Risk Benchmarks for the Siting of Military Explosive Facilities

ABSTRACT

Quantity Distance (QD) criteria, which take into account the quantity and hazard division of explosives to determine a safe separation distance, have been used in the safe siting of military explosive facilities for the past 80 years. Since the 1980s, it has been recognised that the QD approach can be complemented by considering the likelihood of an accident based on the type of activity, the number of people involved and the construction of the facility. Many nations have since developed Quantitative Risk Assessment (QRA) models to understand the risks better. QRA calculates the probability of fatality and predicts the number of fatalities and injuries in the event of an accidental explosion. The information obtained is useful in risk management. However, a pertinent question arises: How safe is safe? This article explores quantitative benchmarks for explosive risk management – based on comparisons with local industrial accident data, common causes of fatalities in Singapore, and precedents in international regulatory standards for explosive risk management. The data are displayed in a Risk Scale format that enables easy comparison of the proposed criteria with various risk figures.

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INTRODUCTION

There are inherent risks in the activities involving military explosives. In the Singapore Armed Forces (SAF), a robust safety management system for military explosives and explosive facilities is in place to reduce the chance of an accident occurring as well as to limit the damage should an accident occur. The latter is managed by imposing limits on the quantity of explosives, and the enforcement of a safe separation distance – Quantity Distance (QD) – between a Potential Explosion Site (PES) and an Exposed Site (ES) where personnel are present. The SAF has adopted the UK JSP 482 as the standard for QD.

In land-scarce Singapore, there are occasionally situations where QD cannot be met. This is due to Singapore's high population density and the proximity of inhabited buildings to military explosive facilities. The consequences of deviating from QD need to be understood, so that decision makers are accurately informed of the risks. Accurate information on the risks facilitates risk management (Figure 1).

The risk-based approach uses Quantitative Risk Assessment (QRA) software to quantify the risk to personnel. The results are compared to a set of criteria and a decision is made to accept, reject or modify the sources of risks. The US, UK, Australia, the Netherlands and Switzerland have adopted the risk-based approach for the siting of explosive facilities when QD cannot be met (Figure 2).

In line with international practices, DSTA recognised that the risk-based approach has the potential to complement the QD approach for the siting of military explosive facilities.

SAFER V3 QUANTITATIVE RISK ASSESSMENT SOFTWARE

Safety Assessment for Explosives Risk (SAFER) is an internationally recognised QRA software model sponsored, developed and approved by the US Department of Defense (DoD) Explosives Safety Board (DDESB) for US DoD risk-based explosives safety siting and risk management analysis. SAFER v3 is used by the US Army, Navy, Air Force and Marine Corps for the siting of military explosive facilities.

In 1997, the DDESB formed the Risk-based Explosives Safety Criteria Team (RBESCT) to develop the risk-based approach for US DoD to manage the siting of explosive facilities. The RBESCT comprised members from DDESB,

Figure 1. Risk management

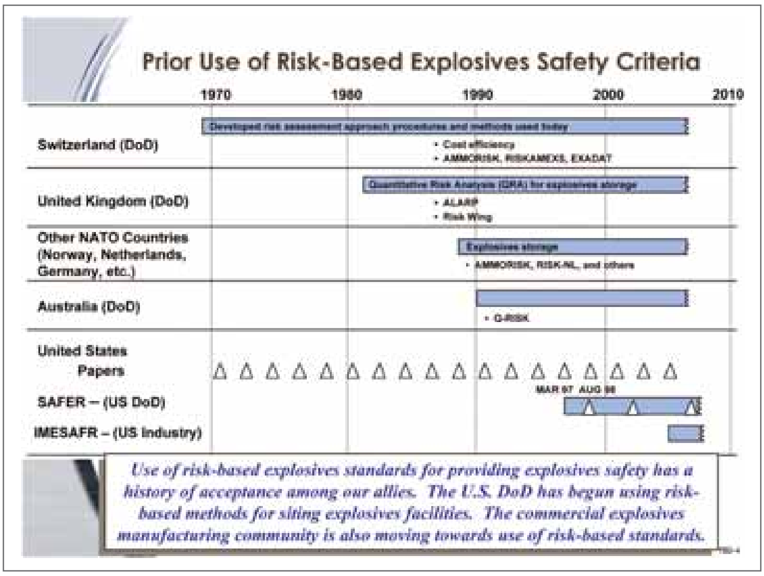

Figure 2. Countries that use QRA software for risk-based explosives siting (Young et al, 2007)

the US Army, Navy, Air Force, Marine Corps, international subject matter experts and risk analysis companies. APT Research Inc, a DoD contractor specialising in safety engineering, developed the SAFER software.

