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# Assessment of technologies for disposing explosive waste

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## Abstract

The environmental impact and safety aspects are assessed for six different techniques for disposing decommissioned ammunition. These are open burning and open detonation (OD), closed detonation (CD), fluidised bed combustion (FBC), rotary kiln (RK) Incineration, and Mobile furnace (MF) Incineration. The assessment is performed in the form of a multi-criteria decision analysis (MCDA). Objectives for minimising environmental impact and risk are defined to enable selection of the "best" technology. A framework for comparing emissions of different air pollutants is proposed. Environmental impacts are described, especially air pollutants. The environmental impacts of traditional OB and OD can be drastically reduced using controlled incineration techniques in combination with high-pressure water washout. This enables the explosive contents to be separated from the casing, and simultaneously the explosive is transformed to a desensitised water-based slurry. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Disposal; Ammunition; Environmental impact; Safety; Emissions

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*Abreviations:* BaP, benz(a)pyrene, an PAH that is used as the reference substance for expressing concentrations of all PAHs having equal toxic impact as the same concentration of BaP; CD, closed detonation; $C_xH_y$, hydrocarbons; EPA, Environmental Protection Agency; EU, European Union; FBC, fluidised bed combustion; IAEHS, Impact Assessment for Environment, Health and Safety; MCDA, multi-criteria decision analysis; MEM, mass of energetic material; MF, mobile furnace; NC, nitro-cellulose; NEQ, equivalent concentration of air pollutants having equal toxic impact as the same concentration of $NO_2$ (only in this study); NERI, Danish National Environmental Research Institute; $NO_x$, nitrogen oxides; OB, open burning; OD, open detonation; PAH, polyaromatic hydrocarbons; PCDD, polychlorinated dibenzo-dioxins; PCDF, polychlorinated dibenzo-furans; RK, rotary kiln; RSP, respirable suspended particulate; TEQ, toxic equivalent, reference concentration of PCDD and PCDF having equal toxic impact as the same concentration of 2,3,7,8-TCDD, using intentional toxic equivalent factors (ITEF) for the different PCDDs and PCDFs; TNT, 2,4,6-trinitrotoluene

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## 1. Introduction

There is a growing community interest that the disposal of explosive waste and demilitarisation of ammunition be carried out with due consideration of their effect on the environment and the associated hazards. In recognition of the need for environmentally acceptable and safe technologies for disposing 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-operative venture 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 (AMA).

Selection of the “best” disposal technique is considered to be a multi-criteria decision problem, in that there are conflicting objectives in terms of e.g. environment, costs and capacity, which can be expressed in different units. Comparison of these conflicting objectives requires multi-criteria decision analysis (MCDA). MCDA aims at structuring decision-making problems involving conflicting objectives, which are expressed in different units. This is done in order to rank solutions.

An Impact Assessment for Environment, Health and Safety (IAEHS) is used to determine the scores (attributes) of the different scenarios or techniques for a number of objectives, which can be formulated with respect to environment, health and safety.

This paper describes, the IAEHS for six alternative scenarios for disposing of ammunition, where the aspects related to environment are considered in some detail. The hazard analysis that covered the health and safety aspects of the IAEHS is published in an accompanying paper (Duijm [1]).

## 2. Description of the scenarios

The scenario selection is restricted to the technologies that have been subject to detailed study during the project, including the “reference scenarios” open burning (OB) and open detonation (OD). This leads to the following list of scenarios, which includes the range of munitions as well as a short description (additional details can be found in Duijm [1] and Lauritzen [2]).

### *2.1. Open burning (OB)*

Mainly propellants, but also high bulk explosives and pyrotechnics are burned on bare soil. In the case of explosives and/or pyrotechnics, an assist fuel is used.

### *2.2. Open detonation (OD)*

Bulk explosives and whole-piece munitions up to maximum weight of about 15 kg of energetic material and/or pyrotechnics are detonated, in most cases covered with half a meter of soil.

### 2.3. *Closed detonation (CD)*

Bulk explosives (e.g. 2,4,6-trinitrotoluene (TNT) or pentrite) and small whole-piece munitions, such as anti-personnel mines, up to maximum weight of a few kilograms of energetic material, and rounds of pyrotechnics, are detonated in a closed, strong metal sphere with a diameter on the order of 1–2 m.

### 2.4. *Fluidised bed combustion (FBC)*

This technique is applicable to bulk explosives like TNT that have been transferred to stable water-based slurries. These slurries can be produced when high-pressure washout is used to remove the TNT from the ammunition shell. The slurry is injected in the central fluidised bed part of a fluidised bed oven. A variation on this scenario is the additional injection of urea in the freeboard of the oven in order to reduce the emission of $NO_2$.

