedo exploded on board the submarine HMS Sidon. It is believed that the explosion was caused by a combination of mechanical faults within the torpedo and bad preparation of the weapon prior to it having been loaded aboard the submarine. It is understood that 12 members of crew were killed in the initial explosion and that a further 12 members of the crew were subsequently drowned. There were no fatalities beyond the vessel.

(iii) Date: 17/07/1969
Location: Bootle, Merseyside
Type of Explosives: Commercial explosives
Cause of accident: Not known

Minor ignition in hold of ship which had previously conveyed explosives. One person injured. All official records of this incident have been lost and it has not been possible to establish the cause of the ignition.

2. Events during rail transport of explosives, 1950 - 1994

(i) Date: 04/09/1951
Location: Feltham, Greater London
Type of Explosives: Ammunition (smoke bombs)
Cause of accident: Unsafe explosives

Smoke was seen coming from a rail wagon containing a quantity of '8.5 lb Mark 2 Practice Bombs White Smoke'. The wagon door was opened and it was seen that a fire had broken out. It appeared that the fire had been caused by a leak of a substance from one of the bombs.

(ii) Date: 23/04/1969
Location: Armathwaite, Cumbria
Type of Explosives: Ammunition (artillery shells)
Cause of accident: Fire

A wagon containing a quantity of 105 mm high explosives shells in metallic cases was detached from a train and placed in a siding following the detection of a hot axle box on the wagon. At 07:50 hours the signalman at the siding reported to Carlisle control that the detached vehicle was on fire. The fire brigade were called at 07:54. They arrived at 08:07 but took no further action due to the imminent danger. The wagon exploded 13 minutes later, scattering debris and unexploded shells over a wide area.

(iii) Date: 14/04/1988
Location: Lancashire
Type of Explosives: Commercial explosives (nitrocellulose)
Cause of accident: Unsafe explosives

Fire spontaneously ignited on a rail wagon as it was moved out of a sidings. Investigations indicated that the cargo of nitrocellulose had dried out and was probably ignited by frictional forces when the wagon was moved.

3. Events during road transport of explosives, 1950 – 1994

(i) Date: 1952
Type of Explosives: Commercial blasting explosives
Cause of accident: Fire

Hot exhaust ignited a tarpaulin sheet on a non-regulation vehicle that was carrying some 6000 lb of blasting explosives. Two boxes of explosives were consumed in the fire, the rest was removed by the fire brigade without further incident.

(ii) Date: 1958
Type of Explosives: Commercial blasting explosives
Cause of accident: Fire

Fire broke out on a vehicle carrying 8000 lb of Burrowite blasting explosives. The cause of the fire was considered to be friction between tyres of twin rear wheels, one of which had become deflated. The fire spread to the load and this subsequently exploded.

(iii) Date: 1959
Type of Explosives: Commercial explosives (safety fuse)
Cause of accident: Fire

Fire broke out on a vehicle carrying 400 cases of safety fuse. All evidence pointed to the fire having started in rear twin-tyred wheel. Only 82 cases of explosives were salvaged.

(iv) Date: 1973
Type of Explosives: Commercial explosives (blasting explosives and detonators)
Cause of accident: Fire

Fire broke out on an unattended landrover parked on a construction site. The vehicle contained detonators and blasting explosives and these subsequently detonated in the fire. It is believed that the fire was ignited by a discarded cigarette stub.

(v) Date: 23/03/1989
Location: Peterborough, Cambridgeshire
Type of Explosives: Commercial explosives (blasting explosives, fuseheads and detonators)
Cause of accident: Unsafe explosives

A van carrying a mixed load of blasting explosives, detonators and fuseheads exploded in an industrial estate. Unsafely packaged fuseheads were ignited by impact/friction when the van went over a ramp. Fire took hold in the cargo section of the vehicle and the load exploded 10 minutes later killing a fireman.

It will be seen that five of the 11 events were caused by the presence of ‘unsafe explosives’ in the load. The term ‘unsafe explosives’ denotes items that have been badly designed, badly manufactured, badly packaged or which are in a deteriorated condition or off-specification in some other way.

A similar pattern can be discerned from the historical record for explosives events worldwide. Details have been obtained of 12 explosives events that have occurred in ports during the period 1950 – 1993. Only a sparse amount of information is available on some of these incidents, and in which case the causes of the accidents cannot be ascertained with any certainty. The information available on some of the other accidents may also be unreliable. This reservation notwithstanding, the causes of the 12 accidents partition as follows:

Cause of accident	No. of incidents
Unsafe explosives	4
Fire	3
Crane accident	2
Unknown	3

Thus unsafe explosives were the primary cause of at least one-third of these accidents.

Appendix 3

The potential causes of explosives events

An accidental initiation of explosives cargo could come about in a number of different ways. However, it is possible to categorise very broadly the various potential causes of explosives events under two headings:

(a) the presence of unsafe items in explosives loads,
(b) the involvement of explosives loads in energetic accidents.

These two broad categories of unintentional initiation are explored in Sections 1 and 2 of this appendix respectively.

Section 1 Unsafe explosives

There are a number of different ways in which explosives can be in a potentially unsafe condition:

(a) Unsafe packaging of impact-sensitive items

Badly packaged impact-sensitive explosives items could be initiated by the knocks and jolts cargoes typically receive in transit. Such an accident occurred on a road vehicle in the UK as recently as 1989. The explosion caused one fatality and widespread damage.

(b) Exudation of explosives material

Exudation is a problem mainly associated with nitroglycerine-based blasting explosives, which may, under certain conditions, exude free nitroglycerine, a substance sensitive to impact and friction. Possible causes of exudation include poor quality control during manufacture, exposure to water, prolonged storage, storage at incorrect temperature and pressure on explosives cartridges. Nitroglycerine-stained packages have been found on a number of occasions within magazines in the UK, and there has been one incident in the last 25 years in which exuding explosives were found on board a ship – the ship was scuttled to avoid the risk of unloading the material. Nitroglycerine-based blasting explosives are currently being phased out and replaced with inherently safer types of explosives.

(c) Poor integrity of packaging

Poor integrity of packaging may result in spillage of explosives substances. This in turn may result in the ignition of fire in the event that the spillage is subjected to impact or friction, or the spillage falls through cracks in the floorboards of a vehicle and lands on a hot surface, such as an exhaust manifold. One or two minor explosives events have occurred within UK manufacturing sites in recent times, caused by vehicles running over spilt explosives material, but no such events have occurred during transport of packaged explosives goods.

(c) Propellant with depleted stabiliser content

Nitrate-ester based propellants with depleted stabiliser content may ignite spontaneously through the process of autocatalytic decomposition. Within the last 25 years there have been several fires in UK storehouses caused by this process. Within the last 10 years there has been one incident of fire on a rail wagon caused by spontaneous ignition of nitrocellulose, a raw material used in the manufacture of propellants.

(d) Leaks from munitions containing white phosphorus

Certain types of munitions contain white phosphorus, a substance that can spontaneously ignite on exposure to air. There have been at least two instances in the UK during the last 45 years when leaks from these munitions have resulted in ignition of fire during rail transport.

(e) Munitions with contaminated components

Physical or chemical reactions between contaminants and explosives fillings may lead to the formation of heat-and impact-sensitive explosives crystals or compounds within munitions. These munitions may then become more susceptible to accidental initiation. Migration of sensitive compounds into screw threads and non-continuous welds may further increase the susceptibility of the munitions to accidental initiation by impact (see (f) below). There was a major explosion in a UK military port in 1950 caused by impact-induced ignition of a depth charge that had been sensitised by the presence of impurities in the main explosives filling. A similar accident occurred in Gibraltar a year later.

(f) Munitions with cracked warheads.

The explosives fillings of certain types of munitions are prone to cracking. Cracking may result in migration of explosives dust into screw threads and non-continuous welds within munitions, and this may increase the susceptibility of the munitions to accidental initiation in two ways: (i) impact accidents may result in nipping of dust between metal surfaces and (ii) the presence of bare explosives crystals in the cracked surface may increase the chance of an initiation proceeding to full detonation. The dangers posed by munitions with cracked warhead fillings are well recognised; such munitions are normally subject to Ordnance Board constraints, which would include restrictions on the height to which such munitions can be lifted.

(g) Munitions with defective electrical components

Certain types of munitions, such as torpedoes, are equipped with power supplies. There is a possibility that electrical short circuits within these types of munitions may ignite fires which may in turn initiate explosives material. So far as is known, no such accidents have occurred in the UK in post-war times.

(h) Spontaneous movement of sensitive items within munitions

Stresses are created when components are installed into certain types of munitions. An explosives event may occur if these stresses relieve spontaneously on some subsequent occasion. There have been a number of such accidents within UK storehouses, though, so far as is known, no such accidents have occurred in ports or during transport.

(i) Defective electro explosives devices (EED)

EEDs that have been badly designed, manufactured or packaged, may be susceptible to initiation by radio frequency radiation. There have been a number of such accidents involving unpackaged items on firing ranges, though so far as is known, no such accidents have occurred in ports or during transport.

(j) Fuze defects

Munitions fitted with defective fuzes may be vulnerable to the sorts of knocks and jolts that cargoes typically receive while in transit. There are three ways in which the safety of a fuze may be compromised:

(i) mis-assembly in which the fuze is assembled in a manner which 'short circuits' the intended safety features;
(ii) severe metal corrosion affecting components such as springs, shutters etc, making inoperative the safety features that rely on the correct functioning of these components;
(iii) chemical reaction in which the chemical composition of some of the explosives compounds are changed, making them more sensitive to external stimuli, eg reaction of lead azide with copper to form copper azide.

In the late '40s, a number of incidents occurred during the loading of ammunition onto rail vehicles; the munitions contained defective fuzes that had been manufactured during wartime conditions.

The above list of categories of unsafe explosives has been compiled from available accident records and safety reports. It is not necessarily exhaustive, as noted in paragraph 24 of the main report, safety flaws in the design, manufacture, processing, keeping, packaging and conveyance of explosives sometimes only come to light after accidents have occurred; future accidents may reveal further types of unsafe explosives material.

Section 2 Energetic accidents

Explosives cargoes which contain unsafe items may initiate spontaneously, ie without involvement of the cargoes in external accidents, such as lorry crashes and falls of loads from cranes. Explosives cargoes that do not contain unsafe items may initiate in the event that they become involved in accidents, such that sufficient energy is imparted to explosives material in the cargo to bring about an explosion or fire. There are a number of different types of accidents that could occur in ports and which could in theory result in an initiation of explosives cargo. These accidents were identified by undertaking a hazard and operability (HAZOP) study of the various methods used for moving explosives through ports, with particular reference to operations at the six locations selected for detailed study.

HAZOP provides a systematic technique for identifying hazards and operability problems that may occur during a process. In simple terms, the process is divided into a number of sequential steps or 'nodes', each of which is examined critically by a specially selected team with the aim of identifying possible causes of deviations in intended actions which might then cause accidents. The members of the team are prompted by a series of parameters and guidewords throughout the exercise, each parameter and guideword being applied to each node in turn. HAZOP is thus essentially a brainstorming technique, and its success depends on the ability of the team members to think laterally about possible causes of accidents when prompted by the parameters and guidewords.

The process of moving explosives through ports was partitioned into five nodes:

(i) transport of cargo from port entrance to berth;
(ii) handling of break-bulk cargo on the quay alongside the berth;
(iii) shore to ship transfer of cargo;
(iv) movement of break-bulk cargo into stowage positions on board ship;
(v) transport of cargo from berth to harbour entrance.

Nodes (ii) and (iv) are only relevant in the case of operations involving break-bulk cargo; no handling of explosives packages or palletised loads takes place on quays or on board ships in the case of operations involving RoRo or containerised cargo.

The parameters and guidewords applied in the study are listed in Table A1.1. It will be seen that the parameters considered in the study are types of energetic stimuli which theoretically may bring about an unintended initiation of explosives material. The guide words (and phrases) used in conjunction with these parameters were derived from experience gained in previous studies into the safety of operations involving explosives.