In 2005, with the permission of DDESB, DSTA acquired the SAFER v3 software and training package to enhance the risk assessment capability of the Singapore Armed Forces Ammunition Command. The software tool provides quantified information of risk, facilitates the comparison of risk and the allocation of resources to mitigate risk, and decision making given the knowledge of the actual risk.

SAFER V3 QUANTITATIVE RISK OUTPUT AND ITS APPLICATIONS

Quantitative risk is typically expressed in terms of probability of accident, probability of fatality given the accident, exposure of personnel, individual risk, group risk, number of fatalities and number of injuries. SAFER v3 computes these risk figures, which are useful for operational explosive risk management in terms of risk identification, assessment, mitigation and acceptance. The definition of the risk terms are described in the following sections.

Definitions

Individual risk P_f is the likelihood that a person in an ES will die from an unexpected explosion. It is computed by multiplying the probability of an event (probability of accident) P_e, the probability of a fatality given the accident has happened $P_{f|e}$, and personnel exposure E_p:

$$P_f = P_e \times P_{f|e} \times E_p$$

Group risk E_f is the risk experienced by a group of people exposed to the explosives hazard. It is the sum of all individual risks in an ES:

$$E_f = \sum (P_e \times P_{f|e} \times E_p)$$

Risk Benchmarks (also known as Risk Criteria) are standards used to translate numerical risk estimates produced by a QRA into value judgements (e.g. negligible risk) that can then be set against other value judgements (e.g. high economic benefit) in the decision-making process. Simply put, risk benchmarks are used to help one decide whether the risk associated with a project or activity is low enough to proceed with the activity (Lewis, 2007).

Risk Figures where the Accident is Possible (Probability of Accident <1)

Probability of Event. This is also known as the probability of accident. Through the RBESCT, US DoD provides the probability of an accident for a specified explosive activity. This could be benchmarked to the limits defined by the UK Health and Safety Executive (HSE): the maximum probability of an accident causing the death of 50 people or more in a single event should be less than 1 in 5,000 (i.e. 2×10^{-4}).

Individual Risk and Group Risk. Individual and group risks can be compared with the risk criteria established by the US and the UK to benchmark safety. When there are many PESs generating risk to a single ES, these risks can also be used to identify the PES that generates the greatest risk.

Consequence Figures when the Accident has Occurred (Probability of Accident = 1)

Number of Fatalities, Major Injuries and Minor Injuries. The fatality and injury predictions can be communicated to commanders to make a risk-informed decision whether or not to proceed with the operation.

Probability of Fatality Given that the Accident has Occurred. SAFER gives the probabilities for 1) overpressure resulting in lung rupture, body displacement or skull fracture; 2) structural failure such as broken glass or building collapse; 3) debris comprising both vertical and horizontal debris; and 4) thermal effects. By comparing the results, the main cause of fatality and injury can be determined. The appropriate mitigation measures to reduce the likelihood of injury can also be implemented.

SAFER increases understanding of the dimensions of risk

Risk has two dimensions – probability of occurrence and consequence. SAFER v3 increases our understanding of risk by giving information on both dimensions. In comparison, the traditional methods (QD) focus only on the consequence aspects of risk.

Examples, explanations and the applications of Quantitative Risk figures are summarised in Tables 1 and 2.

QUANTITATIVE RISK BENCHMARK DEVELOPMENT

Risk criteria are used to help one decide whether the risk associated with an activity is low enough to proceed with the activity. Although the risk criteria of the US and the UK can be used as a guide, different countries have different tolerance levels and attitudes on the amount of resources that should be devoted to mitigate risk.

