Consequence Analysis Software in support of Ammunition and Explosives Risk Assessment Safety Cases: Canadian Department of National Defence

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Introduction

Potential explosion sites (PES) containing Ammunition and Explosives (A&E) present an obvious risk to people and property. Such sites are usually located at carefully calculated distances from each other, other structures, and public assembly areas to ensure the minimum practicable risk to life and property relative to operational necessities. These distances are termed Quantity Distances (QD) and are a function of the Net Explosive Quantity (NEQ) and the Hazard Division (HD) of the ammunition and explosives present at the PES. When QD cannot be met, a risk assessment should be conducted. Risk assessments can be quantitative or qualitative and may involve the use of computer software.

Background

It is impracticable to prescribe distances which would be safe in the true sense, i.e. which would guarantee absolute immunity from propagation, damage to material/infrastructure or injury/death of people. Therefore QDs represent a tolerable compromise between absolute safety and practical considerations. Distances greater than those prescribed may be used, in particular to provide greater protection for vital Exposed Sites (ES) or national contingency stocks.

QD is primarily consequence-based, which means that the occurrence of an accidental explosion is assumed.[i] The probability of an event is thus not considered in a QD calculation. The QDs between a PES and an ES recommended in NATO Allied Ammunition Storage and Transport Publication 1(AASTP-1)[ii] therefore represent a compromise deemed tolerable by the NATO Allied Committee 326 (AC/326) group of experts between absolute safety and practical considerations including costs and operational requirements. The QD are based on the analysis of data collected through allied nations' explosives trials and explosive accidents which have occurred around the world using blast as driving factor. In recognition of the specific requirements for operations, NATO AASTP-5[iii] specifies Field Distances (FD) equivalent to QD for storage structures on deployed missions.

Figure 1 is an illustration of a number of QD typically used when developing an Explosives Safety Siting Plan (ESSP).

