Department of Defense Explosives Safety Criteria: Risk-Based Approach as a Complement to the Quantity-Distance Approach

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Abstract

At present, the Department of Defense uses deterministic explosive safety criteria for operations involving munitions and explosives. This approach provides default criteria over a broad range of diverse applications. A strength of this approach derives from its simplicity and relative ease of application. A weakness of this process is that its criteria are inflexible and require obtaining waivers or exemptions for a noncompliance. The quantitative risk-based approach provides flexibility in site-specific placement or handling of explosives since incremental increases in quantities of explosives may be shown to have acceptable incremental increases in risk. However, the process of a risk-based approach is more complex than a deterministic quantity-distance approach. This paper examines a risk-based approach for explosive safety criteria. Other governments are currently using risk-based criteria. For example, the Department of Defense of Switzerland has been using the risk-based approach for some 25 years. Their approach focuses on lethality as a measure of risk. Although this is a very important risk measure, other measures such as risk to loss of mission may have considerable importance to U.S. operations. The paper includes a comparison of the results from a deterministic analysis and the risk-based approach.

Introduction

For the past 70 years, the U.S. military has successfully used a quantity-distance (Q-D) approach to explosive safety. This method is described in “DoD Ammunition and Explosives Safety Standards,” DOD 6055.9-STD.(1) Recently, however, as population centers have encroached on military facilities where explosives are being stored, military commanders have found it increasingly difficult to meet the distance criteria this standard imposes.

A quantitative risk-based approach developed by the Swiss Department of Defense offers a methodology that could be used in conjunction with the Q-D method when the distance requirements cannot be met. In this paper, the risk-based approach is compared with the Q-D approach through an example of an actual explosive safety situation. Although both the risk-based and the Q-D approaches seek to achieve explosive safety, their methods and the form of their results are significantly different.

An overview of the quantity-distance approach and the risk-based approach is provided first, followed by the example, and then a discussion of the benefits of each.

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Overview of the Quantity-Distance Approach

The basic purpose of the quantity-distance requirement is to ensure an acceptable level of risk to facilities located near explosives. The distance between a Potential Explosive Site (PES) and an Exposed Site (ES) is determined by the hazard class/division of the explosives, the type of explosives, and the type of facility. Specifically, quantity-distance requirements are based on five factors:(2)

1. The type of potential explosion site (facility design and function).

2. The explosives content (hazard class/division and the net explosives weight) of the potential explosive site.

3. The type of exposed site (facility design and function).

4. The explosives content (hazard class/division and the net explosives weight) of the exposed site.

5. The distance separating the potential explosive site from the exposed site and the existence of barricades or natural terrain that provides additional protection.

Once these factors are known, the required distance between the PES and the ES can be determined by use of the formula $D=K*W^{1/3}$, where D is the distance in feet, W is the net equivalent weight of the explosives in pounds, and K is a safety protection factor that depends on the risk assumed or permitted.

If the required distances cannot be obtained, an alternative is to reduce the quantity of explosive. If such a reduction cannot be achieved and the mission is jeopardized, a waiver or exemption may be requested.

Overview of the Risk-Based Approach

In most formal risk studies, risk is defined as the product of a frequency (or likelihood) of an event multiplied by the damage (or consequences) the event causes: $R = F*D$. Where R is risk, F is frequency, and D is damage. To fully describe the danger of an activity, we must distinguish between the so-called individual risk of the persons exposed to this activity and the so-called collective risk the activity poses to all exposed persons.

For example, if three accidents happened in a explosives factory in the last 100 years during a certain operation, each of them having fatally injured two operators,

- the average frequency of that accident would be 3×10^{-2}/year
- the damage per accident would be 2 victims
- the individual risk of one of those operators would be 3×10^{-2}/year x 1 = 3×10^{-2}/year
- the collective risk of this operation would be 3×10^{-2}/year x 2 victims = 6×10^{-2} victims/year.

The number takes on meaning when it is compared with the risk of more well-known events such as those shown in Table 1.

Table 1. Average Annual Risk of Traumatic Occupational Facilities (3)

Activity	Annual Risk
Motor Vehicle	1.61×10^{-5}
Machine	9.5×10^{-6}
Homicide	8.5×10^{-6}
Fall	6.7×10^{-6}
Electrocution	5.0×10^{-6}
Suicide	2.2×10^{-6}
Fire	1.3×10^{-6}
Drowning	1.0×10^{-6}

The risks are determined in the risk analysis. The four major steps (4) in performing a risk analysis are

1. Event Analysis - identifies and describes the likelihood that the explosion will occur and the quantity of explosives(a) causing the various hazardous effects (such as debris density, pressure, thermal).