With reference to how DDESB and RBESCT developed the US risk criteria, we have

Type of Risk Output	Example	Remarks	Use of Risk Figure
Probability of Event P_e	2x10^{-4} event per year	Two explosive events are expected to occur in 10,000 years in this PES.	Benchmark to UK limits for probability of event.
Individual Risk P_f	1x10^{-6} fatality per year	One fatality in a million years, or 10 fatalities in 10 million years.	Compare to individual and group risk criteria to benchmark the safety.
Group Risk E_f	1x10^{-5} fatality per year	If 100,000 persons are exposed for one year, one fatality is expected. Alternatively, if a person is exposed for 100,000 years, one fatality is expected.	Identify the PES that generates the greatest risk to that ES for mitigation efforts.

Table 1. Examples of SAFER output in the event of a possible accident (probability of event < 1)

Type of Risk Output	Example	Remarks	Use of Risk Figure
No. of fatalities N_f	1 person	Fatal, not fully reversible even with medical care.	Communicate to decision makers the number of fatalities, major and minor injuries (assuming an accident happens).
No. of major injuries	10 persons	Hospitalisation required, non-reversible.	
No. of minor injuries	100 persons	Outpatient treatment, reversible.	
Probability of fatality from: 1) overpressure 2) thermal effects 3) building collapse 4) debris	2x10^{-6} fatality per event – person	If one million people are at the ES for one event, two fatalities are expected from overpressure, thermal effects, building collapse or debris. Alternatively, one million events will result in two deaths if one person is present at the ES.	Compare to identify the main cause of fatality (blast, thermal, building collapse or debris) for mitigation efforts.

Table 2. Examples of SAFER output where the accident has happened (probability of event =1)

considered the following factors to support our proposed risk criteria for Singapore:

a. Precedents in international and Singapore regulatory standards

b. Risk levels accepted by workers in other industries in Singapore

c. Experience in using QRA in the SAF

d. The Singapore Universal Risk Scale

INDIVIDUAL RISK CRITERIA

Precedents in International Regulatory Standards

According to the ammunition storage regulations of various countries (Table 3), an individual risk criterion of 1×10^{-6} is a widely accepted level of risk for members of the public i.e. one fatality in a million years, or 10 fatalities in 10 million years. This level of risk is also considered by the UK HSE to be very low (i.e. in the range of broadly acceptable) (JSP 482, 2006).

Precedents in Singapore Standards

The QRA approach is used not only for safety of explosives, but also that of potentially hazardous industries such as nuclear power, space systems and chemical plants. A comparison is done with other standards in Singapore, specifically the criteria set by the National Environment Agency (NEA) for installations which store, transport or use hazardous substances (Table 4). According to NEA, the first contour with an associated risk of 5×10^{-5} and above is the individual risk permissible to workers and the third contour with an associated risk of 1×10^{-6} is the maximum individual risk permissible for the public. The latter supports the statement that "1×10^{-6} is considered as low risk and may be a suitable limit for explosives risk to the public in Singapore".

Ammunition Storage	Individual Risk	
	Worker	Public
US (DDESB)	1.00×10^{-4}	1.00×10^{-6}
Switzerland (TLM 75)	1.00×10^{-4}	1.00×10^{-5}
Norway (MOD)	4.00×10^{-5}	2.00×10^{-7}
Sweden (MOD)	Not Available	1.00×10^{-6}
UK (HSE)	1.00×10^{-3}	1.00×10^{-6}
The Netherlands (existing facilities)	Not Available	1.00×10^{-5}
The Netherlands (new facilities)	Not Available	1.00×10^{-6}
Australia	5.00×10^{-4}	1.00×10^{-6}

Table 3. Precedent regulatory standards for individual risk (TP 14, 2007)

Individual Fatality Risk (IR) Contours	Remarks
5×10^{-5}	Contour remains on-site
5×10^{-6}	Extends into industrial developments only
1×10^{-6}	Extends into commercial and industrial developments only

Table 4. NEA guidelines for Quantitative Risk Assessment (NEA, 2008)

Risk Levels Accepted by Workers in Various Industries in Singapore

The level of risk for the workers in the service sectors is 1.2×10^{-5} from 2006 to 2008. This is lower than all international standards for explosive risk management (Table 3) and is not comparable to typical risk levels for explosives. For reference, the total number of fatalities (67) over the total number of service workers (5,600,166), gives us 1.2×10^{-5}.