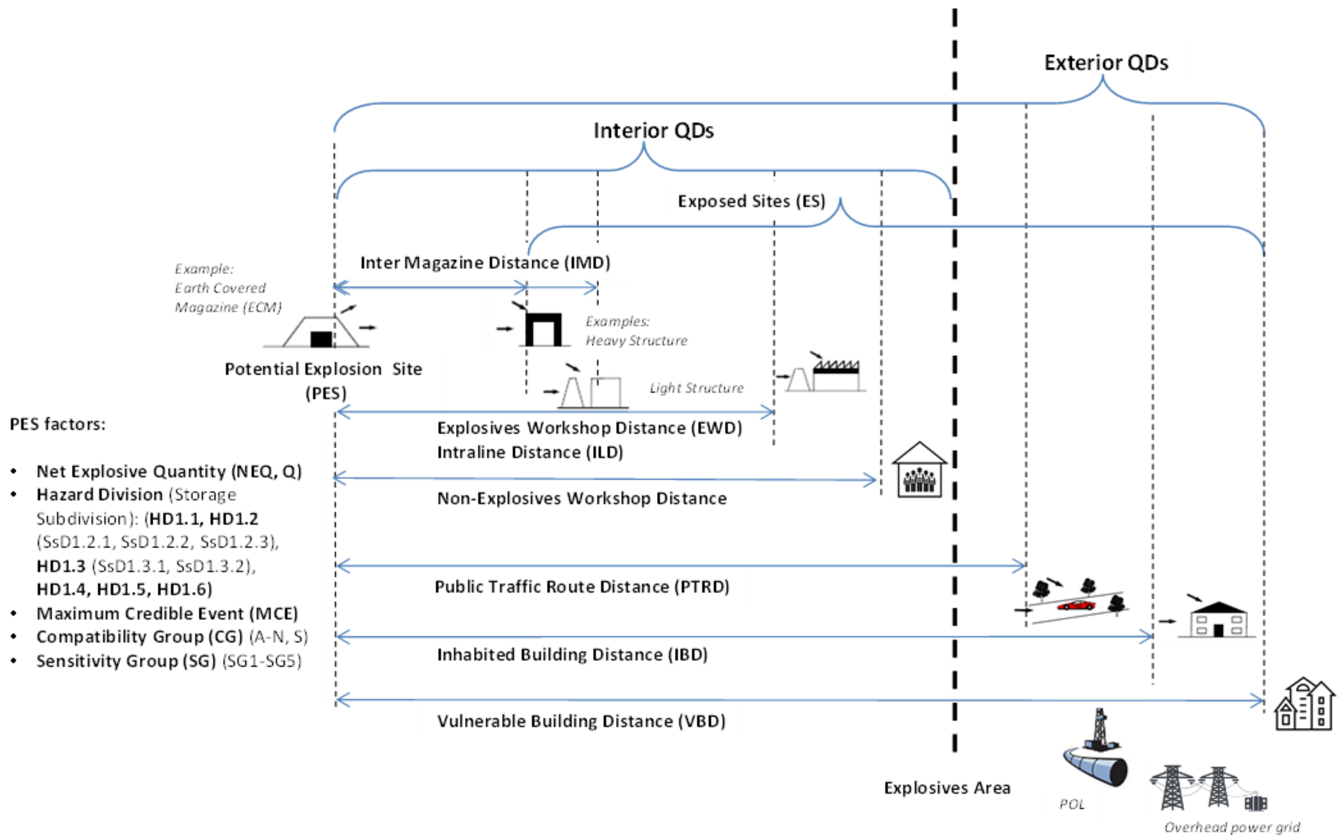

Figure 1: Examples of Quantity Distances

The starting point of an ESSP is to meet QD criteria that prevent prompt propagation, e.g., the Inter-magazine Distances (IMD) and that mitigate the consequences and provide an acceptable level of protection to exposed people and property. However, it may not be possible to meet all QD requirements due to a lack of space or mission requirements. When QD cannot be met, a risk assessment should be conducted.

Over the last three decades, the explosives safety community has been aware of the strained credibility of applying a single minimum separation QD criteria at Inhabited Building Distance (IBD) for debris hazards independent of the PES type and NEQ. Specifically, NATO AASTP-1 defines the minimum separation distance at IBD to account for debris hazards as a constant 400 m.[iv]

As a result of these concerns, significant work was done to address the deficiency of debris IBD in NATO AASTP-1.The outcome is a set of Debris and Fragment Distance (DFD) curves and tables for AASTP-1. These curves are based on empirical and analytical data, where available. In some instances, none of these information sources are available. In these cases, extrapolations were necessary in a finite range of NEQ (e.g., data are known at small and large NEQs but not in between), or in a semi-infinite range of NEQ beyond a certain mass. Subsequently, with AASTP-1 Edition C Version 1, the procedure to determine QD has changed so that a QD assessment is more transparent and has a better empirical basis.

The major change to the QD tables in AASTP-1 is the separate consideration of each of the effects: blast, debris and fragmentation, progressive (Storage sub-Division (SsD) 1.2.1), progressive (SsD 1.2.2), thermal (SsD 1.3.1) and thermal (SsD 1.3.2). Fixed minimum distances that had resulted from treating blast and fragmentation hazards jointly have been removed.

These changes, while being more scientifically defendable, have in some cases led to an increased number of instances where QD cannot be met but operational requirements dictate that A&E in excess of normally permitted NEQ limits must be stored. In such cases a method of identifying, communicating and accepting the additional risk is necessary.

Canadian Ammunition and Explosives Safety Policy

In 2005 an audit of the Department of National Defence (DND) Ammunition Safety program recommended that the department establish a risk-based approach to ammunition safety management and regulation. The recommendation stated that this approach should include policies and processes for identifying, categorizing, and assigning risk decision making authority and accountability; and the development of procedures and tools for performing risk[1] assessments.[v]

Canada had already implemented QD explosive safety siting based primarily on QD data provided in NATO AASTP-1, which in itself incorporates an element of risk, but lacked a coherent method for assessing and documenting additional risk, including identifying the appropriate level of authority and accountability, in cases where QD could not be met but operational requirements dictated NEQ be held in excess of that which would normally be permitted. It was recognised that an approach focused solely on the consequences of a possible accident was inflexible as it did not allow for consideration of options that could be just as safe, but may require less extensive resources in terms of people, materiel, infrastructure and property.

