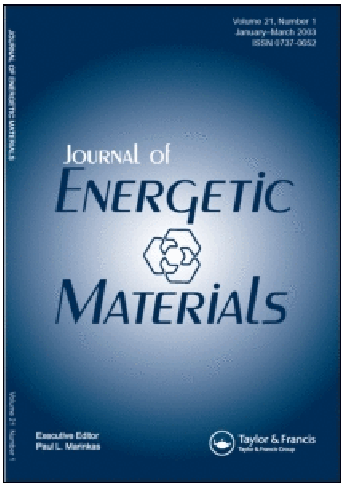

Journal of Energetic Materials
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713770432

Development of risk assessment techniques for use in the field of explosives and ammunition

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To cite this Article Cantrell, F. , Clifton, J. , Edmondson, J. N. , Hartley, F. R. , Michell, P. D. , Moreton, P. A. , Prescott, B. L. and Reeves, A. B.(1989) 'Development of risk assessment techniques for use in the field of explosives and ammunition', Journal of Energetic Materials, 7: 1, 1 — 28
To link to this Article: DOI: 10.1080/07370658908012558
URL: http://dx.doi.org/10.1080/07370658908012558

DEVELOPMENT OF RISK ASSESSMENT TECHNIQUES FOR USE IN THE FIELD OF EXPLOSIVES AND AMMUNITION.

PART I. RISK ANALYSIS IN STORAGE

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ABSTRACT

After reviewing the techniques currently used for ensuring that the risks inherent in the storage of explosives and ammunition are maintained at an acceptably low level, a Risk Assessment technique is developed. The technique is based on a systematic approach to hazard identification through the use of a HAZOP procedure and Fault Trees together with occasional use of Event Trees where a single initiating event, such as a lightning strike, can lead to a number of top events. Quantification of the Fault Trees taking full account of the important contributions of human factors enables the frequency of unintended initiations to be estimated. Analysis of the consequence of these initiations allows the risk levels to be estimated. It is found that the risk levels achieved by application of the current NATO Safety Principles based on Quantity Distances are considerably lower for materials of Hazard Divisions 1.2 and 1.3 than 1.1.

The present approach provides a significant advance over previous work in this field by its detailed analysis of the frequency of accidental initiations. This enables the technique to quantify the different vulnerabilities to accidental initiation of items containing explosives from the same Hazard

Division, such as gunpowder in a trade package as compared to an unfuzed steel-cased 1000lb aircraft bomb. This has the important advantage that it may be possible to reduce the risk levels posed by a facility by ensuring that items that pose a high risk are stored in remote locations whereas items that pose lower risks may be stored closer to either people or other facilities. Evaluation of the risk levels into low, intermediate and high risk situations enables the available resources of time and money to be channelled into those areas where they can be most effective in lowering the overall risk levels posed by a facility.

The robustness of the present method has been demonstrated by its application to a range of explosive items in a number of different types of storehouses, using a range of handling devices within UK depots operated by all three Services.

INTRODUCTION

There has been a growing interest in estimating the risks involved in the manufacture, processing, transport and storage of explosives and ammunition. Evaluation depends on the fact that risk is a function of the frequency and consequence of an unwanted event[1].

$$\text{Risk} = f(\text{frequency})(\text{consequence}) \qquad (1)$$

Equation 1 is a generalised one. For the evaluation of risk it is necessary to define the function involved and the product of frequency and consequence is usually chosen[1] (equation 2).

$$\text{Risk} = \text{frequency} \times \text{consequence} \qquad (2)$$

It is apparent from equation 1 that it is possible to reduce the risk from an event by reducing either the frequency of that event or its consequences. In the field of explosives and ammunition reduction of the frequency with which unintended initiations occur is achieved by careful design, quality assurance throughout manufacture and storage, and by effective management throughout the life of the munition from initial design to final withdrawal from service. However, although much attention is paid to reducing the frequency of unintended initiations, virtually no attention is devoted to determining the value of that residual frequency.

The consequence part of the equation, indicating the probability of harm to people and property, is largely controlled by the segregation distance between the potential explosion site and people and property at risk.

The principal means used throughout NATO for reducing the risk of injury to persons or damage to property from unintended initiations of explosives are the Quantity-Distance (Q-D) Rules[2], whose precise basis is somewhat obscure. It has been stated[3] that they were formulated on the basis of assuming that an incident will occur at some time, in any facility where explosive substances are present and ensuring that the distance between facilities is such that when an unintended initiation occurs, the degree of risk to persons and damage to property will not be unacceptable. It should be noted that:

i Although acceptance is defined in terms of risk, requiring a frequency component, the assumed frequency of incidents is not specified.

ii Since the same basic Rules apply to storage, processing and manufacture, there is the implicit assumption that incident frequencies will be the same for these different functions.

iii There is no guidance as to level of risk that is 'not unacceptable'. This makes it difficult to see how changes in the public's attitude to risk could be reflected in the Rules.

iv Observance of the prescribed Q-D distances does not reduce casualty/damage probabilities for people/property to zero.

