Quantitative Risk-based System Safety Assessment for Ammunition Process Facility

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Abstract

The Ammunition Process Facility (APF) in Singapore will be used for the inspection, testing and maintenance of tri-service ordnance systems for the Singapore Armed Forces (SAF) under the Ministry of Defence. 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 human generated by the handling of ammunition in the facility. This paper outlines the methodology undertaken and conclusions drawn whilst conducting 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 to achieve a comprehensive risk assessment and evaluation.

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). The Defence Science & Technology Agency (DSTA) is the national authority entrusted with the development and construction of the APF. With consideration of the potential operational and explosive hazards at the facility, DSTA decided to conduct a quantitative risk-based system safety assessment with the technical consultancy from Swiss-based Bienz, Kummer & Partner Ltd (BK&P). This risk-based safety concept (ref. 1) has already been implemented for three decades in the Swiss military 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 are 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 will subsequently be operating the facility. Figure 1 shows the integration of the six system elements and the three-tiered steps adopted in the assessment.

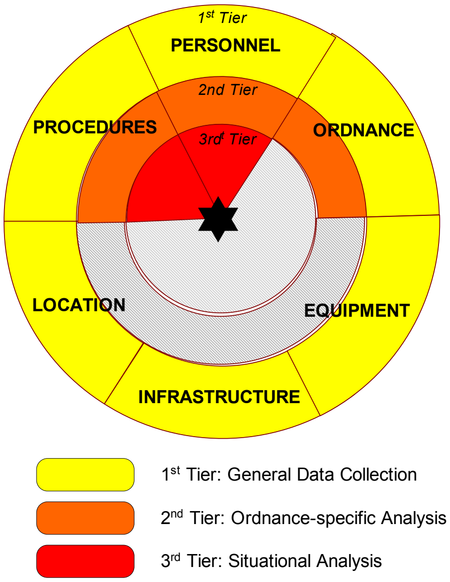

Figure 1 – Integration of six system elements and the three-tiered steps in the data collection and risk analysis

Data Collection

Location:

A schematic layout of the APF is shown in Figure 2. Each of the two zones (A & B) consists of a test cell, a control room, a preparation area, as well as other administrative and utility rooms. As the APF is 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 providing the detailed locations of surrounding buildings and roads, other information sought for the analysis includes the description of activities as well as the density of personnel and vehicle flow.

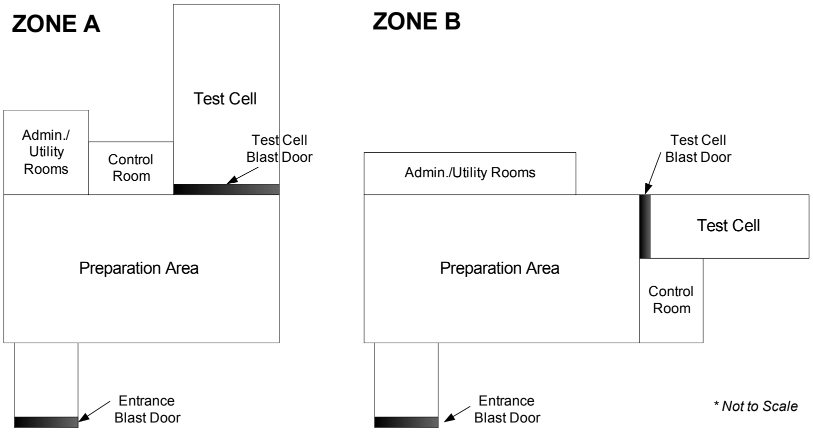

Figure 2 – Schematic layout of the APF

Infrastructure:

With the same location categorisation aforementioned, infrastructure information on the APF and its surrounding buildings were collected. This includes 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] (ref. 2). For the APF, the design '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 includes the hazard classification (i.e., hazard division and compatibility group) according to NATO Allied Ammunition Storage and Transport Publications (AASTP) Standards[2] (ref. 3), ordnance characteristics and packaging, as well as their utilisation rates or in other words, their exposure rates.