### 2.5. *Rotary kiln (RK)*

This technique can be used for water-based slurries of bulk explosives or propellants like nitro-cellulose (NC). A variation of this scenario is the mixing of additives to the slurry in order to reduce the emission of $NO_2$. Results included in the study are based on theoretical considerations and small-scale experiments.

### 2.6. *Mobile furnace (MF)*

Specially designed mobile furnaces (MFs) are applicable to bulk explosives and (small) whole-piece munitions. Results included in the study are based on theoretical considerations.

## 3. The Impact Assessment for Environment, Health and Safety (IAEHS)

The objective of the IAEHS is to analyse the environmental impacts of noise, and emissions to air, water, and soil and to assess the risk of hazards to workers' health and safety as well as to the public, including hazards during transportation and loading of the investigated disposal options.

The IAEHS covers the following activities related to the disposal of ammunition:

- transportation;
- preparation and pre-treatment;
- downsizing (often in the same process as preparation and pre-treatment);
- processing (treatment, recycling and waste handling);
- cleaning of waste streams;
- disposal and discharge of waste in the environment.

The following objectives were selected for translation into operational attributes, which can be used in an MCDA:

1. With respect to environmental impacts during normal operation:
   - minimise the emission of pollutants to the air and comply with the EU emission standards for incineration of hazardous waste (Council of the European Union (EU) [3]);
   - minimise the emission of pollutants to the soil;
   - minimise the exposure of people to noise, vibrations and other direct impacts;
   - minimise the impact on the cultural and natural heritage.
2. With respect to risk for human life and accidental environmental impacts:
   - minimise diseases and accidents at work;
   - minimise the loss of human life;
   - minimise accidental impacts to the environment.

Preliminary identified objectives that were not selected for further use in the MCDA included the minimising of pollutants to surface water. This did not appear to be a discriminative factor between the scenarios. Furthermore, the minimising of energy consumption and consumption of raw materials was not included, as these aspects are covered by an economy-based cost-benefit analysis, which was performed later on in the study (Lauritzen [4]). The conclusions of this study are summarised in the discussion of results.

Selection and definition of operational attributes were constrained by the information available for the selected scenarios. Detailed information was collected from the experimental work within the study, i.e. for fluidised bed combustion (FBC), closed detonation (CD) and rotary kiln (RK) incineration (van Ham and Hesseling [5], van Ham [6], Markert and Egsgård [7], and Markert [8]). Quantitative information about emissions from OB and OD was collected from Mitchell and Suggs [9].

### *3.1. Attributes for emissions to the air*

All selected technologies involve combustion or detonation; therefore, environmental concerns focussed on air pollutant emissions. During the experimental studies, 12 specific air pollutants were investigated. No relevant emissions were identified relevant for ozone depletion and green-house effects. Combustion leads to the emission of carbon dioxide, largely corresponding to the carbon content of the explosive, but in view of the limited amounts of pollution compared to the use of fossil fuels world-wide, this is not considered to be a major concern in relation to the disposal of ammunition. The same reasoning applies to acidification, nitrification and photochemical oxidants, all problems important to large spatial scale (regional, national or global).

The majority of the 12 pollutants investigated are of concern because of human and environmental toxicity. Moreover, except for ammonia, all pollutants relevant for acidification, nitrification and photochemical oxidants play also a direct role in relation to toxicity. Therefore, it was decided to develop a single set of score attributes related to air quality, with emphasis on toxicity aspects and local scale impact.

In the investigation a direct comparison was made of the toxicity and environmental risks related to different substances using techniques like EUSES [10,11], but this was not successful. The EUSES system requires detailed input and cannot handle groups of substances like polyaromatic hydrocarbons (PAH). A more pragmatic approach was followed, using available assessments of toxicity and the emission standards.