The Quantity-Distance Tables consist[2] of four matrices that prescribe about 1300 separate distances which depend upon the nature of the explosive (its Hazard Division), the type of storage building, the type of facility at the exposed site[+] and, in certain situations, the degree of protection available. The result of applying the Quantity-Distance Tables is the construction of what is effectively a "cordon sanitaire" around every building or facility in which explosives are held or handled, the magnitude of which depends on both the facility itself and the nature of the exposed sites surrounding it. This system requires a great deal of space which is not always readily available in regions that are densely populated, such as around ports where a local population has in many cases grown up around the waterfont from which a Navy operates.

There are at least three further areas of concern that arise from the use of the Quantity-Distance procedure to maximise safety:

i There are a significant number of situations in which strict adherence to the prescribed Quantity-Distances results in restrictions on the use of facilities which prevent those facilities being able to be used in a way that is operationally necessary to achieve their mission.

ii Risk is always present from the time the molecules of a chemical explosive are first created until their final destruction. The Quantity-Distance approach readily focusses in on situations in which the explosive is relatively static; it is extremely difficult to accommodate situations in which the explosive is mobile as in transit, although it is recognised that the risk levels are normally greater when the material is moved.

[+] An exposed site is one at which a person or facility may be subjected to blast, projections or thermal radiation.

Thus the Quantity-Distance procedure does not readily take the entire system into account in a single methodology.

iii The third problem is not strictly a problem of the Quantity-Distance procedure itself, but one of the perception of the procedure by many of those involved in applying it. Thus the Quantity-Distance procedure neither reduces the consequence of an accidental initiation to zero nor has any influence in reducing the frequency of such an initiation. Although readily apparent to every reader of this article, this is not understood by many including some with considerable experience in applying the procedure.

AIM

The aim of this series of papers is to describe an approach to the development of a Risk Assessment technique for use in the field of explosives and ammunition. This present paper concentrates on the analysis of risk in storage, although many of the concepts are immediately applicable to manufacture, processing and transport as well. It should be recognised that this paper reflects the views of the authors, but is in no way to be taken as representing the views of the UK Ministry of Defence.

BACKGROUND TO RISK ASSESSMENT

The technique of Risk Assessment was developed in the Nuclear Industry, building on an approach to reliability that was originally developed for the Defence and Aerospace Industries. It has been steadily developed and is now widely used in the Chemical Industry in continuous flow situations such as a petrochemicals complex. It has been used less frequently in batch process situations. A major explosives and ammunition facility introduces the possibility of a domino effect whereby an initial incident provokes a succession of further incidents.

The technique of Risk Assessment enables decisions to be taken to maximise safety within the constraint of reasonable practicability. In the field of explosives, it was first used in the UK in 1978 as the basis for resolving a problem at Garnock Wharf in Scotland, where it was found that a Leisure Centre which could be occupied by 4,500 people at peak times had been built across a river estuary 700 metres from a busy explosives wharf. Risk Assessment enabled a procedure to be developed whereby both the jetty and the Leisure Centre could continue to be used, albeit with restrictions imposed on both which reduced the level of risk from an accident to a point that was thought to be acceptable to the local population[4].

In 1971 the first quantitative Risk Analysis of an ammunition storage installation was presented to the Swiss Explosives Safety Board. The technique has now been adopted by the Swiss Department of Defence in the manufacture, processing, storage and transport of explosives and ammunition, although it has taken time to introduce and it will be not until 1995 that all Swiss facilities will have been assessed and licensed under the new Risk Assessment legislation. The Risk Analysis phase of the Swiss approach[5-10] differs markedly from that described in the present work in that the frequency analysis presented here is far more detailed. In the Swiss approach a combination of an analysis of historical data, a detailed investigation of how an explosion could occur using Fault Tree Analyses, and subjective expert opinion are all combined to determine a single national accident frequency. This single frequency is combined with a detailed consequence analysis[11-13] to determine the risk levels at each site. In contrast the present work determines a frequency that is specific to the munition, its location and how it is handled and stored. The Swiss technique is about to be introduced in Norway.

Since 1980 the French Explosive Regulations have been based on a Risk Assessment approach[14-16]. Materials are classified according to their UN Hazard Division and Compatibility Group;

five levels of initiation probability are defined depending upon the circumstances in which the material is present; five danger zones are defined in terms of the amount of explosive present and the degree of injury it will cause; installations which may be damaged are classified into 10 groups. The combination of initiation probability, danger zone and recipient installation is determined and compared to allowed combinations to determine whether or not a particular proposal is acceptable. The French system therefore incorporates a wider range of frequencies in the risk equation than the Swiss system, but nevertheless falls far short of the present work in that it restricts frequencies to a number of bands rather than treating frequency as a continuous variable.