2. Effect Analysis - determines the potential of death (lethality) from the various explosive effects. For example, given an explosion and a particular location that a person would occupy, the probability of death from a given debris density would be determined. The effects typically considered for detonations are fragment density, debris of structures and crater, and air blast.

3. Exposure Analysis - determines the probability that a person occupies a certain exposed location, given a specific type of explosion.

4. Risk Calculation - combines the information collected above to obtain the individual and collective risks.

The risk appraisal determines whether the calculated risks can be accepted, i.e., the situation in question is safe. The acceptable levels of different risks are determined through studies performed by the Swiss Department of Defense. A plot of individual risks provides a graphical means for selecting risk values for personnel working with explosives that are comparable to risk values for those in industry. The Swiss Department of Defense established a policy that explosive safety workers should incur no higher risk than the average working general public and that the risks from handling military explosives should not dominate the common daily risks of third persons. As a result, individual risk levels were established for directly involved individuals, indirectly involved individuals, and third parties. The risk criteria became applicable to all ammunition and explosive activities such as storage, manufacture, transportation, testing, and training.

Another aspect of this methodology is that of perceived collective risk. The collective risk is the sum of the individual risks. When several people are killed during an event, the public generally perceives the risk to be higher than it actually is. Although the risk is a perceived risk, the reaction is real, and this factor is

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(a) A special feature of the event analysis is that of determining the Q_{TNT} value. The Q_{TNT} takes into account the explosive TNT equivalent, a casing factor, and a participation factor. The casing factor accounts for the energy absorption of fragmenting the casing during the explosion, and the participation factor accounts for the possibility that not all of the munitions explode. These two factors reduce the equivalent TNT which, in turn, reduces the magnitude of the explosive effects. In the U.S., actual experiments are performed to determine the magnitude of explosive effects. Some of these experiments use bare explosives. Therefore, the casing factors and participation factors may not be taken into consideration.

important to oversight organizations, management, and personnel who have to interact with the public. To approximate the perceived risk, an aversion factor is used as a multiplier to the actual risk.

There are no established limits for the perceived collective risk. There is, however, the "willingness-to-pay approach," that is, an established cost permitted to save one life. The willingness-to-pay does not seek to establish the value of one life, rather it sets an upper limit on what is reasonable to pay to save one life. The difference is subtle. The first is a philosophical question that cannot be answered to anyone's satisfaction; the second is a realistic amount that a society or an organization is willing to spend to improve safety. The value established for the willingness-to-pay allows the determination of how safe is safe enough. If safety measures cost more than the product of the perceived collective risk and the willingness-to-pay amount, then no additional safety measures are necessary.

In a practical case of a risk appraisal, the calculated individual risk has to be compared with the approved risk limits for direct personnel, indirect personnel, and third persons and a determination made if additional corrective measures to reduce the perceived collective risk are necessary. If the risks are greater than that permitted, corrective measures are taken to reduce the risks to acceptable levels. If this is not feasible, the project is abandoned.

Example of the Risk-Based Approach

The purpose of this example is to illustrate the results of a risk analysis and a risk appraisal and to demonstrate how these data can be of benefit to military decision makers in explosive safety situations.

The results will show that based on a real life U.S. military example, a situation not in compliance with DoD 6055.9 criteria is well within compliance with the accepted individual risk criteria established by the Swiss. In addition, for the perceived collective risk for this example, the maximum that would have to be spent to improve safety, if such measures could be found, is approximately $28,000. If the cost for any known safety improvement exceeds that amount, the measure would not been undertaken.

Figure 1 gives an overview of the scenario: two maintenance buildings with 28 persons with an Net Explosive Quantity (NEQ) of 7.7 tons each, and an aircraft shelter with 4 persons and an NEQ of 2.3 tons. As shown, the separation distances are not in compliance with DoD 6055.9-STD and thus require corrective action or the granting of an exemption or waiver.

In this example, the change in risk between the initial building distances and desired building distances is computed. In addition, the actual geometry was investigated, assuming smaller NEQs in the buildings for two reasons: 1) this examines the idea of solving the problem by reducing the NEQ permitted and 2) it demonstrates the benefits of considering the casing factor and participation factor if these are not considered when performing a Q-D approach.

The loadings assumed for this example for each of the three buildings (4 tons in each of the maintenance buildings and 1.5 tons in the aircraft shelter) are considered realistic Q_{TNT} values. All individual risks of all persons in all buildings and the collective risks for all donor (PES) buildings and for the overall situation were considered and calculated.

