Quantitative Risk-Based

System Safety Assessment for Ammunition Process Facility

ABSTRACT

The Ammunition Process Facility in Singapore will be used for the inspection, testing and maintenance of tri-service ordnance systems for the Singapore Armed Forces. Due to the hazardous nature of the activities at this facility, a quantitative risk-based system safety assessment was conducted to evaluate the inherent individual and collective fatal risks to humans associated with the handling of ammunition in the facility. This paper outlines the methodology undertaken and conclusions drawn from the situational safety assessment based on location, infrastructure, ordnance, equipment, personnel and activity workflow. The findings from this quantitative risk assessment are also used to focus subsequent facility system safety efforts on achieving a comprehensive risk assessment and evaluation.

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INTRODUCTION

The Ammunition Process Facility (APF) in Singapore, when completed, will be used for the maintenance and testing of tri-service ordnance of the Singapore Armed Forces (SAF). DSTA is responsible for the development and construction of the APF. In consideration of the potential operational and explosive hazards at the facility, DSTA decided to conduct a quantitative risk-based system safety assessment with technical consultancy from Swiss-based Bienz, Kummer & Partner Ltd (BK&P). For three decades, this risk-based safety concept (Swiss Department of Defence, 1991) has been adopted by the Swiss military in its handling of ammunition and explosives. The objectives of this assessment for the APF were two-fold: to validate the engineering and explosive safety designs of the facility, and to assess the quantitative risks associated with its operations.

APPROACH

The scope of this assessment addressed the six important elements of the facility (herein referred to as the system), namely the location, infrastructure, ordnance, equipment, personnel and procedures/workflow. Though distinct, these elements were interfaced and assessed concurrently by first identifying the five primary ordnance systems that would be processed at this facility, and then assessing the quantitative risks based on location-specific activities or situations. A thorough data collection was done to gather relevant information from various stakeholders, such as the designers and engineers developing the facility, as well as the military users and ordnance experts who would subsequently be operating the facility. Figure 1 shows the integration of the six system elements and the three-tier steps adopted in the assessment.

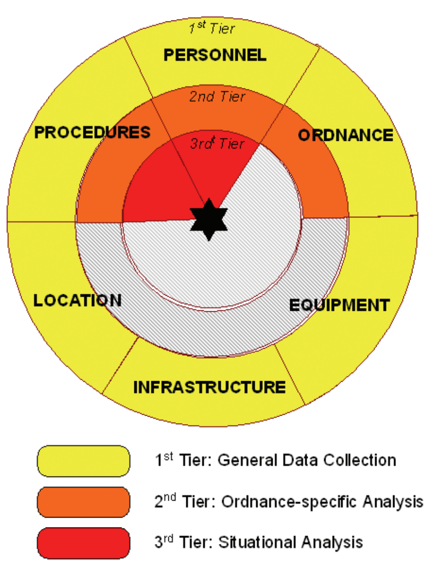

Figure 1 - Integration of six system elements and the three-tier steps in the data collection and risk analysis

DATA COLLECTION

Location

A schematic layout of the APF is shown in Figure 2. Each of the two zones (A and B) consisted of a test cell, a control room, a preparation area, as well as other administrative and utility rooms. As the APF was sited at a disused granite quarry, the data collected for this system element can be further subdivided into three categories: (1) the physical footprint of the APF (2) the surroundings within the quarry and (3) the surroundings outside the quarry. Other than detailed locations of surrounding buildings and roads, the analysis sought the description of activities as well as the density of personnel and vehicle flow.