Table 1
Weighting factors used to translate emissions of specific pollutants into "$NO_2$-equivalent" emissions

| Substance | Weight factor | Argumentation |
|---|---|---|
| CO | 0.007 | The WHO 1 h limit value for CO is 30 mg/m$^3$ compared to 200 μg/m$^3$ for $NO_2$ [9] |
| $NO_2$ | 1 | |
| Particulate | 5 | NERI recommends that the long average air quality level for respirable particles matter is 4 μg/m$^3$ compared to 20 μg/m$^3$ for $NO_2$ [9] |
| Hydrocarbons ($C_xH_y$) | 5 | The EU emission standard in flue gas for organic substances (total organic C) is 10 mg/m$^3$ compared to 50 mg/m$^3$ for $NO_2$ [3] |
| $SO_2$ | 1 | The EU emission standard in flue gas for $SO_2$ is equal to that of $NO_2$ [3] |
| Hg | $10 \times 10^2$ | The EU emission standard in flue gas for Hg an Hg-containing substances is 0.05 mg/m$^3$ compared to 50 mg/m$^3$ for $NO_2$ [3] |
| $NH_3$ | Unknown | No emission standards or concentration limits relevant to toxicity |
| HCl | 5 | The EU emission standard in flue gas for HCl is 10 mg/m$^3$ compared to 50 mg/m$^3$ for $NO_2$ [3] |
| HF | 50 | The EU emission standard in flue gas for HF is 1 mg/m$^3$ compared to 50 mg/m$^3$ for $NO_2$ [3] |
| Heavy metals | 100 | The EU emission standard in flue gas for heavy metals (Sb, As, Pb, Cr, Co, Cu, Mn, V, Sn) is 0.5 mg/m$^3$ compared to 50 mg/m$^3$ for $NO_2$ [3] |
| Dioxins (PCDD or PCDF) (TEQ) | $50 \times 10^7$ | The EU emission standard in flue gas for dioxins is 0.1 ng/m$^3$ (TEQ) compared to 50 mg/m$^3$ for $NO_2$ [3] |
| PAH (BaP) | $20 \times 10^5$ | Danish EPA recommends that the long average air quality level for PAH (BaP) be 0.01 ng/m$^3$ compared to 20 μg/m$^3$ for $NO_2$ [9] |

$NO_2$ is chosen as the "reference" substance. $NO_2$ emissions have been a major concern throughout the project (due to the high content of nitrogen in the form of nitro-groups in explosives, emissions of nitrogen oxides ($NO_x$) are high). Furthermore, quantitative information is available and its toxic effects are well known. In Table 1, the other pollutants are expressed in $NO_2$-equivalents, thus enabling a single score to be made for the air quality impact of the different technologies. The actual emission of a substance can be multiplied by the weight factor listed in Table 1, and the resulting number represents the same total toxic impact as an $NO_2$-emission of the same amount as this number. Of course, there is quite some uncertainty in the assessments, partly due to incompatible data for the different technologies (e.g. some studies don't distinguish between particle sizes in the case of particulate matter). Also, the assessment focuses on toxic effects (including carcinogenic effects) and does not account for acidification, photochemical oxidant formation, etc. Primary sources of information are the EU-emission standards for hazardous waste incineration facilities (Council of the EU [3]) and a toxicological evaluation of air traffic pollutants published by the Danish Environmental Protection Agency (EPA) (Larsen [12]).

Apart from the objective of minimising this “$NO_2$-emission equivalent” (which we will refer to as “NEQ”), meeting the EU emission standards for hazardous waste incineration facilities remained a separate goal.

### *3.2. Attributes for emissions to the soil*

Potential soil pollution problems are identified as follows:

- OD/OB will lead to debris and deposition directly on the soil;
- all burning residues need to be deposited on a waste site (ashes, slag). These residues may be considered as toxic waste due to concerns about dioxins (Colombo et al. [13]).

The total mass of solid waste per kilogram mass of energetic material (MEM) will be a useful score attribute. Most incineration processes will generate comparable amounts of unburned residues, depending on the efficiency of the process. However, some processes (OB and OD) will lead to uncontrolled spreading and deposition of the unburned residues in the surrounding area, while in the other cases the residues are collected and deposited under controlled conditions (controlled landfill, stabilised or immobilised and reused). Uncontrolled deposition will be considered to be 10–100 times more hazardous than controlled deposition. We will use the factor 100 as a weight factor to compare uncontrolled with controlled deposition. The sensitivity of the final result to this arbitrarily chosen weight factor will be commented upon in Section 5.3.

### *3.3. Attributes for exposure of people and impact on cultural and natural heritage*

For a general technology assessment independent of a specific siting, it is hard to define a proper attribute for the direct impact on neighbouring people and environment.

With respect to the exposure of people to noise and vibrations, one can take the total power emitted as pressure waves or sound per kilogram MEM. This does not take into account the different perception of the noise of a series of separate explosions (OD and CD) compared to the constant noise of industrial compressors, etc., which are involved in the use of incinerator facilities.

Therefore, the total area occupied by the technology is used as a simple attribute for the exposure of people and the impact on the cultural and natural heritage. This can be either the physical size of the plant with all its facilities or the restricted zone around sites for OB and OD.