The team that carried out the HAZOP study was made up of members drawn from the HSE, the MoD, the commercial explosives industry and the ports industry. In this way the process of moving explosives through ports was considered from a variety of perspectives.

The record sheets of the study are reproduced on pp A3.7 – A3.23. It will be seen that while a large number of accident scenarios were identified, the study also served to highlight a large number of safeguarding measures in the form of statutory regulations, codes of practice and good working procedures. However, these measures, even if carefully enforced, cannot be guaranteed to prevent explosives accidents but only to reduce the likelihood of their occurrence and consequences: there will always be a residual risk.

The record sheets of the HAZOP study were subsequently examined by a smaller group of explosives experts drawn from the HSE, the MoD and the commercial explosives industry. The aim of this particular exercise was to identify those scenarios that could be considered to pose the dominant threat of an explosives event in a port. An element of judgement was necessarily involved in this exercise, but this was informed judgement based on a knowledge of past accidents as well as an understanding of the susceptibility of different types of explosives to various energetic stimuli. It was clear that some accident scenarios were so improbable that they could be judged *a priori* not to warrant consideration in the further stages of the risk analysis. These scenarios fell into two categories:

(a) accidents that are likely to occur from time to time but which would be most unlikely to result in explosives events, for example falls of explosives packages during unloading of vehicles (providing, of course, that the packages do not contain explosives in an unsafe condition);
(b) accidents that could be expected to result in explosives events but which have an extremely low probability of occurrence, for example, aircraft crashes onto vessels loading or discharging explosives cargo.

In total, nine scenarios, involving fire or impact, were selected for further study:

Fire accidents:
- road vehicle fires
- train fires
- ship fires

Impact accidents:

road vehicle crashes and collisions
train derailments and collisions
crushing or penetration of packages by fork lift trucks
falls of loads from cranes
ship strikings
ship collisions

Table A1.1 Parameters and Guide Words used in HAZOP Study of Explosives Movements through Ports

Parameters	Guide words
Impact/friction	Crash/collision Impact by falling object Impact by projected object Fall of cargo
Fire/thermal effects	Vehicle fire External fire Hot surface
Electrostatic events	Static discharge Lightning
Electromagnetic radiation	RF radiation Other
Chemical reaction	Spillage

The involvement of explosives cargo in any of the above types of accidents would not necessarily result in an explosives event. These accidents can be regarded as ‘dangerous occurrences’ that would pose a threat to the safety of explosives cargo but would not inevitably result in the initiation of either an explosion or a fire within an explosives load. In fact, much would depend on the types of explosives present in the accident affected load, explosives not being all equally susceptible to initiation by fire and impact.

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash/collision	Driver error	Explosives could sustain impact forces. This could result in three possible outcomes: A. Explosives are undamaged B. Explosives are made unsafe (i) fail safe systems could be breached – possible RF hazard if item contains electro explosives device (ii) internal cargo securement (fittings) damaged (iii) packaging damaged, resulting in explosives spillage C. Explosives could initiate (i) impact forces may directly initiate explosives (thought to be highly unlikely) (ii) leaks from munitions containing white phosphorus may ignite spontaneously	1. Various regulations promoting good standard of driving, including: (i) Driver Training Regs, (ii) Road Traffic Acts in general 2. Speed limits in operation in ports 3. Traffic control systems enforced	Freight containers may provide greater degree of protection against impact than curtain-wall lorries
	Mechanical failure (i) poor maintenance (ii) sabotage	See A, B and C above	4. Vehicles carrying military explosives inspected by MoD personnel 5. Vehicles must comply with CER 6. Measures taken to guard against sabotage – Maritime and Aviation Security Act	
	Adverse weather (i) poor visibility (ii) snow/ice	See A, B and C above	7. Port lighting 8. Salting and gritting + work stops in severe weather conditions	
	Badly distributed load on vehicle	See A, B and C above	9. Usually identified before arrival at port 10. Container packing certificate, vehicle declaration, inspection of documentation on arrival, IMO codes, DTp Code of Practice – securing of loads on vehicles, ESTC pamphlet	

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
	Spillage on road	See A, B and C above	11. Port management control – maintenance and cleaning of roads and terminals	
	Train collision/derailment	See A, B and C above	Signalling systems Maintenance of rolling stock and track	
Falling Object	Crane topples over	See A, B and C above	12. Routing of vehicles along delineated roadways and traffic control	
	Aircraft crash	See A, B and C above		May be significant at ports which operate helicopter service
	Container blown from stack/other wind blown objects	See A, B and C above	See 12 above	
	Item falls from overhead structure	See A, B and C above	See 12 above	
	Malicious attack	See A, B and C above	Security systems – see 6 above	
Projected object	Pressure vessel/gas bottle failure	See A, B and C above	13. Separation and segregation of hazardous cargoes by IMDG Code	
	Malicious attack (eg rifle bullet)	See A, B and C above	Security systems – see 6 above	
	Other explosion in port	See A, B and C above	14. Licensing restricts not explosives quantities + 13 above	
Fall of item	Load falls off vehicle		See 9 and 10 above	
	Vehicle falls off quayside or dry dock		15. Lorry stops on quayside. Fencing around dry docks – Shipbuilding and Ship Repairing Regulations 1960	

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
Vehicle fire	Electrical fault	Three possible outcomes:– D. Fire extinguished before load affected E. Load burns F. Load explodes	See 5 above 16. Fire-fighting equipment carried on vehicles 17. Port fire-fighting systems 18. Emergency services	
	Fuel leak onto hot surface	See D, E and F above	See 5, 16, 17 and 18 above	
	Tyre fire – deflated tyre, binding brakes, faulty bearings	See D, E and F above	See 5, 16, 17 and 18 above	
	Smoking/contraband offence	See D, E and F above	See 5, 16, 17 and 18 above	
	Lightning and static discharges	See D, E and F above	See 5, 16, 17 and 18 above	
	Spontaneous ignition of unstable load	See E and F above	See 5 and 18 above	
	Solar radiation	See D, E and F above	See 5, 16, 17 and 18 above	
External fire	Transfer of fire from other vehicle	See D, E and F above	See 16, 17 and 18 above	Drivers of explosives and petroleum vehicles should be advised of hazards and not to park together
	Building fires	See D, E and F above	See 16, 17 and 18 above	
	Cargo fires	See D, E and F above	See 16, 17 and 18 above	
	Storage fires	See D, E and F above	See 17 and 18 above	
	Ship fires	See D, E and F above	See 17 and 18 above 19. Ship's fire fighting capability	
	Fuel fire	See D, E and F above	See 16, 17 and 18 above 20. DSHA, Petroleum (Consolidation) Act 1928 21. Emergency Planning required under CIMAH/ DSHA 22. Explosives loads are capable of being moved if required – ie remain on trailer with cab attached 23. For military and some commercial loads, fire tenders/fire fighting equipment would be present	

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
External fire	Grass fire	See D, E and F above	See 17 and 18 above 24. Good estate management	
	Malicious	See D, E and F above	See 6, 16, 17 and 18 above	
Hot surfaces	As a result of severe collision	See D, E and F above	See 5, 16, 17 and 18 above	
	Hot axle boxes on trains	See D, E and F above	See 16, 17 and 18 above 25. Lack of flammable material present to sustain fire	
	Adjacent 'hot working' – welding etc	See D, E and F above	See 16, 17 and 18 above 26. Control of hot work via permit to work system, routing of vehicles away from hot work	

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: Electrostatic

Guide word	Causes	Consequences	Safeguards	Comments
Static	Nylon protective clothing may cause build up of static			Only considered a problem with exposed explosive/electrically initiated devices
Lighting	Weather conditions	G. Lightning may cause direct inhalation of the explosives Lightning may cause fire – see D, E and F above	27. Use of weather forecasts – (un)loading stops in some locations 28. Other tall structures surround the vehicle which would act as lightning conductors	

Node 1 Transport of explosives cargoes from port entrance to quayside

Parameter: RF

Guide word	Causes	Consequences	Safeguards	Comments
Passing vehicles/ personnel	Communications (including radio, mobile telephone etc)	See G above	29. Packaging serves to protect items 30. Devices sensitive to RF are protectively screened 31. Controlled use of radio, mobile telephones etc around operation involving RF sensitive items 32. Design of weapon – munitions must conform to Ordnance Board Standards	May be more of a problem if packaging is of poor standard or damaged
Other	Radar	See G above	See 29, 30 and 32 above	
	Microwave security systems	See G above	See 29, 30 and 32 above	

Node 2 Handling of general cargo at quayside

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash/collision	Fork lift truck collision	See A, B and C above	See 2 and 3 above 33. Training of fork lift truck drivers 34. Supervision of operations 35. Operator appreciation of hazards of explosives	Package type will have an influence on the response of the explosives to impact
	Collision with other mobile equipment	See A, B and C above	See 2, 3 and 34 above 36. Training of operators of mobile equipment	
	Collision with other vehicles	See A, B and C above	See 1, 2 and 3 above 37. Restriction of vehicular access to area in which explosives are being handled	
	Collision with crane hook	See A, B and C above	See 34 above 38. Training of crane operators	
	Collision with swung load	See A, B and C above	See 34 and 38 above	

Node 2 Handling of general cargo at quayside

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Falling object	Dropped load	See A, B and C above	See 38 above 39. Regular checking of lifting equipment 40. Restriction of lifting height (would mitigate consequences)	
	Falling crane jib	See A, B and C above	See 39 above	
	Item dropped from ship	See A, B and C above	See 34 above	
	Other causes as described for Node 1 (see page 94)	See A, B and C above	See 6 and 12 above	
Projected object	As described for Node 1 (see page 94)	See A, B and C above	See 6, 13 and 14 above	
Fall of item	Item falls off vehicle (eg – failure of lashing, error by FLT operator)	See A, B and C above	See 33 and 34 above 41. Packaging standards should mitigate consequences of a fall 42. Many items are drop tested to determine safe drop heights	
	Item falls off fork lift truck	See A, B and C above	See 33, 34, 41 and 42 above	
	Poor loading/ unloading practice	See A, B and C above	See 33, 34, 41 and 42 above	

Node 2 Handling of general cargo at quayside

Parameters: Fire/Electrostatic/Radio Frequency – as for Node 1

Node 3 Ship to shore transfer

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash/collision	Collision with other vehicle on quay or on board ship	See A, B and C above	See 1, 2 and 3 above 43. Merchant shipping regulations govern matters such as safe movement about ship and correct use of hatches/lifting equipment 44. Loading/ unloading operations are subject to planning and control which address the movement of vehicles to/ from the operation	
	Ship striking	See A, B and C above	See 34, 43 and 44 above	

Node 3 Ship to shore transfer

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash/collision	Vehicle drives off ramp (RoRo)	See A, B and C above	See 34, 43 and 44 above 45. Under the Docks Regs and Merchant Shipping Regs Ro-Ro ramps should be fitted with barriers to prevent vehicles from being driven off	
	Load swung against ship or other cargo	See A, B and C above	See 34, 38 and 39 above 46. Wind may cause a load to swing – loading/ unloading operations not conducted in high wind conditions	Ability of crane operator to view operation clearly may be a factor (obstructed view at some ports). Control by guide lines a further safeguard at some ports
Falling object	Item falls off crane structure	See A, B and C above	See 39 above 47. Good working practices – ensuring fitters, for example, do not leave tools etc lying around on crane	
	Item falls off ship	See A, B and C above	48. Good housekeeping practices on board ship	
Projected object	As described for Node 1 (see page 94)	See A, B and C above	See 6, 13 and 14 above	
Fall of item	Mechanical failure	See A, B and C above	See 34, 39, 40, 41 and 42 above	
	Load incorrectly slung	See A, B and C above	See 34, 40, 41 and 42 above 49. Training of operators slinging load	Appropriate advice from cargo originator may be required for unusual/ special items
	Load fouled on projection	See A, B and C above	See 34, 38, 40, 41 and 42 above	
	Lugs not released – crane attempts to pick up vehicle	See A, B and C above	See 34, 41 and 42 above 50. Overload cut-out on crane	
	Incorrect spreader	See A, B and C above	See 34,40, 41 and 42 above	
	Incorrect lifting procedure	See A, B and C above	See 34, 38, 40, 41 and 42 above	
	Inappropriate equipment	See A, B and C above	See 34, 38, 40, 41, 42 and 49 above	
	Poor banding of palletised load	See A, B and C above	See 34, 40, 41 and 42 above	