Although a number of other countries have considered and indeed use aspects of Risk Analysis in the field of Explosives and Ammunition including Australia and the US Air Force, we are not aware of any further countries where a complete Risk Assessment approach is in use.

FIVE STAGES OF RISK ASSESSMENT

Risk Assessment can be divided into five stages:

i Hazard identification, which determines what can go wrong.

ii Hazard quantification or frequency analysis, which estimates how often things are likely to go wrong.

iii Consequence analysis, which determines the likely consequences of an initial incident.

iv Risk calculation, in which the results from the frenquency and consequence analysis stages are combined to estimate overall risk levels. Two different risk parameters, Individual Risk and Societal Risk, are usually employed.

v Risk evaluation, which considers whether or not the risk is acceptable.

The first three stages form the Risk Analysis and are the subject of this paper, whilst the last two stages are considered in Part II[17].

A most important finding of our work is that each stage of Risk Assessment yields valuable insight into the problems inherent in coping with high energy materials. There will be many situations in which improvements in safety can be achieved through the greater insight that a systematic Risk Assessment gives, without the need to complete all five stages.

HAZARD IDENTIFICATION

Although in the early stages of the work hazard identification was achieved in a brainstorming session involving a combination of people experienced in handling explosives and ammunition as well as those involved in Risk Analysis, this approach has now been systematised as has been done in the oil[1,18,19] and nuclear industries by developing a series of guide words. These guide words are developed by taking the view that any problem, be it a hazard or an operability one, can only arise when there is a deviation from the norm. They are then applied to search for every deviation in what is called a HAZOP study. In the present work 8 guide words were found to be useful:

NONE
MORE OF
LESS OF
PART OF
MORE THAN
LESS THAN
WRONG ADDRESS
OTHER

Towards the end of this work we learnt of a HAZOP study of an explosives manufacturing plant in which 7 guide words were used[20,21]. The 7 guide words which were virtually identical to the 8 used here, were:

NO, NOT, DON'T
MORE
LESS
AS WELL AS
PART OF
REVERSE
OTHER THAN

In order to undertake a HAZOP study an activity is selected and analysed as described in Figure 1. Figure 2 shows each of the guide words and gives examples of the deviations that have been identified using them. Thus it is apparent that MORE OF can arise when:

there is more explosive than expected,
more mechanical stress than is intended is applied,
    e.g. by dropping,
the temperature gets too high,
static electricity is present,
radio-frequency or ionising radiation is present,
overpressure is present,
there is flooding.

Having identified all the deviations that can occur the next stage is to look at their general causes, their specific causes and their consequences. Thus the general causes of overheating are fire and heat. The specific causes may be a grass fire, cigarettes, matches, fires in vehicles and so on. The consequences are that a fire or heat may be communicated to the explosive contents which may themselves burn, burn to detonation, or burn to mass explosion.

The particular advantages of using the HAZOP approach for hazard identification are:

i It is the best method currently available for identifying possible hazards; in particular its exhaustive systematic approach provides a natural