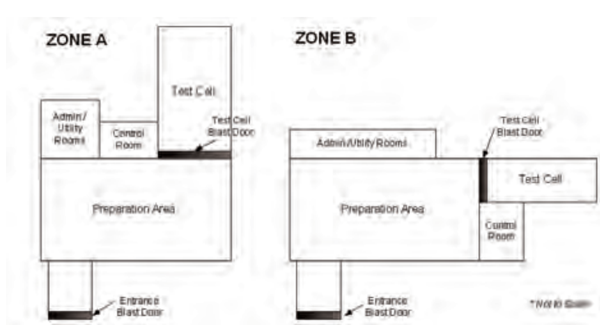

Figure 2 - Schematic layout of the APF

Infrastructure

With the same location categorisation, infrastructure information on the APF and its surrounding buildings were collected. This included their functions with regards to both work processes and protection against explosion effects, the type of building construction (e.g. reinforced concrete or steel-framed), the presence of any hazardous materials or unique building systems, such as blast doors, fire protection system and electrical equipment classification based on JSP 482 Standards[1] (UK Ministry of Defence, 2004). For the APF, the 'net explosive quantity' (NEQ) for its functional areas was also recorded.

Ordnance

Five primary ordnance systems (T1-T5) with the highest NEQ were selected for the assessment. Other necessary information included the hazard classification (i.e. hazard division and compatibility group) according to the NATO Allied Ammunition Storage and Transport Publications (AASTP) Standards[2] (North Atlantic Treaty Organisation, 2003), ordnance characteristics and packaging, as well as their utilisation (i.e. exposure) rates.

Equipment

This information included infrastructure-related equipment such as cranes, compressed air systems, as well as mechanical handling equipment and ordnance transport vehicles, either diesel- or battery-operated, that would be used under normal operations at the facility.

Personnel

The number and locations of personnel operating within the facility and in its surroundings are important in evaluating the hazard exposure rates and subsequently the individual and collective personnel risks. In this assessment, the quantitative fatal risks were calculated with a distinction made for "directly involved personnel" (i.e. working with or handling the ordnance inside the APF) and "indirectly involved personnel" (i.e. other military users in the vicinity). The public or third party was not considered explicitly in the exposure assessment due to the presence of a large out-of-bounds sterilisation area around the facility.

Procedures/Workflow

As explained in Figure 1, the procedures/workflow information collected were based on the normal operational activities of the five primary ordnance systems that would be processed at the facility, and this information was further categorised by locations, where the number of personnel, and the nature and duration of activities were recorded.

QUANTITATIVE RISK ANALYSIS

After data collection, the quantitative risks were evaluated through four systematic procedures: (1) event analysis, (2) effect analysis, (3) exposure analysis and (4) risk calculation, as illustrated in Figure 3.

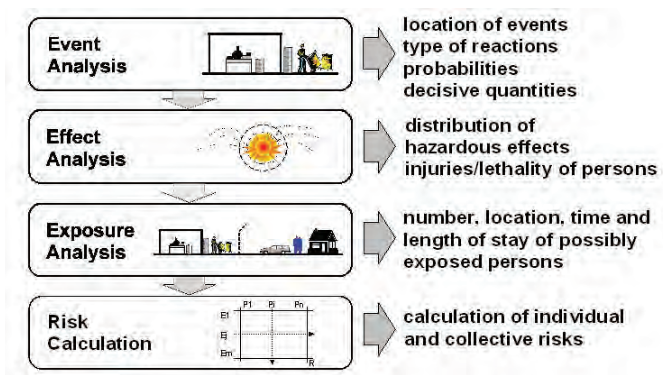

Figure 3 - Risk calculation procedures

Event Analysis

Event analysis identifies the list of hazardous incidents which may occur due to relevant, multi-fold reasons involving infrastructure, ordnance, equipment and procedures prescribed to location, decisive quantities of explosives, nature of activity, and the activity's duration and basic frequency. Table 1 illustrates a sample event list for some randomly chosen ordnance.