Node 3 Ship to shore transfer

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
Vehicle fire	No cause identified			
External fire	Ship fire	See D, E and F above	See 17, 18 and 19 above	
	Other causes as described above for Node 1 (see pages 95 and 96)	See D, E and F above	See 16, 17, 18, 20, 21, 22, 23 and 24 above	
Hot surfaces	No cause identified			

Node 3 Ship to shore transfer

Parameter: Electrostatic

Guide word	Causes	Consequences	Safeguards	Comments
Static	No cause identified			See comment for Node 1 (page 96)
Lightning	As identified for Node 1 (see page 96)	See D, E, F and G above	See 27 and 28 above	Degree of protection offered by surrounding structures would be expected to be even greater in these circumstances

Node 3 Ship to shore transfer

Parameter: RF

Guide word	Causes	Consequences	Safeguards	Comments
Passing vehicles/ personnel, other	As given for Node 1 (see page 97) – note that ship's radio and radar may be a particular problem here	See G above	See 29, 30, 31 and 32 above 51. If RF likely to be a problem, ensure ship's radar is not operating	Note that merchant ship radar is very different to that used by naval vessels The port operators would need to be made aware of the sensitivity of the load to RF by the cargo suppliers RF is not though to affect most commercial explosives

Node 4 Movement of cargo to stowage positions

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash collision	FLT collision	See A, B and C above	See 33, 34 and 35 above	
	Collision with other cargo	See A, B and C above	See 33 and 34 above 52. Use of good handling techniques	
	Ship striking	See A, B and C above	See 33 and 34 above	
	Nails driven into explosives boxes during shoring of cargo	See A, B and C above	See 33 and 52 above	
Falling object	Other loads	See A, B and C above	See 34, 38 and 52 above	
	Items from ship (hatches etc)	See A, B and C above	See 34, 43 and 52 above	
	Shoring	See A, B and C above	See 34 and 52 above	
Projected object	As described for Node 1 (see page 94)	See A, B and C above	See 6, 13 and 14 above	
Fall of item	Collapse of stow	See A, B and C above	See 34 and 52 above	
	Ship movement	See A, B and C above	53. Planning of loading operation to ensure vessel does not become unbalanced	
	Bad loading	See A, B and C above	See 34 and 52 above	
	Inappropriate handling methods	See A, B and C above	See 34 and 52 above 54. Training of personnel performing handling operation	

Node 4 Movement of cargo to stowage positions

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
Vehicle fire	Fire of FLT	See D, E and F above	55. Design standard on FLT (Cat C)	
	Ship fire Lorry fire on RoRo vessel	See D, E and F above See D, E and F above	See 17, 18 and 19 above 56. Port emergency plan – may include measures such as flooding vessel 57. Holds should be clean and tidy. Hold are inspected by MoD personnel for operations involving military explosives 58. Electrical integrity on ship	
			See 17, 18, 19 and 56 above	

Node 4 Movement of cargo to stowage positions

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
External fire	Other cargo fire	See D, E and F above	See 17, 18 and 19 above 59. IMDG code requires segregation of hazardous cargoes	
	Fire on other vessels alongside	See D, E and F above	See 17, 18 and 19 above	
	Fire from portable tools and trailing leads	See D, E and F above	See 17, 18 and 19 above 60. Use low voltage electrical tools and short power leads 61. All electrical circuits in holds should be isolated	
	Other causes as described for Node 1 (see page 95)	See D, E and F above	See 17, 18, 19, 20, 21, 22, 23 and 24 above	
Hot surfaces	Hot working on vessel	See D, E and F above	62. Permit to work system controls hot working on vessels	
	Engine room bulkheads/ accommodation	See D, E and F above	63. IMDG code also requires segregation from 'hot' bulkheads or bulkheads isolating areas where fire is considered more likely	

Node 4 Movement of cargo to stowage positions

Parameter: Electrostatic

Guide word	Causes	Consequences	Safeguards	Comments
Static	No cause			
Lightning	As given for Node 1 (see page 96)	See D, E, F and G above	See 17, 18, 19, 27 and 28 above	

Node 4 Movement of cargo to stowage positions

Parameter: RF

Guide word	Causes	Consequences	Safeguards	Comments
Passing vehicles/ personnel, other	As for Node 1 (see page 97)	See G above	See 29, 30, 31, 32 and 51 above	

Node 4 Movement of cargo to stowage positions

Parameter: Chemical

Guide word	Causes	Consequences	Safeguards	Comments
Spillage	Incompatibility of spilt chemical and explosive (eg – nitric acid and propellant)	See D, E and F above	See 59 above	

Node 5 Transport from quayside to harbour entrance

Parameter: Impact

Guide word	Causes	Consequences	Safeguards	Comments
Crash collision	Ship collides with other vessel	See A, B and C above H. Damage to/ sinking of vessel – vessel may break up	64. VTS control systems 65. Good seamanship 66. Only slow speeds permitted in harbour 67. Signals given by ship (flags/lights) 68. Tug assistance for some vessels 69. Pilotage controls	
	Ship impacts jetty/dock wall/anchored vessel	See A, B, C and H above	See 64, 65, 66, 67, 68 and 69 above	
	Ship strikes crane	See A, B, C and H above	See 64, 65, 66, 68 and 69 above	
	Ship strikes submerged object	See A, B, C and H above	See 65 and 69 above 70. Dredging of channels/ buoyage	
	Grounding	See A, B, C and H above	See 65, 69 and 70 above	

Node 5 Transport from quayside to harbour entrance

Parameter: Fire

Guide word	Causes	Consequences	Safeguards	Comments
Vehicle fire	Ship fire	See D, E and F	See 17, 18, 19 and 56 above	Harbour master has power to forbid ship's entry to port (and is likely to do so) if there is anything wrong with ship/ cargo/packaging

Appendix 4

Determination of ship fire rates

Ship fire statistics have been collated from records kept by the Marine Accident Investigation Branch of the Department of Transport (MAIB of DTp) and the Fire Statistics Unit of the Home Office. The statistics have been analysed to ascertain the most common causes of cargo-damaging ship fires and to obtain estimates for the rates with which these fires might occur on explosives carrying ships. The analysis of the statistics is described in the following sub-sections of the appendix.

MAIB data

The MAIB maintain a log of shipping accidents that are reportable to the DTp under various regulations, including the Merchant Shipping (Accident Investigation) Regulations 1989[12] and the Merchant Shipping (Safety Officials and Reporting of Accidents and Dangerous Occurrences) Regulations 1982[13]. Fires that occur on UK ships and result in material damage are reportable under these regulations. The log records details of such fires under various headings depending on the location of the ship at the time of ignition (port or sea) and the area of the ship affected (engine room, accommodation, cargo section etc). Fires in cargo sections of docked ships are recorded under the heading 'Fires in Cargo in Port'. The details recorded in this section of the log include: date of ignition, name and type of ship affected, area of ship first ignited, source of ignition (eg smoking, welding, electrical faults etc) and extent of damage caused by the fire.

The entries recorded in this section of the log have been analysed to ascertain the significant sources of cargo-damaging ship fires. The period examined was 1975 – 1991, during which time a total of 69 incidents were recorded. Three of these incidents occurred in dry dock and were accordingly excluded from the analysis. The other 66 incidents were partitioned by year, type of ship and source of ignition. The results of this analysis are recorded in Table A4.1, and a number of conclusions can be drawn:

(a) All fires that resulted in cargo damage were initially ignited in the cargo section of the vessel. There are no records of cargo damage caused by spread of fire from a ship's engine room or accommodation.

(b) The majority of the fires (46 out of 66) occurred on general-cargo/bulk-carrier ships. This result may merely reflect the greater number of movements of general cargo ships relative to other types of vessel in the period examined; it may also reflect the more extensive handling involved in the loading and unloading of general cargo relative to RoRo and containerised cargo – and hence the greater opportunity for exposure to various sources of ignition, smokers' materials in particular.

(c) The most frequent sources of ignition of cargo-damaging fires on general-cargo/bulk-carrier vessels, in descending order, were found to be:

Smoking	22
Hot work (welding etc)	5
Electrical faults	3
Hot exhaust of moving equipment (bulldozers etc)	3
Spontaneous ignition (animal feed etc)	3
Electrostatic discharge	1
Hot lamp	1
Cause unknown	8

It should be noted that the two most frequent sources of ignition, smoking and hot work, are prohibited during the handling of explosives cargo.

(d) The sources of ignition of fires in the cargo sections of RoRo vessels were found to be:

Electrical and mechanical faults on vehicles (cars, lorries, tugs)	6
Hot work	1
Fuel leak from oil tank	1

This result suggests that the most likely source of ignition of fire for an explosives carrying lorry on the vehicle deck of a RoRo vessel would be a fire in a vehicle alongside.

(e) Cargo fires on container ships appear to be comparatively rare events. Only one record of such an event was found. In this particular incident the plastic moulding on a flat rack container was ignited by an unknown source. The fire did not spread to other containers.

Most of these incidents involved UK registered ships, but included in the statistics is a small number of incidents that occurred on foreign vessels in UK waters (and so came to the attention of the MAIB).

Table A4.1 Cargo fires on ships in port

Data collected from MAIB casualty log

Year	Type of ship			
	General Cargo/Bulk carrier	RoRo/Ferry	Container	Tanker
1975	3 S 1 SI 1 E Total = 5			
1976	5 S 2 NK Total = 7	1 CF Total = 1		
1977	2 S 2 NK 1 Hw 1 HE Total = 6			
1978	3 S 1 SI 1 HW Total = 5			
1979	1 E 1 NK 1 S 1 SI Total = 4		1 SI Total = 1	1 HW Total = 1
1980	2 S Total = 2			
1981	3 S 1 ESD 1 NK Total = 5			
1982	1 NK Total = 1			1 LS Total = 1
1983	1 HW Total = 1	1 LF Total = 1		1 HW Total = 1
1984	1 E 1 HE 1 S Total = 3	1 HW Total = 1		1 HW 1 NF 1 NK Total = 3
1985	1 HL Total = 1		1 NK Total = 1	
1986	1 HE 1 HW 1 S Total = 3			1 HW 1 NF Total = 2
1987	1 HW Total = 1	1 LF Total = 1		
1988		1 CF 1 FL 1 VF Total = 3		
1989				1 NF Total = 1
1990				1 NK Total = 1
1991	1 NK 1 S Total = 2	1 CF Total = 1		

Home Office data

Ship fire statistics have also been collated from an analysis of FDR1 forms produced by the regional fire brigades. These forms constitute the most comprehensive source of data on ship fires in UK ports*. FDR1 forms are held centrally by the Fire Statistics Unit of the Home Office, where certain information is extracted from the forms and encoded onto a computerised database. Incidents involving fires on 'watercraft' are encoded by type of vessel and location of fire as follows:

Type of vessel	*Location*
Houseboat Barge	Inland (includes inland ports, eg Manchester)
Other small craft	Port and harbour
Hovercraft	Construction, demolition
Oil tanker	Repair
Passenger vessel/ferry	At sea
Other ship	Elsewhere or unspecified
Oil rig	

The types of watercraft of interest in the present study are those covered by the headings 'passenger vessel/ferry' and 'other ship', and the locations of interest are 'inland' and 'port and harbour'. A computer search was carried out to identify relevant FDR1 forms for the period 1985 – 1991. The forms were then examined individually and the following information extracted for each incident of ship fire: type of ship, area of ship first ignited, source of ignition and the extent of damage caused. Ships were re-categorised into general-cargo/bulk carriers, RoRo vessels/sea-going freight ferries, container ships and tankers to provide a breakdown of ship types pertinent to this study. The results of the analysis are summarised in Table A4.2.