Figure 1

Flowchart for a HAZOP Investigation

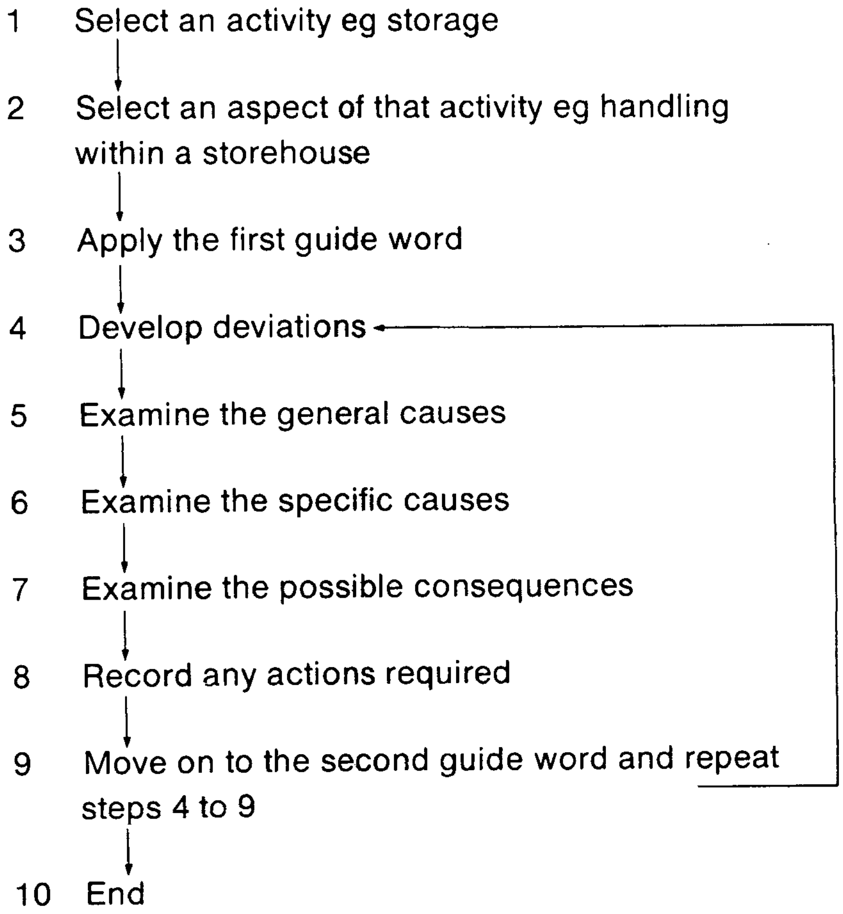


Figure 2

Use of Guide Words to Seek Deviations from the Intended Method of Operation

GUIDE WORD	DEVIATIONS
NONE	Actual intended operation not carried out - ie receipt not undertaken immediately or not carried out. Conveyance not completed, or not completed within usual time span Despatch not undertaken, or not undertaken immediately. Emptying wagons/vehicles not undertaken or not undertaken immediately Loading wagons/vehicles not undertaken, or not undertaken immediately.
MORE OF	More explosive present than expected Too much mechanical stress (impact/crushing) Higher temperature present than intended Electricity, eg static, present Radio frequency present Ionizing] radiation present Overpressure Water (flooding)
LESS OF	Less mass of explosive Low temperature (cold weather) Less of radio frequency, ionizing radiation, static electricity, overpressure or water are not applicable
PART OF	Misidentification Wrong packaging
MORE THAN	More explosive (eg 1.1) delivered Extra categories of explosive delivered (eg 1.2 and 1.1) Fuse detonator installed Check quality, eg impurities present or more active ingredients present than expected
LESS THAN	Package integrity Package not secure Safety devices missing
WRONG ADDRESS	Load delivered to wrong location, eg incorrect storehouse
OTHER	Other deviations from normal operations not included in above guide words

defence against any preconceived ideas the team undertaking the analysis may have.

ii It is particularly valuable for identifying hazards which involve extensive operator intervention, since it does not require preconceived ideas of a multitude of human error modes.

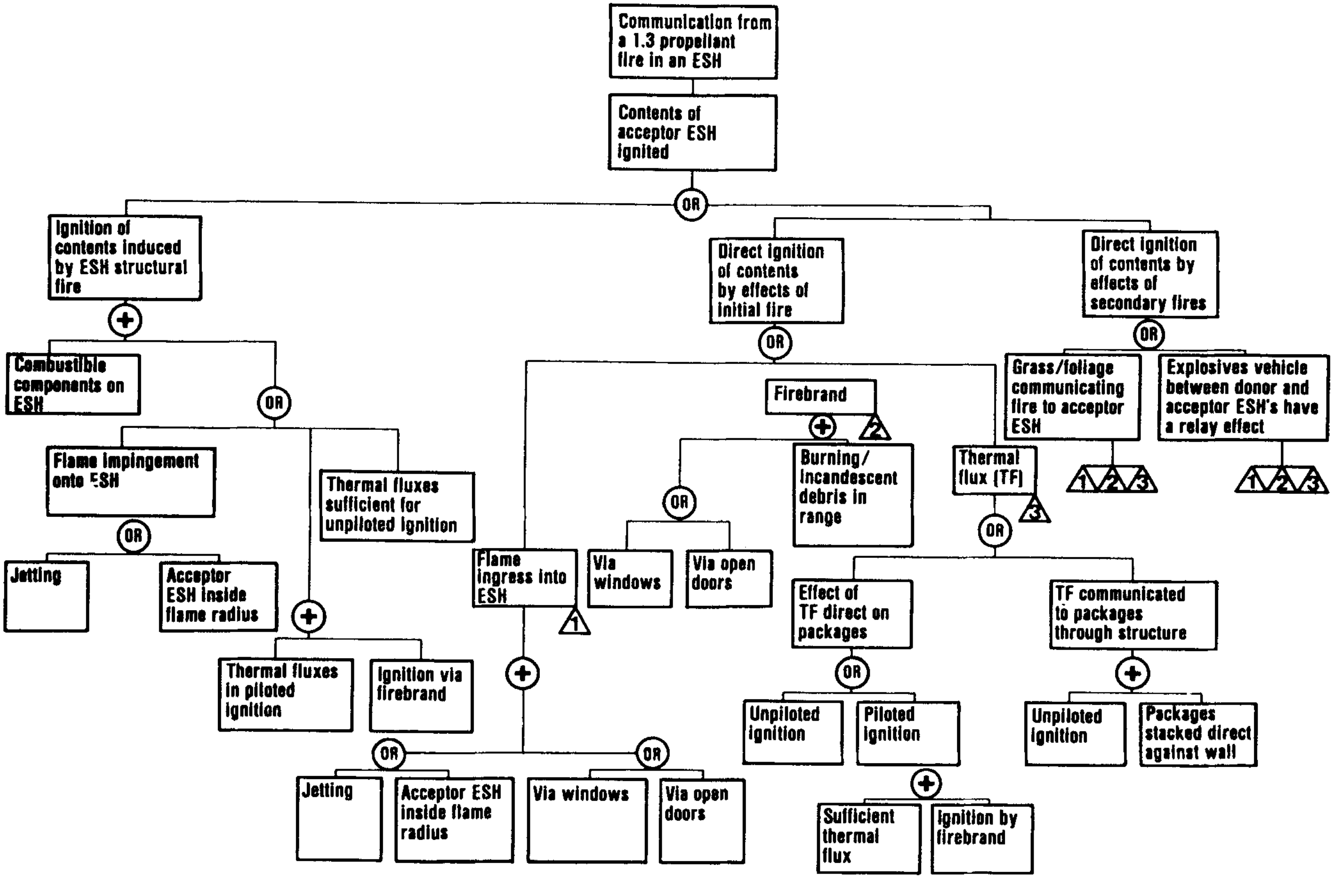
iii It provides a precise description of how a system should be operated, which enables realistic operating and maintenance procedures to be compiled.