Due to the confidentiality of the ordnance data, the maximum NEQs were assumed as the effect-wise decisive quantity of the highly explosive TNT (QTNT). The possibilities of explosion propagation were assessed according

S/N	Ordnance	Location	NEQ (kg)	Activity	Duration (hr)	Basic Frequency (1/yr)
1.1	T1	Preparation Area	2000	Unpack/Pack	2	1.00E-05
1.2			2000	Drain/Refuel	2	1.00E-04
1.3			1600	Change/Clean	2	1.00E-05
1.4		Test Cell	600	Prepare		3.00E-05
1.5		Preparation Area	1600	Change/Clean	2	1.00E-05
1.6		Test Cell	600	Testing		1.00E-03

Table 1 - Event Analysis: Sample list of decisive events for ordnance T1

to the layout, geometry and design of the facility. The basic frequencies or probabilities (see Table 1) were determined based on BK&P's Basic Frequency Rate System, which tabulates a database of event probabilities from a combination of statistical, analytical and experiential approaches (Bienz, Willi and Nussbaumer, 2004). The Basic Frequency used in Table 1 defines one year as 8766 hours.

Effect Analysis

The general risk-relevant effects associated with an explosion are airblast, debris and fragments, ground shock, fire and heat. The dangerous effects of the possible events (analysed earlier) to personnel in the facility and the surroundings were determined based on current technical knowledge about such effects.

These effects or consequences were normalised in terms of lethality rates for three locations: (1) the donor zone in the APF, where the hazardous events might take place (2) the acceptor zone, which refers to neighbouring or adjacent parts of the APF that had been designed to withstand such explosion effects (3) the surroundings of the APF within and outside the quarry. In all three locations, the lethality rates are dependent mainly on NEQ/QTNT and the distance from the donor zone. For locations (1) and (2), the presence of barriers or doors separating the donor and acceptor zones as well as their opening/closing concept were considered. For location (3), the lethality rates were based on the assumption that all personnel were exposed in open air, and hence the effect of debris throw was dominant and taken into account. Tables 2-4 show the lethality rates resulting from all relevant effects used in the effect analysis (Bienz, Willi and Nussbaumer, 2004).

Event in		Lethality (λ) in Donor Zone		
Donor Zone	NEQ/Q_{TNT}	Preparation Area	Test Cell	Control Rooms
Preparation Area	1 - 4 ton	100%	100%	100%
	200 - 400 kg	5% - 100%	2% - 13%	5% - 20%
Test Cell	X00 kg	75% - 100%	100%	1%
	50 kg	1%	100%	0%

Table 2 - Donor Zone of APF

Event in Donor Zone NEQ/Q_{TNT}	Lethality (λ) in Acceptor Zone
2 - 4 ton	0.5%
1 - 2 ton	0.2%
0.3 - 1 ton	0.1%
< 0.3 ton	0%

Table 3 - Acceptor Zone

Effects		Distance (m) for NEQ/Q_{TNT}		
Lethality (λ)	Debris Mass Density (kg/m^2)	1 ton	2 ton	3 ton
75%	7	20	40	70
30%	1.8	110	130	160
5%	0.25	240	260	290
0.5%	0.025	400	420	450
0.05%	0.0025	550	570	600

Table 4 - Outside APF

Exposure Analysis

The actual number of victims resulting from the explosion effects depends not only on the lethality of the effects but also the exposure rates of personnel at possibly hazardous areas. The exposure data collected were both duration- and location-specific, with the latter being categorised into the donor zone, the acceptor zone and the surroundings as aforementioned. The exposure rate in the donor zone was differentiated into situations according to the procedures/workflow. In the acceptor zone, with regards to the low-risk relevance due to the low lethality rates and the more or less random operation of the ordnance, an average exposure rate was assumed instead of introducing different situations. The exposure rate in the surroundings outside the APF was determined based on the nature of activity, as well as the number and duration of personnel and/or vehicle presence.