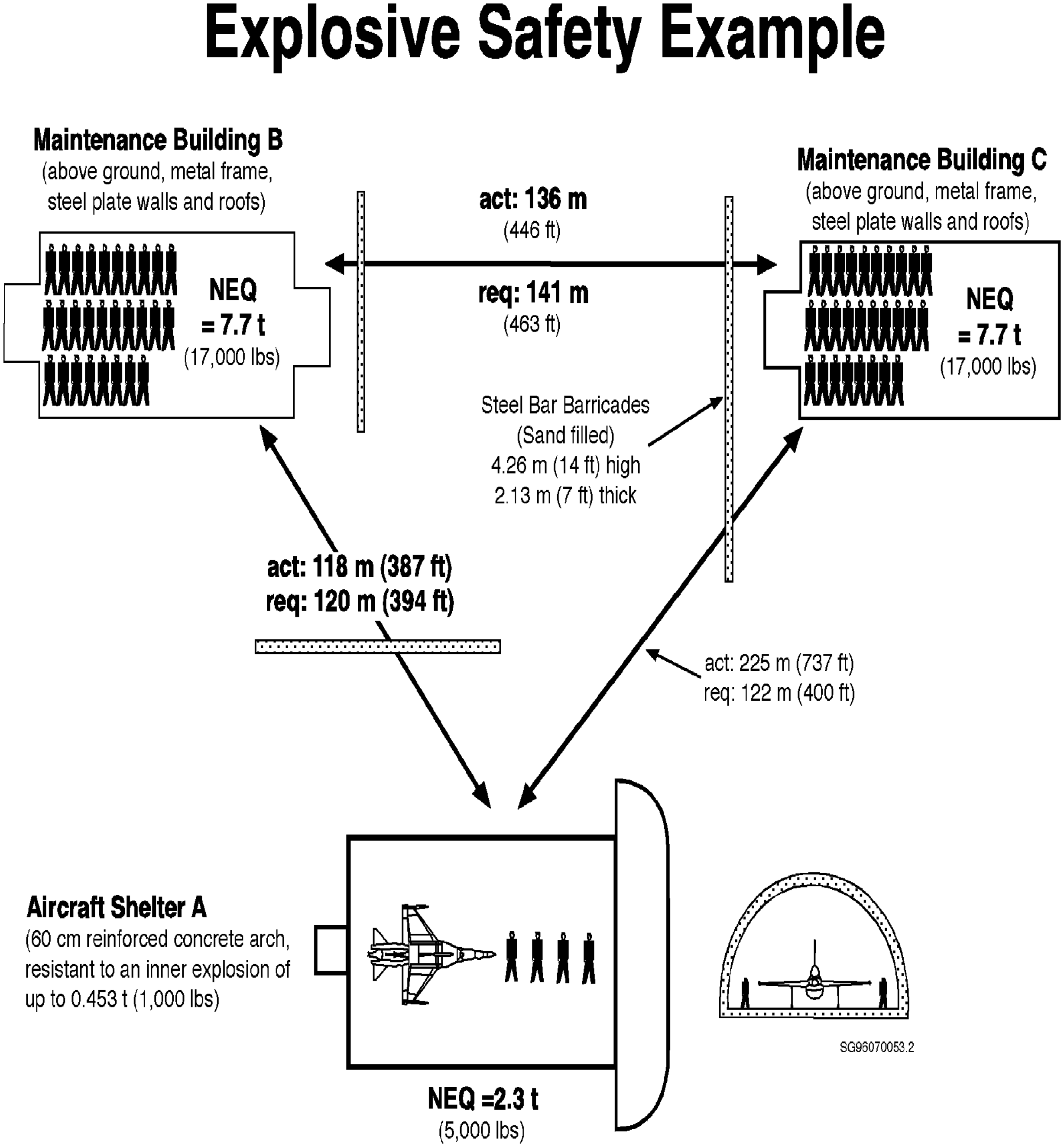

Figure 1. Layout of Example Scenario

Although the example presented here is that of an actual U.S. military installation, exact details of the explosives and the times when personnel would be in the building were not known, thus assumptions based on experiences at similar facilities were used for demonstration purposes. The activities were assumed to be loading bomb material on aircraft and moving aircraft into and out of the shelters; activity times of 8 hours/day for 200 working days/year were assumed.

In this particular case, it was assumed that an event in the aircraft shelter would always affect the total amount of explosive items; explosive items were assumed to be Class 1 Division 1 (mass detonating) explosives. In the maintenance buildings, a lower probability was assumed for the maximum event because not every event would be expected to cause an explosion of all the items in the building.