* An FDR1 form is completed by the fire brigade following attendance at an incident. The form records various details of the incident, including location, the type of property involved, the source of ignition, the severity of the fire and the fire-fighting action taken.

The following points are noted:

(a) A total of 91 records were found for fires that ignited initially in engine rooms, accommodation areas and all other areas of ship other than cargo sections. None of these fires spread to cargo. By type of ship, the fires partition as follows:

general cargo/bulk carriers	64
RoRo/sea-going ferry	22
container ship	5

It is seen that most of these fires occurred on general cargo/bulk carriers. However, when the statistics are combined with port traffic data and converted into accident rates (fires per ship arrival in port), the incident of non-cargo fires is found to be similar for various types of ship:

general cargo/bulk carriers	2.10^{-4} per ship arrival
RoRo/sea-going ferry	5.10^{-5} per ship arrival
container ship	2.10^{-4} per ship arrival*

(b) Of the 33 cases of cargo recorded, 30 occurred on general-cargo/bulk-carriers and three occurred on RoRo vessels; no records were found for cargo fires on container ships.

(iv) **All cargo-damaging fires were initially ignited in the cargo section of the vessel** and the most common sources of ignition were found to be:

Hot work (welding etc)	6
Hot exhaust of moving equipment (bulldozers, FLTs etc)	6
Spontaneous ignition (animal feed etc)	6
Smoking	5
Hot lamp	4
Electrical and mechanical faults on moving equipment (bulldozers, FLTs etc)	3
Lorry fires	2
Car fires	1

The statistics presented in Table A4.2 may be converted into fire rates (ie fires ignited per ship arrival in port). The process requires the statistics to be divided by the appropriate number of ship arrivals in UK ports, data for which are published by the DTp[(14)]. The rates so derived are generic – ie the rates are averages for cargo ships as a whole. In order to derive rates appropriate for this study, it is necessary to modify the statistics to take account of (a) statutory requirements that prohibit some of the above sources of ignition on explosives carrying ships and (b) the IMDG code that requires segregation of explosives cargoes from any goods that are susceptible to spontaneous ignition.

* This value is corroborated by data supplied by the operators of Port A. One cabin fire and one engine room fire were recorded in a period in which there were 16,000 ship arrivals in the port. Therefore, mean fire rate (2/16,000) – 1.10^{-4}.

Hot work and smoking

Hot work and smoking are prohibited within the cargo section of any ship carrying explosives carrying ships. However, absolute compliance with regulations cannot be guaranteed.

Hot exhaust and electrical and mechanical faults on moving equipment

A number of records were found for fires on ships that were started by electrical or mechanical faults on moving equipment (bulldozers, FLTs etc), or as a result of hot exhaust from such equipment igniting flammable cargo, such as paper. In all cases the fire was confined to the cargo first ignited, though there was a potential for spread of fire to other types of cargo on board ship. In this regard it may be noted that there are currently no statutory requirements for explosives to be segregated from non-hazardous but readily ignitable cargoes, such as paper.

Hot lamps

These considerations also apply to a number of incidents caused by hot lamps. In one such incident, 10 pallets of chipboard were destroyed following ignition of polythene wrapping around one of the pallets.

Spontaneous ignition

The IMDG Code requires segregation of explosives from cargoes that are susceptible to spontaneous ignition, such as animal feed, cotton waste, sunflower seed extract etc. Segregation may not always be effective and there is always a potential for non-compliance with the code.

The approach adopted in this study has been to ‘factor down’ generic accident statistics in consideration of statutory regulations and at the same time to make some allowance for non-compliance with these regulations. An adjustment factor of 0.01 has been applied to the statistics collated for fires ignited by hot work, smoking, mechanical equipment, hot lamps and spontaneous ignition.

Table A4.2 Ship fires in UK ports

Data collated from Home Office FDR1 forms

Year	Area of Ship first ignited	Type of ship			
		General Cargo/Bulk carrier	RoRo/Sea-going Ferry	Container	Tanker
1985	Cargo	3S, 2HE, 2HW, 2SI, 1HL Total = 10			
	Engine Room	5FL, 3HW, 2E Total = 10			1 E Total = 1
	Accommodation	4HW, 2S, 1FL Total = 7			
	Other	2HW, 1S Total = 3			
1986	Cargo	2HE, 2SQ, 1S Total = 5	1 LF Total = 1		
	Engine Room	1FL, 1NK, 1S Total = 3	1HE Total = 1		2E, 1HS, 1FI Total = 4
	Accommodation	1E Total = 1			
	Other	1HW Total = 1	2HW Total = 2		
1987	Cargo	1HW Total = 1	1LF Total = 1		
	Engine Room	2FL, 1HS Total = 3	1E, 1HW Total = 2	1HW Total =1	1 HW Total = 1
	Accommodation	1HS Total = 1			
	Other	1E, 1NK Total = 2			
1988	Cargo	1HE, 1S, 1TF Total = 3	1LF* Total = 1		
	Engine Room	2HS, 1E Total = 3	2HS Total = 2	1E Total = 1	
	Accommodation	2HS, 2S Total = 4	1E, 1KN, 1M, 1HS Total = 4		
	Other	2HW Total = 2			
1989	Cargo	1HL, 1HW, SI, 1TF	1CF Total = 1		
	Engine room	4HS, 3HW Total = 7	1HS, 1NK Total = 2	1HW Total = 1	
	Accommodation		1S Total = 1	1HS Total = 1	
	Other		1C Total = 1		
1990	Cargo	2HL, 1HE, 1TF* Total = 4	1VF* Total = 1		
	Engine Room	7HS, 1HW, 1W Total = 9	1E, 1HS Total = 2	1HS Total = 1	
	Accommodation	1EF, 1S Total = 2	1E Total = 1		
	Other				
1991	Cargo	2HW, 1SI, 1TF Total = 4	1NK* Total = 1		
	Engine Room	2HS, 1E, 1HW Total = 4	2HS Total = 2		
	Accommodation	1E, 1S Total = 2	1HS Total = 1		
	Other		1HW Total = 1		

*Fire did not damage cargo

Spread of fire from ship's engine room or accommodation

In addition to the threat of fire igniting in the cargo section of a vessel, there is also the possibility of fire spreading to cargo from a ship's engine room or accommodation. Although no record has been found of such an event within a UK port in the period examined, a number of incidents at sea* indicate a potential for similar occurrences in ports. In general it would be expected that the probability of a fire spreading through a ship would be lower in port than at sea, as shore-based fire-fighting assistance could be summoned in the former case. In the absence of any direct historical data, the probability of such an event has been quantified from the results of a previous study(15) that considered the circumstances under which fire could spread through a general cargo ship used to carry explosives. This study took account of such factors as: the probability of smoke detection and fire suppression systems failing; the probability of fire doors being left open; the probability of fire-fighting crews failing to take effective action. The results of this study suggested that the probability of fire spreading from the engine room or accommodation of a vessel to the cargo section was of the order of 4.10-3 ie about one chance in 250.

This value has been applied in the present study to the probability of fire spread through general cargo and RoRo ships. However, it was judged that a lower value would be appropriate for container ships, and this was for two reasons: the cargo sections of container ships contain very little exposed flammable material; explosives containers, being the last loaded onto ships, could quickly be removed in the event of an emergency. In consideration of these factors, the above value of probability was 'factored down' an order of magnitude.

Estimation of cargo-damaging fire rates

Cargo-damaging fire rates were estimated for three types of explosives carrying ships: RoRo, general cargo and container.

* One of the most recent incidents involved a refrigerated cargo vessel near Falmouth: an explosion in the vessel's starboard engine ignited a fire in the engine room which then spread to both the accommodation and cargo holds; the spread of the fire was facilitated by the crew's failure to activate the fire suppression system in the engine room.

RoRo vessels

The fire brigade attended a total of 28 fires on RoRo vessels in UK ports during the period 1985 – 1991.

By source of ignition and area of vessel first ignited these fires partition as follows:

Cargo section	3	fires ignited on lorries
	1	fire ignited on a FLT
	1	fire ignited on a car
	1	fire ignited amongst some rubbish on the lorry deck (source of ignition unknown)
Engine room	2	fires ignited by electrical faults
	7	fire ignited by fuel leak's/hot surfaces
	1	fire ignited by hot work
	1	fire ignited by unknown source
Accommodation	2	fires ignited by electrical faults
	2	fires ignited by hot surfaces
	1	fire ignited by smokers' materials
	1	fire ignited maliciously
	1	fire ignited by unknown source
Other	3	fires ignited by hot work
	1	fire ignition by a collision

Three of these fires resulted in damage to cargo, the details are as follows:

12/03/1986: Argyll
Lorry severely damaged by fire following ignition of defective electrical harness in engine compartment of the vehicle.

10/09/1987: Gt Yarmouth
Short circuit in refrigeration unit ignited a fire which completely destroyed the unit and spread fire to two trailers alongside. Both trailers were severely damaged.

02/02/89: Dover
An electrical fault in the wiring harness of a car ignited a fire which quickly spread to two tilt trailers alongside.

Thus a total of six road freight units were damaged by fire during the period examined (1985 – 1991). Port statistics published by the DTp[14] show that there were approximately 447,000 arrivals of RoRo vessels in British ports during these years and that approximately 25,000,000 road freight units were carried on these vessels. Thus a mean cargo-damaging fire rate can be derived as 6/25,000,000 = 2.10^{-7} per road vehicle. The 90% confidence limits (assuming a Poisson distribution) are:

upper limit	5.10^{-6} per road vehicle
mean value	2.10^{-7} per road vehicle
lower limit	1.10^{-7} per road vehicle

To this value must be added rates for cargo damage caused by spread of fire from other areas of the ship. These rates are derived by applying the appropriate adjustment factors (see page 109) to the statistics for fires in the engine room and other areas of the ship.

Thus:

	Number of incidents	*Adjustment factor*	*Modified statistic*
Engine room fires			
Hot surfaces	7		7
Electrical	2		2
Unknown	1		1
Hot work	1	0.01	0.01
Accommodation			
Hot surfaces	2		2
Electrical	2		2
Smoking	1		1
Malicious	1		1
Not known	1		1
Other fires			
Hot work	4	0.01	0.04
		Total	17.05

Assuming the probability of fire spread to cargo is 4.10^{-3} (see page 111), the cargo-damaging rate for fires starting in the engine room and other areas of the ship is found to be:

$$17.05 \times 4.10^{-3}/447{,}000 = 2.10^{-7} \text{ per ship arrival}$$

The overall rate of ignition for cargo-damaging fires on explosives-carrying RoRo vessels is thus estimated as:

Fires ignited in cargo section	8.10^{-7} per ship arrival
Fires ignited elsewhere	2.10^{-7} per ship arrival
Total	1.10^{-6} per ship arrival

It is seen that 80% of the risk is estimated to come from fire initially ignited in the cargo section of the vessel.

This rate can be checked against the zero incident data recorded at Port C. In the period for which accident records are available, approximately 7800 freight RoRo vessels berthed at the port without incident. If the above cargo-damaging rate is applicable to Port C, then the number of cargo-damaging fires that could have been expected to have occurred in this time can be calculated as 7830 x 1.10^{-6} per ship arrival. The probability of there having been zero incidents can then be calculated, assuming a Poisson process, as

$$P = \frac{e^{-m}.m^{r}}{r!}$$

where m is the expected number of incidents and r is the number of incidents observed.

