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Hazard analysis of technologies for disposing explosive waste

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Abstract

Hazards are identified for six different techniques for disposing decommissioned ammunition. Use has been made of functional modelling as a basis for hazard identification. Risk levels are estimated based on general accident rates in the chemical industry. The disposal techniques are "open burning" (OB), "open detonation" (OD), "closed detonation" (CD), "fluidised bed combustion" (FBC), "rotary kiln (RK) incineration", "mobile incineration". Closed detonation leads to most hazards and highest risk, followed by open burning and open detonation. The other three techniques are considerably safer. Risk due to transport is included in the analysis. Transport risk is not negligible for fluidised bed combustion and rotary kiln incineration at centrally located sites.

Keywords: Disposal; Ammunition; Detonation; Incineration; Hazard identification

1. Introduction

There is a growing community concern that disposing explosive waste and demilitarisation of ammunition be performed by taking due consideration of the environment and associated hazards. In recognition of the need for environmentally acceptable and safe technologies for disposing of explosive waste and ammunition, the European Commission has supported a multinational project to develop and assess new technologies for this purpose in the framework of LIFE Environment 1996. This project was a co-operation between DEMEX Consulting Engineers A/S, Denmark, Risø National Laboratory, Denmark, TNO Prins Maurits Laboratory, The Netherlands, the chemical waste destruction company "KommuneKemi A/S", Denmark, and the Danish Army Ammunitions Arsenal.

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In the framework of a comparative assessment of promising technologies, an identification and assessment of hazards was performed. The technologies are either centralised or decentralised (decentralised means close to the storage facilities), which means that there are different transportation requirements. Risks related to transport are, therefore, included in the assessment. Rather than obtaining quantitative risk levels, the aim of the study is to provide comparative information so as to be able to select the most appropriate solution.

2. Description of scenarios

The traditional ways to dispose ammunition are open burning (OB) and open detonation (OD). These are performed in open air, and the waste products (solid residues, dust, and combustion gases) are directly emitted to the environment, without any control or treatment (although sometimes the solid residues are collected). The alternative technologies considered in this paper are closed detonation (CD), closed incineration, primarily using existing stationary facilities like a rotary kiln (RK), and fluidised bed combustion (FBC).

2.1. Open burning

The OB is performed at suitable remote areas, typically military training grounds. The munitions are placed on the ground and the fire is ignited by use of liquid fuel or other flammable means. Small quantities will normally burn at rather low temperatures, not exceeding 500 °C, and the products are not combusted completely. A variant to OB is open-pit burning. In open-pit burning, the material to be burned is placed in a pit, often made of concrete. The OB of larger bulk quantities will create higher temperatures, and the combustion might well transfer into detonation, depending on the critical mass of explosives, temperature, and pressure. The OB is one of the most widely applied methods. In principle it can be applied to all munitions, small calibre ammunitions can be burned as whole pieces, larger munitions require downsizing prior to burning [1,2].

2.2. Open detonation

The disposal of ammunition by OD takes place by initiating the ammunition with an explosive charge. The resulting products may be more completely chemically degraded than those of OB, but the process results in the dispersion of heavy metal dust particles over a large area, polluting both air and ground. The OD is one of the most commonly used demilitarisation methods together with OB. The OD can be used on a vast variety of munitions. Downsizing is generally not required [1,2].

2.3. Closed detonation

In most aspects, CD is similar to open detonation, but because the ammunition is placed in a closed chamber, this technology permits the control of emissions to the environment. Downsizing of munitions may be required, depending on the type of ammunition and the size of the detonation chamber. The CD facilities can be transported.

2.4. Rotary kiln incineration

A RK incinerator is a thick-walled, rotating, cylindrical, refractory-lined steel drum inclined at an angle of 3–5° to the horizontal. Solid wastes are fed in the raised end. The slowly rotating drum (2–5 rpm) causes the solids to cascade down the tube. By the time they reach the end of the drum, they have been burnt out and the residues fall or run out of the lower end of the kiln. Liquid waste and support fuel are fired horizontally into the kiln through nozzles. This type of incinerator is also used for disposing hazardous waste in general, fitted with facilities for the control and cleaning of gases. Existing hazardous waste incinerators will generally require some type of pre-treatment of munitions, also in view of the increased demands on safe transport to these facilities [1,2].