The hazardous effects were calculated with the computer code RISKAMEXS.(5) Air blast and debris throw were considered decisive, whereas the fragments were assumed to be blocked by the barricades. The fact that the effects might be intensified by aircraft exploding in the shelter was not considered.

The risk calculation took into account that the total risk to the personnel working in the maintenance buildings is produced not only by the maximum event in their building, but also by the handling of ammunition, which may also cause smaller events that endanger only the personnel in that building (but not in other buildings). Because most of the events in the aircraft shelter were expected to be the maximum ones, the internal risk in the shelter is already included in the calculation of the maximum event.

Risks of the Actual Situation

The results of the risk calculation are presented in the risk tables. Table 2 shows the individual risks for the actual NEQ and the actual distances. The cells contain the share of the individual risk of each person in the acceptor buildings (columns) caused by the possible events in the donor (PES) buildings (rows). For example, the risk to an individual in the aircraft shelter of an event in the aircraft shelter is 10^{-5}/year, while the risk to an individual in building C is 1.23×10^{-8}/year. The total individual risk of a person is the sum of these risk shares. That is, a person in maintenance building B bears an individual risk of 5.37×10^{-5}/year.

Table 2. Individual Risks (fatalities/year) for Maximum NEQs and Actual Distances

	Acceptor		
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C
Aircraft shelter A Q= 2.3t $p=1.00 \times 10^{-5}$	1.00×10^{-5}	4.62×10^{-7}	1.23×10^{-8}
Maint. Building B Q=7.7t $p= 3.00 \times 10^{-6}$	8.61×10^{-8}	3.00×10^{-6}	2.77×10^{-7}
Maint. Building C Q=7.7t $p=3.00 \times 10^{-6}$	6.51×10^{-9}	2.77×10^{-7}	3.00×10^{-6}
Internal Risk		5.00×10^{-5}	5.00×10^{-5}
Total	1.01×10^{-5}	5.37×10^{-5}	5.33×10^{-5}

Table 3 shows the perceived collective risks. In the cells, the portion of the perceived collective risk to the acceptor buildings of the NEQs in the donor buildings is shown. The cells in the last column show the total perceived collective risk produced by the respective building. The row “Internal Risk” contains the risk of events smaller than the allowed NEQ, events that have no impact on the neighboring buildings. The total risk of the whole situation is the sum of the risks of all buildings and the internal risks.

Table 3. Perceived Collective Risks (fatalities/year) for Maximum NEQs and Actual Distances

	Acceptor			
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C	All
Aircraft Shelter A Q=2.3t $p=1.00x10^{-5}$	$8.37x10^{-5}$	$2.71x10^{-5}$	$7.22x10^{-7}$	$1.12x10^{-4}$
Maint. Building B Q=7.7t $p=3.00x10^{-6}$	$5.51x10^{-6}$	$1.34x10^{-3}$	$1.24x10^{-4}$	$1.47x10^{-3}$
Maint. Building C Q=7.7t $p=3.00x10^{-6}$	$4.16x10^{-7}$	$1.24x10^{-4}$	$1.34x10^{-3}$	$1.47x10^{-3}$
Internal Risk		$1.85x10^{-3}$	$1.85x10^{-3}$	$3.69x10^{-3}$
			Total Risk Rp	$6.75x10^{-3}$

Figure 2 compares the collective risks of all the buildings and shows the composition of the risks. The maintenance buildings generate the same risk, and this risk is more than 100 times greater than that produced by the shelter. The risk is the same because 1) people in these buildings bear a basic risk of their own activities representing more than 50% and 2) in case of an event of the maximum NEQ within these buildings, 28 persons are affected with 100% lethality (equal 40% of the total risk). Thus, only 4% of the total risk is generated by the surroundings. Also the risk of the aircraft shelter is dominated by the internal risk of the four persons (about 75%).