If the likelihood of an A&E accident and its consequences are taken into account, decisions based on knowledge that is more complete are possible. Modern, risk-based processes can therefore be applied to A&E activities over the entire life cycle that will identify risk, consider mitigation activity, inform the appropriate approval command authority and ensure such activities are monitored. By so-doing, an organisation can continue to appropriately manage its responsibilities for A&E safety in accordance with applicable legislation and the public expectation for due diligence.

In order to address the identified gap, a risk based approach for managing A&E storage and storage-related activities that do not conform to regulations in support of deployed operations, certain domestic operations, and high readiness training, was required. Such an approach would enable senior leaders to delegate authority to the applicable Operational Commander to risk

[1] For the purposes of this paper risk is defined as a combination of the likelihood and consequences of an event.

manage those activities. In addition, the ability for the Operational Commander to provide written authority to Subordinate Commanders and Task Force (TF) Commanders for moderate risk management was seen as desirable. This approach would permit commanders at all levels to make informed risk based decisions, particularly when time is a critical factor in operational success.

These requirements led to the development of the Ammunition and Explosives Risk Assessment Safety Case (AERASC) process. The 5 step AERASC process shown in Figure 2 is based on qualitative and quantitative risk assessment principles to ensure that the residual risk is As Low As Reasonably Practicable (ALARP) and that the approval and acceptance of risk is specifically assigned to appropriate authorities within the chain of command.

Figure 2: 5 Step AERASC Process

The ability of A&E practitioners within the Department of National Defence (DND) and the Canadian Armed Forces (CAF) to conduct a quantitative risk assessment is limited, often requiring the purchase of expensive commercial software and stand-alone computers. This, coupled with the frequent turnover of military personnel due to postings, makes training and maintenance of skills problematic. Therefore, in order to provide guidance for A&E practitioners, a set of qualitative probability tables has been published (see Figures 3a and 3b), similar descriptive tables have been published for hazard consequence. However, the interpretation of these tables varies greatly depending on an individual's experience and training.

Unlike some countries, such as the UK and the Netherlands, Canada does not have federally mandated risk acceptance criteria. Consequently the DND and CAF have established the following risk acceptance criteria for A&E activities:

- Individual risk –
    - Worker - Limit the maximum risk to 1×10^{-4}. Risks below 1×10^{-4} are accepted.

- Public - Limit the maximum risk to 1 x 10^{-6}. Risks below 1 x 10^{-6} are accepted.
- Group risk –
  - Workers - Attempt to lower the risk to 1 x 10^{-3}. If above, apply the As Low As Reasonably Practicable principle.
  - Public – Attempt to lower the risk if above 1 x 10^{-5}. Risks below 1 x 10^{-5} are accepted.

When the risk of an A&E activity exceeds the risk acceptance criteria an AERASC is required and the risk must be accepted at the appropriate level.

Description	Qualitative Definition	All Exposed Personnel	Threshold
Likely	Frequent, almost certain. Likely to occur many times.	Over a lifetime, can be expected to occur intermittently or occasionally.	Greater than 1 x 10^{-3}
Probable	Very possible. Expected to occur one or more times.	Over a lifetime, can be expected to occur randomly.	Less than 1 x 10^{-3}
Remote	Moderate, occasional. Unlikely, but possible to occur.	Over a lifetime, can be expected to occur.	Less than 1 x 10^{-5}
Improbable	Unlikely, seldom. Not expected to occur.	Over a lifetime, can be expected to occur rarely.	Less than 1 x 10^{-7}
Extremely Improbable	Rare, practically impossible. So unlikely it may be assumed it will never occur.	Over a lifetime, is not expected to occur.	Less than 1 x 10^{-9}