### *3.4. Attributes for safety and environmental risks due to accidents*

The hazard analysis (see Duijm [1]) resulted in four sets of data that could be used as attributes. Relative risk scores were derived from the number of identified serious hazards for: (1) fatality or acute injury; (2) health effects; and (3) environmental impact, weighted with the manpower required per disposed kilogram MEM. The fourth set is the estimated total accident risk for a fatality or injury, which also includes the risk related to transportation. Meanwhile, there is the problem of the continuous environmental impact of OB and OD, which precludes the making of any comparison of the relative risk score for (accidental) environmental impact. To express the risk of an acute fatality or injury a 50–50 combination of estimated total risk and the corresponding relative risk score were selected, leaving two operational attributes in place, namely one expressing the risk of an acute fatality or injury and another expressing the risk of health damage.

### 3.5. Summary of selected attributes

The following five attributes are extracted from the IAEHS in order to perform the MCDA:

- an equivalent toxic air-pollutant emission expressed in $NO_2$-toxic equivalent (TEQ) concentrations (NEQ) per kilogram MEM;
- total mass of controlled and uncontrolled deposited waste per kilogram MEM, where uncontrolled depositions are weighed with an extra factor;
- the total area occupation;
- a hazard score related to safeguarding human life;
- a hazard score related to safeguarding health.

Apart from these, compliance with the EU emission standard for flue gases is maintained as a separate goal.

## 4. Overview of the results of the IAEHS

In this chapter, the selected technologies will be analysed with respect to environmental impacts. The processes are split up into different phases. In the last section, the results will be combined into an overall assessment.

### 4.1. Transportation

Table 2 describes the transport requirements for the different technologies. The table only mentions the route the load has to be carried; the vehicles are required to return, so the total demand on transport is twice the distances noted. Table 2 has taken a typical Danish situation, i.e. the ammunition depot is located at Frederikshavn (in northern Jutland), and central incineration facilities are located at Nyborg (Island of Fyn). As transport vehicle a 12 tonnes truck is considered, with an average payload of two-third of its weight (8 tonnes). The main environmental impact of transport is air pollution. Emission factors for trucks are derived from EMEP [14], with additional information on PAH emissions from Miguel et al. [15]. The relative potency of various PAHs is expressed as Benz(a)pyrene (BaP) TEQs, following the suggestions by the ICF-CA [16]. Particle emissions (fine particles or respirable suspended particulate (RSP)) are derived from Annema et al. [17]. The resulting toxic emission indicator, expressed in $NO_2$-equivalents (NEQ), is presented in Table 2. These transport emissions are based on emission data on CO, $NO_2$, volatile organic compounds and PAH. It appears that the NEQ-emission is dominated by that of PAH (almost 75%). As emission factors for PAH are derived from a single scientific reference, and calculations of BaP-TEQs are questioned, these results should be used with care.

Table 2
Transport requirements and corresponding air pollutant emissions for the selected technologies

| Scenario | Transport requirement | Transport emissions in g NEQ per kg MEM |
|---|---|---|
| Open burning | The ammunition is transported from storage to burning site, typical distance 80 km. Weight of packaging material, shells, etc. will be the same as the weight of MEM, so 1 kg MEM requires 0.04 km vehicle | 4.3 |
| Open detonation | As for open burning | 4.3 |
| Closed detonation | Closed detonation is performed on site, i.e. this will not require substantial transport. Waste products (e.g. active coal filters) need to be transported to a hazardous waste incinerator at a distance of 335 km. It is expected that CD will generate 0.1 kg waste per kilogram MEM. This means that each kilogram MEM requires 0.008 km vehicle | 0.9 |
| Fluidised bed combustion | Washout takes place at the ammunition depot. The slurries (50% MEM) are transported to a central FBC installation, distance 335 km. Rest products, mainly fly ash, need to be deposited at a land fill site at a distance of about 20 km from the incinerator. The ash production is about 0.027 kg per kilogram MEM. This means that 1 kg MEM requires 0.17 km vehicle | 18.4 |
| Rotary kiln | As for FBC | 18.4 |
| Mobile furnace | As for closed detonation | 0.9 |

### 4.2. Preparation, pre-treatment and downsizing

The environmental impact from the preparation, pre-treatment and/or downsizing is limited. OB, OD and CD require manual preparations, e.g. joining a certain number of munitions together and mounting a detonator.