We identified both the construction and manufacturing industries as suitable benchmarks to find the upper limit of the risk levels acceptable by workers in jobs with higher risk. Employment and fatality statistics (Ministry of Manpower, 2009 and 1996-2008) are tabulated to obtain the average annual fatality risk for these two industries. Statistics are taken only from

Industry (2001 – 2008)	Average Annual Fatality Rate
Construction	1.10×10^{-4}
Manufacturing (including shipbuilding and repairs)	1.17×10^{-4}

Table 5. Average annual fatality rate for other industry workers in Singapore

years 2001 to 2008 for a more conservative estimation of risk as earlier years reflect higher fatality rates. The risk figures derived are shown in Table 5.

Possible Risk Levels for Explosives Workers in Singapore

Considering the level of risk experienced by workers in the construction and manufacturing industries in Singapore, it seems appropriate for us to adopt 1×10^{-4} as the upper limit for explosives workers. This is to ensure that the level of explosive risk is not higher than the risk experienced by workers in high-risk industries in Singapore. 1×10^{-4} is also the individual risk limit for Swiss and US explosives workers.

Past Experience in Using QRA in the Singapore Military

For the Underground Ammunition Facility (UAF) in Singapore, QRA was conducted for the engineering systems as well as other systems, sub-systems, as well as explosives storage and processes. The results of these analyses were integrated to form the overall safety case for the facility. During the integration and endorsement process, the question was asked – how many fatalities could be expected during the design life of the facility? The summation of risks was conducted to arrive at the total expected fatalities for the UAF. It was concluded that the summation of risks represented a good indication of the overall safety integrity of the facility and made it easier for the risk acceptance authority in decision making. It also facilitated comparison of the risk of a single high-risk hazard to the cumulative risk of many low-risk hazards, thereby providing better resource allocation to tackle scenarios that warrant the highest attention (Zhou et al, 2008).

The proposed criterion of 1×10^{-4} for the individual risk of personnel directly involved is comparable with the summed individual risks in the UAF. This indicates that the figure of 1×10^{-4} can be a reasonable and practicable individual risk criterion for explosives workers.

UNIVERSAL RISK SCALE

The US RBESCT uses the Universal Risk Scale (URS) to assist in selecting the appropriate risk criteria (Rufe and Pfitzer, 2001). Decision makers are able to compare explosives risk to other common risks in order to better understand the risk figures. The URS uses a log scale to display the wide spread of data. This is not only for the convenience of displaying many different risks in a single space, but also to allow for better comparisons of relative risk in orders of magnitude so that the concept of risk can be more properly understood.

There are two types of information shown in the URS. The first comprises various risk-related legal precedents and governmental standards, while the second comprises real-world statistical data derived from documented accident experience (TP 14, 2007). Voluntary and involuntary risks associated with different modes of fatalities are shown in the scales and compared against regulatory standards, where voluntary risks are used for