For zero incidents,

$$P(0) = \frac{e^{-8.E-03}.(8.10^{-3})^{0}}{0!} = 0.99$$

This is a very high level of probability and the result shows that the zero incident record at Port C does not provide evidence that the cargo-damaging rate derived in this analysis is incorrect. This result, however, provides only very limited corroboration for the rate*. Rates for cargo-damaging fires on explosives carrying general-cargo and container vessels have been estimated from similar procedures:

General cargo vessels	1.10^{-6} per ship arrival in port
Container vessels	2.10^{-8} per ship arrival in port

Key to Tables A4.1 and A4.2

C	Collision
CF	Car fire
E	Electrical
EF	Emergency Flare
ESD	Electrostatic discharge
FL	Fuel leak onto hot surface
HE	Hot exhaust from moving equipment (bulldozers etc)
HL	Hot lamp
HS	Hot surface
HW	Hot work (welding etc)
LF	Lorry fire
LS	Lightning strike
M	Malicious
NF	Naked flame
NK	Cause of fire not known
S	Smoking
SI	Spontaneous ignition of unstable cargo (cotton waste, animal feed etc)
TF	Electrical or mechanical fault on moving equipment
VF	Vehicle fire (other than car or lorry fire)

* Further corroboration is provided by the results of a recently established study into the fire safety of ships carrying nuclear flasks[16]. The authors of the study carried out a detailed analysis to establish the circumstances under which a fire on a RoRo vessel (the Nord Pas-de-Calais) used to carry nuclear flasks across the English Channel could develop into a severe fire. The analysis considered such factors as smoke detectors failing to work, fire-fighting systems failing to operate on demand, fire breaching bulkheads etc. The following fire frequencies were derived:

severe fire on freight deck during loading/unloading	7.10^{-4} per year
severe fire in machinery space (capable of affecting cargo)	4.10^{-3} per year

When these frequencies are converted into fire rates, per ship arrival, the following values are obtained:

severe fire on freight deck		$3.5.10^{-7}$ per ship arrival
severe fire in machinery space		$9.5.10^{-7}$ per ship arrival
	Total	$1.3.10^{-6}$ per ship arrival

It will be seen that this rate (to one significant figure) is identical to that derived in the present study.

Appendix 5

Emergency planning

The Dangerous Substances in Harbour Area Regulations 1987 (DSHA) require the authorities of those harbours where dangerous substances are handled to prepare and keep up to date an emergency plan. This plan must cover the whole of the harbour area as well as those berths where dangerous goods are handled. One of the most important requirements of the plan, however, is the provision of means whereby port authorities can effect an evacuation of a dangerous goods berth and surrounding areas in the event of an emergency.

There are two types of dangerous situation that could arise at an explosives berth where prompt evacuation would have a significant mitigatory effect; the ignition of fire on board an explosives-laden ship; the initiation of part of an explosives load, resulting in a fire that spreads to but does not immediately initiate the rest of the load (an incident of this type could be expected in the event of an initiation of an item within a cargo comprising articles of HD 1.2 – see paragraph 93). The emergency plan should contain measures for dealing with both types of incidents. In respect of the first type of incident the plan should specify the circumstances under which fire-fighting should be attempted and the circumstances of imminent danger under which such action should not be attempted or should be abandoned; the plan should also specify measures to ensure that personnel on and off ship are evacuated to a place of safety should the incident escalate out of control. In respect of the second type of incident the plan should specify the circumstances and means under which attempts should be made to rescue casualties from the initial event and measures to ensure that uninjured persons are evacuated to a place of safety. Guidance on appropriate evacuation distances is available from the HSE[17].

In practice, the success of an emergency plan will be largely governed by two factors:

(a) the provision of adequate measures within the plan for dealing with all types of incidents that might arise and against which some form of mitigatory action could be taken;
(b) effective implementation of the plan.

The success of these factors will in turn be partly dependent on ‘human factors’.

Human factors

There are three areas in emergency planning where human factors can be expected to plan an important role:

(a) formulation of the plan;
(b) effective implementation of the plan;
(c) on the spot remedial action.

Formulation of the plan
The formulation of a successful emergency plan requires comprehensive identification of all potential hazards and risks. Techniques, such as HAZOP (see Appendix 3), have been developed to identify in a systematic way the problems that might arise during a hazardous activity. The success of these techniques depends on the skill and background knowledge of the people applying them. The techniques are clearly subject to human fallibility and as such may not identify all dangerous situations that may arise in reality.

The plan for the evacuation of berths and other areas of the port will be based on the hazards identified. Ideally, the plan should specify methods of evacuation based on best practice. Best practice is often based on past experience, but this is also an area subject to human fallibility and the plan may not always match perfectly all situations that arise in the future. The effects of omissions from the plan caused by human error can be minimised by carrying out emergency exercises, provided the successes and failures of the exercises are analysed and the lessons learnt incorporated into revised plans.

Implementation of the Plan
There are at least three human factors that will have an important bearing on the successful implementation of any emergency plan:

(a) training;
(b) communication;
(c) responsiveness of personnel to the plan.

Clearly it is important that personnel should be properly informed of and trained in emergency procedures. The effective implementation of evacuation plans will depend on personnel recognising alarm signals, knowing the location of muster points and the routes to those points. Personnel must also be willing to respond to alarm signals and follow any instructions issued by management during an emergency. A possible danger here is complacency – most alarms are false alarms.

On-spot Remedial Action
Formulation of an emergency plan and training will provide a good basis for success in the event that a situation arises where emergency action needs to be taken. However, for the reasons just discussed, neither of these factors can be guaranteed to be completely successful and there will always exist a residual risk out with the control of the plan – ie unforeseen circumstances or unpredicted actions of people. The only way these problems can be tackled is by good on-the-spot decision making or remedial action consistent with the plan. Such action will only be as effective as the person or people in charge of the emergency. This constitutes a further area for human factors consideration as the response of people under stress can never be fully predicted. Problems will be minimised if all the people covered by the plan have a clear understanding their role, and this will be enhanced by good training including practical exercises.

Appendix 6

Circumstances in which passenger vessels could be affected by explosives events

The Dangerous Substances in Harbour Area Regulations 1987[3] require ports that import/export explosives to be licensed by the Health and Safety Executive (HSE). The HSE currently licence these ports on the principle of hazard limitation: in practice this means that restrictions are placed on the quantities of explosives that can be present at berths, and certain other places of loading and unloading within ports, so as to try to ensure low casualty levels in the event of accidental explosion. An important part of the licensing procedure is the provision of an adequate level of protection for any passenger vessels docked in the port. The licence specifically restricts the quantities of explosives that can be handled at a berth when a passenger vessel is docked nearby.

However, it is still possible to foresee circumstances in which passenger vessels could be affected by explosives events within port/harbour areas, viz:

(a) if an explosives event were to occur at a berth at a time when a passenger vessel was close by in the navigation channel;
(b) if a passenger vessel were to strike an explosives laden ship at a berth;
(c) if an explosives event were to occur on a ship as it passed a berth where a passenger vessel was moored;
(d) if an explosives event were to occur on a ship as it passed a passenger vessel in the navigation channel;
(d) if a passenger vessel were to collide with a ship carrying explosives.

The licensing procedure does not specifically guard against high numbers of fatalities from these scenarios. At the time of the study, passenger ships and explosives carrying vessels could have operated simultaneously out of two of the locations studied in detail in this report – Port A and Port F. The possibility of an explosion causing large numbers of fatalities on passenger ships is explored in the following sections of this appendix.

Explosives event at berth affects passenger vessel in navigation channel

Passenger ships sail within the hazard range of explosives cargo loaded at the jetty at Port F. Thus an explosion at the jetty would have the potential to cause fatalities on board a passing ship.

Ships passing in the direction of the sea typically sail to within 325 metres of the jetty. At this distance a passing ship would be exposed to blast and fragments in the event of an explosion of one of the larger sizes of load handled. An explosion involving the largest notional size of load handled at the time of the study (240 tonnes of HD 1.1) could expose a passing ship to a peak incident pressure of 42 kPa and an incident impulse of 3778 kPa-msec. Standard blast damage criteria (see Table A6.1) suggest that this level of overpressure could damage the ship but would be unlikely to result in its destruction. Further research would be required to obtain a precise estimate of the numbers of fatalities that could be expected from such an event*. The explosion effects models used elsewhere in this study for estimating risks to shore-based population indicate that at an explosion at the jetty at a time when a passenger ship was at its closest point of approach would expose persons on board to roughly a 4% fatality probability, and this would fall to 1% at the slightly further distance of 570 metres. Since the largest size passenger ships that pass the jetty carry up to 1500 persons, the number of fatalities that might be expected on board these ships in such circumstances is of the order of 10 – 60.

Passenger ship strikes vessel loading explosives at the jetty

Much severer consequences could be expected from an explosion initiated by a passenger ship loosing steerage and striking an explosive laden vessel at the jetty. In such circumstances it could be expected that most of the persons on board the striking ship would be killed. An estimate for the frequency with which such events might potentially occur is obtained by substituting appropriate values into the following formula:

$$F = N * S\ P(I \setminus S) * P(E \setminus I)$$

where F is the frequency of the event
N is the annual number of passenger vessels that pass the jetty when explosives are present
S is the striking rate
P(IS) is the conditional probability that explosives cargo would be exposed to impact forces in the event of a passenger ship striking an explosives vessel
P(EI) is the conditional probability that explosives cargo would explode on sustaining impact force

* The models used in this study predict fatality probabilities for persons located in buildings or in the open on shore; the models have not been specifically developed to predict fatality probabilities for persons on board ships and thus the hazard ranges quoted can only be approximate. Generally speaking persons on board ships could be expected to be exposed to a lower hazard than persons on shore; ships are more resilient to blast than buildings and also offer better protection against fragments. The hazard ranges quoted in this report might thus be pessimistic but a more detailed study would be required to show whether this is so.

At the time of the study, approximately 90 passenger ships passed the jetty annually. These ships could be partitioned into two sizes: those that carried up to 700 persons and those that carried up to 1500 persons. The smaller ships accounted for approximately 75% of passenger ship movements past the jetty, ie the annual number of passings of the smaller ships was approximately 67 while the annual number of passings of the larger ships was approximately 23. Explosives were present at the jetty for approximately 28 days per year at the time of the study. Thus the number of passenger ships passing within the hazard range of explosives loads was estimated as follows:

Size of ship	*No. of passings (N)*
700 persons on board	(28/365) x 67 = 5
1500 persons on board	(28/365) x 23 = 2

Striking rates were derived in the first phase of the ACDS study (which considered the risks from the marine transport of dangerous substances in bulk). The following rate was derived for wide estuary ports:

Striking rate: 4.10^{-6} per passing

The conditional probability that explosives cargo on board a ship would sustain impact forces following a striking incident would depend on a number of factors – primarily the size and speed of the striking ship, the angle of striking, the area of the ship struck and its structural strength. These factors were investigated in the first phase of the ACDS study; it was judged that only oblique angle collisions (probability = 0.38) were likely to result in rupturing of the hull of the ship and that in such an event the probability of cargo section penetration was 0.15 – in the case of gas carriers. In the absence of any further data, these figures have been used in the present study. Thus:

conditional probability that explosives cargo would be exposed to impact forces in the event of a passenger ship striking an explosives vessel: 0.38 x 0.15 = 6.10^{-2}

The types of explosives loaded at the jetty at the time of the study belonged to the lowest impact risk group, I3 (see paragraph 75). These are the most robust types of explosives and are very unlikely to initiate in the event of an impact accident. However, the possibility of impact-induced initiation of I3 items has not been completely ruled out; the conditional probability of initiation in the event of a severe impact accident is taken as 1.10^{-4} (see paragraph 75).

Thus frequency estimates for explosives events initiated by passenger ships striking explosives vessels at the jetty are calculated as:

Size of Striking Ship	*Estimated Frequency of Explosion (year $^{-1}$)*
700 persons on board	$5 \times 4.10^{-6} \times 6.10^{-2} \times 1.10^{-4} = 1.10^{-10}$
1500 persons on board	$2 \times 4.10^{-6} \times 6.10^{-2} \times 1.10^{-4} = 5.10^{-11}$

An explosion involving the smaller passenger ship might cause in excess of 500 fatalities while an explosion involving the larger ship might cause in excess of 1000 fatalities. The chance of such accidents happening at the time of the study was negligibly low, given the types of explosives handled and the low volume of both explosives and passenger traffic.