Washout and preparation of a TNT slurry, as in connection to FBC, makes use of a closed loop of circulating water. A part of the water is used in the slurry and no wastewater is produced (an environmental hazard related to a possible loss of containment is included in the hazard analysis, see Duijm [1]). Filters to clean the circulating water need to be considered as hazardous waste and will be disposed of by incineration in a conventional hazardous waste incinerator. The amount of this waste stream is negligible compared to, e.g. the amount of ashes (fly ash) produced in FBC.

The washout and preparation of the TNT slurry uses a fixed facility on the order of 100 $m^2$, which will be included as an indicator for impact on the natural and cultural heritage.

### 4.3. Processing, cleaning, disposal and discharge of waste streams

The main impact of the disposal processes occurs during processing, i.e. detonation or incineration. Cleaning and disposal of waste streams are often strongly integrated in the technology and will be included in this section as well. In the following subsections, we will comment on the impact for each of the environmental issues.

### *4.3.1. Air pollution*

Information about OB and OD has been retrieved from the US-EPA database (Mitchell and Sluggs [9]). In order to obtain the respirable fraction of the dust emission, we use the estimated value of 20% of the total dust emission, using data derived from Annema et al. [17]. The available air pollution data is presented in Table 3. As for the transport emissions, the results are presented as $NO_2$-equivalent emissions in Table 4. These numbers are based only on CO, $NO_2$ and respirable particulate matter, because for only these substances was information or estimates available for all technologies (except for the MF). For FBC, information on dioxin emission is available. If this is included, it does not change the NEQ results significantly, so we expect that the ranking of the technologies will not be sensitive to the exclusion of PAH and dioxins.

Data for CD is based on CO and $NO_x$-measurements for experiments in the experimental facility at AMA (Markert and Egsgård [16]). The RSP emissions are estimated from the OB/OD data from the US-EPA, assuming a filter efficiency of 95% for RSP. Data for FBC are directly retrieved from the pilot plant experiments (van Ham and Hesseling [5]).

Data for the RK are based on DIN-oven experiments on TNT (Markert [17]). The RSP emissions are considered to be equal to those for FBC based on comparable collection efficiencies of the filters.

It should be noted that none of the emissions mentioned here would fulfil the emission requirements according to EU-standards, mainly because of emissions of $NO_x$. However, when urea is injected, the $NO_x$-levels in the flue gas of FBC and the RK will lie within ranges that can be treated using existing denitrification techniques. Weidenhagen [18] claims that mobile incinerator facilities equipped with chemical treatment of the flue gases are able to comply with the emission regulations.

### *4.3.2. Soil pollution*

All incinerator processes lead to some solid waste that needs to be disposed of. The solid waste residue consists of bottom residue and fly ash. It is usually disposed of in a landfill, although some residues can be used in building materials (cement, asphalt). In some countries (e.g. Germany and the Netherlands) solid waste residue from incineration is classified as toxic hazardous waste, due to concern about dioxins (Colombo et al. [13]). Fly ash and other smoke particles will also be the main carrier of PAH.

OB and OD lead to deposition of these solids in the near vicinity of the burning or detonation site. This uncontrolled disposal may well be considered as the most important negative environmental impact of OB and OD. We consider uncontrolled disposal a hundred times more serious than controlled disposal. Estimates of the amount of solid waste for OB and OD are taken from the US-EPA data on total dust emissions (0.36 and 0.13 kg/kg MEM, respectively, see Mitchell and Sluggs [9]).

Incompletely incinerated waste products from CD, including active coal filters and the like, are considered as hazardous waste that needs to be incinerated using an existing RK. Final rest products are considered to be about 5% of the MEM. Table 5 presents the solid waste and soil pollution scores for the different technologies. This table shows that even if we fail to apply an extra factor between 10 and 100 to stress the seriousness of uncontrolled solid waste deposition, OB and OD show the worst results, still.

Table 3
Mean process emissions derived from the US-EPA database [9] for OB and OD, experiments in this study on FBC, closed detonation, and rotary kiln[a]