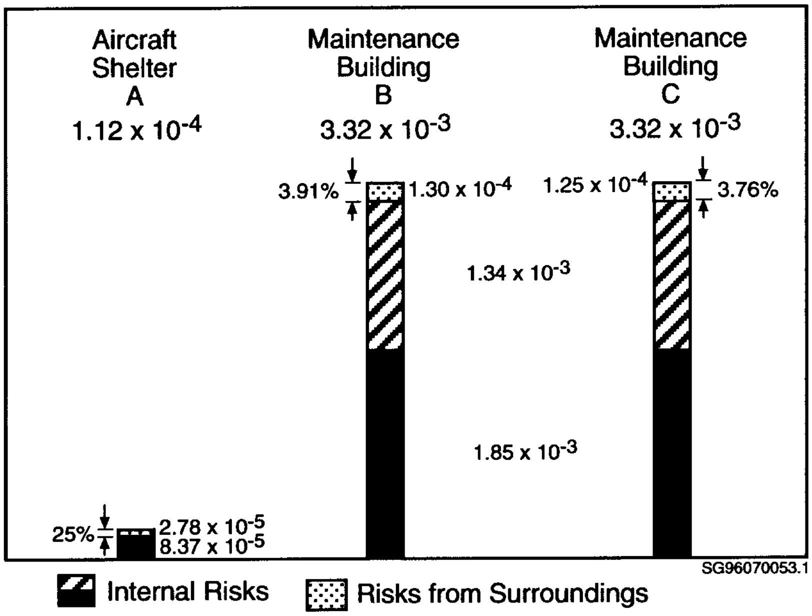

Figure 2. Comparison and Composition of the Perceived Collective Risks for NEQs and Actual Distances (internal risk includes risk from both the maximum event and a smaller building-specific event)

Risk Reduction by Enlarging the Separation Distances

Tables 4 and 5 show the risk calculated for the required distances.

Table 4. Individual Risks (fatalities/year) for Maximum NEQs and Required Distances

	Acceptor		
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C
Aircraft Shelter A Q=2.3t $p=1.00 \times 10^{-5}$	1.00×10^{-5}	4.18×10^{-7}	1.23×10^{-8}
Maint. Building B Q=7.7t $p=3.00 \times 10^{-6}$	7.93×10^{-8}	3.00×10^{-6}	2.44×10^{-7}
Maint. Building C Q=7.7t $p=3.00 \times 10^{-6}$	6.51×10^{-9}	2.44×10^{-7}	3.00×10^{-6}
Internal Risk		5.00×10^{-5}	5.00×10^{-5}
Total	1.01×10^{-5}	5.37×10^{-5}	5.33×10^{-5}

Table 5. Perceived Collective Risks (fatalities/year) for Maximum NEQs and Required Distances

	Acceptor			
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C	All
Aircraft Shelter A Q=2.3t $p=1.00 \times 10^{-5}$	8.23×10^{-5}	2.41×10^{-5}	7.10×10^{-7}	1.07×10^{-4}
Maint. Building B Q=7.7t $p=3.00 \times 10^{-6}$	5.08×10^{-6}	1.34×10^{-3}	1.09×10^{-4}	1.46×10^{-3}
Maint. Building C Q=7.7t $p=3.00 \times 10^{-6}$	4.16×10^{-7}	1.09×10^{-4}	1.34×10^{-3}	1.45×10^{-3}
Internal Risk		1.85×10^{-3}	1.85×10^{-3}	3.69×10^{-3}
			Total Risk Rp	6.71×10^{-3}

In Figure 3, the individual risk for personnel in Building B for the actual distance is compared with the required distance and the total perceived collective risk for the actual distance is compared with the required distance. Only the perceived collective risk is affected by increasing the distances and only by -0.6%, which is hardly perceptible. There is no actual safety gain by enlarging the distances; in other words, the actual distance is as safe as the required distance. The individual risk does not change because of the overriding internal risk for Building B.

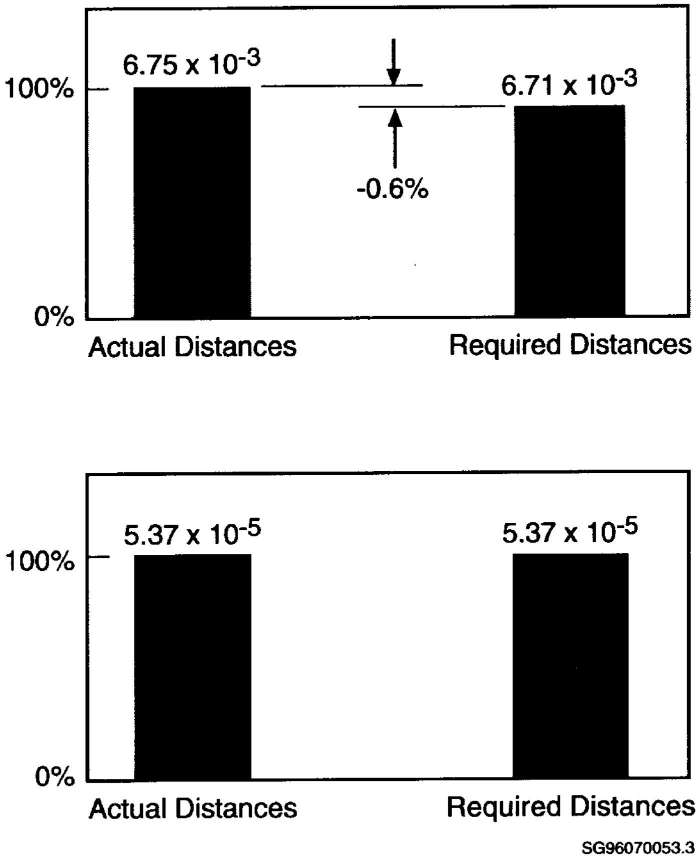

Figure 3. Comparison of Actual versus Required Distance. Top graphic shows total perceived collective risks Rp (fatalities/year) for maximum NEQ. Bottom graphic shows the maximum individual risk (fatalities/year) for a person in Building B