Figure 3a: Hazard Probability Table

Likelihood	A&E Activity Type					
	Storage	Maintenance, Inspection, Assembly, Disassembly	Operations	Transportation	Destruction	Testing
Likely. Over the typical service person's career, an undesired event can be expected to occur a number of times on an intermittent basis.		Dangerously unserviceable items being prepared for destruction.				Initial tests of new systems
						Manufacture of ammunition or explosives
Probable. Over a typical career, an undesired event can be expected to occur randomly one or more times.	Operating stocks in an area subject to hostile action such as rockets, missiles, air attacks, artillery or terrorist activity	Any operating location in an area subject to hostile actions such as rockets, missiles, air attacks, artillery or terrorist activity.	Any explosives operation in an area subject to hostile actions such as rockets, missiles, air attacks, artillery or terrorist activity.	Any transportation of A&E in an area subject to hostile actions such as rockets, missiles, air attacks, artillery or terrorist activity.	During burning, detonation operations when subject to possible hostile attacks.	
	Dangerously unserviceable items awaiting destruction.	When there exists a hazardous environment with gases, dusts, fibres, etc.	Deployed flight line activities with periods of ramp congestion.			

Figure 3b: Example of Likelihood of Event for Military A&E Activities Table

In order to remove the subjectivity from AERASC submissions introduced by the use of qualitative tables, Canada identified the requirement for a comprehensive and accurate modelling capability that would inform on safety risks associated with A&E storage and siting in support of domestic and expeditionary operations. The software would have to provide fast and accurate advanced prediction of both vulnerability to injury or death of people and damage to material and infrastructure from PES containing A&E. In addition a graphic representation using satellite imagery showing the predicted consequences was identified as a key enabler for briefing senior leadership.

The next section provides some brief details of risk assessment software used by other nations that was reviewed to determine if it met the requirement. The information has been taken primarily from NATO AASTP-4 and more detail is available in that publication. In each case the software reviewed was either not available to Canada or was perceived to not meet the requirement in some area.

International Risk Assessment Software Examples

MSIAC QD Consequence Analysis Tool (MQDCAT)[2] - The objective of the MQDCAT is to perform an experimentally validated consequence analysis of the initiation of various types and

[2] MQDCAT v2.4 is available to all MSIAC member nations and can be accessed through the MSIAC secure website: https://portal.msiac.nato.int/cas/login/?next=/

quantities of munitions in various types of magazines (PES) and with possible mitigation measures in place. MQDCAT is consistent with the QD in AASTP-1 (Edition C Version 1) for all HD and over the full range of NEQ. MQDCAT gives insight into the consequences that are to be expected when QD cannot be met and provides input for both qualitative and quantitative risk analysis. The tool is relatively new and does not meet the full requirement identified but it is permitted to use it to obtain a quantitative assessment of the consequences of an unplanned event in support of an AERASC.

US Risk Based Explosives Safety Siting (RBESS) – Department of Defence (DoD) sponsored software developed for use by all DoD services. The software was developed and is maintained by NAVFAC EXWC on behalf of the DDESB. It is used for:

- Automated calculation and display of explosives safety quantity distance (ESQD) arcs;
- Automated and standardized Site Plan Package development; and
- Automated and standardized Potential Explosion Site (PES) data.

RBESS encompasses multiple tools that are designed to model various explosives effects and consequences. These various tools have been organized into groups, referred to as "Tiers" which are delineated by the level of input required and the level of analysis detail required in the model. RBESS was not available to other nations at the time Canada was researching software options.

UK eXplosion Risk Assessment Tool (XRA) - XRA outputs the individual and societal risks, which it calculates via the combination of the frequency of explosion initiation with the conditional probability of fatality at an exposed site (ES) and the relevant target population data for that ES. XRA was not available to other nations at the time Canada was researching software options.

UN SaferGuard Quantity Distance Map[vi] - A web-based application in support of the implementation of the International Ammunition Technical Guidelines (IATG). The scientific background of the underlying formulae is summarized and referenced in IATG 1.80. This application meets some, but not all, of the identified requirements and is authorised for use on deployed operations for temporary storage sites.

Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR)[vii] – This software is a supplement to the longstanding American Table of Distances (ATD) and other QD systems. Whereas QD provides a level of safety based on explosives quantity and distance, IMESAFR determines a level of safety based upon risk. In addition to explosives quantity and distance, IMESAFR uses the donor structure, the activity at the donor, and the structure of the exposed sites to determine the level of safety. One of the challenges identified with this software is that it uses the American Table of Distances rather than NATO QD. However, the DND and CAF do allow the use of IMESAFR to perform a quantitative assessment of probability in support of an AERASC.

Canadian Ammunition and Explosives Consequence Analysis Tool

During research into possible software solutions an existing Canadian project, Rapid City Planner (RCP) was identified. RCP is a fast and accurate Computational Fluid Dynamics (CFD)-based urban blast analysis capability for user-specified explosion scenarios in any real city. It uses interfaces to GIS location, satellite imagery, geospatial terrain, and 3D building data for the city of interest. The software was designed to be used by security forces in real-world explosive threats (non-ideal, confined, near-field) scenarios to predict structural damage and human casualty estimates.

Discussions with the program team indicated that it would be possible to adapt the existing RCP software and leverage the potential of modern computer hardware, software, fast CFD technologies, and efficient physical/chemical models with web-based interface (Google Earth, Google Maps) to meet the requirements for a comprehensive and accurate modelling capability in support of AERASCs. Subsequently a project was initiated in 2019 to develop the Ammunition and Explosives Consequence Analysis Tool (AECAT).

AECAT can use the data in NATO AASTP-1 Edition C Version 1 to generate a graphic representation using satellite imagery of the QD boundaries similar to many of the models reviewed. When QD cannot be met, the software can generate a graphic representation using satellite imagery the predicted consequences (debris and fragmentation, blast and thermal) of an accidental explosion based on the NEQ and storage structure taking into account terrain and surrounding structures.

In addition to providing comprehensive reporting features, including graphical representation of the predicted consequences of an unplanned event (Figure 4) in support of AERASCs, it is intended to use the software to validate selected QD compliant activities. It is anticipated that this work will show that in some cases the QD are very conservative when terrain and infrastructure features are taken into account.