iv It is relatively simple, so that the training needed to enable team members to take part is minimal. This enables experts in the operation and management of the facility being studied to be involved. Only the team leader requires the more comprehensive knowledge of the method such as a full-time safety analyst would have.

After considerable experience in applying the HAZOP technique the study team found that its use tended to become very mechanical. It is a lengthy process and tends to become routine and to dull the brain. As a team gains experience it may find it possible to distil that experience into a form of accident scenario checklists which effectively answer a series of "What If?" questions. The HAZOP procedure, however, provides an essential systematic approach for developing this experience.

In spite of its systematic approach the HAZOP technique would not normally be expected to identify every possible mechanism of failure, although it should identify most of the significant events by encouraging a systematic consideration of the relevant operations. The next stage is to fully systematise the operation by developing a series of Fault Trees[1,18], which take every top event possible and systematically determine their causes. Fault Trees can become extremely complex and there is always a need to balance the desire to include every possibility and so produce a completely general Fault Tree which may be

Figure 3 Communication of a Fire Arising from Burning Propellant from one Storehouse to other Explosive Storehouses (ESH)



applied to any site, with the problem that the resulting overcomplexity may make it extremely difficult to handle the Fault Trees, and identify the key sources of unintended initiations. In the present work Fault Trees were found to be very useful indeed. A typical Fault Tree for the communication of a propellant fire in one storehouse to another explosive storehouse is shown in Figure 3.

Fault Trees are a top down approach. Event trees[1,18] provide a bottom up approach to Risk Analysis which were used on a number of specific occasions when a single initiating event, such as a lightning strike, could lead to a number of top events. Event Trees were not, however as generally useful as Fault Trees.

Hazard identification using a combination of HAZOP, accident scenario checklists, Fault Trees and Event Trees is a complex process. It was therefore useful to use an independent team to check the thoroughness with which a Risk Analysis team could analyse a situation as complex as a major ammunition and explosive storage depot. The independent checking team found that:

i There were no accident scenarios that had been found to occur in the past[22,23] which had been missed.

ii The Fault Trees included all the credible events that the independent team was able to predict.

Thus the procedure described here yields a systematic and thorough understanding of what can go wrong in the facility being studied. And so, at the end of this first stage of Risk Assessment there is already a major advantage over the Quantity-Distance procedure which would be worth having even if Risk Assessment is taken no further, namely a detailed and thorough knowledge of the problems that the staff are trying to manage when dealing with explosives and ammunition.

Whilst the HAZOP approach provided a very valuable tool for analysing simple weapons, with more complex weapon systems, such as torpedoes, it was necessary to develop a "systems approach". This was achieved by developing the well-known Failure Modes and Effects Analysis (FMEA)[18] approach in such a way that:

i The analysis is based around a goal, which is the initiation of explosives.

ii Only failure events/scenarios which lead to the goal are investigated in depth. Individual causes of particular failure events are investigated if they are perceived by the participating experts as possibly significant.

This approach was called a Failure Modes Cause and Effects Analysis (FMCEA).

An FMCEA analysis is effected by first subdividing the complete weapon system into sub-systems. For a battery driven torpedo these are:

battery
fuze
warhead
homing/receiving unit
stabiliser section
control section
propulsion/motor section
afterbody.