| | OB bulk | OD bulk | OD encapsulated | CD[b] | FBC bulk TNT | FBC/ureum bulk TNT | RK bulk NC |
|---|---|---|---|---|---|---|---|
| CO | 2460 | 34040 | | 0 | 1264 | 2297 | 2600 |
| $No_x$ | 5408 | 10816 | | 7912 | 69030 | 3470 | 24300 |
| $NO_x$ (% of N in MEM) | 0.89% | 1.78% | | 1.30% | 11.36% | 0.57% | |
| PM10/RSP | 56000 | 26000 | 60000 | 1300 | 208 | 56 | 50 |
| Total $C_xH_y$ | 28.80 | 184.0 | 859.0 | | 0.11 | 0.06 | |
| Total saturated $C_xH_y$ | 4.70 | 11.0 | 55.0 | | | | |
| Ethylene | 3.70 | 69.0 | 256.0 | | | | |
| Propene | 1.00 | 14.0 | 50.0 | | | | |
| Acetylene | 4.60 | 56.0 | 300.0 | | | | |
| Other unsaturated $C_xH_y$ | 3.00 | 11.0 | 61.0 | | | | |
| Benzene | 3.00 | 9.0 | 69.0 | | | | |
| Toluene | 0.80 | 4.0 | 26.0 | | | | |
| Other aromatics | 8.00 | 10.0 | 42.0 | | | | |
| $SO_2$ | DOC[c] | | | | 0.11 | 0.07 | |
| Hg | | | | | 0.06 | 0.05 | |
| $NH_3$ | | | | | 18.1 | 5135.0 | |
| HCl | DOC | | | | 3.9 | 4.8 | |
| HF | | | | | 0.3 | 0.3 | |
| Heavy metals | DOC | DOC | DOC | | 0.2 | 0.1 | |
| PAH (BaP) | | | | | | | |
| Dioxins MEM (ng/kg) | | | | | 0.5 | 0.4 | |

[a] If not stated otherwise, emissions are in mg/kg MEM.

[b] Closed detonation tests included pentrite, TNT and tetryl in bulk and encapsulated form.

[c] Depends on contents of the chemicals in the explosive.

Table 4
Air pollutant emissions as equivalent $NO_2$-emissions in g/kg MEM[a]

| | Process emissions (gram NEQ per kilogram MEM) |
|---|---|
| Open burning | 285 |
| Open detonation | 141 |
| Closed detonation | 14 |
| Fluidised bed oven | 70 |
| FBC—urea injection | 4 |
| Rotary kiln | 25 |
| Mobile furnace | Unknown |

[a] Equivalent $NO_2$ emissions include emissions of CO, $NO_2$ and respirable particles.

Table 5
Amounts of solid waste and total attribute score

| | Total solid waste per kilogram MEM (kg) | Uncontrolled/controlled disposal | Score |
|---|---|---|---|
| Open burning | 0.36 (US-EPA) | Uncontrolled | 36 |
| Open detonation | 0.13 (US-EPA) | Uncontrolled | 13 |
| Closed detonation | 0.05 (estimate) | Controlled | 0.05 |
| Fluidised bed combustion | 0.027 (test result) | Controlled | 0.027 |
| Rotary kiln | 0.02 (estimated for NC-slurries) | Controlled | 0.02 |
| Mobile furnace | 0.05 (estimate) | Controlled | 0.05 |

### 4.3.3. Area occupation

Area occupation is used as a measure for the level of distortion and the impact on the cultural and natural heritage. The smaller the area needed, the lesser will be the distortion. The area occupation is included in Table 6. The area occupation includes safety zones and other areas of restriction, as well as all facilities needed to operate the process. It is clear that the safety zone used for OB and OD dominates the impact: compared to OD and OB, the area occupation of the other facilities, even if one includes the actual size of an existing RK site, is negligible (>1%).

Table 6
Area occupation of the different technologies

| | Area occupation ($m^2$) |
|---|---|
| Open burning (reference scenario) | 3200000 (safety zone of 1 km radius in case explosives are included) |
| Open detonation (reference scenario) | 3200000 (safety zone of 1 km radius) |
| Closed detonation | Ca. 5000 |
| Fluidised bed combustion | Ca. 5000 (wash-out plant and incinerator without gas cleaning) |
| Rotary kiln | Ca. 20000 (half of KommuneKemi’s site at Nyborg, Denmark) |
| Mobile furnace | Ca. 800 (a number of 40 ft. container elements plus surrounding space) |

## 5. Multi-criteria decision analysis

In order to combine the scores for the five separate objectives that are finally included in the IAEHS, two methods are used, viz. the reference point technique and the use of subjective weight factors derived from expert consultation. As MCDA does not offer a single method, we will apply both methods in order to investigate the robustness and sensitivity of the results, depending on which method is selected.

### *5.1. Reference point technique*

The reference point technique is based on ranking alternative solutions with respect to their “distance” to the optimal solution. We have five objectives, so each alternative solution or technology can be represented by a point in five-dimensional space where the scores for the objectives make up the co-ordinates of that point.

For each of the objectives, we will find both an optimal score (in our case, where all objectives are to *minimise* certain impacts, the optimal score is the smallest score) and a worst score.