Equipment:

This information includes 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 had not been considered explicitly in the exposure assessment due to the presence of a large out-of-bound 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 is further categorised by locations, where the number of personnel, nature and duration of activities were recorded.

Quantitative Risk Analysis

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

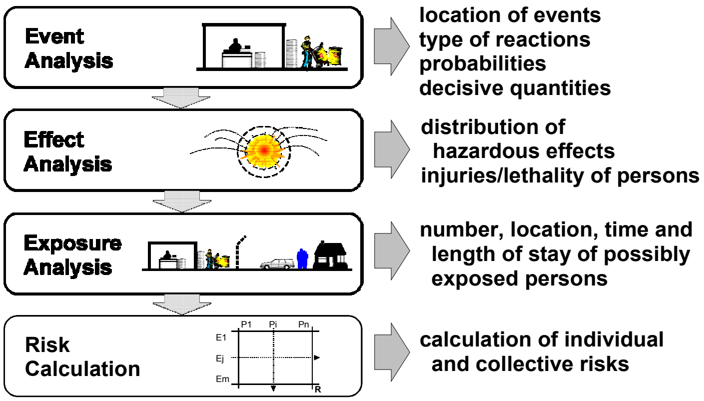

Figure 3 – Risk Calculation Procedures.

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[1] JSP 482 refers to the UK Ministry of Defence (MoD) Explosives Regulations, wherein 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, wherein the NATO principles for the hazard classification of military ammunition and explosives during transport and storage are prescribed.

Event Analysis:

Event analysis identifies the list of hazardous incidents which may occur due to relevant, multi-folded reasons involving infrastructure, ordnance, equipment and procedures that were prescribed to location, decisive quantities of explosives, nature of activity, its duration and basic frequency. Table 1 illustrates an example event list for some randomly chosen ordnance.

Table 1 – Event Analysis: Example list of decisive events for ordnance T1.

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

Due to the confidentiality of the ordnance data, the maximum NEQs were assumed as the effect-wise decisive quantity of the high-explosive TNT (Q_{TNT}). The possibilities of explosion propagation were assessed according to the layout, geometry and design of the facility. The basic frequencies or probabilities (see Table 1, ref. 4) 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. 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/fragments, ground shock, fire and heat. The dangerous effects of the possible events (analysed above) to personnel in the facility and the surroundings were determined based the 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 may 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; and (3) the surroundings of the APF within and outside the quarry. In all three locations, the lethality rates are dependent mainly on NEQ/Q_{TNT} 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 (λ) resulting from all relevant effects used in the effect analysis (ref. 4).

Table 2 – λ values in Donor Zone of APF

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 3 – λ values in Acceptor Zone

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 4 – λ values outside APF

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

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, where the latter is 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 above. 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 how and how many other people are also at risks;
ii) Real collective risk (also called group risk) – total risk of the (group of) particularly endangered persons representing the entire hazard of the activity, which the anonymous society is mainly and 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 represents the quantification of the three risk types.

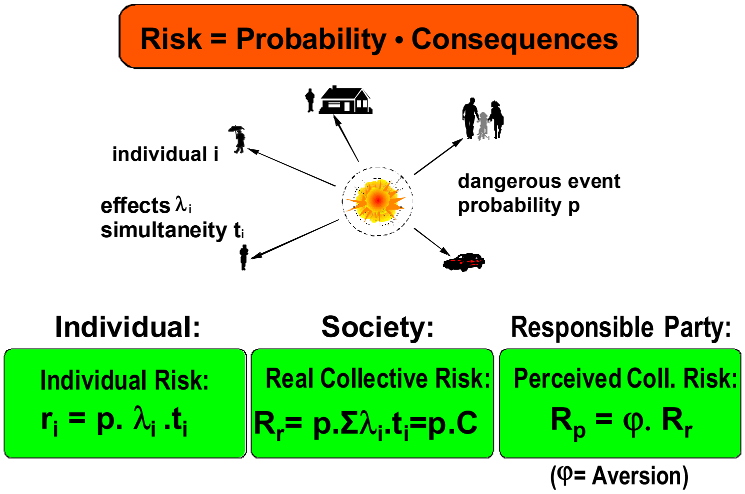

Figure 4 – Quantification of Risks (Simplified formulae).