2.5. Fluidised bed combustion

The FBC makes use of a flow of hot air through a packed bed of, e.g. silicon oxide particles (sand). Due to the action of the airflow, the sand particles of the bed are floated and act like a liquid. The fuel is injected into this floating bed in the form of fine droplets or particles ensuring optimal mixing with air. A catalyst can be added to the bed to facilitate the decomposition of explosives and suppress NO_x formation. FBC requires that the munitions be pre-treated and transferred into a kind of slurry that can be injected. The procedure is described by van Ham [3]. During the project, TNO proved that FBC is effective to incinerate slurries based on TNT [4]. It may be effective to incinerate other energetic materials and fillers from a variety of munitions.

2.6. Mobile incineration

Special movable kilns are developed to incinerate munitions on location. Munitions are charged batch-wise into a strong container and heated indirectly. The container can withstand eventual detonations of the charge. Some kilns are provided with flue-gas cleaning. Typical capacities of the kilns are 20–40 kg TNT/h. Whole-piece ammunitions can be destructed, but downsizing may be required for large munitions, similar to CD. Mobile incineration has not been studied in practice during this study, which means that findings are based only on a literature study and extrapolations from other techniques [5].

3. Hazard analysis

3.1. Accident cases

The UK Health and Safety Executive and the Explosives Storage and Transport Committee of the UK Ministry of Defence developed and maintains the Explosives Incident Database Advisory Service (EIDAS). This database confirms that handling and disposal of explosives is not without risk. Table 1 presents accidents related to the disposal or transport of explosives that are reported in the database for the period July 1997–June 1998. For the same period, the database includes even more accidents related to storage and

Table 1
Accidents involving disposal and transport of explosives, as reported in the EIDAS database for the period July 1997–June 1998

Date	Country	Description
1 August 1997	Greece	One worker is reported to have been killed and at least five others injured in an explosion at an ammunition plant. It is believed that the accident occurred during disposal of a composition that contained excess potassium nitrate.
19 September 1997	Russia	A Russian officer is reported to have been killed and two servicemen injured in an explosion that occurred during disposal of obsolete ammunition.
6 October 1997	UK	A truck carrying 100 kg of explosives caught fire in a quarry. Firemen tackled the blaze, no explosion was reported.
13 May 1998	South Africa	Four men are reported to have been killed and another seriously injured in an explosion at a firing range. The explosion occurred as the men were attempting to dispose of ammunition.

the manufacturing of ammunition and fireworks. The Danish Defence Explosives Safety Commission [6] kindly made the information available following publishing permission from the UK HSE and UK MOD. A recent study by the US Department of Defence Explosive Safety Board [7] indicates that the probability of explosives accidents is highest at sites used for demilitarisation, demolition, disposal and as burning ground. Unfortunately, this study doesn't distinct between these activities, and the data is therefore of limited use for our purpose of comparing different disposal techniques.

3.2. Transport risks

Transport risks are based on recent results from the Danish Council of Road Safety Research [8]. The total risk, i.e. the risk for truck drivers as well as other road users to be killed or seriously injured due to truck driving has been falling over the years to about three incidents per 10 million truck kilometres. This value has been used to calculate the risk related to transport in connection with the disposal of munitions, using the transport requirements as included in Table 2. These requirements are based on the assumption that

Table 2
Characteristic data for the alternative ammunition disposal techniques

Disposal techniques	Location	Pre-treatment/ downsizing required	Typical capacity (kg TNT/h)	Typical distance from storage (km)	Transport including disposal of waste (vehicle km/kg MEM[a])
OB	Remote site	No	10	80	0.04
OD	Remote site	No	10	80	0.04
CD	Mobile	For large munitions	4	nil	0.008
RK	Central facility	Yes	130	335	0.17
FB	Central facility	Yes	130 (0.5 m i.d. oven)	335	0.17
MI	Mobile	For large munitions	40	nil	0.008

[a] MEM: mass of energetic material.

a 12 tonnes truck is used with a payload, two-thirds of its capacity and includes the return trip. It includes the transport of solid waste to a controlled waste disposal, based on estimates of solid waste for the alternative disposal techniques. The possibility of detonating munitions or energetic materials during transport or transport accidents has been neglected. This risk is considered small compared to "normal" transport risks, also because the technologies that require most transport (RK and FBC) use desensitised slurries, i.e. materials that have been proven not to be able to behave as explosives and which can be regarded as "normal" dangerous goods. The results are included in Table 4.