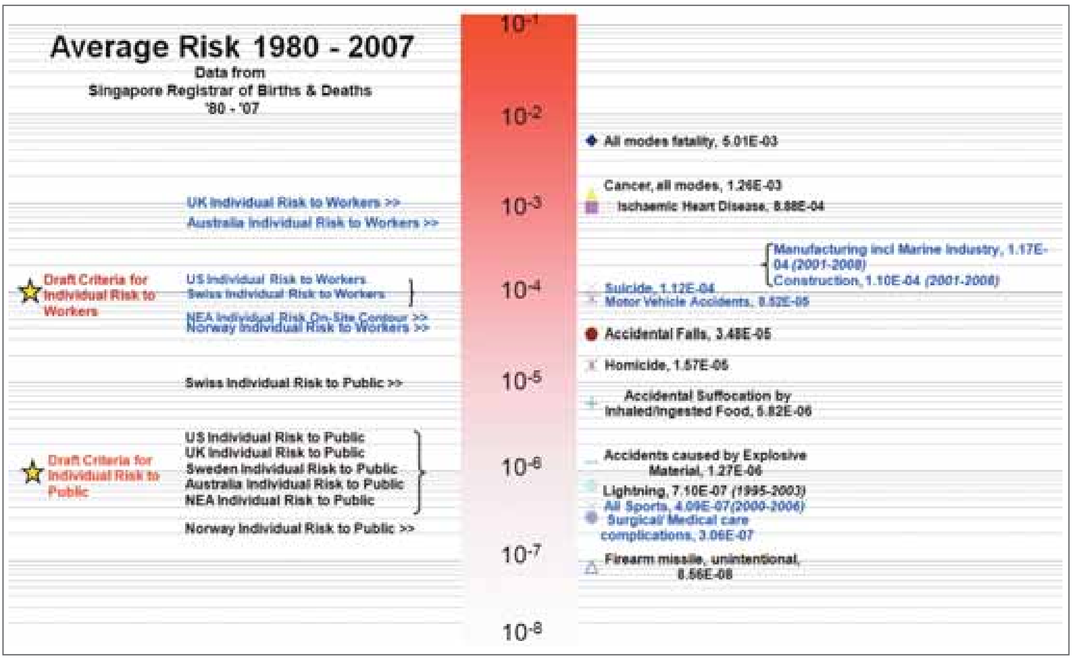

Figure 3. Singapore URS for individual risk (proposed worker and public individual risk criteria for explosives risk)

workers and involuntary risks for the general public. All data are shown in terms of annual risk.

Singapore's Universal Risk Scale. To understand risks for Singapore, voluntary and involuntary Individual Risk and Group Risk URS were prepared (Figure 3). Data from explosive risk criteria established for use in foreign countries (TP 14, 2007) as well as Singapore death statistics (Registrar for Births and Deaths, 1980 to 2007) were used. The average annual risk from each cause of fatality e.g. cancer was calculated by summing the total deaths from cancer from 1980 to 2007, then dividing it by the summed population from 1980 to 2007.

The right side of the Singapore URS for Individual Risk consists of all the data compiled from Singapore statistics and the left side consists of regulatory standards as well as the two proposed draft criteria for explosive risk. The items in blue refer to voluntary risks and are compared to risks undertaken by explosives workers.

Proposal Individual Risk Criteria for Singapore. As shown on the Individual Risk Singapore URS (Figure 3), the proposed individual risk criteria of 1×10^{-4} for explosives workers, and 1×10^{-6} for the public are widely accepted by various other countries and compare reasonably with other common risks in Singapore.

GROUP RISK CRITERIA

Individual risk does not take into account the total number of people at risk from a particular event. Hence, an individual risk criterion alone is insufficient to regulate explosives risk. Realised hazards that affect society can have adverse repercussions for institutions responsible for putting in place provisions and arrangements for protecting people e.g. Parliament and the Government. This type of concern is associated with high-casualty or multiple-fatality events which are likely to provoke a socio-political response (HSE 2001). There is hence a need for regulation to control the explosives risk exposure to a group of people. Group risk criteria would be an overlay of protection to the individual risk criteria.

UK Approach to Group Risk

The SAF adopts the UK standard, JSP 482, for explosives siting. JSP 482 primarily contains guidance for QD siting. However, JSP 482 also advises adopting a risk-based approach when QD cannot be met, along with UK-approved individual and group risk criteria. We should therefore assess the suitability of the UK risk criteria for application to the Singapore context. The UK individual risk criteria are shown in Figure 3.

The UK approach to group risk (known as societal risk) for explosive hazards is an *f-N* graph. The frequency, *f*, of any individual event which may lead to *N* fatalities is plotted as a scattering of points. The rationale for multiple pairs of *f-N* data is that explosive accidents have wide ranges of frequencies and outcomes, depending on the individual circumstances such as weather conditions.