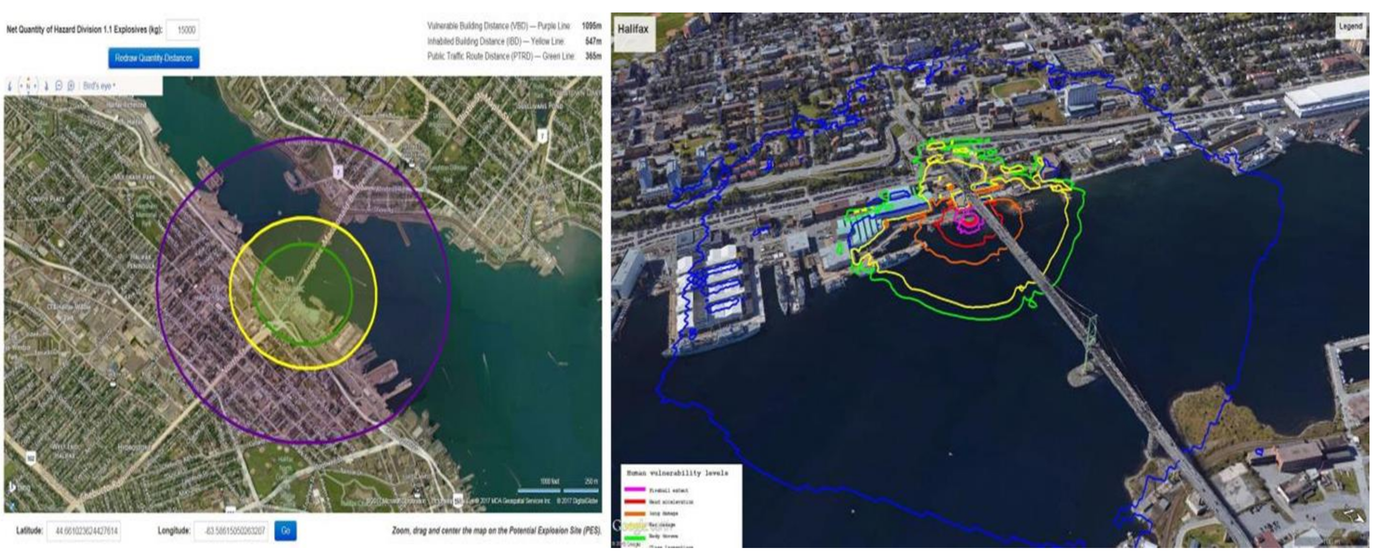

Figure 4: Comparison between UN SaferGuard QD Tool and AECAT outcomes

Conclusion

The current AECAT software project is expected to be completed in early 2023. Validation of the models against real world tests, in addition to that which has already been completed, is underway. The product will meet the capability deficiency identified in the statement of work enabling commanders at all levels to make informed risk based decisions in cases where QD could not be met but operational requirements dictate NEQ be held in excess of that which would normally be permitted, particularly when time is a critical factor in operational success. Future enhancements to the software are already being discussed, specifically in the areas of probabilistic outcomes and modelling the consequences of unplanned explosions onboard naval vessels.

List of Abbreviations

ALARP	- As Low As Reasonably Practicable
DFD	- Debris and Fragmentation Distance
DND	- Department of National Defence (Canada)
ES	- Exposed Site
HD	- Hazard Division
IBD	- Inhabited Building Distance
IMD	- Inter-magazine Distance
NEQ	- Net Explosive Quantity
PES	- Potential Explosive Site
QD	- Quantity Distance
SsD	- Storage sub-Division

Glossary

Exposed Site (ES) - A magazine, cell, stack, truck or trailer loaded with ammunition, explosives workshop, inhabited building, assembly place or public traffic route, which is exposed to the effects of an explosion (or fire) at the potential explosion site under consideration.

Hazard Division (HD) - Indication of the type of hazard to be expected in the event of an accident (e.g. HD 1.1 Blast; HD 1.2 Projection effects; HD 1.3 Fire and radiant heat).

Inhabited Building Distance (IBD) - Tolerable levels of damage expected from a side-on overpressure of 5 kPa; debris produced in an accidental explosion does not exceed one hazardous fragment (energy > 80 J) per 56 m^2.

Net Explosive Quantity (NEQ) - The total explosives contents of an ammunition, unless it has been determined that the effective quantity is significantly different from the actual quantity.

Risk - A combination of the likelihood and consequences. (Mathematically: risk = frequency × consequences.) The risk to a person or group of people when they are exposed to a hazard can be estimated from the likelihood of the hazardous event, and the probability that a particular level of harm to people would result[viii].

Quantitative Risk - Quantitative risk is usually expressed using numerical values for probability of accident, probability of fatality given the accident, exposure of personnel, individual risk, group risk, number of fatalities and number of injuries.

Qualitative Risk – Qualitative Risk can be expressed using descriptive terms for probability of event (e.g., possible, seldom, unlikely, improbable, practically impossible) and the severity of consequences (e.g., catastrophic, critical, marginal, negligible).

References

[i] Standards Related Document AASTP-1.1, Manual for the Development of an Explosives Safety Site Plan Based on AASTP-1, Edition A, Version 1 (NATO, December 2021)

[ii] AASTP-1, NATO Guidelines for the Storage of Military Ammunition and Explosives, Edition C Version 1, NATO, Brussels, 2021 (to be published)

[iii] AASTP-5 NATO Guidelines for the Storage, Maintenance and Transport of Ammunition on Deployed Missions and Operations, Edition 1 Version 3, NATO, Brussels, June 2016

[iv] Standards Related Document AASTP-1.2, Development of NATO Debris and Fragment Distance Curves for AASTP-1, Edition A, Version 1 (NATO, October 2021)

[v] Evaluation of DND/CF Ammunition Safety program, Recommendation 5. Risk Management (Chief Review Services, February 2005)

[vi] UN SaferGuard IATG Implementation Support Toolkit https://unsaferguard.org/

[vii] Institute of Makers of Explosives Safety Analysis for Risk (IMESAFR) IMESAFR

[viii] AASTP-4, NATO Explosives Safety Risk Analysis Part I: Guidelines For Risk-Based Decisions