Risk Reduction by Reducing the Maximum Quantities

Tables 6 and 7 show the risks for reduced maximum explosive quantities. As expected, again there is no distinctive safety gain, primarily because the main risks are generated in the donor buildings and not in the surroundings.

For the same reason, it could be argued that the Q_{TNT} concept does not produce a relevant safety effect. Actually, the Q_{TNT} concept has its roots in the ammunition storage where the main risks are those in the surroundings of the magazines. Thus, one view might be that the concept of taking the casing and participation factors (Q_{TNT}) into consideration does not produce a relevant safety effect. This example masks the benefit because of the high internal risk. The benefit of the Q_{TNT} is realized when the only risk is from the surroundings. In Figure 4, the risks from the surroundings generated by the actual NEQs are compared with those of the Q_{TNT}. Because the range of the hazardous effects is smaller in the surroundings, both the collective and the individual risks are reduced considerably, in this particular case more than 50%.

Table 6. Individual Risks (fatalities/year)for Reduced NEQs (i.e., Q_{TNT}) and Required Distances

	Acceptor		
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C
Aircraft Shelter A Q=1.5t p=1.00x10^{-5}	1.00x10^{-5}	2.46x10^{-7}	4.56x10^{-9}
Maint. Building C Q=4.0t p=3.00x10^{-6}	3.76x10^{-8}	3.00x10^{-6}	9.19x10^{-8}
Maint. Building C Q=4.0t p=3.00x10^{-6}	2.18x10^{-9}	9.19x10^{-8}	3.00x10^{-6}
Internal Risk		5.00x10^{-5}	5.00x10^{-5}
Total	1.00x10^{-5}	5.33x10^{-5}	5.31x10^{-5}

Table 7. Perceived Collective Risks (fatalities/year) for Reduced
NEQs (i.e., Q_{TNT}) and Required Distances

	Acceptor			
Donor	Aircraft Shelter A	Maintenance Building B	Maintenance Building C	All
Aircraft Shelter A Q=1.5t p=1.00x10^{-5}	7.67x10^{-5}	1.32x10^{-5}	2.45x10^{-7}	9.02x10^{-5}
Maint. Building B Q=4.0t p=3.00x10^{-6}	2.41x10^{-6}	1.34x10^{-3}	4.12x10^{-5}	1.39x10^{-3}
Maint. Building C Q=4.0t P=3.00x10^{-6}	1.39x10^{-7}	4.12x10^{-5}	1.34x10^{-3}	1.39x10^{-3}
Internal Risk		1.85x10^{-3}	1.85x10^{-3}	3.69x10^{-3}
			Total Risk Rp	6.56x10^{-3}

Risk Appraisal

The Swiss safety criteria are formulated for three risk groups: the directly involved, the indirectly involved, and third parties. In this particular case, only directly involved (personnel in the donor building) and indirectly involved (personnel in the acceptor buildings) are affected.

For the individual risks the upper limiting values are

5.10^{-5}/year for the indirectly involved
10^{-4}/year for directly involved (including both direct and indirect values).