3.3. Hazard identification

For the hazard analysis, use has been made mainly of a functional description of the methodologies. Based on the functional description, a hazard identification has been performed [9]. Such a hazard identification leads to recognition of several hazards in the operations. For such a hazard moment, the seriousness can be assessed as well as the number of barriers in place that prevent the hazard from developing into an accident. The hazards are classified according to the type of impact:

- hazards that can cause diseases at work (health risks);
- hazards that can cause acute serious injury or loss of human life, including both risks to personnel and the public (people nearby);
- hazards that can have a negative impact on the environment.

Apart from this, hazards that can cause loss of property and operating time can be distinguished, but these are not considered separately in this study.

As an example, the analysis for CD is reproduced. The graphical decompositions of the functions are presented in Fig. 1. For all functions recognised in this graph, one can identify inputs and outputs, which are mainly physical quantities (munitions and emissions), but for the hazard identification, the description of the process is equally important, if not more so. A simple semantic model can describe the process for fulfilling the intent of a function:

< Intent > by < Method > with < Constraints >

Each method can again be considered as a function, and in that way the overall function of, e.g. a facility can be broken down into lower level functions using the conventions for pleoname of structured analysis and design techniques (SADT) (see Ross [10]) as in

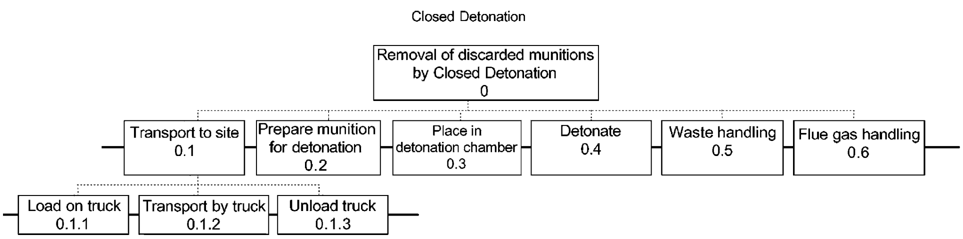

Fig. 1. Graphical decomposition of the functions implied by the disposal technique CD.

Fig. 1. The identification of constraints (e.g. established procedures and necessary physical conditions) is important for hazard identification, as constraints either indicate possible deviations from the desired condition or they can be interpreted as barriers to prevent accidents.

Table 3 presents the hazard identification for CD. Each recognised function has a reference number corresponding to the decomposition of the overall process (see Fig. 1). The table shows the intent of the function, inputs, outputs, methods and constraints. For the functions that have not been broken down to lower level functions, possible hazards related to the methods, constraints and substances handled are listed, together with the possible consequences. In the last column, additional remarks are listed related to the seriousness of the consequences and the number of barriers (independent measures to prevent the hazard from developing into unwanted events). A grey code is used to indicate the seriousness of primary hazards in this study, i.e. black for hazards that can cause acute serious injury or loss of human life, dark grey for hazards to health, and light grey for those that can have negative impact to the environment. These hazards are considered serious because of their consequences and the possibility of a single failure (failure of a single barrier) causing an incident.

Based on such analyses for all techniques (except mobile incineration), hazards or hazard moments at the subsequent functional steps in the process have been identified.

3.3.1. Open burning

The following four hazards for accidents that result in fatalities have been identified.

1. Premature ignition of the munitions that have been prepared for burning (i.e. munitions that are fused).
2. Ignition while one or more people are nearby.
3. Fire gets out of control and vegetation is set on fire (wild fire).
4. Destruction of energetic material is incomplete.

The following three hazards in which personnel are contaminated with hazardous/toxic substances have been identified.

1. Contamination from polluted ground during placement of munitions.
2. Contamination from dust and smoke during burning.
3. Contamination from polluted soil when scrap material is removed.

It is noted that hazardous/toxic residues are left on site. This will have an impact on the environment (soil pollution). This can be considered as a non-accidental but continuous environmental problem rather than a hazard, but one should realise that trespassers can be contaminated and suffer health problems.

3.3.2. Open detonation

The following four hazards for accidents causing fatalities have been identified.

1. Premature ignition of the munitions during preparation for detonation, especially due to the use of sensitive detonators that can be triggered by thunderstorms and mobile phones.