Risk Calculation and Evaluation

The final step in the assessment was to calculate the quantitative risks using basic risk matrices that combine the data from the event, effect and exposure analyses described earlier. Risk, understood as a statistical value, is usually quantified mathematically as the product of probability and consequences. However, the definition of risk (or conversely safety) is not universal, unambiguous and objective. Hence, a comprehensive risk-based safety assessment has to consider the following different risk types at the same time:

i) Individual risk - risk to the endangered individual who focuses mainly on his own hazards, regardless of the number of people who are also at risk;

ii) Real collective risk (also known as group risk) - total risk of the (group of) particularly endangered persons representing the entire hazard of the activity, which society is primarily interested in;

iii) Perceived collective risk - the real collective risk increased by an aversion factor or function according to how the parties responsible for the hazardous activity, and who are interested in limiting the hazard in such a way that public opinion will not object to this activity, predict the over-proportional response of the society to accidents with large consequences due to the specific field of dangerous activity.

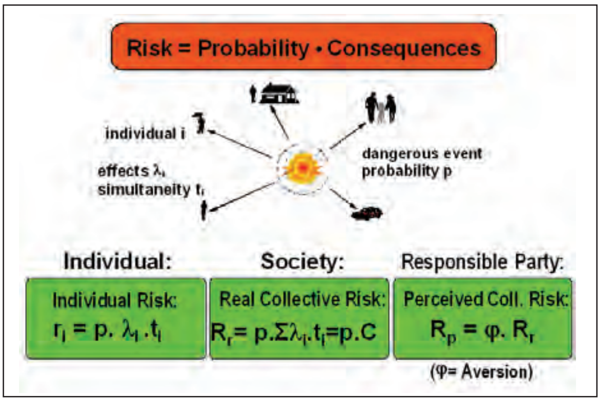

Figure 4 - Quantification of Risks (Simplified formulae)

Figure 4 represents the quantification of the three risk types.

Table 5 shows an example of the individual risk matrix (Bienz, Willi and Nussbaumer, 2004), which basically summarises the interaction of the six system elements and contributions of the three sets of analysis data (event probability, lethality effect and exposure duration) for the three locations: donor zone, acceptor zone and the surroundings outside the APF.

Risk Calculation — Zone: A; Ammo Type: T1; Situation No: 1 - 2

Period of Situation (1 Shift) [h/8766 h]: 0.22

Event				Persons j								
Room No.	Event No.			Pers. n	PW1-1 4	PW1-2 3	PW1-3 1	PW1-B 9	PW1-EO1 2	PW1-EO2 20	PW1-EO3 20	PW1-EO4 20
A	A1/1-1	fbi	1.00E-05	tij	25	25	25	25	1.25	2.5	2.5	1.25
				λAB	100	100	100	0.5				
				λDT					90	50	0.1	20
				λBD								
				λFr								
				λFi								
				λij	100	100	100	0.5	90	50	0.1	20
		Rri	5.14E-06	rij	5.50E-07	5.50E-07	5.50E-07	2.75E-09	2.48E-08	2.75E-08	5.50E-11	5.50E-09
A	A1/2-1	fbi	1.00E-04	tij	25	25	25	25	1.25	2.5	2.5	1.25
				λAB	100	100	100	0.5				
				λDT					90	50	0.1	20
				λBD								
				λFr								
				λFi								
				λij	100	100	100	0.5	90	50	0.1	20
		Rri	5.14E-05	rij	5.50E-06	5.50E-06	5.50E-06	2.75E-08	2.48E-07	2.75E-07	5.50E-10	5.50E-08

Legend:	Risks in Donor Zone (A)	Risks in Acceptor Zone (B)	Risks outside IAPF
	λAB - Lethality rate due to air blast		
	λDT - Lethality rate due to debris throw		