The optimal solution or *reference point* is defined as the point that is represented by the set of optimal scores. The distance between the optimal score and the worst score becomes a scaling factor for each objective.

Using this scaling factor, all alternative technologies can be appointed a position with the reference point as origin, with the scaled, relative scores as co-ordinates. The relative scores indicate how well a technology performs for a certain objective lying in between the best and worst performance. All these relative scores thus have values between 0 and 1. The relative scores are presented in Table 8.

The “distance” of each point to the reference point can now be calculated. In this analysis we use the Cartesian distance, i.e. the square root of the sum of squares of the relative scores. It should be noted that here all objectives have equal weight.

### *5.2. Subjective weight factors*

Another approach makes use of weighting factors, representing the importance that “experts” assign to the different objectives. The information used here is adopted from the weighting factors elicited during Task 2 from the project partners using a questionnaire (Duijm et al. [19]). The results from the questionnaire were reanalysed in order to match the five finally selected attributes for the MCDA (Duijm and Markert [20]). The results of this analysis are presented in Table 7.

During the project, it was discussed to what extent the results of a questionnaire reflect the actual priorities during decision-making. In the present analysis, where cost aspects are excluded, the information in Table 7 provides probably a good representation of the perceived importance of the various environmental and safety concerns and the way they will affect decision-making, possibly with the exception of *distortion*. Based on the discussions in the project group, we expect that *distortion* (as expressed by area occupation) will have a higher priority in real decision-making than is expressed in Table 7.

Table 7
Average weight factors for the five objectives based on a questionnaire response from five institutions involved in the project (Risø, TNO, DEMEX, Ammunitions Arsenalet and Kommunekemi)

| Environment | % |
|---|---|
| The equivalent toxic air pollutant emission expressed in $NO_2$-toxic equivalent concentrations | 17 |
| Total mass of controlled and uncontrolled deposited waste per kg MEM | 11 |
| The total area occupation | 7 |
| Safety | |
| Hazard scores related to safeguarding human life | 43 |
| Hazard scores related to safeguarding health | 22 |

The subjective weights are multiplied with the relative scores (see previous section as well as Table 8) and the results are summed. This leads to a single number, which reflects the importance apportioned to the different concerns or objectives.

### *5.3. Results*

The results of both the reference point technique and subjective weight factors are included in Table 8 and Fig. 1. In this graph, the results are related to an optimal value of 1, i.e. the “best” solution will have the highest performance.

The figure shows the clear difference between the (objective) reference point method and the use of subjective weights. Due to the emphasis on safety aspects, the reference technologies (OB and OD) receive quite a bit of “compensation” for their safety performance as compared to the performance of CD in this respect, causing relatively high scores for all

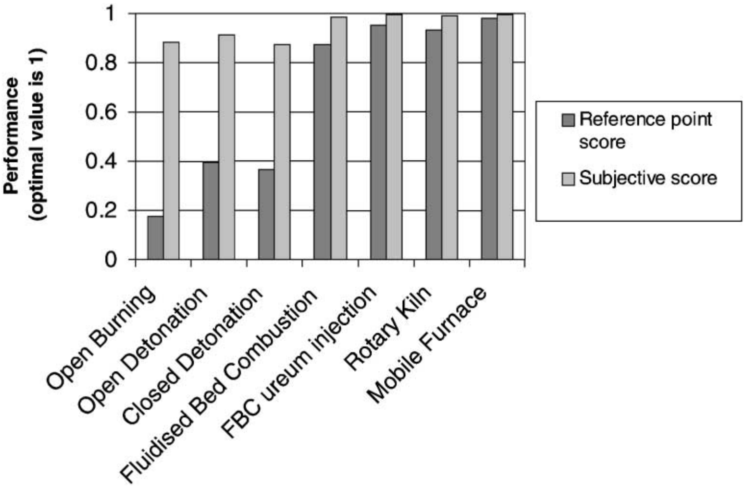

Fig. 1. Compilation of the different scores in a single ranking using the reference point technique and subjective weights.