The UK Explosives Storage and Transport Committee (ESTC) has established criteria for societal risk in the form of a red line with slope of -1. This is shown in Figure 4. The maximum probability of an accident causing the death of 50 people or more in a single event should be less than 1 in 5,000 (2×10^{-4}), and any situation which could give rise to a societal risk of greater than 50 fatalities overall, or more than 10 fatalities of members of the general public, must be viewed with great concern. The *f-N* graph plotted for the situation under study must fall below the ESTC societal risk criteria.

The *f-N* curve is resource intensive and the required software, country-specific empirical/field data and skills necessary for this approach are not available to us. Hence, the implementation of the f-N graph would not be feasible in our local context.

US Approach to Group Risk

The US has also derived their group risk criteria using a graph of the accident frequency versus the number of fatalities with lines of slope -1, which can be described by the risk measure of annual expected number of fatalities (Pfitzer, 2008). The DDESB group risk acceptance criterion for all workers is 1×10^{-3} to 1×10^{-2}, while the US group risk acceptance criterion for the public is 1×10^{-5} to 1×10^{-3} (TP 14, 2007).

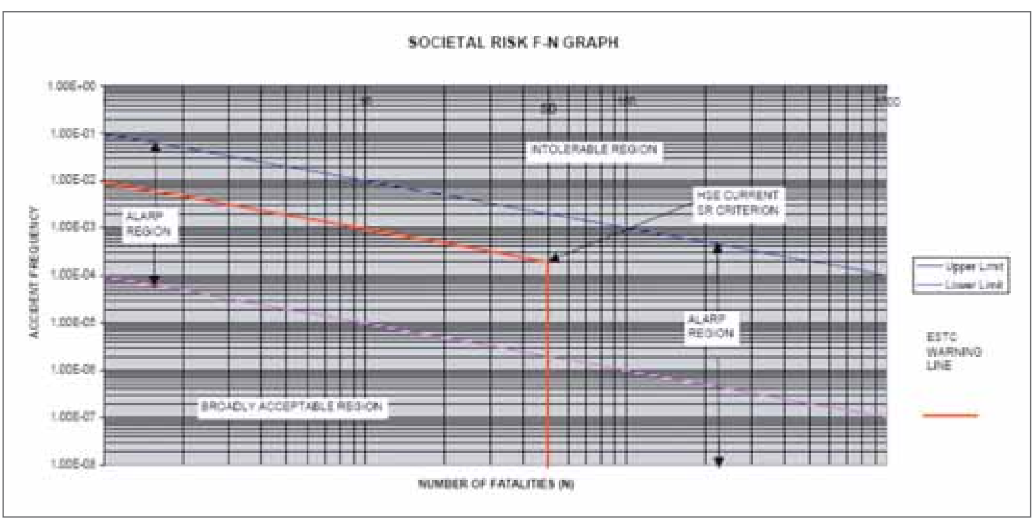

Figure 4. UK ESTC societal risk criteria (JSP 482)

The implication is that for workers in explosive facilities in the US, there are attempts to lower the group risk to 1 x 10^{-3} as a workers' group risk above 1x 10^{-2} is only accepted with significant national need. The lower limit can be considered the actual risk criteria. The upper limit can be considered an 'intolerable' limit. The region between the lower and upper limits is known as the 'ALARP' region, where efforts must be made to decrease the risk to As Low As Reasonably Practicable (ALARP).

The approach is similar for the US public group risk, but with more stringent upper and lower criteria.

Proposed Group Risk Criteria for Singapore

In evaluating the actual figures for group risk, we propose to use the URS for voluntary and involuntary risks. For the US RBESCT, the number of persons surrounding a post, camp or station may be 1,000 (Rufe and Pfitzer, 2001). In our context, our ammunition depots are usually situated away from built-up areas. Nevertheless, taking into account our population density of 5,000 per square kilometre, we believe that 1,000 is a conservative and reasonable figure. Hence, we propose to use 1,000 as the normalisation for voluntary and involuntary group risks in our URS as well.

In addition, due to societal concerns, it is appropriate to recommend an ALARP region, where risk mitigation is performed for any activities which have associated risks above the lower limit.