Table 5 - Example of Individual Risk Calculation Matrix

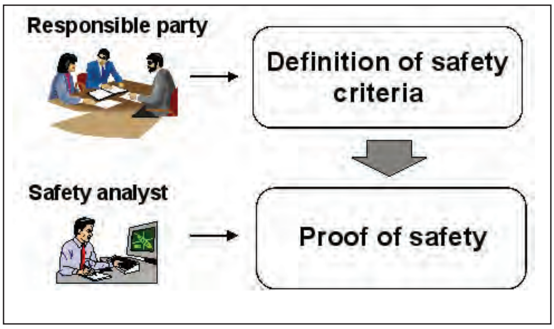

Figure 5 - Levels of Risk Evaluation

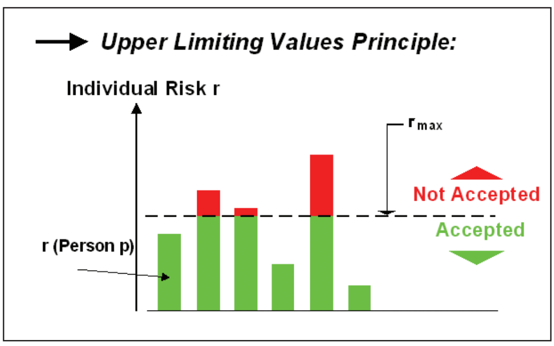

Figure 6a

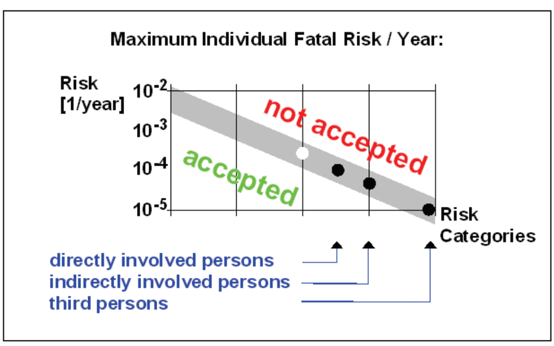

Figure 6b

While the systematic risk analysis procedures outlined earlier describe the hazards emanating from an activity meaningfully and quantitatively, they do not deal with the question of whether these hazards can be accepted, i.e. the activity can be considered safe. A complete safety assessment, however, has to address with equal importance risk evaluation - What is acceptable? Risk evaluation in an actual case is usually conducted by the procedures as shown in Figure 5. For the proof of safety, the risks of the actual case are compared to the safety criteria (i.e. accepted risks) laid down by the responsible party (Swiss Department of Defence, 1991; Bienz, 2002).

The safety (or risk acceptance) criteria for individual risk are enacted as upper limiting values (see Figure 6a). The current Swiss safety criteria for individual risk are illustrated in Figure 6b.

For collective risk, the willingness-to-pay and marginal cost principles were used to determine the acceptable risk, which corresponded to the point where the marginal reduction in collective risk was equal to the marginal cost of implementing safety measures to mitigate this risk. Graphically, the accepted (perceived) collective risk corresponds to the point on the plot in Figure 7a, where the tangent of the risk/cost curve is equal to the marginal cost value (Kummer, 2004). The current Swiss safety criteria for collective risk (the marginal cost for preventing one fatality) are shown in Figure 7b.