Table 3
Hazard identification of CD based on a functional decomposition of the technique

Ref	Function	Input	Output	Methods	Constraints	Hazards	Consequences	Remarks (seriousness and barriers)
0	*Removal of discarded munitions by Closed Detonation*	*Munitions*	*Solid Waste, Air pollutants, Deposited pollutants, Shock waves, Noise*	*Transport to site, Prepare munitions for detonation, Place in detonation chamber, Detonate, Waste handling*	*Remote sites, Working procedures, Safety distances*			
0.1	Transport to site	Munitions, Fuel to truck	Munitions, Air pollutants from truck	Load on truck, Transport by truck, Unload truck	Working procedures, Regulations related to transport of dangerous goods, Labelling, Packaging, Routing,			
0.1.1	Load on truck	Munitions in stock	Munitions on truck	register amount, place on truck	Maximum amount to be destroyed on one day, Registration of amounts taken from stock, 2 persons present at hand out	wrong amount	Munitions outside military control	Requires human failure from 2 persons
						wrong registration	Munitions outside military control	Munitions outside military control
						Irresponsible action, not qualified personnel		
0.1.2	Transport by truck	Munitions	Munitions	Follow route	Public road, Prescribed route, Type of vehicle. Escort	Accident with truck,	Fatality/injury of personnel, 3rd party damage/injury	Ordinary traffic accident, explosion in case of fire or detonation of sensitive charges in the car
						Theft of munitions	Munitions outside military control	Robbery requires engagement with more than one person
0.1.3	Unload truck	Munitions	Munitions	Place in shed	Working procedures	Fire in stored munitions	Fatality/injury of personnel.	Requires fire ignition and failure to extinguish fire before fatal hazard occurs
						Static electricity	Fatality/injury of personnel.	
0.2	Prepare munitions for detonation	Munitions, detonator	Munitions with mounted detonator	Take approved number of munitions, Put munitions together, put weighted amount of pentrite together with munitions, Put detonator together with pentrite	Working procedures, Qualified personnel, Use calibrated scale,	Too much/too little pentrite	Damage to detonation chamber or incomplete detonation	Without supervision a single error may cause hazard
					Protective clothing	contamination with toxic material	Health risk to personnel	Comparable to other activities related to manual handling of explosives
					Open shed	Premature ignition	Fatality/injury of personnel.	2 persons needed to initiate ignition, thunderstorms and mobile communication equipment can initiate sensitive detonators

Table 3 (*Continued*)

0.3	Place for detonation	Munitions with mounted detonator	Munitions with mounted detonator	Carry munitions into chamber. Position munitions,	Working procedures, 2 persons needed	Premature ignition	Fatality/injury of personnel	see above
						Handling error (sensitive detonator)	Fatality/injury of personnel	see above
						failure in positioning	Damage to detonation chamber	Without supervision a single error may cause hazard.
0.4	Detonate	Munitions, Ignitor	Solid Waste, Flue gas, Heat, Noise	Close Chamber, Ignite, Release pressure, Open chamber	Ignition from distance, Maintain safety distance, Working procedures,	Ignition while chamber open	Fatality/injury of personnel	Requires a two procedural errors before fatal hazard occurs
					Monitor pressure and temperature, access to site and site around the	Damage to detonation chamber	Physical damage. Fatality/injury of public	Requires several failures before fatal hazard occurs
					chamber is video controlled	Incomplete detonation	Fatality/injury of personnel	Requires a single failure before fatal hazard occurs
						Failure to depressurise	Fatality/injury of personnel.	Requires several failures before fatal hazard occurs
0.5	Waste handling	Solid waste	Solid waste	Remove ashes dry/mechanically (vacuum cleaner)	Working procedures, Protective cloth. Fresh air supply to operator,	Contamination by toxic substances	Health risk to personnel	Cloth and fresh air supply is the only protection present.
					Avoid dust to blow.	Contamination of environment	Environmental damage	Manual operation makes environmental contamination probable.
0.6	Flue gas treatment	Flue gases, airborne particulate	Flue gases, filter material	Pass flue gasses through particle filter and active coal filter. Ventilate chamber before opening	Working procedures, pressure regulation	Catastrophic failure of system (overpressure)	Fatality/injury of personnel.	If system is NOT remotely operated a single technical failure may cause a fatal hazard
						Failure of cleaning system	Contamination of environment	If system is NOT remotely operated may a single
							Health risk to personnel	technical failure cause an environmental and health hazard
						Release of uncleaned gases through other openings (door)	Contamination of environment	Failure or inefficient ventilation will cause environmental hazard
							Health risk to personnel	Failure or inefficient ventilation will cause health hazard

2. Premature ignition while munitions are put in place.
3. Handling error with the fused munitions in view of the mechanical sensitivity.
4. Destruction of energetic material is incomplete.