Explosion in navigation channel affects docked passenger vessel

At none of the ports studied in detail were explosives vessels found to pass passenger berths within the hazard ranges of the explosives cargoes carried. Further studies would be required to determine whether this finding applied to all licensed ports.

Explosion in navigation channel affects passing vessel

At the time of the study, explosives carrying vessels leaving the harbour at Port A could in theory have passed passenger ships in the navigation channel at a separation distance of just 150 metres. At this range, an explosion of the largest notional size of load carried (142 tonnes of HD 1.1) could have exposed a passing ship to a peak incident pressure of 137 kPa and an incident impulse of 5362 kPa-msec. Standard blast damage criteria (see Table A6.1) suggest that such a level of overpressure could have caused severe damage to the ship and possibly have sunk it. In excess of 1000 fatalities could have been expected had one of the larger passenger vessels been involved in such an event. However, the chance of such an accident was extremely low. Ships carrying large quantities of explosives (in excess of 50 tonnes NEQ) left the berth at times when passenger ships were not scheduled to arrive in or depart from the harbour. There was a possibility that an explosives vessel might have passed a passenger ferry running late due to bad weather or other operational problems, but the probability of this event was considered by the harbour authorities to have been very low and could not be reliably determined with the available data. Since the completion of the study, the operators of Port A have taken measures to eliminate this risk entirely by instituting a traffic management system that effectively segregates explosives carrying ships and passenger ships. The details of this system are presented in Annex 1.

Explosives carrying vessels leaving the jetty at Port F could pass passenger ships in the navigation channel of the estuary at a distance of 250 metres. At this distance, an explosion of the largest notional size of load carried at the time of the study (240 tonnes of HD 1.1) could expose a passing ship to a peak incident pressure of 69 kPa and an incident impulse of 4755 kPa-msec. Standard blast damage criteria (see Table A6.1) suggest that such a level of overpressure could cause severe damage to passing ships. As noted in paragraph 4, further research would be required to obtain a precise estimate of the numbers of fatalities that might be expected from such an event. The explosion effects models used in this study for estimating risks to shore-based population indicate that, at the closest point of approach, a person on board a passing vessel would stand in the region of a 5 – 10% chance of being killed from an explosion involving the highest notional size of load; this fatality probability would fall off to 1% at a slightly further distance of about 550 metres. Since the largest passenger vessels carry up to 1500 persons, an explosion in the navigation channel at a time when these vessels are within the hazard range of the explosives cargo might cause 15 – 150 fatalities on board. The most likely source of such an event would be ignition of fire on the explosives vessel, but in this instance there should be time to raise the alarm and clear shipping from the area of danger in the estuary. There is also a possibility that an explosion may occur without warning as a result of an unsafe explosives item initiating spontaneously, but the chance of such an event occurring at the time of the study was considered negligibly small, given the robust nature of the explosives items that were handled. Thus the chance of an explosion occurring in the navigation channel without warning and while passenger ships are within the hazard range of explosives cargo can be judged to be extremely low in the present instance.

Passenger ship collides with explosives carrying vessel

An explosion initiated by a collision between an explosives carrying vessel and a passenger ship could potentially cause the most catastrophic consequences. In such circumstances it could be expected that most of the persons on board the ships would be killed. An estimate for the frequency with which such events might potentially occur is obtained by substituting appropriate values into the following formula:

$$F = N * S * P(I \setminus C) * P(E \setminus I)$$

where F is the frequency of the event
N is the annual number of passenger ships/explosives vessel encounters in the navigation channel
C is the collision rate
P(IC) is the conditional probability that explosives cargo would be exposed to impact forces in the event of a collision
P(EI) is the conditional probability that explosives cargo would explode on sustaining impact force

In the case of Port F, the number of encounters, N, is the product of the number of explosives vessels that leave the jetty in the period of one year and the number of passenger ships that arrive in the navigation channel during the time taken by explosives vessels to reach the anchorage or the harbour entrance. The anchorage is located some 16 kilometres downstream of the jetty while the (geographical) entrance to the harbour is taken to be 20 km downstream of the jetty. Two types of vessels carry explosives from the jetty: lighters, which carry explosives to the anchorage; and ocean-going ships which carry explosives directly to the open sea. In the year in which the study was undertaken, there were approximately 16 lighter journeys and 18 ship journeys from the jetty annually. Both types of vessel sail at 7 knots (3.6 metres per second) while in the estuary. The time taken to reach the anchorage is thus about 1.2 hours while the time taken to reach the harbour entrance is about 1.5 hours. The annual number of passenger ship arrivals in the estuary at the time of the study was previously noted in paragraph x to be 67 in the case of smaller passenger ships (up to 700 persons on board) and 23 in the case of larger passenger ships (up to 1500 persons on board). Thus the number of encounters per year is calculated as:

Type of encounter	*No. of encounters (N)*
small passenger ship/lighter	$\frac{1.2*16*67}{365*24} = 0.15$
small passenger ship/ocean-going explosives ship	$\frac{1.5*18*67}{365*24} = 0.21$
large passenger ship/lighter	$\frac{1.2*16*23}{365*24} = 0.05$
large passenger ship/ocean-going explosives ship	$\frac{1.5*18*23}{365*24} = 0.07$

Collision rates were derived in the first phase of the ACDS study (which considered the risks from the marine transport of dangerous substances in bulk). The following rate was derived for wide estuary ports:

Collision rate: 4.10^{-5} per encounter

The conditional probability that explosives cargo on board a ship would sustain impact forces following a collision would depend on a number of factors, of which the primary factors would be the speed and size of the ships, the angle of collision, the point of impact and the structural strength of the ships. These factors were investigated in the first phase of the ACDS study, it has judged that only oblique angle collisions (probability = 0.38) were likely to result in rupturing of the hull of the ship and that in such an event the probability of penetration of the cargo section was 0.15 – in the case of gas carriers. In the absence of any further data, these figures have been used in the present study. Thus:

> conditional probability that explosives cargo would be exposed to impact forces in the event of a passenger ship colliding with an explosives vessel: $0.38 \times 0.15 = 6.10^{-2}$

All types of explosives loaded at the jetty at the time of the study belonged to the lowest impact risk group, I3 (see paragraph 75). These are the most robust types of explosives and are particularly unlikely to initiate in the event of an impact accident. The conditional probability of initiation for I3 items in the event of a severe impact accident is taken as 1.10^{-4} (see paragraph 75).

Thus frequency estimates for explosives events initiated by passenger ships colliding with explosives vessels are calculated as:

Size of colliding Ship	*Estimated Frequency of Explosion (year $^{-1}$)*
700 persons on board	$0.36 \times 4.10^{-5} \times 6.10^{-2} \times 1.10^{-4} = 9.10^{-11}$
1500 persons on board	$0.12 \times 4.10^{-5} \times 6.10^{-2} \times 1.10^{-4} = 3.10^{-11}$

Events involving the smaller passenger ship might cause in excess of 500 fatalities while events involving the larger ship might cause in excess of 1000 fatalities. Similar calculations were performed to estimate the chance of these accidents occurring at the anchorage; the values derived were again found to be negligibly small.

Conclusion

It was found that there was a potential for passenger ships to receive the detrimental effects of explosions at two of the ports studied in detail and for large numbers of fatalities to result from these events. The chance of such accidents occurring could not be determined with a high degree of accuracy but the available data showed this chance to be negligibly small. The analysis, however, served to demonstrate the theoretical possibility of such accidents. The operators of Port A have subsequently taken measures to eliminate the risk of these accidents entirely by instituting a traffic management system that effectively segregates explosives carrying vessels from passenger ships. The details of this system are presented in Annex 1.

Table A6.1 Blast damage criteria for explosion 100 te TNT[18]

Structural element	Failure mode	Over-pressure	Scaled distance (m.kg$^{-1/3}$)
Window panes	5% broken	0.7	96
	50% broken	1.5	58
	90% broken	3.8	29
Primary missiles	Limit of travel	0.8	84
Houses	Tiles displaced	2.7	37
	Door frames blown in	5.4	22
	Category D damage*	2.9	37
	Category Ca damage*	7.7	17
	Category Cb damage*	16	9.5
	Category B damage*	35	5.7
	Category A damage*	77	3.7
Rail wagons	Superficial damage	17	9.0
	Damaged but repairable	38	5.4
	Bodywork crushed	59	4.2
	Limit of derailment	77	3.7
Telegraph poles	Snapped	168	2.5
Large trees	Destroyed	168	2.5
Railway line	Limit of destruction	650	1.4

* These categories relate to levels of house damage caused by bomb attacks in World War II.

Category A damage: Houses completely demolished.

Category B damage: Houses so badly damaged that they are beyond repair and must be demolished when the opportunity arises. Property is included in this category if 50 – 75% of external brickwork is destroyed, or in the case of less severe damage if the remaining walls have gaping cracks rendering them unsafe.

Category Cb damage: Houses rendered uninhabitable and which need repairs so extensive that they must be postponed until after the war. Examples of damage resulting in such conditions include partial or total collapse of roof structure, partial demolition of one or two external walls up to 25% of the whole, and severe damage to load bearing partitions necessitating demolition and replacement.

Category Ca damage: Houses rendered uninhabitable but which can be repaired reasonably quickly under wartime conditions. The damage sustained does not exceed minor structural damage, for example as partitions and joinery wrenched from fittings.

Category D damage: Houses requiring repairs to remedy serious inconveniences but remaining inhabitable. Houses in this category may have sustained damage to ceilings and tilings, batons and roof coverings and minor fragmentation effects on walls and window glazing. Cases in which the only damage amounts to broken glass in less than 10% of the windows are not included.

Annex 1

Details of traffic management scheme instituted by operators of port A to segregate explosives vessels and passenger vessels

An Explosives Vessel for this purpose is defined as a vessel carrying in excess of 50 tonnes NEQ of Class 1.1, 1.2 or 1.3 cargo.

A 'Passenger Vessel' for this purpose is defined as a vessel carrying in excess of 12 passengers.

Segregation between Explosives Vessels and Passenger Vessels is to be maintained at all times as follows:

(a) No Explosives Vessel is to be allowed to meet and pass a Passenger Vessel or another Explosives Vessel in the area of the Main Deep Water Channel between the narrow part of the channel and the vessel's berth.
(b) A minimum buffer zone of 5 cables is to be enforced between the Explosives Vessel and a Passenger Vessel or another Explosives Vessel travelling in the same direction through the harbour between the narrow part of the channel and the vessel's berth. While travelling in the same channel overtaking is not to be permitted.
(c) If traffic and/or weather conditions warrant, the VTS Manager has the authority to restrict the movement of Explosives Vessels.
(d) If conflict of movement between Explosives Vessels and Passenger Vessels arises, the VTS Manager is to instruct the Explosives Vessel to remain alongside or not to enter the harbour until clear transit within this rule is possible.
(e) The Information Officer is to ensure that all Explosives Vessel notifications are passed verbally to the VTS Manager and, in addition, on the computer card for the vessel an entry in the movement notes is to be made to read 'EXPOSIVES VESSEL' INFO FROM..... DATE TIME'.

Appendix 7

Uncertainties in the risk results

Quantitative risk assessment, by definition, attempts to express the risk of a hazardous activity in quantitative terms, such as, the chance of an accident resulting in x or more fatalities is y parts per million per year. However, this procedure is not an exact science: its results are subject to uncertainty. This uncertainty arises from many sources, including doubts about whether all potentially significant causes of accidents have been identified, use of simplified models to represent complex systems, lack of appropriate data from which to derive frequency estimates for various hypothetical accidents, incomplete understanding of how systems respond in accident conditions and lack of accurate and comprehensive models on which to base estimates for the consequences of accidents. In reality, most analyses of industrial risks involve the use of judgement and simplifying assumptions.