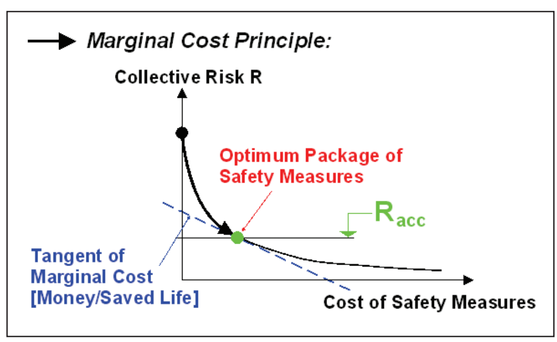

Figure 7a

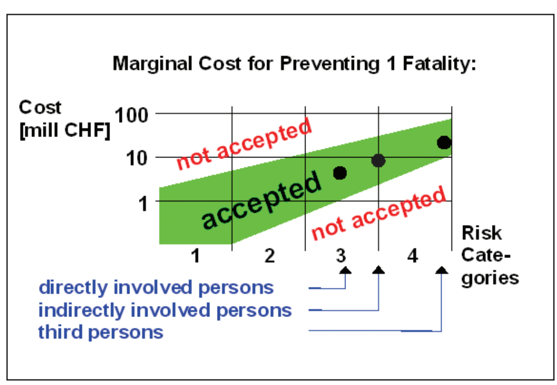

Figure 7b

Safety Check	(for 1 shift and 1 working year)					Ammo Type: T1				(Donor-) Zone: A						
Events	Collective Risk				Individual Risk											
	Grp Adj.	DI + II	DI	II	PW1-1		PW1-2		PW1-3		PW1-B		PW1-E01		PW1-E02	
					n=4	n=4	n=3	n=3	n=1	n=1	n=9	n=9	n=2	n=2	n=20	n=20
	Rr [1/y]	Rr [1/y]	Rr [1/y]	Rr [1/y]	II	DI	II	DI	II	DI	II	DI	II	DI	II	DI
Safety Check	✔				✔		✔		✔		✔		✔		✔	
Requ. Safety Investment	582 [S$/y]				r1 = 8.65E-06		r2 = 9.36E-06		r3 = 8.40E-06		r4 = 3.74E-08		r5 = 3.73E-07		r6 = 9.34E-07	
Total R	1.16E-04	9.37E-05	7.10E-05	2.27E-05	1.04E-08	8.64E-06	1.04E-08	9.35E-06	1.04E-08	8.39E-06	3.74E-08	0.00E+00	3.73E-07	0.00E+00	9.34E-07	0.00E+00
Individual Risks from Zone B		Ammo Type T2		62%	7.08E-09		7.08E-09		7.08E-09		-		7.08E-09		7.08E-09	
		Ammo Type T3		9%	1.50E-09		1.50E-09		1.50E-09		-		1.50E-09		1.50E-09	
		Ammo Type T4		12%	0.00E+00		0.00E+00		0.00E+00		-		0.00E+00		0.00E+00	
		Ammo Type T5		18%	1.83E-09		1.83E-09		1.83E-09		-		1.83E-09		1.83E-09	
A1/1-1	6.13E-06	5.27E-06	4.40E-06	8.66E-07		5.50E-07		5.50E-07		5.50E-07	2.75E-09		2.48E-08		2.75E-08	
A1/2-1	6.13E-05	5.27E-05	4.40E-05	8.66E-06		5.50E-06		5.50E-06		5.50E-06	2.75E-08		2.48E-07		2.75E-07	
A1/3-1	6.13E-06	5.27E-06	4.40E-06	8.66E-07		5.50E-07		5.50E-07		5.50E-07	2.75E-09		2.48E-08		2.75E-08	
A1/3-2	1.30E-05	1.26E-05	1.21E-05	4.60E-07		1.49E-06		1.65E-06		1.24E-06	1.65E-09		4.13E-08		1.65E-08	
A1/4-1	6.13E-06	5.27E-06	4.40E-06	8.66E-07		5.50E-07		5.50E-07		5.50E-07	2.75E-09		2.48E-08		2.75E-08	
A1/4-2	2.37E-05	1.27E-05	1.65E-06	1.10E-05		0.00E+00		5.50E-07		0.00E+00	0.00E+00		0.00E+00		5.50E-07	

Table 6 - Excerpt from Summary of Results for Individual Risks

Ordn.	A Zone (Donor)							B Zone (Donor)							
	Duration	A Zone	B Zone	External Objects	Real Risk (Grp. Adj.)	Estim. Avers.	Perceived Risk [1/y]	Duration	B Zone	A Zone	External Objects	Real Risk (Grp. Adj.)	Estim. Avers.	Perceived Risk [1/y]
T1	47%	6.67E-05	3.16E-07	2.10E-05	1.09E-04	4.00	4.38E-04	-	-	-	-	-	-	-
T2	-	-	-	-	-	-	-	62%	7.68E-05	1.41E-07	9.12E-06	9.54E-05	3.48	3.32E-04
T3	8.5%	7.85E-06	2.70E-08	2.05E-06	1.20E-05	2.30	2.76E-05	8.5%	7.84E-06	2.99E-08	2.52E-06	1.29E-05	2.30	2.97E-05
T4	12%	1.15E-05	1.54E-08	1.33E-07	1.18E-05	2.00	2.36E-05	12%	1.08E-05	0.00E+00	9.25E-08	1.10E-05	2.00	2.21E-05
T5	32%	6.09E-05	1.90E-07	6.85E-06	7.50E-05	10.56	7.92E-04	18%	3.43E-05	7.13E-08	3.53E-06	4.15E-05	9.19	3.81E-04
Total	100%	1.47E-04	5.49E-07	3.01E-05	2.08E-04	-	1.28E-03	100%	1.30E-04	2.42E-07	1.53E-05	1.61E-04	-	7.65E-04
	Marginal Cost in S$						6,403	Marginal Cost in S$						3,825
	Perceived Collective Risk [1/year]						2.05E-03	Marginal Cost [S$/year]		10,228				