Each sub-system is then examined as shown in Figure 4. In the case of the battery, FAILURE SCENARIOS at stage 3 would include:

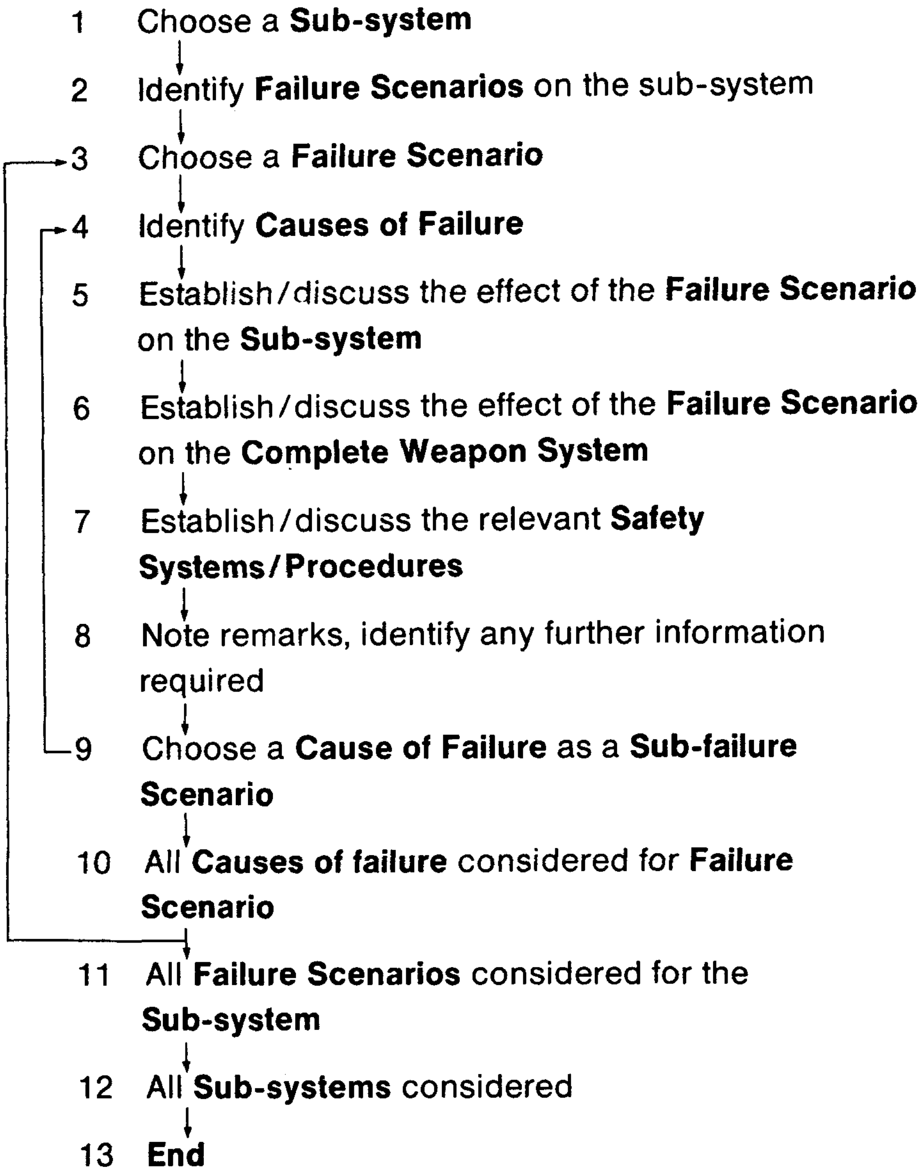
full priming of battery
partial priming of battery
electrolyte released into torpedo body.

SUB-FAILURE SCENARIOS at stage 9 that could lead to full-priming of the battery would include

mechanical damage/shock
turning of propeller blades
external fire

Figure 4

The FMCEA Methodology



1 Choose a **Sub-system**

2 Identify **Failure Scenarios** on the sub-system

3 Choose a **Failure Scenario**

4 Identify **Causes of Failure**

5 Establish/discuss the effect of the **Failure Scenario** on the **Sub-system**

6 Establish/discuss the effect of the **Failure Scenario** on the **Complete Weapon System**

7 Establish/discuss the relevant **Safety Systems/Procedures**

8 Note remarks, identify any further information required

9 Choose a **Cause of Failure** as a **Sub-failure Scenario**

10 All **Causes of failure** considered for **Failure Scenario**

11 All **Failure Scenarios** considered for the **Sub-system**

12 All **Sub-systems** considered

13 **End**

sudden pressure change or high nitrogen
filling pressure leading to body rupture
spurious electrical signal activates battery
solenoid.

The particularly valuable features of the FMCEA methodology include:

i Whole SUB-SYSTEMS can be considered and possibly eliminated from the analysis "at a stroke".

ii Particular CAUSES OF FAILURE can be investigated individually to any degree of detail required.

iii FMCEA sessions are reasonably successful in encouraging "brainstorming" to identify events; as already noted this can sometimes be stifled when too rigid and structured analysis such as HAZOP is used.