Table 5 shows an example of the individual risk matrix (ref. 4), 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) into the three locations: donor zone, acceptor zone and the surroundings outside the APF.

Table 5 – Example of Individual Risk Calculation Matrix.

Risk Calculation

Zone: A
Ammo Type: T1
Period of Situation (1 Shift) [h/8766 h]: 0.22
Situation No: 1 - 2

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		

While the systematic risk analysis procedures outlined above describe the hazards emanating from an activity meaningfully and quantitatively, they do not deal with the question if 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. As 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 (ref. 1,5).

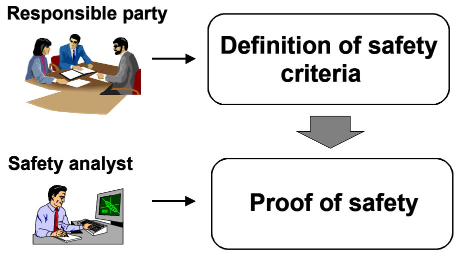

Figure 5 – Levels of Risk Evaluation.

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.

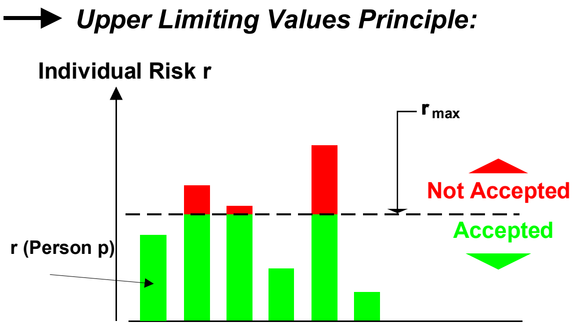

Figure 6a

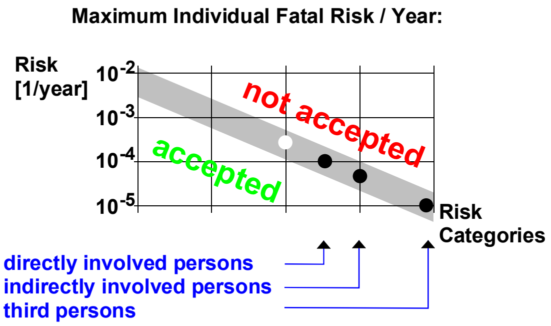

Figure 6b

For collective risk, the willingness-to-pay and marginal cost principles are used to determine the acceptable risk which corresponds to the point where the marginal reduction in collective risk is equal to the marginal cost of implementing safety measures to mitigate this risk. Graphically speaking, the accepted (perceived) collective risk corresponds to the point on the plot in Figure 7a where the tangent of the risk/cost curve equals the marginal cost value (ref. 6). The current Swiss safety criteria for collective risk, i.e. marginal cost for preventing one fatality, are shown in Figure 7b.

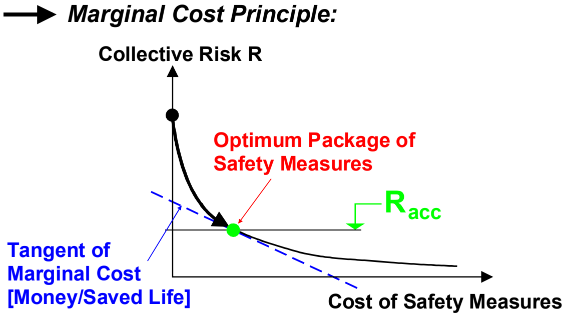

Figure 7a

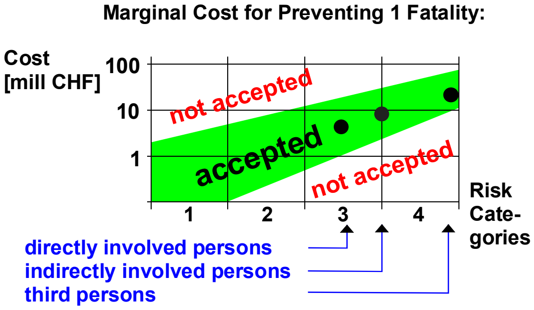

Figure 7b

Summary of Results

The results on individual risks (see excerpt in Table 6, ref. 4) had 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. Therefore in terms of individual risks, the existing design and proposed operations at the APF are considered safe.