Table 7 - Summary of Results for Collective Risks

SUMMARY OF RESULTS

The results on individual risks (see Table 6) have shown that they are all relatively small and lie below the current Swiss safety criteria for individual risks: 10-4/year for directly involved (DI) personnel, and 5x10-5/year for indirectly involved (II) personnel (Bienz, Willi and Nussbaumer, 2004). Therefore, in terms of individual risks, the existing design and proposed operations at the APF are considered safe.

A summary of the real and perceived collective risks is given in Table 7 (Bienz, Willi and Nussbaumer, 2004). From Figure 7b, the marginal cost to prevent one directly involved (DI) fatality according to the Swiss safety criteria is approximately US$3 million (or S$5 million).

Applying this marginal cost to the perceived collective risk (2.05x10-3/year), the maximum actual cost for significant risk mitigation is approximately S$10,000/year. For this amount, further effective risk-reducing measures can hardly be found. Hence, it is reasonable to consider the APF safe against collective risks.

Another aspect of the results that was exceptionally interesting to the facility designers and operators was the respective collective risk contributions of the five ordnance systems identified for the assessment. This finding (see Figure 8) provided an overview of the risk environment and a fair comparison of the risks inherent in the processing of each ordnance system, based on its utilisation rate, explosive characteristics and quantities, as well as the location and number of operators performing the activity (Bienz, Willi and Nussbaumer, 2004).

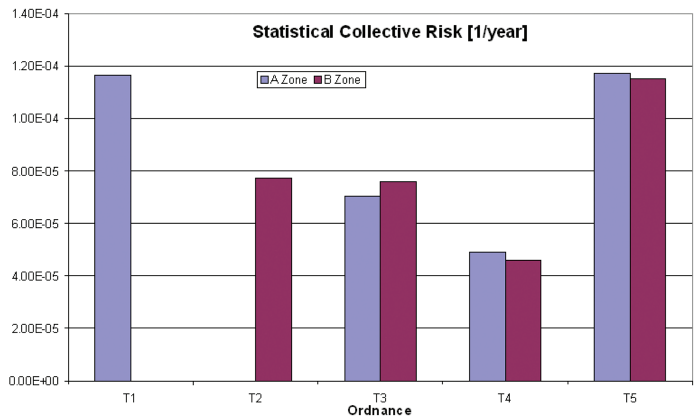

Figure 8 - Statistical Collective Risks of Different Ordnance

BENEFITS FROM THE QUANTITATIVE RISK ANALYSIS

Addressing the Maximum Credible Mishap

This quantitative risk-based system safety assessment has provided the project team with a theoretical and mathematical perspective on the maximum credible mishap of an accidental explosion in the facility through the situational appraisal of the ammunition processing activities. This is especially important in view of the dire consequences of an occurrence of an accidental explosion. The numerical risks and the corresponding costs of safety measures to mitigate these risks reinforced the project team's rationale on safety design provisions and the future users' appreciation of the operational risks.