Proposed Public Group Risk Criterion. From the URS (Figure 5), it seems reasonable to propose the preliminary risk criterion for the public as 1 x 10^{-5} to 1 x 10^{-4}. The upper limit is set in view of the fact that it is below most involuntary risks. The US has set the public group risk criterion to 1 x 10^{-5}. This is deemed conservative but may be appropriate for the lower limit.

Proposed Explosives Workers Group Risk Criterion. For explosives workers, the

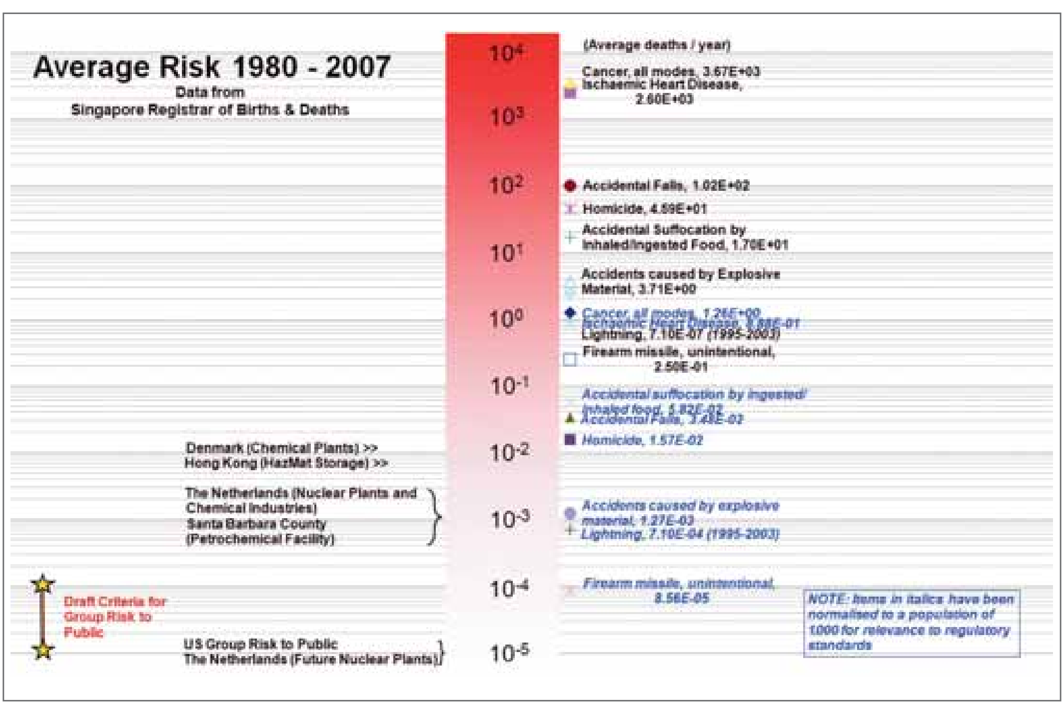

Figure 5. Singapore URS for involuntary group risk (proposed public group risk criterion)

Figure 6. Singapore URS for voluntary group risk (proposed explosives workers group risk criterion)

recommended criterion is 1 x 10^{-4} to 1 x 10^{-3} (Figure 6). It should be noted that 1 x 10^{-3} is the UK maximum tolerable limit for workers, and is the same risk criterion for US. The lower limit of 1 x 10^{-4} is proposed to express a desire to limit the explosives risk to be below that of other risks, such as the risk of fatality from sports, surgical or medical care complications.

RECOMMENDATIONS

Risk benchmarks are used to help decision makers decide whether the risk associated with an explosive related activity is low enough to proceed with the activity. The upper limit is a measure of management's tolerance of risk. Defining the risk benchmarks for individual and group risk to workers and to the public demonstrates transparency in the QRA process.

In the selection of the US criteria, RBESCT had first recommended a 'Strawman Criteria' (Pfitzer and Rhodes, 1998) for trial use. Upon further review and examination, this was amended to arrive at the final risk criteria approved by the DDESB in December 1999 (TP 14, 2007).