The following three hazards in which personnel are contaminated with hazardous/toxic substances have been identified.

1. Contamination from polluted ground during placement of munitions (digging).
2. Contamination from dust and smoke during detonation.
3. Contamination from polluted soil when scrap material is removed.

As for OB, it is noted that hazardous/toxic residues are left on site. This will have an impact on the environment as described under OB.

3.3.3. Closed detonation

The following five hazards for accidents causing fatalities or serious injury have been identified.

1. Premature ignition of the munitions during preparation for detonation, especially due to the use of sensitive detonators that can be triggered by thunderstorms and mobile phones.
2. Premature ignition while munitions are put into the detonation chamber.
3. Handling error with the fused munitions in view of the mechanical sensitivity.
4. Destruction of energetic material is incomplete.
5. Catastrophic failure of the gas cleaning system because of overpressure.

The following two hazards for contamination of personnel with hazardous/toxic substances have been identified.

1. Contamination during removal of waste products from the detonation chamber.
2. Contamination in case the gas cleaning system (leakage) fails.

The following two hazards in which the environment has been contaminated have been identified.

1. Contamination during removal of waste products from the detonation chamber.
2. Contamination in case the gas cleaning system (leakage) fails.

3.3.4. Fluidised bed combustion

No hazards were identified that pose a direct threat to a person's life. This is a result of the use of protective clothes and restricted areas and remote operation during washout. Furthermore, it is proven that no TNT remains unburned in the process. Injection of slurry is aborted if the burning process deviates beyond accepted conditions.

Two hazards are identified for contaminating personnel, viz. contaminating during manual handling of drums when producing the slurry and when connecting the slurry injection system to the drums.

Also, one hazard moment is identified for the environmental damage, viz. failure (loss of containment) of the closed-circuit high-pressure washout system (soil pollution).

3.3.5. Rotary kiln

The hazards for the RK using slurry injection are very similar to those of the FBC. However, as no practical demonstration of this technology was performed, it cannot be excluded that the incineration of slurries containing explosives causes irregular burning (with violent bursts) or reacts with other products incinerated at the same time. However, based on theoretical considerations, confirmed by an independent safety consultant's review, this is considered to be very unlikely. Nevertheless, for the time being this will be considered as one hazard moment.

Two hazard moments are identified for contamination of personnel, viz. contamination during manual handling of drums when producing the slurry and when connecting the slurry injection system to the drums.

Also, one hazard moment is identified for environmental damage, viz. failure (loss of containment) of the slurry preparation facility (soil pollution).

3.3.6. Mobile furnace

For the mobile furnace, no detailed hazard identification has been performed. However, based on similarities with OB and CD, we expect two hazards for accidents causing fatalities or serious injury.

1. Destruction of energetic material is incomplete.
2. Catastrophic failure of the gas cleaning system because of overpressure.

A single hazard in which personnel are contaminated with hazardous/toxic substances is expected in case of failure of the gas cleaning system (leakage).

This failure is also expected to be a hazard for contaminating the environment.

3.4. Compilation of the hazard identification

In Table 4, the numbers of identified hazards are included. These numbers represent qualitative information. In order to come to a kind of semi-quantitative risk score, these numbers are multiplied by the amount of person-hours required to dispose 1 kg of energetic material. This seems to be justified, as most of the identified primary hazards are related to human actions, so human reliability will be the dominant factor for risk. The required manpower was determined on the basis of tests performed with the techniques. This risk score is a rough indicator of the probability that an accident will take place.

The environmental hazards related to OB and OD cannot be compared with those of the other technologies, which are based on containing the hazardous and waste substances. The OB and OD leave all hazardous waste on site, posing a continuous impact on the environment with considerable risks of contaminating passers by (several OB/OD sites, e.g. in Denmark and The Netherlands, are publicly accessible when not in use).

Apart from identifying primary hazards as input to decision analysis for selecting the appropriate disposal technique, the hazard identification led to extensive lists of recommendations to manage all identified hazards, also the less serious ones.