The result of the FMCEA analysis is the identification of all the possible failure events. These failure events can then be used as a basis for constructing Fault Trees.

HAZARD QUANTIFICATION

The second stage of Risk Assessment is to estimate how often things can go wrong. This is done by quantifying all the Fault Trees. This is a difficult and time-consuming exercise. The events on the Fault Trees fall into two major groups:

i Events that are specific to the explosives industry, such as the probability of a munition that is dropped accidentally initiating.

ii Events that apply to a much wider range of industries, such as the probability of a fork lift truck accident.

Determination of the frequencies of events that are specific to the explosives industry is difficult for two reasons:

i Incidents are mercifully relatively rare.

ii Testing is usually insufficient to give quantitative probabilities to rare events. For example, a drop test in which a given store is dropped 5 or 10 times from a given height does not give a lot of information about whether the probability of initiation is one in one hundred or one in a million.

Quantification of events that are common to many industries is relatively easy because there is a lot of data available. Where there is no historical data available to indicate the probability of a particular incident occurring then it is necessary, either to undertake some experimental determinations, or to use a panel of experts to provide estimates.

A very important aspect of hazard quantification is the assessment of human factors. Some of the more important factors which must be considered during the assessment of operator actions include:

effectiveness of management control,
effectiveness of supervision,
competence of personnel involved with explosives,
training of personnel,
time pressure for completion of tasks,
perceived vulnerabilities of explosives being handled.

Three main types of operator error arise:

i Operator actions which provide stimuli for the initiation or ignition of explosives, e.g. dropping material or piercing the container with a fork lift truck.

ii Ineffective mitigating action by the operator, including fire brigade personnel.

iii Failure of operators to detect a fire, damaged material or a damaged container.

The probability of an operator error arising is determined using a technique known as the SLIM-MAUD technique (SLIM = Success Likelihood Index Method)[24-28], which was developed for the US Nuclear Regulatory Commission. The technique assumes that the likelihood of an error occurring in a particular situation depends on the combined effects of a relatively small set of Performance Shaping Factors (PSFs). PSFs include human traits as well as characteristics of the task and the environment in which it is carried out. Human traits include operator competence (as determined by training and experience), morale, motivation etc. Characteristics of the task which affect performance include the time available, the complexity of the task and the quality of the procedures. Expert judges, who include both people with a detailed knowledge of the situation being assessed and experts in human reliability assessment, are used to identify the major PSFs that influence reliability for the performance of particular tasks. The SLIM procedure enables the judges to estimate the relative importance of the PSFs in determining reliability, and to rate each task on the PSFs.

When all the contributing events in the Fault Trees have been quantified either from historical accident data, or by experiment, or by estimation, the frequencies of the top events can be calculated. As soon as this has been done two further checks must be made:

i The sensitivity of the frequency of the top event to each of the estimated frequencies must be determined by altering the estimates and repeating the calculations. When this is done it is typically found that the frequency of the top event is only really sensitive to a few of the component Fault Tree frequencies. These frequencies are then examined with great care. If it is not possible to get a series of experts to agree on reasonable values for each of these frequencies, it may be necessary to undertake some trials to determine them experimentally. In looking at sensitivity, it should be appreciated that the proposed risk acceptance criteria are defined in terms of order of magnitude bands so that for example, sensitivity runs that brought about changes in the expected event frequency of say 20% → 30% would not be regarded as very significant in overall situations.

ii The calculated frequency of the top event must be compared with known historical experience; it is essential that frequencies synthesised from Fault Trees should be compatible with the actual frequencies with which such events have been observed to occur in the past or that there be valid reasons to explain any differences that are found (comparisons of this type are also useful for picking up any absurdities in the analysis).

The net result of quantifying the hazard is to allow those operating a facility to quickly identify the factors that primarily determine the frequency with which unintended initiations may occur, so enabling them to concentrate their resources in reducing these factors. In this way resources are developed to maximum advantage in terms of increasing safety.

CONSEQUENCE ANALYSIS

The analysis of the consequences of an initial incident depend critically on its location. In the UK explosives and ammunition are normally handled and stored either above ground or within about 100 feet of the surface in underground magazines. Accordingly the consequence of an event can be analysed in terms of:

i Blast overpressure created.

ii Projections emitted both from the ammunition itself, as fragments from the buildings in which it was contained, and from craters developed.

iii Thermal radiation emitted.

The absence of any magazines buried deeply into hard-rock mountains made it unnecessary to consider the effects of ground shock since any effects due to ground shock were always significantly less than those due to blast overpressure and projections.

The data on which the consequence analysis for the effects of blast and projections was based was essentially that which underpin the Quantity-Distance Rules[2] together with data available to the UK Ministry of Defence from a number of recent trials. In developing the consequence analysis it was necessary to examine in detail the original experimental data, during the course of which it became apparent that not all the original data are well-documented.