The proposed risk-based acceptance criteria for explosives safety in the Singapore context, summarised in Table 6, should similarly be reviewed after a trial period of a few years to ensure that it is robust for risk management and yet practical for use.

Type of Explosives Risk Benchmark	Proposed Quantitative Risk Benchmark
Individual Risk to Workers	1 x 10^{-4}
Individual Risk to the Public	1 x 10^{-6}
Group Risk to Workers	1 x 10^{-4} to 1 x 10^{-3}
Group Risk to the Public	1 x 10^{-5} to 1 x 10^{-4}

Table 6. Summary of proposed quantitative risk benchmarks

CONCLUSION

QRA is not a replacement for QD. Risk-based explosives siting using QRA should only be applied when QD requirements cannot be met. QRA may be used in conjunction with systems safety as QRA enables a better understanding of the actual risk. The risk can then be effectively mitigated and reduced and also appropriately communicated to decision makers. Risk criteria serve as guidelines in risk management by providing benchmarks on the level that is considered tolerable. However, risk should always be reduced to ALARP and risk mitigation has to remain as a key defence against accidents.

REFERENCE

Hirst, L., and D. A. Carter. 2002. A 'Worst Case' Methodology for Obtaining a Rough but Rapid Indication of the Societal Risk from a Major Accident Hazard Installation. Journal of Hazardous Materials A92: 223 – 237.

Institution of Chemical Engineers. 2006. An Independent Review of HSE Methodology for Assessing Societal Risk. UK Health and Safety Executive.

Lewis, S. 2007. Risk Criteria – When is low enough good enough? Risktec Solutions Limited.

Pfitzer, T. 2008. Roadsigns in Risk Space. Presentation at the 3rd International Association for the Advancement of Space Safety Conference, 21–23 October, in Rome, Italy.

Pfitzer, T., and M. H. Rhodes. 1998. Risk-Based Explosive Safety Methods. APT Research, Inc.

Rufe, J., and T. Pfitzer. 2001. Criteria Selection for Risk-Based Explosive Safety Standards. APT Research, Inc.

Singapore Immigration and Checkpoints Authority. Registry of Births and Deaths 1980 – 2007. Report on Registration of Births and Deaths.

Singapore Ministry of Manpower. 2009. Employment Statistics. http://www.mom.gov.sg/publish/momportal/en/communities/others/mrsd/statistics/Employment.html (accessed 1 August 2009)

Singapore Ministry of Manpower. 1996 – 2008. Workplace Injuries by Industry and Degree of Disablement.

Singapore National Environment Agency. 2008. Pollution Control Department (PCD) Guidelines for Quantitative Risk Assessment (QRA) Study (For Installations Which Store, Transport Or Use Hazardous Substances).

UK Ministry of Defence Explosives Storage and Transport Committee. 2006. JSP 482 MoD Explosives Regulations. Explosives Storage and Transport Committee, UK Ministry of Defence.

US Department of Defense Explosives Safety Board. 2007. Technical Paper 14 Approved Methods and Algorithms for DoD Risk-Based Explosives Siting.

Young, P.G., C.D. Douthat, and R. Baker. 2007. Risk-Based Siting Process For Ordnance Removal Operations Utilizing Safety Assessment for Explosive Risk. Presentation at the National Defense Industrial Association Demilitarization Conference on 17 May, in Reno, Nevada, US.

Zhou, Y., H.L. Ong, Y.M. Tan, and Y.S. Fan. 2008. Quantification and Summation of Hazard Risks in Facility System Safety Analysis. Paper presented at the International System Safety Regional Conference, 25 April, in Singapore.

BIOGRAPHY

Audrey Lao Linmei is a Senior Engineer (Armament Systems – Explosives Safety). She is involved in safety assessment reports for the safe storage of explosives on board surface ships and submarines and has conducted hazard classification testing of ammunition. Audrey is developing a hazard classification implementation policy and is leading the development of the risk-based explosives safety siting in the Singapore Armed Forces (SAF). She graduated with a Bachelor degree in Chemical Engineering (Honours) from the National University of Singapore (NUS) in 2005.

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