Table 4
Risk and hazard scores of disposal technologies[a]

Disposal technologies	Required man-hours per kg MEM	Process risk (per kg MEM)	Transport risk (per kg MEM)	Total accident risk (per kg MEM)	Number of hazards			Relative risk score		
					Fatality/ injury	Health	Environment	Fatality/ injury	Health	Environment
OB	0.2	7.9×10^{-7}	1.2×10^{-8}	8.0×10^{-7}	4	3	See text	0.8	0.6	N/A
OD	0.2	7.9×10^{-7}	1.2×10^{-8}	8.0×10^{-7}	4	3	See text	0.8	0.6	N/A
CD	0.5	2.0×10^{-6}	2.4×10^{-9}	2.0×10^{-6}	5	2	3	2.5	1.0	1.5
FBC	0.09	3.4×10^{-7}	5.1×10^{-8}	3.9×10^{-7}	0	2	1	0.0	0.2	0.1
RK	0.09	3.4×10^{-7}	5.1×10^{-8}	3.9×10^{-7}	1	2	1	0.1	0.2	0.1
Mobile furnace	0.1	4.0×10^{-7}	2.4×10^{-9}	4.0×10^{-7}	2	1	1	0.2	0.1	0.1

[a] The primary weight factor is the number of person-hours required for the disposal of 1 kg energetic material (MEM). Process risk is calculated using the general accident rates for the chemical industry. Total accident risk is the sum of process risk and transport risk. The number of hazards are derived from the hazard identification of the technologies. The relative risk score is the number of hazards weighed with the required person-hours.

3.5. Estimating risk using occupational accident rates

Complementary to using a ranking list, the number of identified hazards, an estimate of the number of incidents per kilogram disposed energetic material is given, based on general accident rates in industry. This is justified by the fact that the safety performance at the Danish Ammunition Arsenal (AMA) seems to be better (considering the limited statistical material) than the average performance in Danish industry and, as stated before, that risk for these techniques is dominated by human reliability. At AMA, no serious injury or fatality in relation to disposal (detonation) and production of munitions occurred during the last 20 years, covering about 2 million person-hours of activity involving explosives. This corresponds to an accident rate of less than 5–10 per 10 million h. Unfortunately, information from databases like EIDAS, although useful for supporting hazard identification, does not allow making independent similar assessments. The general accident rate in Denmark [11] for fatalities and very serious injuries [1] is about 14 per 10 million h. Risk in basic chemical industry is expected to be most representative for risk in handling explosives, as both are related to hazardous materials. For the Danish basic chemical industry, the fatal accident rate (FAR) and the accident rate for very serious accidents are 0.3 and 39 per 10 million h, respectively (numbers for 1985 and 1986). The last number has been used to calculate "process risk" in Table 4. This number can be used for comparison with transport risk. It appears that using the general chemical industry's accident rate, process risk dominates transport risks, although transport risk is not negligible for the technologies requiring transport to a central facility (FBC and RK). If one would use AMA's recent performance, transport risk and process risk become equal for these two technologies, but it would not lead to a different ranking of all technologies.

4. Conclusions

Comparative risk levels for alternative disposal techniques for ammunition have been derived using hazard identification based on functional modelling of the techniques in combination with the required manpower to perform the operations. This combination is justified as most hazards are related to human actions.

An alternative method is to use general accident rates in industry in combination with required manpower. This does not reflect the difference of the hazardous operations for each of the alternative techniques, but it is not in conflict with actual records of work with ammunition. As an advantage, it provides more "absolute" numbers on the levels of risk, allowing a comparison to be made with other risk levels, e.g. risks due to transport. Both methods of risk characterisation lead to the same ranking of the techniques with respect to safety, albeit that the differences are more pronounced if the hazard identification is included.

With respect to risks for persons (especially personnel), it appears that CD leads to the highest risk per unit disposed energetic material. This is due to the relatively high

[1] In the statistics of the Danish Labour Inspectorate, "very serious accidents" include amputations, broken bones, and other injuries involving damage of large parts of the body, excluding contamination and poisoning.

requirements for manpower, the use of sensitive detonators as well as the use of a pressurised system.

With respect to the environmental risks, one can say that OB and OD pose a high risk to the environment, as all waste products are dispersed on site. This risk is related to normal operation rather than to incidents. The other technologies aim at containing the waste products.

FBC, RK and mobile incineration perform considerably better. The hazard identification suggest that FBC is the "safest" approach, but differences in the perceived risk level may be due to conservative analyses for the RK and mobile incineration, for which no full-scale testing was performed.

For disposal using centrally located facilities, such as existing RK or FBC, the risk related to transport between storage of munitions and these sites is not negligible.

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