Most of the available data for determining the effects of thermal radiation from propellant fires are based on experiments using stacks of bare propellant. It was necessary to modify the results of such fires involving a very short sharp efflux of energy, to allow for the real situation in which both the packaging and the building surrounding the munition cause less intense fires of longer duration to burn. The effects of thermal radiation on people and structures were analysed using the considerable experimental data base built up within the chemical industry.

RISK LEVELS

As mentioned previously, the risks posed to the general public by potentially hazardous installations such as store-houses containing ammunition and explosives, are normally defined in terms of two parameters, Individual Risk and Societal Risk. Both are estimated using the data obtained from the frequency and consequence analysis stages. The precise process for calculating Individual Risk and Societal Risk will be described in Part II where the significance of each parameter will also be discussed. When risk levels were estimated it was of interest to find the facilities that were filled to capacity with material of Hazard Divisions 1.2 and 1.3, according to the limits determined from the current Quantity-Distance Rules[2], posed considerably lower risk levels than facilities filled with material of Hazard Division 1.1. Thus the current Quantity-Distance procedure does not result in equalisation of risk. Furthermore the Quantity-Distance procedure does not take account of the differences in vulnerability between different stores of the same Hazard Division. For example 1 kilogramme of gunpowder in a trade package is accorded the same weighting in the Quantity-Distance calculations as 1 kilogramme of high explosive within an unfuzed 1000 lb aircaft bomb encased in steel. When experts were questioned as to their view on the relative likelihood of a store-house accident involving these two materials, there was a clear expectation that an incident involving gunpowder was much more likely. This expectation was mirrored in the results from the Risk Assessment.

Once the risk levels have been estimated it is possible to identify low risk, intermediate risk and high risk situations. This is very important in that:

i It enables the very low risk situations to be neglected with confidence.

ii It enables the available resources to be concentrated initially in tackling the very high risk situations.

iii Once the high risk situations have been eliminated, resources can be devoted to determining how it is possible to reduce the risk levels of the intermediate situations.

The reduction of risk levels will not always involve the expenditure of money. The detailed understanding of the situation that the Fault Tree analysis gives may well indicate that a change of procedure can reduce the level of risk very significantly. Wherever risk levels can be reduced without the expenditure of excessive sums of money they must be. In this way the facility will be made as safe as is reasonably practicable.

This concept is developed further in Part II[17].

Once the level of risk posed by a facility to both its workforce and to those living, working and travelling nearby has been estimated, it may be possible to use this information in one of two further ways:

Either i it may be possible to reduce the risk levels still further by rearranging the contents of the various storehouses;

and/or ii it may be possible to repack the storehouses in such a way that more material is stored within the depot at no increased level of risk.

These possibilities arise because different stores containing explosives in the same Hazard Division have different risk levels associated with them. Thus it may be possible to repack a depot in such a way that high risk stores are placed in very remote locations whilst stores that pose a much lower risk are placed closer to locations where people or other facilities are present.

APPLICATION

The Risk Analysis method described in this paper has been applied to three major facilities, an Army storage depot, the explosives storage area of an operational Air Force base, and a Naval Ammunition Depot. These three facilities were manned by significantly different types of staff varying from all Service staff on limited-term tours of duty, through a mixture of Service staff on limited-term tours and civilian staff on relatively long or indefinite tours of duty, to an all civilian staffed depot. In this way the robustness of the method to three very different management structures was confirmed.

During the course of the work the technique has been applied to explosives and propellants in trade packaging, plastic explosive in the form of 8 oz cylindrical charges wrapped in wax paper and stored in boxes, complete rounds of ammunition, guided missiles and torpedoes. A number of different types of store have been examined including traversed open-air bomb bays, and traversed stores of both nissen hut and brick infill on a steel frame construction. A range of different mechanical handling devices have been studied including cranes, fork lift trucks, narrow gauge railways, road based tractors and trailers, lorries and standard gauge railways. Although the list of explosive items, stores and mechanical handling devices studied is not comprehensive, it is sufficiently representative to give confidence that the method is capable of extension to all explosive and ammunition storage facilities.

CONCLUSIONS

A method has been developed for analysing the risks inherent in storing explosives and ammunition. The particular contribution of the present work lies in the development of a means for estimating the frequencies with which unintended initiations may be expected to occur. Previous work in other countries has not involved a detailed analysis and determination of individual event frequencies. The method has been successfully applied to a wide range of explosive items, stores and mechanical handling devices within facilities operated under the different management structures of the three Services.

The criteria for assessment of risk levels are considered in the following paper[17]. Further work will involve extension of the technique to the processing, manufacture and transport of explosives and ammunition.

ACKNOWLEDGEMENT

The generous cooperation of the three Services in providing access to their facilities, and the advice and pertinent comment of Mr B. H. Harvey CBE are all gratefully acknowledged.

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