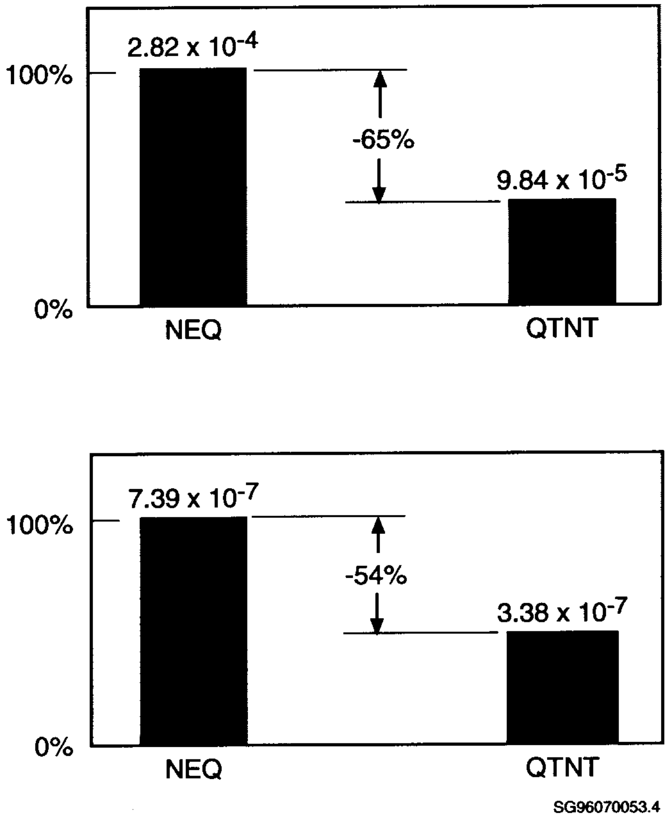

Figure 4. Comparison of Actual and Reduced (Q_{TNT}) Explosive Quantities on the Risks Generated in the Surroundings. Top graphic shows total perceived collective risks Rp (fatalities/year) in surroundings and actual situation. Bottom graphic shows individual risk (fatalities/year) in surroundings, e.g. Building B, actual situation.

The perceived collective risks have to be limited by applying the cost criterion for risk-reducing measures. The marginal costs are

8 million $/life saved for indirectly involved
4 million $/life saved for directly involved.

As Figure 5 shows, the individual risk of all personnel complies with the safety criteria. According to Swiss criteria for individual risk, the situation with NEQs and actual distances can be considered safe.

The perceived collective risk has to be appraised in a risk/cost-diagram. Figure 6 shows such a diagram with the total risk-group adjusted(a) perceived risk and the straight line of marginal cost entered.

(a) Because it is only possible to enter one tangent of marginal cost, the collective risks belonging to different risk groups (with different marginal cost) have to be adjusted against one group. In this particular case, the tangent of the directly involved was chosen. Thus, the risks generated in the neighboring buildings, belonging to the group of indirectly involved, had to be multiplied by the factor given by the different marginal cost (8 million/4 million = 2). This calculation results in a total group adjusted collective risk (7.03×10^{-3}) that is higher than the total risk in the matrix of Table 3 (6.75×10^{-3}).