Table 8
Scaled distances to the reference point for individual objectives and overall scores using the reference point technique (Cartesian distance to reference point) and using subjective weight factors

| | Open burning | Open detonation | Closed detonation | Fluidised bed oven | FBC urea injection | Rotary kiln | Mobile furnace |
|---|---|---|---|---|---|---|---|
| Environment | | | | | | | |
| The equivalent toxic air pollutant emission | 1.000 | 0.474 | 0.000 | 0.267 | 0.025 | 0.101 | – |
| Total mass of controlled and uncontrolled deposited waste | 1.000 | 0.464 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 |
| The total area occupation | 1.000 | 1.000 | 0.001 | 0.001 | 0.001 | 0.006 | 0.000 |
| Safety | | | | | | | |
| Hazard scores related to safeguarding human life | 0.287 | 0.287 | 1.000 | 0.000 | 0.000 | 0.020 | – |
| Hazard scores related to safeguarding health | 0.556 | 0.556 | 1.000 | 0.111 | 0.111 | 0.111 | – |
| Reference point score (0 is optimal) | 0.824 | 0.605 | 0.632 | 0.129 | 0.051 | 0.068 | – |
| Subjective score (0 is optimal) | 0.119 | 0.090 | 0.129 | 0.014 | 0.006 | 0.010 | – |

technologies. Still, the ranking between FBC, FBC with $NO_x$-mitigation (ureum injection) and the RK remains the same.

Using the reference point technique, the results are more transparent, with a low performance for OB and OD because of environmental impacts and correspondingly for CD because of safety. The results are not sensitive to the value of the weight factor introduced to stress the seriousness of uncontrolled solid waste deposition. If this factor were changed from 100 to 10, the relative scores for the "new" technologies would increase from 0.1 to only 1%.

By inspecting Table 8 we discover solutions that, using the terminology of MCDA, are not dominant, i.e. the technologies for which one can find another technology that has the same scores plus at least one better score.

1. FBC and RK have better scores than OB and OD for all objectives.
2. FBC with urea injection dominates FBC without injection.
3. The RK is dominated by FBC with urea injection. However, we can expect that a similar technology as urea injection applied to the RK can achieve comparable low $NO_x$-emissions.

At this point we will summarise the conclusions from the cost-benefit analysis [4], which will be incorporated in any decision-making. Open Burning and Open Detonation are relatively cheap, but they are considered to be unacceptable in view of the environmental impacts. These methods are expected to become prohibited by regulators in the European Union and considerations on value trade-offs for these methods are therefore irrelevant. If suitable facilities are available beforehand, the analysis shows that Fluid Bed Combustion will cost about 150 EUR and a Rotary Kiln between 150 and 700 EUR per tonne energetic material (year 2000 prices). Mobile Furnaces are expected to be more expensive than a Rotary Kiln. Closed Detonation will cost more than 10 times as much and will only be competitive for minor stocks of explosive items, such as detonators, pyrotechnics and fuses.

## 6. Conclusions

The most dominant environmental impacts are the emissions of toxic air pollutants, uncontrolled deposition of solid waste and the occupied area. Global/regional air pollution problems and wastewater problems are less relevant. With respect to these three main environmental problems, the reference scenarios OB and OD perform badly. All the "new" technologies avoid uncontrolled solid waste deposition and excessive area occupation. Air pollution emissions can be reduced considerably, by at least a factor 10 if $NO_x$-reduction techniques are applied.

Safety issues are relevant for explosive waste disposal. For all technologies, safety requires permanent attention. Risk can be reduced effectively by transforming explosives into de-sensitised, water-based slurries at an early stage in the disposal process. This reduces the possibilities for explosion and fire. On the other hand, activities that require extensive manual handling of explosives, like CD, remain risky.

Modern technologies like high-pressure water washout and FBC provide safe and environmentally acceptable solutions for demilitarisation. The environmental impact from the traditional techniques OB and OD can be drastically reduced.

High-pressure water washout in combination with FBC combined with $NO_x$-reduction using urea injection is the “best” technology according to this study. This technology can be used for large/medium-sized calibre munitions, but additional removal of $NO_x$ from the flue gases is required in order to comply with European emission standards.

It has been made credible that existing RK used for general hazardous waste can be used to incinerate de-sensitised, downsized munitions (slurries), with a performance with respect to environmental and safety aspects similar to FBC.

The use of a CD chamber with flue gas cleaning has important environmental advantages compared to OB and OD, especially for small munitions (e.g. fuses, anti-personnel mines, pyrotechnics). However, because CD is labour-intensive and requires the operation of complex, pressurised systems, it poses more risk on the personnel. For that reason, it is recommended to use or develop other systems to demilitarise small munitions.

Traffic emissions seem to be a significant source of air pollutant emissions compared to the process emissions of the “cleanest” technologies. Similarly, risks related to transport (due to ordinary accidents involving trucks) are not dominant, but cannot be ignored compared to process risks. These facts should be considered in the decision process about selecting, constructing, adapting or retrofitting either central and/or decentral (or mobile) facilities with or without advanced flue gas cleaning.

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