Table 6 – Excerpt Summary of Results for Individual Risks.

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-EO1**		**PW1-EO2**	
					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	

A summary of the real and perceived collective risks is given in Table 7 (ref. 4). From Figure 8b, the marginal cost to prevent one directly involved (DI) fatality according to the Swiss safety criteria is approximately US$ 3M (or S$5M or CHF 4M). Applying this marginal cost to the perceived collective risk ($2.05x10^{-3}$/year), the maximum actual costs for significant risk mitigation is approximately S$10,000/yr. For this amount, further effective risk-reducing measures can hardly be found. Hence, it is reasonable to consider that the APF is safe against collective risks

Table 7 – Summary of Results for Collective Risks.

Ordn.	**A Zone (Donor)**							**B Zone (Donor)**						
	Dura-tion	**A Zone**	**B Zone**	**External Objects**	**Real Risk (Grp. Adj.)**	**Estim. Avers.**	**Perceived Risk [1/y]**	**Dura-tion**	**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$/y]**		**10,228**				

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, ref. 4) provided an overview of the risk environment and a fair comparison of the risks inherent to 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.

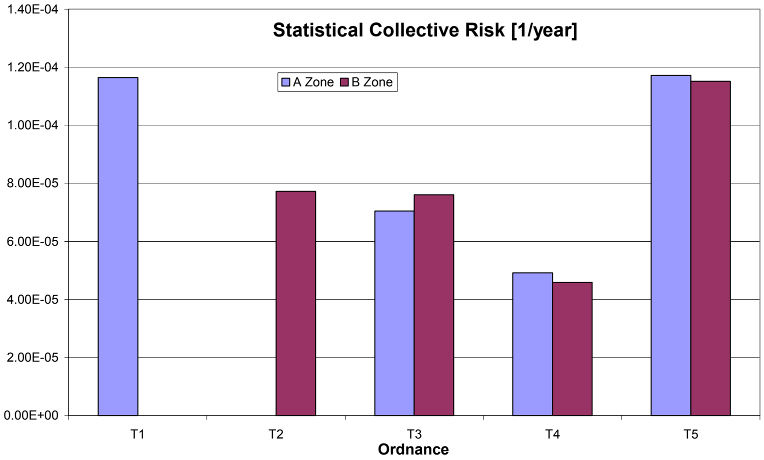

Figure 8 – Statistical Collective Risks of Different Ordnance

Benefits from the Quantitative Risk Analysis

Addressing the Maximum Credible Mishap:

This quantitative risk-based system safety assessment had provided the project team with a theoretical and mathematical perspective to 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 that can transcend should an accidental explosion occur. 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 (ref. 7) is based on a qualitative assessment characterised by the categorisation of risk probability and risk severity into a few generic levels and endorsed as the risk evaluation criteria by the relevant safety authorities. Albeit 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 authority members. 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 calculation as specific inputs were sought.

Appreciation of Activity Interfacing:

The interfacing between activities could be easily appreciated through this quantitative approach by considering their simultaneity in terms of occurrence rates, or in other words, the exposure rates of personnel to possibly hazardous events. For instance, the individual risk to an ammunition truck driver driving on a nearby access road whilst testing is ongoing at 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) using 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 system 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. Inadvertently, the project team had to carry out a thorough and systematic analysis of the operators' workflow and procedures. This in turn benefited the team to consolidate and better understand the operations at the APF after its completion.

Subsequent Actions 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 on its engineering and explosive safety designs. The numerical results also verified that the inherent mishap risks at the facility are considered safe according to acceptable 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 of those unique and specialised systems, as well as a qualitative O&S safety assessment to incorporate operators' directives or procedures to further mitigate the residual risks.

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Biographies

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