Objectivity and Details

The system safety practice advocated in the Mil-Std-882D (US Department of Defense, 2000) is based on a qualitative assessment characterised by the categorisation of risk probability and risk severity into a few generic levels. These practices are endorsed as the risk evaluation criteria by the relevant safety authorities. Despite its simplicity and efficiency in allocating hazard risk indices, this risk assessment approach is often too general and subjective, leading to contentions among the safety authorities. The quantitative approach taken in this assessment maintained a high level of objectivity through the perspectives of the risk analysts, which were supported by statistical data. Moreover, more detailed results were obtained through the numerical calculations for cases in which the input data were specified.

Appreciation of Interface between Activities

The interface between activities could be easily appreciated through this quantitative approach by considering their simultaneity in terms of occurrence rates of personnel exposure to possibly hazardous events. For instance, the individual risk to an ammunition truck driver driving on a nearby access road while testing is ongoing in the APF can be easily calculated by this approach. Thus, the extent of interaction between these two activities is mathematically measurable.

On the other hand, the operating and support hazard analysis (O&SHA), which uses the qualitative approach, usually starts by regarding the listed O&S hazards as distinct and independent occurrences. Therefore, activity interfacing is not apparent at the outset to the systems engineer.

Thorough Consideration of Workflow and Procedures

In the course of collecting data for this risk assessment, one of the problems encountered was the lack of an overall systemic view of the facility when it is operational. The project team had to carry out a thorough and systematic analysis of the operators' workflow and procedures. This in turn benefited the team, as they had a better understanding of the operations at the APF after its completion.

SUBSEQUENT ACTION AND CONCLUSION

In summary, this quantitative risk-based system safety assessment has addressed the maximum credible mishap of an accidental explosion at the APF and the findings have provided an overall safety assurance for its engineering and explosive safety designs. The numerical results also verified that the inherent mishap risks at the facility are considered safe according to Swiss standards for individual and collective risks. Furthermore, these results allowed risk comparisons to be made between various hazardous ordnance processing activities, thereby increasing the risk awareness of its future operators.

The next stages in the continuing system safety efforts for the APF include a close-up qualitative analysis and safety documentation of its engineering systems, especially the unique and specialised systems, as well as a qualitative O&S safety assessment which will incorporate operators' directives or procedures in order to further mitigate the residual risks.

ENDNOTES

1 JSP 482 refers to the UK Ministry of Defence (MoD) Explosives Regulations, in which safety requirements and standards for electrical installations and equipment, lightning protection, electrostatic protection for above and underground explosives facilities are prescribed.

2 AASTP-3 refers to the NATO Allied Ammunition Storage and Transport Publications-3, in which the NATO principles for the hazard classification of military ammunition and explosives during transport and storage are prescribed.

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BIOGRAPHY

Alfred Tan is Programme Manager (Protective Structure). He graduated from the Nanyang Technological Institute with a Bachelor of Engineering (Civil Engineering) in 1985 and a Master of Science in Weapons Effects on Structures from the Royal Military College of Science, Srivenham, UK in 1992. As programme manager for the explosive storage programme, he specialises in the planning, design and construction of explosive storage-related building infrastructure. He is also in charge of explosive storage-related R&D projects on debris modelling and prediction, glazing control guidelines and hazard mitigation.

Francis Loi is Engineer (Protective Structure). He graduated with a Bachelor of Science in Civil Engineering from the University of Michigan, Ann Arbor, in 2002 and a Master of Science in Engineering from the University of California, Berkeley, in 2003. He is currently working on the Underground Ammunition Facility project.

Andreas Bienz is Chief Executive Officer, founder, co-owner and chief safety expert of Bienz, Kummer & Partner Ltd, which provides consultancy on risk-based safety planning and risk management and is the main consultant to Swiss Department of Defence for risk-based safety principles, regulations, methodology, technical models, data and applications. Andreas graduated with a Diploma (EUR ING) in Civil Engineering from the Swiss Federal Institute of Technology at Zürich in 1970, and has more than 30 years' experience in risk-based system safety assessment (methodology, models and data applications), risk appraisal / safety criteria, probabilities, explosion effects, conceptual planning of safety / protective systems and structures, as well as regulations and training.