The question may be asked whether the results produced by this procedure have any real meaning in view of their inherent uncertainty. Where these results cannot be verified from historical experience, the answer must be that the results are hypothetical and are not necessarily meaningful in an absolute sense but are useful in relation to other comparable results. The results of a QRA do not constitute a prediction of the future frequency of occurrence of accidents so much as a numerical statement concerning the assessed safety of a hazardous activity. As an illustration of this point, Figure A7.1 shows an FN curve constructed from the results of a hypothetical QRA of an industrial activity. It is seen that the curve passes through the point 10^{-3}, 1000, ie it is estimated that there is a 1 in 1000 chance per year of an accident resulting in 1000 or more fatalities. This result does not mean that such an accident would definitely occur once in every 1000 years of operating experience; rather this curve places the risk of the activity into a context where its significance can be judged. For example, if the line denoting the upper threshold of tolerable risk were drawn through a lower point on the FN plot (say) 10^{-4}, 1000, then this would mean that safety standards would have to be improved, regardless of cost, or the activity would have to cease.

Approach adopted in this study to deal with uncertainty

A clear strategy is required to deal with the uncertainty inherent in the QRA procedure. The strategy adopted in this study is that defined by the HSE as the 'cautious best estimate approach' to risk analysis(19). This means that every attempt has been made to use realistic best-estimate values for the various parameters that appear in the equations throughout the analysis – such as, the probability that a particular type of explosive would burn to explosion following ignition – but whenever there has been any doubt about the exact value of a parameter, some overestimate has been preferred to produce a conservative output. A limited number of sensitivity tests also have been carried out to determine the variability of the overall results to the assumptions made. The HSE has noted that the 'cautious best estimate' approach has the merit of helping to offset any uncertainty arising from unquantified causes of accidents. In the present study, the risk of explosives loads detonating in accident conditions has probably been exaggerated, but this helps to offset any underestimate of the likelihood of an explosives event due to 'freak accidents' not considered in the analysis, aircraft crashes, for example. The overall aim has been to produce results that are likely to err on the side of caution but which at the same time are not grossly pessimistic.

Assumptions and judgements applied in this study

The various assumptions and judgements giving risk to uncertainty in the results of the study can be grouped under six headings:

selection of accident scenarios
categorisation of explosives loads
derivation of frequency estimates for dangerous occurrences
incomplete knowledge concerning the behaviour of explosives in accident conditions
derivation of fatality estimates for explosives
assumptions concerning standards of safety management

Selection of accident scenarios

An initiation of an explosives cargo in a port could arise from various types of accidents, but in particular from those involving impact or more especially fire. The QRA was confined to nine such types of accident judged by a small group of explosives experts to be the most likely source of any future explosives events in ports:

fires on road vehicles
fires on rail vehicles
fires on ships
crashes/collisions of road vehicles
derailments/collisions of rail vehicles
crane accidents
fork lift trucks
striking of ships
ship collisions

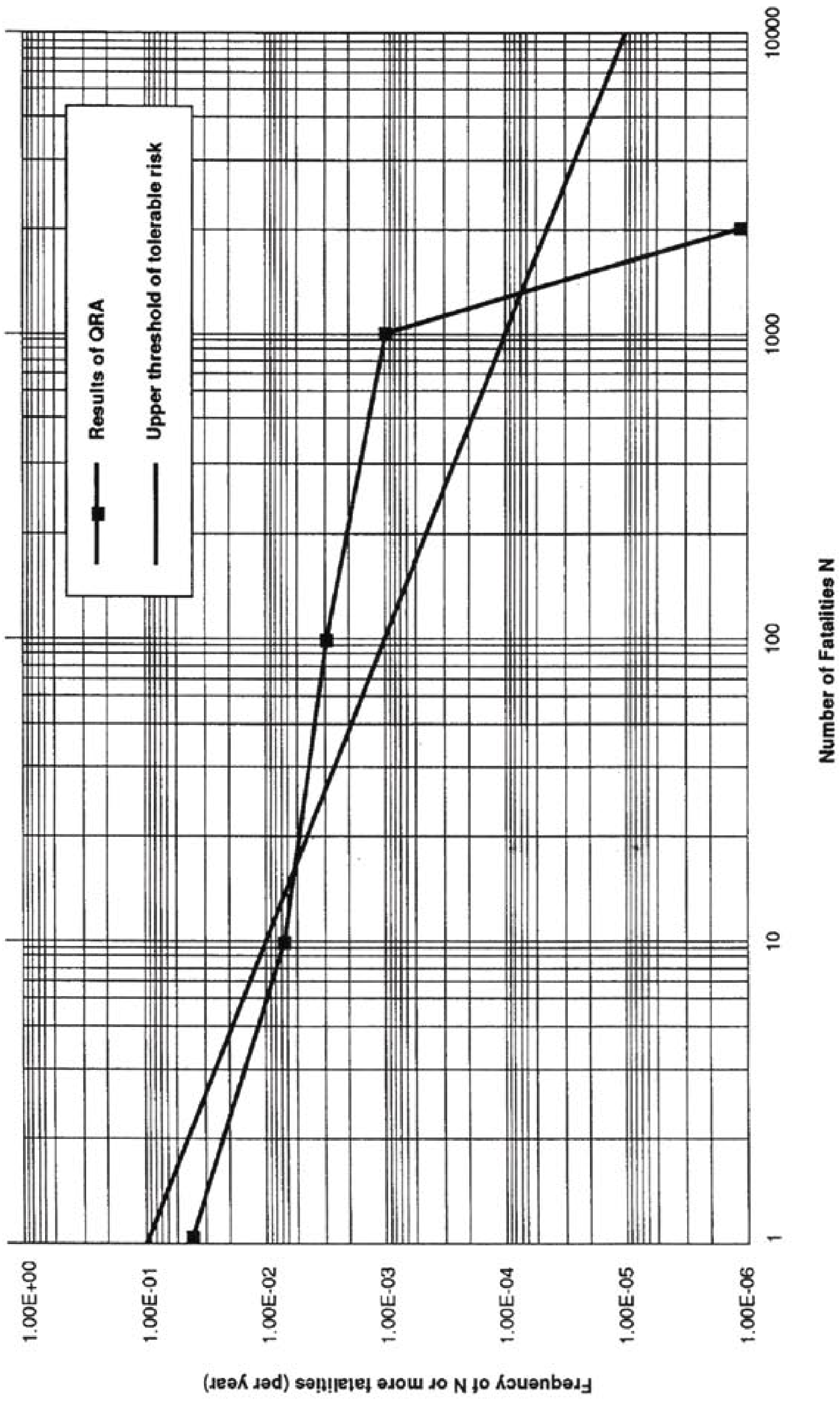
Various other potential causes of explosive events were identified at the outset of the study but were judged not to be significant and were not considered further. Included amongst these were certain 'freak accidents', such as aircraft crashes, and a number of minor types of accidents, such as falls of explosives packages during the unloading of vehicles. The procedure by which accident scenarios were selected for detailed analysis was necessarily based on **judgement**, but this judgement was informed by a knowledge of past causes of accidents and an appreciation of the susceptibility of different types of explosives to accidental initiation.

Categorisation of explosives loads

Many different types of explosives substances and articles are moved through ports in Great Britain (an analysis of cargo data provided by the five ports and one licensed jetty selected for detailed study revealed that 80 different types of explosives items were handled in these locations collectively during the period of the study). It would have been impracticable to have analysed separately the risks from the many different types and sizes of explosives cargoes moved. Accordingly the approach adopted has been to categorise the cargoes into a small number of groups with respect to the important risk factors, which are:

(a) hazard, ie the types of harmful effects that would be produced by the cargo on initiating;
(b) susceptibility of the cargo to accidental initiation by impact;
(c) susceptibility of the cargo to accidental initiation by fire;
(d) size of cargo, ie net explosives quantity (NEQ).

Figure A7.1 Results of a hypothetical QRA



Separate categorisation schemes have been developed for each of these factors, the objective of each scheme being to partition explosives into a small number of groups such that all items placed into a particular group may be considered either to produce similar effects on initiating or to be roughly equally susceptible to initiating stimuli, as the case may be. In devising suitable categorisation schemes, a **compromise** inevitably had to be struck between a high degree of accuracy of analysis for which only a few broad categories could be considered. The point is considered further in the following paragraphs.

Categorisation by hazard
The scheme employed was basically on a slightly modified version of the UN system of Hazard Divisions[1]. The analysis proceeded on the **assumption** that all explosives items within a particular hazard group would produce essentially identical effects on initiating. However, this assumption is true only in a broad sense. For example, while all articles of HD 1.2 present mainly a fragment hazard, some articles in this division contain detonating explosives that would shatter casing material and produce high energy fragments, while others contain deflagrating explosives that would not shatter casing material but project articles more or less intact. Thus a range of fragment densities could be expected from initiations of HD 1.2 cargoes depending on the types of items present in the load. For the purpose of this study, the **assumption** has been made that all articles of HD 1.2 are of the fragmenting type, thus introducing an element of conservatism into the analysis. Similarly, initiations of cargoes comprising articles of HD 1.1 could produce a range of primary fragment patterns depending on the exact types of articles present in the cargo. Again, the assumption has been made that all articles of HD 1.1 are of a more energetic type.

Categorisation by susceptibility to accidental initiation
Based on limited trials data and accident experience, explosives have been partitioned into three groups with respect to susceptibility to accidental initiation by impact. Items placed into the highest risk group (I1) can be considered likely to initiate in particularly severe impact accidents, though the chance of these accidents occurring in ports can generally be considered likely to be low; items placed into the intermediate group (I2) can be considered likely to remain safe in most foreseeable impact accidents, though the possibility that these items might initiate in these circumstances cannot be entirely dismissed; while items placed into the lowest risk group (I3) can be considered particularly insensitive to impact. Explosives have also been partitioned with respect to susceptibility to initiation on exposure to fire. This categorisation scheme, like that for impact, was based on limited trials data and accident experience. Two fire risk groups were defined: items assigned to the higher group (F1) can be considered likely to react explosively in the event of ignition, while items assigned to the lower group (F2) can be considered to be more likely to burn rather than explode.

2 Two of these divisions, HD 1.1 and HD 1.3 were subdivided into substances and articles. This distinction was considered to be particularly important in the case of explosives of HD 1.1, as articles of this division can be expected to produce primary fragments (shrapnel) in addition to the blast effects produced by substances.

Judgement had to be exercised in assigning items to a particular risk group. Where there was any doubt about the most appropriate group for a particular item, a decision was taken to assign the item to the higher of two possible groups. For example, all items containing rocket motors fuelled with solid propellant were assigned to the highest impact risk group, the rationale for this decision being the results of some drop trials performed with a few specific weapons containing these types of rocket motors –which showed the weapons to be comparatively sensitive to impact. This decision may lead to conservative results for other weapons of this type, particularly when they are transported in robust freight containers. Further research would be required to show whether the risks from these weapons have been overstated. The effect of any possible conservatism arising from this decision is not significant as items containing rocket motors accounted for only a very small proportion of the overall quantities of explosives moved through commercial ports at the time of the study.

The analysis proceeded on the **assumption** that all items assigned to a particular group could be considered equally sensitive to fire or impact. This was undoubtedly a **simplification** of the true situation; some items in a particular risk group would almost certainly be more susceptible to accidental initiation than others. For example, nitroglycerine-based blasting explosives, such as dynamite, and certain types of military explosives, such as flaked TNT and phlegmatised RDX compositions, have all been assigned to the higher fire risk group, though there is a certain amount of evidence to suggest that the former are more likely to burn to explosion in accident conditions.

The net effect of this has been to produce a conservative result in keeping with the conservative best estimate approach to the analysis.

Typical load size selection
Explosives are moved through ports in many different sizes of load. In order to keep the analysis within manageable proportions it was necessary to group the loads into a small number of notional sizes of cargo. This was done by determining the mean net explosives quantity of loads within the following logarithmic bands:

1–99 kg
100–999 kg
1000–9999 kg
10,000–99,999 kg
100,000–999,999 kg

The effect that has been to condense the range of load sizes analysed, possibly leading to some underestimate of high N events and consequently a shallower FN curve.