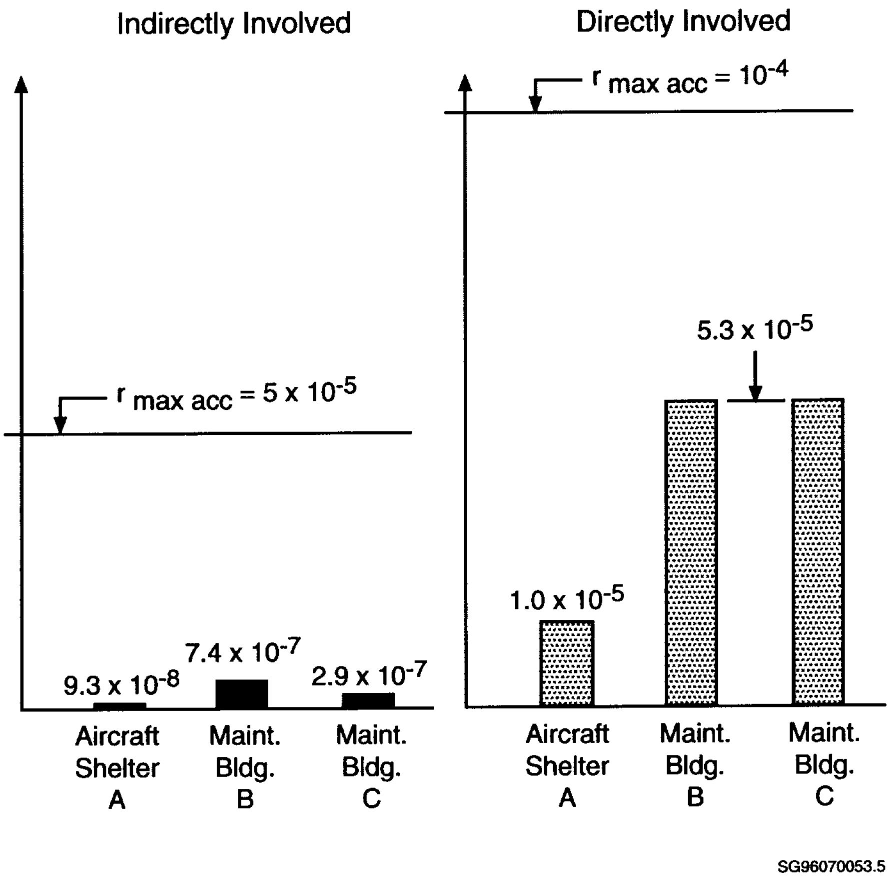

Figure 5. Appraisal of the Individual Risk versus the Swiss Safety Criteria

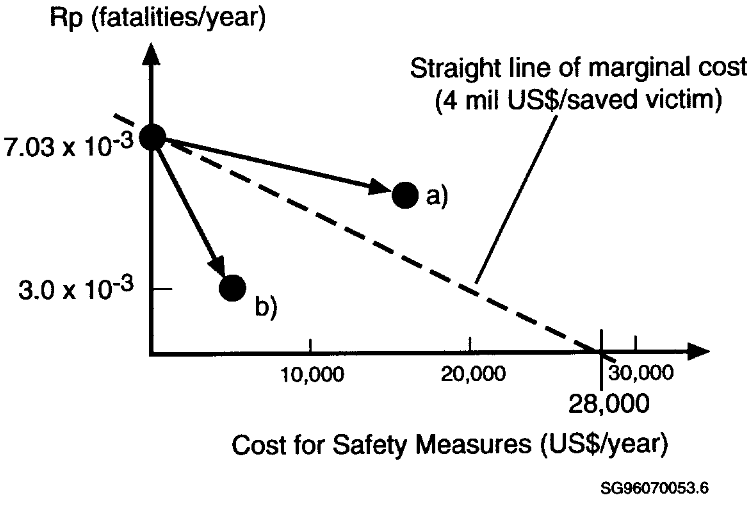

Figure 6. Appraisal of the Collective Risk versus the Swiss Safety Criteria

Additional safety measures, their costs, and the amount of risk reduction have to be identified and added to the risk/cost diagram. If all values are above the marginal cost line (Case A), the situation is declared safe. If values appear below the line, i.e., if additional measures that have a better risk-reduction/cost effect than the marginal cost can actually be taken (Case B), the funds necessary to reduce the risk by the determined amount (in this case, about $5000/year) have to be spent. Thus, the situation is declared unsafe until these corrective measures are taken. If no more sufficiently cost-effective measures apart from Case B can be found, Case B is declared safe with an accepted residual collective risk of 3.0×10^{-3} in this particular example.

Other Uses of Risk-Based Approach

In terms of military readiness, the ability to perform a required mission is paramount. An explosion has the potential to prevent the accomplishment of the mission. A variation of the risk-based approach can be used to determine the likelihood and the expected damages or losses from an explosion that could jeopardize the mission.

The probability of loss of mission given an explosion could be determined by conducting, for example, a fault tree analysis. The fault tree analysis would identify the potential failures that could impact the mission. The probability that the potential failure would occur from the explosion could be determined; for example, the probability of loss of electrical distribution, the probability of loss of a main computing center, etc. Quantifying the fault tree would provide the probability of loss of mission. The product of the initiating event frequency times the probability of loss of mission would provide a measure of the risk of losing the mission. Quantitative information on loss of life and on loss of mission on which to base siting decisions would then be available.

Summary

The two methods use significantly different approaches to achieve the same goal: explosive safety. The Q-D approach is simpler to implement, is more conservative than the risk-based approach, and usually affords an acceptable degree of risk. If the required distance is not difficult to achieve, compliance with the standard is straightforward. However, if it is not desirable to reduce the quantity of explosives and the required distance cannot be achieved, alternative solutions for achieving compliance must be examined. With the risk-based approach, an unrealizable distance derived using the Q-D approach could be well within the safety criteria. In addition, if the distances required by the Q-D approach are met, the incremental risk reduction might be insignificant.

The example presented shows that, although the situation is not in compliance with DoD 6055.9, it is well within the allowable risk for individuals using the Swiss criteria, without reducing safety. This is possible because the probability of an explosion is not unity, as assumed by the Q-D approach, and because it is also not a certainty that given an explosion, the exposed individuals will actually be in attendance.

The willingness-to-pay and marginal cost approach also fully identifies how much money would be permitted to reduce the perceived collective risk. The risk-based approach provides considerable quantitative data to assist management in making decisions.

Although the risk-based approach provides considerable important information for explosive siting decisions, its use would be most beneficial as an adjunct to the Q-D approach, to be used when noncompliant conditions occur. This is because of the relative degree of safety afforded by the Q-D approach and its simplicity. If the risk-based approach were used, it is likely that many noncompliant siting situations would in fact meet the safety criteria, and base commanders would need take no further action.

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