Derivation of frequency estimates for explosives events
The procedure used to calculate estimates for the frequency (annual probability) of explosives events occurring in ports was described in some detail in Section 4. It was noted that these estimates were computed from:

rates for dangerous occurrences
conditional probabilities of initiation
annual numbers of movements for different types and sizes of explosive cargoes

The derivation of values for each of these three parameters in turn required the use of judgement.

Estimates for the numbers of different types and sizes of explosives loads moved through ports were derived from traffic data supplied by port operators. These data were supplied for a period of time **judged** to be sufficiently representative to allow **reasonably** accurate scaling to a year's traffic. The judgement and assumptions made in deriving values for conditional probabilities of initiation are discussed in the next section of this appendix.

Rates for dangerous occurrences ideally would have been derived from historical experience of accidents involving explosives cargoes at the five ports and one licensed jetty selected for detailed study. However, the operators reported that they had no records for the involvement of explosives cargoes in any of the dangerous occurrences of interest. This was mostly due to the non-occurrence of accidents rather than the non-reporting or non-recording of accidents. Accordingly, rates for dangerous occurrences had to be derived from accident databases covering a broader range of locations, types of cargo and types of operation than those that are the specific subject of this study.

It could be expected that the use of such databases will in general lead to conservative results as more care tends to be exercised when explosives cargoes (as opposed to non-hazardous cargoes) are handled.

In some case rates had to be derived from small accident databases. Accident rates derived from small numbers of incidents are subject to a large measure of statistical uncertainty and cannot be regarded as robust. For example, records kept by the operators of Port A showed the occurrence of one cargo-damaging container-lorry traffic accident in a period in which 2,240,000 container lorries passed through the port. These statistics, when combined with the average length of lorry route through the port (2 km), produce a mean cargo-damaging crash collision rate of 2/(2,240,000 x 2) = 2.10^{-7} per vehicle-km. Assuming a Poisson distribution, the symmetrical 90% confidence limits are:

upper bound value = 1.10^{-6}
mean value = 2.10^{-7}
lower bound value = 1.10^{-8}

When an accident rate was found to be subject to a large measure of statistical uncertainty, as in this case, efforts were made to compare it with more robust rates derived from generic accident data. In the present case this was achieved by using data provided by the commercial explosives industry for a larger number of cargo-damaging traffic accidents on the public highway. The rate derived, 8.10^{-8} per vehicle-km, agreed with the mean rate derived from the port accident data within a factor of 2.5. Use of generic traffic accident rates in this study would implicitly assume that accidents were as likely to occur in ports as on the public highway. This assumption may be conservative with respect to vehicle crashes and collisions in view of the speed restrictions applying to ports, though the greater density of junctions in ports may militate against this view. The average of the two rates, rounded to one significant figure, ie 1.10^{-7} per vehicle-km was used in the further stages of the study.

In other cases, rates derived from generic accident databases were not directly applicable to the handling of explosives in ports and had to be modified by use of expert **judgement**. An example of this type of analysis was described in some detail in Appendix 3, where the derivation of rates of ignition of cargo-damaging fires on explosives carrying ships was considered. Certain adjustment factors had to be applied to the generic fire rates derived for general cargo ships to take account of the various fire precautions observed on ships with explosives on board.

Derivation of frequency estimates for explosives events caused by unsafe explosives

The historical accident record for explosives transport in the UK (see Appendix 2) clearly demonstrates the significance of the threat posed by unsafe explosives, ie explosives that have been badly designed, manufactured, packaged, or are in a deteriorated condition. About 50% of all transport events that have occurred in the UK since 1950 have been caused by unsafe explosives of one type or another.

This historical record suggests that a detailed examination of possible causes of breakdown in quality control procedures that would allow unsafe explosives to enter the transport chain might be desirable.

However, such a study would require detailed analysis of manufacturing, maintenance and checking procedures for many different types of explosives substances and articles. Such a study was beyond the scope of the present project.

In the present study it has been possible to do no more than examine the historical record for transport events in order to draw some broad conclusion about the potential threat posed by unsafe explosives. As previously noted, this record suggests that unsafe explosives are as likely a source of events as fire and impact accidents. Based on this observation, an allowance for the risks of unsafe explosives has been made by **simply** doubling the event frequencies derived for the fire and impact accidents considered in this study. This is a major source of uncertainty and further work in this area would be desirable.

Incomplete knowledge concerning the behaviour of explosives in accident conditions

The process whereby a value was estimated for the conditional probability that a particular type of explosive cargo would initiate given its involvement in certain types of accident was discussed in Section 4 of the main report. It was noted that this process inevitably involved **judgement** as there are insufficient trials or accident data available to allow objective values of conditional probability to be derived.

It was noted that fire generally could be considered to pose a greater threat to explosives cargoes than impact. Most explosives could be expected to react explosively following ignition though a few types of explosives substances could be expected to burn rather than explode in fire accidents. The former types of explosives were assigned to the higher of two fire risk groups, F1, for which a value of unity was considered appropriate for the conditional probability of initiation in the event of ignition. This value was known to be conservative as records had been found of a few incidents in which explosives cargoes categorised as belonging to F1 had burned rather than exploded following ignition. Nevertheless, experience has shown that such cargoes are more likely than not to burn to explosion in fire accidents, particularly if confined in the cargo space of a vehicle or a ship. It was considered that any conservatism introduced into the analysis by the use of a unity conditional probability of initiation would not be significant.

Substances assigned to the lower of the two fire risk groups, F2, have been shown in trials carried out by the MoD or other organisations to be unlikely to burn to explosion in accident conditions.

It was noted that only a small number of trials have been performed for each substance of this type and while an explosives reaction has not been observed in any of these trials, the small amount of data collated does not allow any firm conclusions to be drawn about whether there is still a small chance that these substances could explode in accident conditions particularly if heavily confined in a freight container or the hold of a ship. The available evidence suggests that such an outcome is unlikely, but a cautious view has been taken and a burn-to explosion probability of unity has been **judged** appropriate. Further work in this area may well justify the use of lower conditional probabilities of initiation.

Quantification of the conditional probability that an explosives cargo would initiate, given its involvement in an impact accident, proved more difficult than quantification of the probability that the cargo would burn to explosion following ignition. The values of conditional probability derived for impact-induced initiation are undoubtedly subject to a greater degree of uncertainty that those derived for fire-induced initiation. It was noted in Section 4 of the main report that all correctly packaged explosives items are unlikely to initiate in impact accidents, though the possibility of such an event cannot be entirely dismissed. The robustness of correctly packaged explosives items has been demonstrated by accident experience and the results obtained from various drop trials.

For the purpose of this study it has been **judged** that there would be no greater than a 10^{-3} probability majority of explosives items (ie those belonging to Impact Risk Group 2) would initiate were they to be involved in any foreseeable impact accident that might occur in a port. The value of this probability is based on an upper statistical limit derived from zero events in a large number of drop-hammer trials carried out with cartridges containing a comparatively sensitive type of blasting explosive, and as such it is likely to be conservative to a considerable degree with regard to the more robust items assigned to I2. This probability has been used in the absence of any more extensive data from which to quantify impact-induced probabilities for items in this risk group.

The corresponding value of probability applied to the most robust munitions (ie those belonging to Impact Risk Group 3) has been cautiously set one order of magnitude lower, ie 10^{-4}. This value is **judged** by many explosives experts to be conservative, but it has been used in this study in the absence of any empirical evidence in support of a lower value.

In addition to uncertainty about the likelihood of explosives cargoes initiating in accidents, there is also uncertainty about the effects that initiating events would produce. It has been **assumed** that all cargoes classified as HD 1.1 would explode *en masse*. Experience would suggest that this assumption is pessimistic in the case of loads consisting of articles of HD 1.1; there have been a number of incidents in which such cargoes have given rise to a series of explosions over time, rather than one large instantaneous explosion. It has been **assumed** that substances of HD 1.3 in soft packaging would produce idealised fires while articles of HD 1.3 would produce non-idealised fires.

Derivation of fatality estimates for explosives events

The explosion effects models employed in the study can only give estimates, and not exact predictions, of the numbers of fatalities to be expected from explosives events. It is unlikely that any 'easy to use' model could be relied upon to give highly accurate estimates of fatality levels, given the complexity of the response of different types of structures to various explosion effects. Within the constraints of being relatively quick and simple to apply, the objective of the models chosen for use in this study is that they should produce estimates that are reasonably accurate over a fairly wide range and which result in conservative estimates where uncertainty exists – ie the consequences of explosives events should not be underestimated. The sources of uncertainty in the results generated by the models are summarised below for each type of explosion effect.

Blast
The blast model that has been used does not distinguish between different types of buildings. Some types of modern buildings, particularly those of curtain wall construction, are more easily damaged by blast than brick buildings with smaller areas of unsupported wall and smaller openings. However, the licensing technique recognises this and affords a greater degree of protection, by distance, to such buildings than to small, brick built structures. The blast model used in the present study is largely based on incidents which occurred in the First or Second World Wars, ie before the advent of buildings of curtain wall construction, and may underestimate fatality probabilities in ports which contain these types of buildings. On the other hand, modern building of steel-framed construction are more resilient to blast (ie less likely to collapse) than many older types of buildings. Also watercraft generally can be expected to be more resilient to blast than buildings. Thus the model is likely to give conservative results when applied to population on board vessels.

The model does not take account of topographical features that could alter the parameters of a blast wave. For example, container stacks immediately adjacent to explosion sites could be expected to attenuate the blast wave, and reduce the detrimental effects of the explosion.

Fragments
Considerable variations in primary fragment densities can be expected across the range of explosives articles. The primary fragment model used in the present study is based on results obtained from one particular type of fragmenting munition (500 lb general purpose bombs) and will give conservative results when applied to less energetic types of articles. The model also does not allow for shielding of the type that might be provided by container stacks, cranes and other types of port infrastructure.

Thermal effects
The model used is appropriate for fires producing vertical flames. It does not allow for the effects of flame tilt produced by high winds, nor does it allow for jetting – which may be produced in the event of only part of the containment failing – or shielding – which may be provided by structural features.

Assumptions concerning standards of safety management

All frequency estimates for explosives events derived in this study are based to some extent on historical experience. This means that past rates of failures have been used to deduce estimates for the present likelihood of occurrence explosive accidents. The **assumption** implicit in this analysis is that standards of safety management will remain constant over time. This assumption is pessimistic if it can be shown that lessons are learnt from accidents and steps taken so far as practicable to prevent any recurrence of these accidents.

Many statutory regulations are based to some extent on lessons learnt from past accidents and good management systems, including those derived from modern philosophies, ie risk assessment, ensure that procedures comply with these regulations and help prevent recurrence of accidents. Legislation is intended to help operators understand the needs of their management systems and improvements in these systems have in general been achieved. At the same time it is clear that some accidents have occurred as a result of non-compliance with legislation (albeit in some cases inadvertently, ie as result of a failure of safety management). This study assumes that standards of safety management will remain essentially constant over time. If these standards were to deteriorate, for whatever reason, then the results of this study would no longer be valid.

Confidence limits

It is impossible to calculate the uncertainty in the many complex assumptions and judgements made in this study; hence it is not possible to quantify overall confidence limits for the risk estimates presented in this report. The approach adopted in this study has been to use realistic best estimate values for the various parameters in the risk calculations, but wherever there has been any doubt about the exact value of a parameter some overestimate has been preferred to produce a conservative output. This approach to the risk analysis has been defined by the HSE by the term ‘cautious best estimate approach’. The overall aim has been to produce results that are likely to err on the side of caution but which are not at the same time grossly pessimistic. In view of the uncertainty inherent in the results, it follows that risk estimates presented in this report should be used with care and not taken out of this context of this study.

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This document contains notes on good practice which are not compulsory but which you may find helpful in considering what you need to do.

This document is available at: www.hse.gov.uk/pubns/priced/explosives-ports.pdf

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